Assessing the Viability of Index Insurance as an Adaptation Tool in a Changing Climate Context: Case Study in the West African Sahel

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ABSTRACT OF THE DISSERTATION

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This dissertation contributes to the literatures on climate extremes, climate change, and financial adaptation. In a developing world context, weather based index insurance is emerging as a potential financial adaptation for poor populations that have historically been excluded from financial markets. Index insurance has potential drawbacks as well as benefits and there are a number of practical implementation challenges. However, as index insurance is sensitive to threshold crossing extreme event (TCE) frequency and as climate change renders the climate system non-stationary, there is a need to assess how the frequency of extreme events may change as the climate system evolves.

In an effort to address this research question for both hydroclimatological extremes (floods and droughts) and their associated risks, this dissertation explores the potential long-term viability of drought index insurance contracts for subsistence millet farmers and flood index insurance contracts for irrigated rice farmers in the West African Sahel nations of Mali, Burkina Faso and Niger.

Potential hypothetical contracts were chosen on the basis of correlation analysis and Gerrity skill analysis between multiple potential geophysical indices and national crop production data.

Monte Carlo statistical methods are used extensively to simulate future streamflow and precipitation scenarios and are integrated with global climate model projections of precipitation. TCE frequency is found to be particularly sensitive to multi-decadal variability (MDV) and to changes in the mean (and less sensitive to changes in the variability). Moderate changes in the mean can have a more than two fold impact on the TCE frequency and multi-decadal variability typical of the region is shown to have a significant effect on the likelihood of a large number of TCEs in a specified time window. These changes to TCE frequency have important implications for both the actuarial and uncertainty related costs of index insurance over time; thereby creating challenges for long term index insurance viability. While specific results are simulation dependent, the more extreme scenarios indicate that there may be important limitations to the viability of index insurance in the future.

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Chapter 1: Introduction and Motivation

1.1. Global Climate Change: Many of the natural and human impacts and challenges associated with anthropogenic global climate change are well understood and have been studied deeply. The causal mechanisms are relatively well known and understood. Emissions of greenhouse gases (CO_2, CH_4, N_2O, tropospheric O_3, HFCs and CFCs), and to a lesser degree certain types of aerosols (particularly black carbon) from industrial, agricultural and deforestation activities have a collective warming effect on the surface of the Earth by changing the radiative balance of the climate system. Projections of global surface temperature from global climate modeling studies anticipate a global average rise in temperature of between 1.5 and 5 degrees C by the end of the 21st century relative to the late 20th century. This being said, the warming is geographically (and temporally) uneven with more warming over continents than over the ocean (because of the high heat capacity of water) and more warming at high latitude than at low latitude (because of the ice-albedo feedback and the conveyance of heat from the low latitudes to the poles) (Christensen et al., 2007; IPCC, 2013).

Atmospheric carbon concentrations are now at a level not seen in the better part of a million years (ESRL Global Monitoring Division). A considerable amount of the anthropogenic carbon humanity has produced has been absorbed by the world ocean, causing ocean acidification (Orr et al., 2005). In the 1980s, this amounted to about 40% of the total of anthropogenic greenhouse gas emissions from fossil fuel burning) (Sarmiento et al., 1992), but this proportion of oceanic carbon uptake as a share of total carbon loading has been declining (Wanninkhof et al., 2013). Likewise, a considerable amount of the heating of the climate system has penetrated into the ocean (Levitus et al., 2009). These large changes in atmospheric and ocean temperatures are arguably already having a considerable effect on the world's biosphere and are affecting the geographic ranges and even the potential survival of many species (Thomas et al., 2004; Cheung et al., 2014).

There is still considerable scientific uncertainty surrounding the expected magnitude of global mean sea level rise, because much is yet unknown about the nuances of ice melt dynamics in the Greenland ice sheet and the West Antarctic ice sheet, including with regard to albedo change-melt feedbacks (Rennermalm et al., 2013; Moustafa et al., 2014). While it is highly unlikely that the entirety of the GIS and WAIS would collapse within the 21st century, it is understood that the implicit equilibrium sea level rise of such an event would be on the order of 12 meters. This being said, the lower bound estimate of the latest IPCC report is on the order of half a meter by the end of the 21st century.

Anthropogenic climate change is expected to imply significant changes to the hydrologic cycle. The Clausius Clapeyron equation implies that in a warmer world, there will be more water vapor in the atmosphere. While this may lead to higher precipitation rates overall, the timing and spatial distribution are expected to be highly variable. For most regions of the world, there is an expectation of both an increase in precipitation intensity on days with precipitation and an increase in the length of dry spells (Christensen et al., 2007; Field et al., 2012). This being said, some regions of the world (particularly the arid subtropics) are expected to get systematically drier (while simultaneously expanding poleward), while other areas (particularly the humid tropics and the mid to high latitudes) are expected to generally get systematically wetter (Hirabayashi et al., 2008; Christensen et al., 2007; Huntington, 2006; Seager et al., 2010). There is even some evidence that some types of winter storms may become more common in a warmer climate (Francis and Vavrus, 2012).

Clearly, rising baselines in sea level and global and regional temperatures will systematically elevate the risks of storm surges and heat waves. The "intensification" of the hydrologic cycle will lead to an elevated risk of both floods and droughts and their attendant consequences for many regions of the world.

1.2. Global Climate Adaptation/Risk Management: The challenges of climate change and variability pose serious threats to the future of human populations around the world. Addressing these challenges will require a mix of both mitigation (greenhouse gas reduction activities) and adaptation (activities designed to improve the resilience of human populations to the adverse impacts of such climate change and variability). From both scientific and human perspectives, extreme events (extreme heat waves, droughts and floods) are of particular concern in a changing climate context. A wide range of observational evidence and theory (Field et al., 2012; Meehl et al., 2000; Tebaldi et al., 2006) suggests that observed and anticipated changes in climate are likely to result in an increase in the frequency of such extreme events.

Such events have clear, well-established negative impacts on vulnerable populations throughout the world (egs. Hurricane Katrina, Typhoon Haiyan, the Horn of Africa drought). Social science research shows that human populations vulnerable to the detrimental impacts of globalization also tend to be vulnerable to the detrimental impacts of environmental crises (Leichenko and O'Brien, 2008; Leichenko and O'Brien, 2010; Cutter et al., 2003).

Financial adaptations in the climate risk discourse have taken various forms, but in aggregate, funding for international adaptation efforts has historically been rather limited; the United Nations Framework Convention on Climate Change's (UNFCCC) Global Adaptation Fund has dispensed roughly 230 million USD over the past three years to some 40 countries in need of climate financing (Adaptation Fund). However, while estimates vary, many international organizations and scholars have assessed the total monetary cost of meaningful, fair adaptation to climate change as being at least in the range of 75-100 billion USD/year (World Bank, 2010) and perhaps as much as several hundred billion USD/year (Montes, 2012). While more money dedicated for the purpose of international climate adaptation finance is disbursed through the Least Developed Country Fund, the Special Climate Change Fund and the Global Climate Change Alliance, the overarching international framework for adaptation financing remains far short of the real need and the disbursal of funds remains far short of the pledge as shown in Figure I-1 and Table I.1 (Schalatek et al., 2012).

The Global Adaptation Fund relies in part on public and private donors and draws two percent of the proceeds from the certified emissions reductions credits under the Clean Development Mechanism of the Kyoto Protocol (Adaptation Fund). This sluggish start acknowledged, the Adaptation Fund strives to give voice to small island states and least developed countries, giving it a sense of legitimacy in international climate policy negotiation (Trujillo and Nakhooda, 2013).

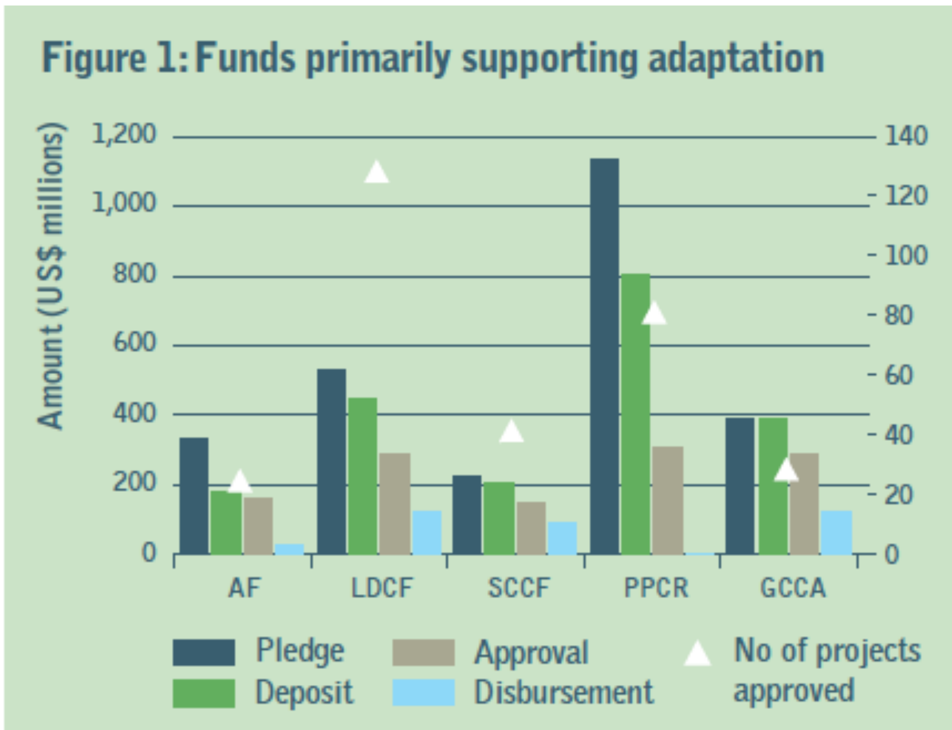

Figure 1.1: Graph of funds pledged, deposited, approved and disbursed for global climate change adaptation purposes (as of 2012) for the Adaptation Fund (AF), Least Developed Country Fund (LDCF), Special Climate Change Fund (SCCF), Pilot Programs for Climate Resilience (PPCR) and the Global Climate Change Alliance (GCCA) (Schalatek et al., 2012).

Fund	Pledge	Deposit	Approval	Disbursement	No of projects approved
Adaptation Fund (AF)	323.05	186.48	166.36	29.14	25
Least Developed Country Fund (LDCF)	536.65	435.46	286.73	126.63	126
Special Climate Change Fund (SCCF)	241.61	196.4	147.25	100.23	39
Pilot Programe for Climate Resillience (PPCR)	1119	804.8	317.48	8	79
Global Climate Change Alliance (GCCA)	385.36	365.36	296.81	130.99	29

Table 1-1: Numerical values for the same information presented in Figure 1.1 (Schalatek et al., 2012)

The Special Climate Change Fund (SCCF) is also part of the UNDP GEF and has funds for both adaptation and technology transfer purposes (Special Climate Change Fund). The Global Climate Change Alliance is an outgrowth of the European Union dedicated to building a partnership between EU member states and poor developing countries to facilitate adaptation and capacity building (Global Climate Change Alliance). The Pilot Program for Climate Resilience (PPCR) is a targeted project of the Strategic Climate Fund of the World Bank. While over a billion USD has been pledged to date, disbursal is still lagging (Climate Investment Funds, PPCR). Adaptation financing through these mechanisms has been primarily directed towards Africa and Asia (Schalatek et al., 2012). Part of the reason for the disconnect between the pledged aid and disbursal has to do with coordination, ownership, access and efficiency and there is a number of important lessons to be learned from practice on how access can be improved (Bird, 2014).

Clearly, the profound disconnect between the true costs of adaptation and negative impacts of climate change and the financial commitment thus far illustrates a collective failure to react appropriately to the needs created by climate change. It is clear to many onlookers of the UNFCCC process that large, multilateral negotiations have produced and will probably continue to produce relatively little deep, binding commitments on either the mitigation or adaptation fronts (Brand, 2012; Anderson and Chandani, 2008). There are also those that argue that even if such a framework were to achieve binding commitments, the form of those commitments would often tend to reinforce, rather than alleviate existing power asymmetries. These failures can be ascribed to many causes; the hegemonic influence of capitalism (Marino and Ribot, 2012; Wainwright and Mann, 2013), the bureaucratic and political challenges of international negotiation in the context of such a wide assortment of national and international interests (Heyward, 2007; Van Asselt, 2007), fundamental post-structuralist critiques of top-down international project development (Verweij et al., 2006), and the sheer size and complexity of the problem of global climate change (even if all actors were of good intent and unencumbered agency). In light of this discourse, there is an evident need for alternative, bottom-up, scalable and market driven approaches to adaptation (Adger, 2003; Rayner, 2010).

1.3. Index Insurance: One particular financial climate risk management strategy that has been explored is index insurance (Hellmuth et al., 2009; Brown et al. 2011). The concept behind index insurance is relatively simple: an index insurance contract is an insurance contract based on an index that quantifies a climate related risk. When this index exceeds or falls below a certain critical value as defined by the contract (often called the strike or trigger level), the index insurance contract will pay out to the client (insured) population. Index insurance contracts have been explored for extremes of heat, flooding extremes, and drought extremes and have been used to compliment a range of other purposes (Hellmuth et al., 2009; Balzer and Hess, 2009). Some index insurance contracts have been used in concert with larger initiatives to promote development in developing and deprived economies (Hellmuth et al., 2009). Other index insurance contracts have been used to help bolster resilience to natural disasters (Warner et al., 2009).

There are a number of key practical challenges to the implementation of index insurance including a need for an appropriate legal framework, adoption by the intended client population, appropriate and sufficient data quality to support the implementation of index insurance, high enough correlation between the index variable and the livelihood variable, and a large enough variability in the index to capture the cycle of positive and negative years (Hartell and Skees, 2009).

But these psychological issues, regulatory issues and data quality issues noted, there are also other technical challenges that are deeply interwoven with the statistics and dynamics of climate itself. At a regional climate scale, multi-decadal variability has been shown to and/or is expected to play as significant a role in determining the frequency of extreme events as systematic climate change does (Katz and Brown, 1992). Prior research has already shown that the frequency of extreme events can change significantly not only as a result of a modest systematic global change trend (Meehl et al., 2000; Tebaldi et al., 2006), but also as a result of multi-decadal variability (Siebert and Ward, 2011; Siebert and Ward, 2013; Meehl and Hu, 2006; Kiem et al., 2003; Field et al. 2012). Furthermore, changes in the shape of the distribution of the climate variable (changes in the scale or shape parameters of daily rainfall distributions, (Katz, 1999)) or in the higher order statistical moments (variance, skew and kurtosis) may have important impacts on the frequency of threshold crossing extreme events (Siebert and Ward, 2011; Beniston and Stephenson, 2004). Further, such index insurance schemes will themselves have to adapt to the evolving climate context. Existing knowledge on seasonal climate forecasting may also intersect with such climate risk management schemes producing new synergies and challenges (Carriquiry and Osgood, 2012).

1.4. Purpose Statement/Motivation: The purpose of this dissertation is to explore issues relating the sensitivity and viability of index insurance in a changing climate context. While the broader hope is that the results can be generalized to a range of specific climate contexts, the specific application here is to the West African nations of Niger, Burkina Faso and Mali. Much of these nations comprise part of the Sahel[1]. As each of these nations has a considerable proportion of its population engaged in subsistence agriculture in the semi-arid Sahel region and as each of these nations is landlocked and dependent on the Niger River system for freshwater resources, there is a degree of biophysical similarity to the selection. Furthermore, as each of these countries is collectively quite poor, experiencing a high fertility rate and relatively short life expectancy, economically predominantly agro-pastoral and predominantly Muslim, there are a number of cultural and socio-economic similarities as well.

Beyond the similarities between the nations mentioned above, the motivation for this choice of region of study is both human and scientific. This

[1] The word Sahel is Arabic for "shore" and it is a region of transition between the Sahara desert to the north and more humid tropical seasonal forests to the south. According of one common definition (i.e. the zone from 200 to 600 mm average annual rainfall during the 20th century), the Sahel includes portions of Mauritania, Senegal, Mali, Burkina Faso, Niger, Nigeria, Chad, Sudan, and Eritrea – although for the purpose of this dissertation we will primarily focus the Sahel in Niger, Burkina Faso and Mali. Biologically, it is typified by savanna vegetation punctuated by some hardy tree species, such as the acacia.

region is one of the poorest regions of the world and faces very pronounced climate related vulnerability and variability. The vast majority of the population (70+%) is engaged in subsistence agriculture with no real access to “modern” farming equipment, irrigation and very little if any cash capital. Droughts and floods can hit human populations especially hard and often have a significant impact in terms of mortality, population displacement, and diminished resilience/increased vulnerability (Adejuwon, 2006).

The West African Sahel has experienced a roughly 30% reduction of rainfall in the late 20th century relative to the wetter period in the 1950s and 1960s (Dai et al., 2004). Some evidence indicates that the rains have recovered somewhat in the last decade to decade and a half (L’Hote et al., 2002; Greene et al., 2009). This pronounced multi-decadal variability poses a significant challenge to thinking about near term climate futures. However, interrogation of this subject may yield more broadly applicable insights on climate risk management across the globe. Such insights are likely to emerge in the conclusion of the dissertation.

While a recent project initiated by the company Planet Guarantee[2] has created index insurance contracts for the maize crop in parts of Burkina Faso and Mali through the International Finance Corporation, these projects at present serve a relatively small proportion of the total farming population (about 8,000 farmers in Burkina Faso and about 17,000 in Mali as of 2014) (International Finance Corporation).

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[2] Planet Guarantee, created in 2007, is a subsidiary of the Planet Finance Group and is based in France. The overall objective of the Planet Finance Group is to provide microinsurance to populations in developing countries that would otherwise not have access to financial services.

Due to the current absence of large scale index insurance projects in these nations, and the need to ask deeper, more long term research questions, this dissertation will explore the theoretical performance and sensitivity of hypothetical national scale crop index insurance by drawing in national and district level crop yield data (available through the Food and Agriculture Organization), rainfall data (gauge, satellite and station data), vegetation indices, (eg. Normalized Difference Vegetation Index (NDVI)), and hydrological data (from the Niger Basin Authority[3]). One important insight from a research visit to Niger in 2010 is that a bundled index insurance plan that seeks to insure both dryland rainfed subsistence farmers against drought risk and irrigated farmers against flooding risk may prove constructive. This approach has the dual advantage of addressing negatively correlated risks and addressing different populations. Indices will be explored to address both flooding and drought risk. In a practical sense, use of (or consultation of) remotely sensed data along with the in situ data can also help to ensure that the proposed indices are more fair and equitable by providing multiple avenues of confirmation of an extreme event.

Chapter 2 will situate this discourse broadly by drawing on the literature of climate change and insurance and financial adaptation more broadly. A more detailed case for and description of the potential and challenges of index insurance will be included. Chapter 3 will offer an overview both of West African Sahelian climate variability and cultural and historical practices and adaptations to the challenges of managing the hydroclimatic variability of the region. Chapter 4

[3] Daily streamflow data for three locations on the Niger River was acquired for 1950-2009 from the Niger Basin Authority during a prior field visit to Niamey, Niger.

provides a quantitative analysis of the potential indices to serve as the basis for hypothetical index insurance contracts for specific crops in the countries analyzed. Chapter 5 examines historical hydrological data for three different sites on the Niger River and simulates future scenarios of hydroclimatological change through Monte Carlo simulation of future flooding and low flow events on the Niger River. Chapter 6 provides an overview of what several global climate models imply regarding the region's climatic future. The Monte Carlo simulation methods developed in Chapter 5 are then expanded upon and integrated with the GCM projections to inform an understanding of how the hypothetical index insurance contract price may vary over time. Chapter 7 will give an overview of concluding thoughts and future research possibilities.

1.5. Research Questions: The primary research questions this dissertation seeks to address pertain to the technical/scientific analysis of the sensitivity and viability of index insurance in the changing climate context.

Questions relevant to this analysis can be divided into contextual or background questions and research questions. There are a number of contextual and background questions related to index insurance that can be addressed through literature review in the following two chapters:

1. How has, how can and what are the potential challenges to using index insurance as a means of climate risk management – both broadly and more specifically in a West African Sahel context?
2. Who are the most appropriate potential user populations of index insurance?

3. What is the extent, nature and spatiotemporal variability of adaptive capacity, vulnerability and resilience to climate related risks in the West African Sahel?

4. What are other existing climate risk management practices and how might those approaches interact with proposed or existing insurance policies?

It should be noted that any practical implementation of index insurance would require ongoing stakeholder involvement, which would help to guide the selection of appropriate index much more directly, but such stakeholder involvement is beyond the scope of this dissertation research.

Beyond these human and implementation related questions, there are a number of scientific and technical question related to the sensitivity and viability of index insurance as an adaptation tool in the context of a changing climate. The central research questions are as follows:

1. What attributes make an index optimal for index insurance contract design? Taking a historical approach to studying potential indices, what can be learned about their potential performance?

2. How has the region's hydro-climatology varied in the past? What can be learned about the characteristics of the region's past climate and hydrology from existing data?

3. How do potential indices, the implicit payout frequency and price evolution respond to systematic changes in regional hydro-climatology and the region's multi-decadal variability?

4. On the basis of GCM data, what are the projected changes to the region's hydro-climatic means and variability? What implications do these changes in the

mean, variability and shape of the hydro-climatic distributions carry for the long-term sensitivity and viability of index insurance?

Research structured around these core questions will help to improve scientific understanding of the implications of regional climate variability and change on extreme events and will offer insight into the how the payout frequency and price of potential index insurance contracts may perform over time in a non-stationary climate. Some thematic findings may be generalizable to other geographic contexts.

References

-Adejuwon, J., (2006). Food Security, Climate Variability and Climate Change in SubSaharan West Africa. Report Submitted to the *Assessment of Impacts and Adaptations to Climate Change* (AIACC, Project No. AF 23).
-Adger, W. N., (2003). Social Capital, Collective Action and Adaptation to Climate Change. *Economic Geography, 79,* 387-404.
-Anderson, S., and A. Chandani, (2008). Adaptation in Africa: the global failure to deliver on funding, *International Institute for Environment and Development Briefing.*
-Balzer, N. and U. Hess, (2009). Climate change and weather risk management: evidence from index-based insurance schemes in China and Ethiopia, chapter in WFP report.
-Beniston, M., and D. Stephenson, (2004). Extreme Climatic Events and their Evolution under Changing Climatic Conditions. *Global and Planetary Change, 44,* 1-9.
-Bird, N., (2014). Improving Access to International Climate Finance within Sub-Saharan Africa. *Overseas Development Institute Working Paper.*
-Brand, U., (2012). Green Economy – the Next Oxymoron? *GAIA*, *21,* 28-32.
-Brown, M., D. Osgood, and M. Carriquiry, (2011). Science-Based Insurance. *Nature Geoscience, 4,* 213-214.
-Carriquiry, M., and D. Osgood, (2012). Index Insurance, Probabilistic Climate Forecasts, and Production. *Journal of Risk Insurance, 79,* 287-300.
-Cheung, W., V. Lam, J. Sarmiento, K. Kearney, R. Watson, D. Pauly, (2009). Projecting global marine biodiversity impacts under climate change scenarios", *Fish and Fisheries, 10,* 235-251.
-Christensen, J.H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R.K., Kwon, W.-T., Laprise, R., Magaña Rueda, V., Mearns, L., Menéndez, C.G., Räisänen, J., Rinke, A., Sarr, A.,and Whetton, P. (2007). Regional climate projections. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (eds.), Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University, Press.
-Cutter, S., B. Boruff, and W. Lynn Shirley, (2003). Social Vulnerability to Environmental Hazards. *Social Science Quarterly, 84,* 242-261.
-Dai, A., P. Lamb., K. Trenberth, M. Hulme, P. Jones and P. Xie, (2004). The Recent Sahel Drought is Real. *International Journal of Climatology, 24,* 1323-1331.
-Field, C. B., and Coauthors, Eds., (2012). Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Summary for Policy- makers. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change, 19 pp.
-Francis, J. and S. Vavrus, (2012). Evidence linking Arctic amplification to extreme weather in mid-latitudes. *Geophysical Research Letters, 39,* L06801.
-Greene, A. M., A. Giannini, and S. E. Zebiak, (2009). Drought Return Times in the Sahel: A Question of Attribution. *Geophysical Research Letters, 36*, L12701.
-Hartell, J. and J. Skees, (2009). Pre-Feasibility Analysis: Index Based Weather Risk Transfer in Mali. Save the Children Foundation.
-Hellmuth M.E., Osgood D.E., Hess U., Moorhead A. and Bhojwani H. (eds) (2009). Index insurance and climate risk: Prospects for development and disaster management. Climate and Society No. 2. International Research Institute for Climate and Society (IRI), Columbia University, New York, USA.
-Heyward, M., (2007). Equity and international climate change negotiations: a matter of perspective. *Climate Policy, 7,* 518-534.
-Hirabayashi, Y., S. Kanae, S. Emori, T. Oki, and M. Kimoto, (2008). Global projections of changing risks of floods and droughts in a changing climate. *Hydrological Sciences, 53,* 754-772.

-Huntington, T., (2006). Evidence for intensification of the global water cycle: Review and synthesis. *Journal of Hydrology, 319,* 83-95.
-IPCC (2013). Summary for policymakers. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M, Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. (eds) Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.
-Katz, R. W., and B. G. Brown, (1992). Extreme events in a changing climate: Variability is more important than averages. *Climatic Change, 21,* 289–302.
-Katz, R., (1999). Extreme value theory for precipitation: sensitivity analysis for climate change, *Advances in Water Resources, 23,* 133-139.
-Kiem, A., S. Franks, and G. Kuczera, (2003). Multi-decadal Variability of Flood Risk. *Geophysical Research Letters, 30*, 1035.
-Leichenko, R., K. O'Brien and W. Solecki, (2010). Climate Change and the Global Financial Crisis: A Case of Double Exposure. *Annals of the Association of American Geographers, 100,* 963-972.
-Leichenko R. M., and K. L. O'Brien, (2008). Environmental Change and Globalization: Double Exposures. Oxford University Press, Oxford and New York.
-Levitus, S., J. I. Antonov, T. P. Boyer, R. A. Locarnini, H. E. Garcia andA. V. Mishonov, (2009). Global Ocean Heat Content 1955–2008 in Light of Recently Revealed Instrumentation Problems. *Geophysical Research Letters, 36*, L07608.
-L'Hote, Y., G. Mahe, B. Some, and J. P. Triboulet, (2002). Analysis of a Sahelian annual rainfall index from 1896 to 2000: The drought continues. *Hydrological Sciences Journal. 47,* 563– 572.
-Marino, E., and J. Ribot (2012). Special Issue Introduction: Adding insult to injury: Climate change and the inequities of climate intervention. *Global Environmental Change, 22,* 323-328.
-Meehl, G. A., T. Karl, D. R. Easterling, S. Changnon, R. Pielke Jr., D. Changnon, J. Evans, P. V. Groisman, T. R. Knutson, K. E. Kunkel, L. O. Mearns, C. Parmesan, R. Pulwarty, T. Root, R. T. Sylves, P. Whetton, and F. Zwiers, (2000). An Introduction to Trends in Weather and Climate Events; Observations, Socioeconomic Impacts, Terrestrial Ecological Impacts, and Model Projections. *Bulletin of the American Meteorological Society, 81,* 413-416.
Meehl, G. and A. Hu, (2006). Megadroughts in the Indian Monsoon Region and Southwest North America and a Mechanism for Associated Multidecadal Pacific Sea Surface Temperature Anomalies. *Journal of Climate, 19,* 1605-1623.
-Montes, M., (2012). Understanding Long-Term Finance Needs of Developing Countries. UNFCCC presentation, Bonn, Germany.
-Moustafa, S., A. K. Rennermalm, L. C. Smith, M. A. Miller, and J. R. Mioduszewski, (2014). Bimodal albedo distributions in the ablation zone of the southwestern Greenland Ice Sheet. *The Cryosphere Discussions, 8,* 4737-4778.
-Orr, J., and coauthors, (2005). Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature, 437*, 681-686.
-Rayner, S., (2010). How to eat an elephant: a bottom-up approach to climate policy. *Climate Policy*, *10,* 615-621.
-Rennermalm, A., S. Moustafa, J. Mioduszewski, V. Chu, R. Forster, B. Hagedorn, J. T. Harper, T. L. Mote, D. A. Robinson, C. A. Shuman, L. C. Smith and M. Tedesco, (2013). Understanding Greenland ice sheet hydrology using an integrated multi-scale approach. *Environmental Research Letters, 8,* 015017.
-Sarmiento, J., J. Orr, and U. Siegenthaler, (1992). A Perturbation Simulation of CO2 uptake in an Ocean General Circulation Model. *Journal of Geophysical Research, Oceans, 97,* 3621-3645.

-Schalatek, L. H. Stiftung, S. Nakhooda, S. Barnard, A. Caravani, (2012). Climate Finance Thematic Briefing: Adaptation Finance. *Overseas Development Institute Climate Funds Update.*
-Seager, R., N. Naik, and G Vecchi, (2010). Thermodynamic and Dynamic Mechanisms for Large-Scale Changes in the Hydrological Cycle in Response to Global Warming. *Journal of Climate, 23,* 4651-4668.
-Siebert, A., and M. N. Ward, (2011). Future Occurrence of Threshold-Crossing Seasonal Rainfall Totals: Methodology and Application to Sites in Africa. *Journal of Applied Meteorology and Climatology, 50,* 560-578.
-Siebert, A., and M. N. Ward, (2013). Exploring the Frequency of Hydroclimate Extremes on the River Niger Using Historical Data Analysis and Monte Carlo Methods. *African Geographical Review*, online publication.
-Tebaldi C., K. Hayhoe, J. Arblaster and G. Meehl, (2006). Going to the Extremes: An Intercomparison of Model Simulated Historical and Future Changes in Extreme Events. *Climatic Change,* DOI: 10.1007/s10584-006-9051-4.
-Thomas, C., and coauthors, (2009). Extinction Risk from Climate Change. *Nature, 427,* 145-148.
-Trujillo, N., and S. Nakhooda, (2013). The effectiveness of climate finance: a review of the Adaptation Fund. Working Paper 373, *Overseas Development Institute.*
-Van Asselt, H., (2007). From UN-ity to Diversity? The UNFCCC, the Asia-Pacific Partnership, and the Future of International Law on Climate Change. *Carbon and Climate Law Review, 1,* 17-28.
-Verweij, M., M. Douglas, R. Ellis, C. Engel, F. Hendriks, S. Lohmann, S. Ney, S. Rayner and M. Thompson, (2006). Clumsy Solutions for a Complex World: The Case of Climate Change. *Public Administration, 84,* 817-843.
-Wainwright, J., and G. Mann, (2013). Climate Leviathan. *Antipode*, *45,* 1-22.
-Wanninkhof, R., G. -H. Park, T. Takahashi, C. Sweeney, R. Feely, Y. Nojiri, N. Gruber, S. C. Doney, G. A. McKinley, A. Lenton, C. Le Quere, C. Heinze, J. Schwinger, H. Graven, and S. Khatiwala, (2013). Global ocean carbon uptake: magnitude, variability and trends. *Biogeosciences*, *10,* 1983-2000.
-Warner, K., N. Ranger, S. Surminski, M. Arnold, J. Linnerooth-Bayer, E. Michel-Kerjan, P. Kovacs, C. Herweijer, (2009). Adaptation to Climate Change: Linking Disaster Risk Reduction and Insurance, a publication managed by United Nations International Strategy for Disaster Reduction Secretariat (UNISDR).
-World Bank, (2010). Economics of Adaptation to Climate Change: A Synthesis Report.

Websites

-Adaptation Fund. (n.d.). Retrieved from https://www.adaptation-fund.org/
-Climate Investment Funds. (n.d.). Retrieved from https://www.climateinvestmentfunds.org/cif/ -ESRL Global Monitoring Division - Global Greenhouse Gas Reference Network. (n.d.). Retrieved from http://www.esrl.noaa.gov/gmd/ccgg/trends/history.html
--Global Climate Change Alliance - Climate Funds Update. (n.d.). Retrieved from http://www.climatefundsupdate.org/listing/global-climate-change-allianc
-International Finance Corporation; PlaNet Guarantee (2014). Retrieved from http://www.ifc.org/wps/wcm/connect/industry_ext_content/ifc_external_corporate_site/industries/financial+markets/retail+finance/insurance/planet+guarantee
-Least Developed Countries Fund (LDCF) | Global Environment Facility. (n.d.). Retrieved from http://www.thegef.org/gef/LDCF
-Special Climate Change Fund (SCCF) | Global Environment Facility. (n.d.). Retrieved from http://www.thegef.org/gef/SCCF

Chapter 2: Climate Change and Insurance

2.1. Climate Change, Extremes and Vulnerability: Extensive climate literature connects the rise of extreme events to climate change. This is found in observations at the global scale (Rosenzweig et al., 2007; Trenberth et al., 2007) and at the regional scale (eg., New et al., 2006; Field et al., 2012; Kunkel et al., 2009; Easterling et al. 2000). Simplistic statistical models demonstrate how small changes in the mean of a geophysical variable can greatly effect the frequency and magnitude of extreme events (Meehl et al., 2000; Meehl and Tebaldi, 2004; Katz and Brown, 1992) and modeling studies connect increased extreme event frequency to the dynamics of a changing climate (Kharin and Zwiers, 2007; Tebaldi et al., 2006). One of the major findings of climate research is that there is an expectation that extremes of precipitation are likely to increase in response to anthropogenic forcing and are connected to the "intensification" of the hydrologic cycle in both space and time (Christensen et al, 2007). Some studies suggest that this process is already underway and can be shown in the empirical late 20th and early 21st century data (Min et al., 2011), while others take a more cautious approach (Zeigler et al., 2003; Huntington et al., 2006). Other research points out that from a dynamical perspective, while the spatial and temporal pattern of evaporation-precipitation is likely to intensify along with horizontal moisture transport, vertical convective mass fluxes are likely to decrease (Held and Soden, 2006).

Furthermore, a wide array of literature and lived experience connects extreme climate events to property and agricultural losses (Bienert, 2014; Field et al., 2012; McHale and Leurig, 2012; McLeman and Smit, 2006; Warner et al., 2009; Union of Concerned Scientists, 2013). Frequently, these losses impact groups that are already quite vulnerable, creating a sort of "double exposure" (Leichenko and O'Brien, 2008; Leichenko and O'Brien, 2010). Modeling studies of the economic impacts of repeated extreme events in quick succession show that the impact of climate shocks on GDP can rapidly escalate and for nations or regions that are unable to do a certain level of reconstruction between events, the losses may be much more severe and long lasting (Hallegate and Hourcade, 2006). Some studies of the climate change impact on agriculture suggest that added heat stress for major cereal crops globally has already caused an estimated 5 billion USD of losses per year from the 1980s to 2002 (Lobell and Field, 2007).

Clearly, there is a wealth of literature in the natural hazard community and the financial sector demonstrating that the significant increase in losses (including insured losses) is largely a product of a growing global population and economy and the increasing value at risk, especially in coastal areas (Smolka, 2006; Wisner et al., 2004). This being said, the changing frequency of extreme events also has arguably begun to affect the natural hazard part of the risk equation (van Aalst, 2006), although this point is still debated (Bouwer, 2011). From a global insurance perspective, the attribution of losses to date to increasing hazard versus increasing vulnerability and exposure is arguably of secondary importance to understanding how losses are expected to change because of all causative factors.

While many of the losses that accompany extreme climate events are not measurable in monetary terms, many losses can be measured and insured. This analysis begins with these central, large questions of how climate change has impacted the insurance industry thus far and what the potential is for adapting to the reality of a changing climate.

To begin this analysis of climate change and insurance, it is useful to examine the role of insurer's responses to climate change in the "developed" world. While the wealthier regions of the world constitute a very different economic context than the case study of the West African Sahel, the range of insurance products available in the "developed" world far exceeds that in the "developing" world[4]. Consequently, by beginning with a brief overview of this issue in the "developed" world, some insight can be gained regarding lessons learned and pitfalls to avoid.

This introductory chapter will begin by considering various "conventional" types of insurance: property insurance, crop insurance, flood insurance, the role of reinsurance, the role of catastrophe bonds and weather derivatives and consideration of single-year versus multi-year contracts in a "developed" world context. The later portion of this chapter will provide more of an in depth analysis of index insurance and its potential role as a climate risk management tool for "developing" world contexts.

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[4] My use of quotation marks around "developed" and "developing" countries is intended to acknowledge that there are many poor countries whose economic growth is stagnant or even negative (as well as many experiencing rapid growth) and there are many ways in which many wealthy countries could improve (not necessarily by more rapid economic growth, but by less economic stratification and better environmental stewardship, etc.).

2.2. Framing of Insurance Questions: Where possible, this research will seek to focus its discussion on insurance products – both real and hypothetical that are strongly tied to climate based risks and for which the bulk of the pricing calculations are based on climate related risks. However, it is acknowledged that many insurance products and certainly many insurance companies do not offer products targeted specifically or exclusively to climate/weather related risks. As such, other factors may enter the pricing equation. For example, standard homeowner's insurance policies will cover a good proportion of wind related damage in many parts of the US, Canada and Europe, but clearly, premium calculations are based on many non-weather/climate related variables (AccuWeather, 2010). The additional dynamic socioeconomic factors that may influence the pricing of an insurance contract beyond the climate related risk are considered to be beyond the scope of this research.

However, changing baseline climate related risks pose challenges to insurance products, the frequency of claims, the magnitude of insured losses, etc.. Consequently, many insurance policies intended to address multiple perils (such as homeowner insurance) are being redesigned with a keener awareness of the changing landscape of climate risks (Insurance Information Institute, 2014). These issues, while being explored in specific regional contexts in this research do connect to a broader global discourse on insurance, financial adaptation and climate change. Clearly, climate change as a whole poses a significant challenge to the global insurance industry (GAO report, 2007).

At this broad level, there are institutional challenges regarding how the insurance industry has and may continue to address climate change. Much of the history of climate related hazard insurance has been retrospective and has been founded on an assumption of a stationary climate (Herweijer et al., 2009; Sarewitz et al., 2003; Berz, 1999). Clearly, quantification of the range and magnitude of risks faced will be central to intelligent contract design in the future. Further, much of the history of climate related insurance products does relatively little to encourage smarter behavior after a disaster occurs and efforts and incentives need to be integrated to reduce risk as well as to insure them (Thomas and Leichenko, 2011; Michaels et al., 1997). There are likely to be significant challenges to controlling the cost and availability of insurance products in light of a changing climate. There is also a growing interest within the insurance community to not only address the "adaptation" side of the climate change challenge, but to integrate with products that address the "mitigation" side by promoting green building design, a growing interest on carbon markets and many other mitigation oriented activities (Mills, 2009a; Mills, 2007; McHale and Leurig, 2012).

Dramatic increases in insured losses from extreme weather in the early 21st century have already started to cause concern about the long-term financial viability of insurance in the framework of a changing climate at both a global level due to aggregate trends (Munich Re Report, 2012; McHale and Leurig, 2012) and on a national and subnational level on the basis of individual events (RMS report, Hurricane Katrina, 2005). In a climate of changing risks, there are a range of potential insurance industry responses, but also a range of potential avenues for innovation. Responses to the challenges of climate change have met with differentiated responses globally. As the climate system itself changes, there are several potential response options to a changing climate risk framework.

One (rather maladaptive) option is for the insurer to fail to acknowledge that the risk framework is changing and that the statistical basis for the insurance product is changing. This strategy is likely to end problematically for both insurer and client. A changing expected climate risk may render the intended insurance product insolvent after some time and if the insurer does not have the capital backing or the reinsurance to cover a particularly disastrous string of events. The client will also suffer not only from the climate events themselves but from the insurer's default.

Another relatively blunt approach that insurers can take to dealing with a changing risk framework is to limit coverage or to pass on the full cost of a changing basis risk through elevated premiums. This mentality is clearly advantageous to the bottom line of the insurer and will protect against default and insolvency. However, it also places the insurer and client in a relationship that has a sense of being more adversarial and will tend to deepen, rather than alleviate pre-existing socioeconomic divisions. Those who can afford to pay higher insurance premiums and/or to live in areas that are less of an insurance risk and have more insurance options will be insured and those who can't afford to pay higher premiums and are forced to live in high-risk areas by circumstance will have little recourse and little protection (Leichenko and O'Brien, 2008).

One potentially forward thinking approach is to use the fact that droughts and floods, being episodic and being less spatially coherent than the global trend towards warming offer the insurance industry the possibility of spreading risk through different regions, communities and sectors that may have negatively-correlated risk profiles.

Another adaptive option is to address the changing context of climate risk. One theoretical option (specifically with regard to index insurance) is to use an evolving, rather than fixed definition of the threshold of insurance protection. This way, a statistically non-stationary risk can be translated to a still relatively stable expected liability (Siebert and Ward, 2011). This can help the insurer stay in business and can help the client receive some level of protection even if the risk level at which the protection is triggered changes with time.

In practice, some aggressive multilateral action has been taken by prominent European insurance agencies leading to the “Statement of Environmental Commitment by the Insurance Industry”, adopted in 1995 by the UN Insurance Industry Initiative (UNEP Finance Initiative). Notably, Swiss Re has been very proactive on the front of addressing the challenges of climate change. Swiss Re’s progressiveness on the climate change front is motivated both by the financial incentive and a strong culture of sustainability and environmental awareness (Anderson, 2003). Among other projects, Swiss Re has funded research on and implementation of drought index insurance contracts in a range of developing world contexts across Latin America, Africa and Asia.

One of the other key areas of discourse is the role of government subsidy in insurance. Strong government subsidization of crop and flood insurance is found to encourage more risky behavior and that tends to lead to greater insured losses (McLeman and Smith, 2006; Burby, 2006). This is an important result that needs to be considered in the context of the broader discourse on climate change and insurance and in the details of structuring index insurance for developing world contexts.

Some preliminary statistical and econometric analyses of the impact of extreme events on the insurance sector offer some key insights: transparency and precautionary beliefs on the part of the insurance sector is beneficial to the sustainability and utility of the resulting policies. Furthermore, a social security system that brings the insurance closer to an actuarially fair price is preferable to insurance charging an overhead and passing that cost onto the client. This last point is not only found to be (obviously) beneficial to the client, but to the insurer and the sustainability of the insurance itself (Muller-Furstenberger and Schumacher, 2009). Another modeling study finds that in order to predict future losses and minimize surprises, a Bayesian approach based on Markov chain Monte Carlo methods is often fruitful (Smith, 2003). Detailed mathematical analysis will be reserved for later chapters.

Studies of innovations in the insurance industry suggest that in order to cope with rising losses, the insurance industry is likely to employ a number of strategies including: alternative risk transfer, bundling dissimilar risks, public sector involvement through catastrophe bonds and weather derivatives and the expanded use of microinsurance in the developing world (Dlugolecki, 2007).

2.3. Property/Casualty Insurance: Property/casualty insurance products offer clients compensation for property damaged by a range of potential sources of harm. Clearly, property insurance claims are the result of a large range of causes – not just those related to climate and weather events. However, climate and weather events certainly have been making quite a difference in the frequency and size of claims throughout the world.

It is estimated that in the United States, extreme weather events cost property and casualty insurers around 32 billion USD in 2011 (McHale and Leurig, 2012). In the United States, it is estimated that Superstorm Sandy in 2012 by itself cost the insurance industry on the order of 25 billion USD, although a portion of that insurance is related to flooding. While total damages from 2005's Hurricane Katrina were in excess of 100 billion USD, the insured losses have different estimates (Insurance Information Institute claims 41 billion 2005 USD 2005 and Swiss Re claims 76 billion 2012 USD), making it the single costliest disaster in history for the insurance industry (Karl et al., 2013, 2014).

Figure 2.1 from the Munich Re Year In Review Report shows overall and insured losses in the United States over time from 1980 to 2012. Figure 2.2 shows overall and insured losses at the global scale from 1980-2013.

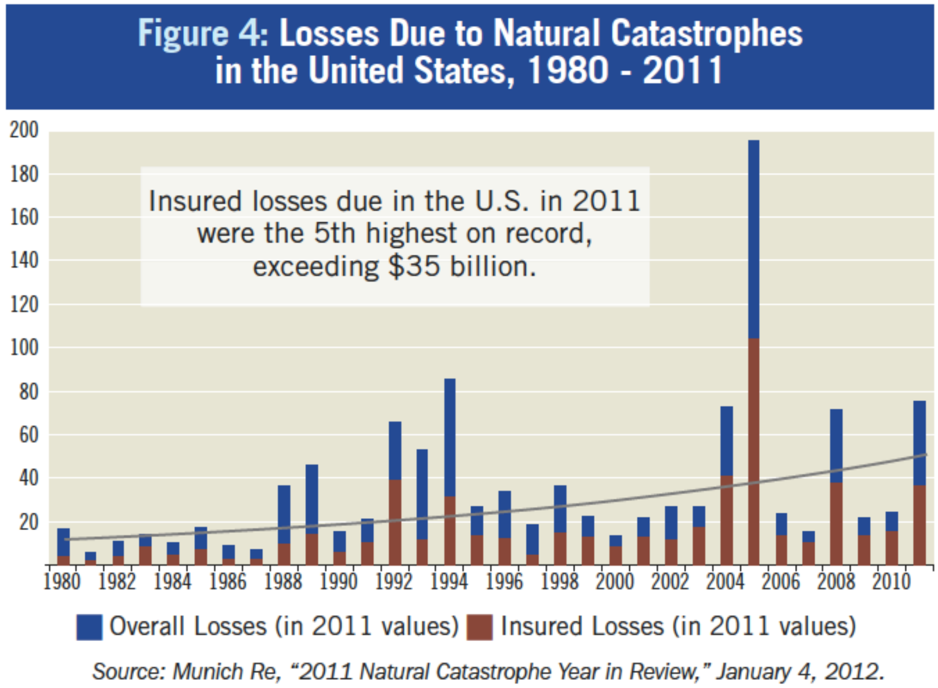

Figure 2.1: Graph of overall and insured losses from natural catastrophes in the US from 1980-2011 (from McHale and Leurig, 2012; source, Munich Re)

The trendlines of both graphs are clearly positive, although both time series are punctuated by very large proportional inter-annual variability. By visual inspection, it appears that the proportional variability of insured losses is even greater than the proportional variability of the total losses.

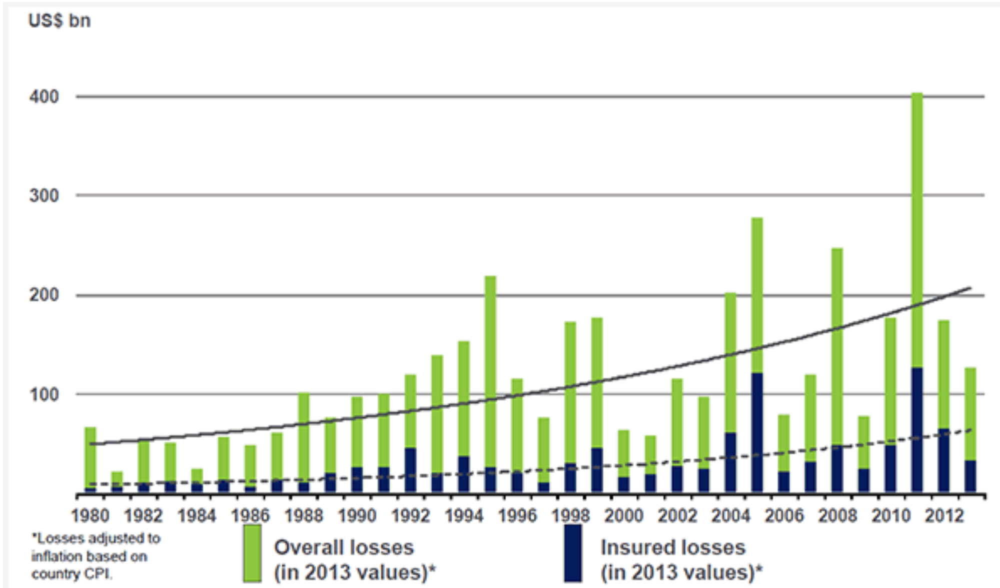

Figure 2.2: Graph of global overall and insured losses 1980-2013. Source; Munich Re.

There is also research to suggest that the share of total property/casualty insurance losses that are weather related (relative to total property/casualty losses) has been increasing over the same period (Mills, 2005). Given observed trends in climate risk exposure, by 2030, it is expected that there will be somewhat significant increases in geographic exposure risk, on top of the absolute growth in the economy and increased value at risk (Dlugolecki, 2007). The analysis contained in (Dlugolecki, 2007) extrapolates on the basis of historical trends, rather than making a specific GCM informed projection of future hazard risks. In addition to projected trends, there is also considerable scientific uncertainty regarding many of the region specific implications of global climate change. This poses an additional challenge to insurers seeking to quantify their expected losses and adapt policies in an anticipatory manner (Valverde and Andrews, 2006).

2.4. Crop Insurance (Developed World): Crop insurance in the developed world plays a pivotal role in both protecting developed world farmers from climate risks and in the broader market economics of developed world food production. In the United States for example, in 2012, federally subsidized crop insurance amounted to about 15.8 billion USD/year, (Farm Subsidy Database, Environmental Working Group, 2013). Substantial federally subsidized programs for multi-peril crop insurance also exist in Canada, Japan, Spain, Italy and various other European countries (Smith and Glauber, 2012). Clearly, not all crop insurance in the developed world is government subsidized and the whole topic of government subsidization for crop insurance is a deep topic with many perspectives.

Critics of government crop insurance subsidy argue that often such programs favor large agribusiness and encourage the observed trend towards giant, monoculture (and in the United States, often genetically modified) crop production (Wender, 2011). Critics of such government subsidy also often argue that these programs, in addition to making it harder for smaller and/or organic farmers to compete in the developed world, also cause price distortion on international markets. This then enables food produced in the developed world to be sold on international markets at a price that is often below the true production cost, thereby marginalizing farmers from poorer countries that lack the financial protections that exist in the developed world and potentially leading to major price shocks in developing world markets (Collier, 2008).

Proponents of government crop insurance subsidy, or more general subsidy point to the collective interest of having enough food production to meet consumption needs of the national or global population and argue that without government subsidy of agriculture (both through insurance and other means), food prices might very well be higher, which could very easily put many more people in peril of hunger, disease and malnourishment. There is also an economic argument made that prior to the 1990s in the US, farmer participation rates in crop insurance schemes was relatively low, leading to adverse selection[5] (Serra et al., 2003). With the advent of a significant increase in federal subsidization, participation rates increased, leading to some improvement of actuarial soundness (Shaik et al., 2008). While this discourse on the merits and drawbacks of government subsidization in "developed" world agricultural insurance is a very rich topic, this dissertation research does not take a particular firm stance on the normative value of such subsidization, either in the developed world or in the case study region of the West African Sahel. It seems clear from the foregoing discussion that some level of subsidization in the developed world context has some benefit, while excessive subsidization in the developed world has many deep problems. It also seems evident that in some of the poorest countries in the world, such as those in the case study region, some measure of government subsidy may be absolutely necessary to get a project off the ground.

However, as a broad generalization, many of these programs are reactive rather than anticipatory on issues of climate and are based on historical data (that is, based on an assumption of statistical stationarity) (Kapphan et al., 2011; Stohs and LaFrance, 2003). Subsidization arguably has the additional impact of

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[5] Adverse selection is a term used in several contexts, but in the insurance literature, it refers to situations in which participation in insurance is correlated to insurable risk and in which the insurer cannot adjust for this reality in pricing the contract.

suppressing the “real” cost of agricultural risk, which can feed into unsustainable and risky behaviors. Many government subsidized agricultural assistance and/or insurance programs in North America, Japan, Australia and Europe do relatively little to incentivize more climate adaptive behavior or to anticipate the consequences of climate change on the agricultural sector (Davies and Male, 2014; McLeman and Smit, 2006).

This lack of engagement with the statistical non-stationarity of the climate system is to some degree true of private weather related insurance products, like multi-peril crop insurance products offered through companies such as GlobalAg, and Agrilogic. While private agricultural insurance in the developed world arguably may avoid compounding the problems of subsidization mentioned above, anticipatory use of climate information is not widespread in the field of agricultural insurance providers.

2.5. Flood Insurance: Flood insurance, like crop insurance, has a great deal of both controversy and government subsidy in the developed world. Critics of government subsidized flood insurance make many arguments similar to those against subsidy for crop insurance. Subsidized flood insurance can encourage the risky behavior of encouraging the development of a high value at risk in flood prone areas (Cleetus, 2013; Michel-Kerjan and Kunreuther, 2011). Moreover, flood insurance that is not sufficiently refined in its application and policy framework can reproduce existing socioeconomic divisions by offering advantage to wealthy individuals who build second homes near the shore out of choice over those of more modest means who live near the shore in their primary residences (McLeman and Smit, 2006). As with many forms of climate related insurance, many flood insurance programs have been historically focused and largely reactive, rather than anticipatory and informed by more current understanding of climate dynamics. This has created significant issues with solvency for projects like the US National Flood Insurance Program (NFIP) (Thomas and Leichenko, 2010). Furthermore, under the NFIP, actual premiums paid by individuals have historically amounted to less than half the true cost of the insurance (McLeman and Smit, 2006; Burby, 2001). This introduces issues of fairness between taxpayers in inland, higher elevation areas and those who live near the coast at high risk. One retrospective proposal is to advocate for the increase of coverage limits to gain more revenue for NFIP (GAO, 2013).

While many densely inhabited coastal areas derive much of their risk of insurance (and non-insured) losses from a large value at risk, a recent case study of projected future losses for New York State suggests that by the 2080s, the additional costs of sea level rise without proper adaptation could account for over 40% of total costs (Major et al., 2013). It’s estimated that in the US coastal properties account for about 16% of all property value (AIR Worldwide Report, 2013).

In Europe as well, there are similar discourses of socioeconomic inequity and flood risk (Fielding, 2007). This is also occurring against a backdrop of increasing exposure to flood risk (Mitchell, 2003). Between 1970 and 2013, six of the ten largest flooding events (in terms of insured and total economic losses) occurred in Europe (Karl et al., 2014). On a global scale, while there is a broad tendency for human losses to be greater in the "developing" world and economic losses (in absolute rather than relative terms) to be greater in the "developed" world, certain mega-catastrophes in developing countries can amount to extreme economic loss in addition to the devastating human toll. The Thailand flooding of 2011 was by far the costliest (non-storm) flooding event in history (Karl et al., 2014) and the total cost for Typhoon Haiyan measured in the billions of USD. Flood and storm related hazards for both coastal and inland contexts should also be understood in the context of a changing risk of and cost associated with tropical cyclones, potentially amounting to a doubling of losses (Mendelsohn et al., 2011).

2.6. Reinsurance: Climate change is of particular concern to reinsurance companies because of the special role that reinsurance firms play as a backstop against devastating losses to smaller insurance companies. Reinsurance firms engage in a wide range of practices, but most fundamentally, they serve to insure other insurers against the risk of devastating losses. In 2010, the premiums of the ten largest reinsurance companies in the world totaled some 128 billion USD (Risk Management Monitor, 2011). While total global sum of premiums paid across all forms of insurance is considerably higher (arguably over 1 trillion USD/year), the role and responsibility of reinsurance companies is critical to the functioning and safeguarding of the global insurance industry. In 2012, the total estimated economic losses from natural and man-made disasters were on the order of 186 billion, of which 77 billion was insured (this was disproportionately a consequence of Hurricane/post-tropical cyclone Sandy in the Northeast US) and an estimated 14,000 people died from such events. In 2013, the human toll was larger (~26,000 – in no small part because of Typhoon Haiyan in the Philippines), but the economic impact was somewhat reduced (140 billion USD total losses, 45 billion USD insured losses) (Karl et al. 2014, 2013).

In this sense, the non-stationarity of the emerging climate context poses a serious challenge to the reinsurance industry. While a string of weather related large losses may cause a conventional property insurance company to turn to a reinsurer for help, if the reinsurance industry defaults, massive governmental intervention may be the only way to avoid devastating economic consequences.

A 2013 report on the implications of warming oceans on the reinsurance community posits several recommendations regarding the business practices of reinsurers. One recommendation is to abandon the constraints of historically-based insurance models and to adopt more progressive scenario-based and tail risk modeling models in the context of a changing climate. Another recommendation to couple risk transfer and risk mitigation endeavors (Niehorster et al., 2013). There is an acknowledgement that ambiguity in the nature of some of the anticipated risk changes in a changing climate makes pricing on the basis of utility functions challenging and introduces additional costs to prepare for the probability of catastrophe (Niehorster et al., 2013; Valverde and Andrews, 2006). In addition to the acknowledged impacts on the property/casualty, flooding and crop insurance worlds, there is also a growing understanding that climate change poses challenges to the natural and managed biosphere and that there may be additional challenges to the life and health insurance industries down the road if vector borne disease and or food/water related disease burdens change significantly (Niehorster et al., 2013; Anderson, 2003). Furthermore, climate related risks figure to some degree in the assessment of travel insurance and construction insurance. There is also concern about the insurance implications of abrupt climate changes (Perroy, 2005). These additional strains could place that much more pressure on reinsurers.

As mentioned previously, among large European reinsurance companies, Swiss Re has been particularly proactive in the arena of climate risks on both the adaptation front and on the side of encouraging emissions reductions (including through participation in carbon disclosure) (Anderson, 2003; Mills, 2009b; Mills, 2009a). As of the early 2000s, this approach was held to be in contrast with American based insurance companies, who arguably had more of a “wait and see” approach (Anderson, 2003). New and important partnerships are also emerging and deepening between the insurance industry, the global climate science community, the global adaptation community (eg. through the UNEP Finance Initiative and Climate Wise) and CAT modeling firms like RMS (Mills, 2009b).

In 2005, Munich Re, one of the world’s largest reinsurers, began the Munich Climate Insurance Initiative, a non-profit initiative consisting of insurers, scientists and representatives of NGOs. The goal was to devise and implement insurance related solutions to global and regional climate change and foster cross-institutional partnerships and collaboration between the UN, international financial institutions, international donors and the private sector (Munich Re Climate Insurance Initiative). The reinsurance industry in general and Munich Re and Swiss Re have been particularly instrumental in the expansion of microinsurance and weather related index insurance in the developing world (Mills, 2009b).

2.7. Catastrophe Bonds: One of the ways in which the risks born by the insurance industry can be shared publicly is through the use of catastrophe bonds, or cat bonds for short. Cat bonds are risk-linked securities issued by insurance companies to private investors to help safeguard the insurance companies against excessive losses due to adverse events and their use began to be widespread in the 1990s following the Northridge Earthquake and Hurricane Andrew (Lewis, 2007). Cat bonds can be designed and implemented for any number of (generally geophysical) hazards. They can be risky investments for the investors and are generally placed in a multi-year framework (many cat bond maturity dates are about three years from purchase) (Mann and Green, 2013). The investors who purchase the cat bond will pay a premium to hold the bond for some period of years (length of the contract). If the specified catastrophe type does not occur in the term of the cat bond contract, the insurance firm pays a coupon to the investors for the premium+interest at the end of the term of the cat bond. Interest rates are typically, relatively high (8-15%/year) because the investor assumes a low probability risk of a large loss (Mann and Green, 2013). If, however, the specified catastrophe does occur within the period of the contract, the insurance company does not have to pay the investor and can instead use the money already gained from the cat bond sales to defray the loss claims following the catastrophe. In 2000, risk linked securities constituted about 0.5% of total catastrophe risk (GAO report, 2002). There has been somewhat substantial growth in this market in the last 13 years and currently, the global cat bond market is about 13 billion USD of capital outstanding, but there is a large volume of trade on a daily basis (Mann and Green, 2013).

There are several designs of cat bond contracts with different types of triggers. Indemnity based triggers are based on the issuer's actual losses. Triggers can also be based on mathematically modeled loss. Cat bonds can also be issued on the basis of insurance industry wide losses rather than individual issuer losses. Another potential cat bond design is to base the contract on a "parametric" basis; in other words, on the basis of a threshold value being crossed for a geophysical variable like wind speed, rainfall, storm surge depth. Cat bonds can also be issued on a parametric basis or on a coupled parametric/modeled loss basis where either the geophysical variable or the expected losses or some combination thereof functions as the trigger. (Lalonde and Karsenti, 2008). It should be noted that parametric cat bonds bear conceptual resemblance to the design of index insurance contracts, although the populations involved in the transactions tend to be quite different. There is considerable potential for the expansion of the cat bond market.

2.8. Weather Derivatives: Another form of investment innovation that began in the mid-1990s to trade in climate and weather related risk is the weather derivative. Despite their relative youth, weather derivatives are assessed to be the fastest growing derivative market, according to the Chicago Mercantile Exchange (Brockett et al., 2008). Weather derivatives are financial instruments that bear some resemblance to weather based index insurance. Parties involved with weather derivative markets include market makers, brokers, insurance and reinsurance companies, utility companies, and market participants from retail, agriculture, travel, transport and distribution, leisure and tourism firms (Garman et al., 2000). While weather derivative contracts are not as exclusively linked to insurance risk as are catastrophe bonds, transaction of weather derivatives can still help facilitate insurance risk spreading and risk absorption by parties outside the insurance industry.

A person or agency can purchase a weather derivative to hedge against an adverse weather event happening. Farmers can purchase weather derivatives to hedge against drought or flooding conditions at inopportune times in the growing cycle of their crops. Sporting event managers can buy weather derivative contracts to hedge against bad weather on the scheduled game – an event that would lower ticket sales and therefore revenue. Energy utility companies can use weather derivatives to hedge against excessive heating or cooling degree-days (Garman et al., 2000). Weather derivative contract sales have increased significantly in the recent past, reaching on the order of 19 billion USD in 2007 (Robison, 2007). There are several conceptual models of weather derivatives.

One type of weather derivative is based on a business model that assumes that the purchaser of the weather derivative understands his/her business's vulnerability to the adverse weather event and the derivative is priced on the basis of the impact of an adverse weather event on the particular business. Another model of weather derivative contract is based on a historical burn analysis[6] that simply examines how the weather derivative contract would have performed over some number of past years. Yet another conceptual model of weather derivative contract is based on a sort of index model that can be based on parametric or non-parametric indices. Parametric statistical indices can include relatively simple forms, like the Gaussian distribution or more complex methods like autoregressive moving average (ARMA) methods and/or Fourier transforms (Jewson et al., 2005). Weather derivative contracts can also be written on the basis of physical/numerical models of the weather or a blend of statistical/physical models. Longer-term weather derivative contracts can also be framed to some degree on the basis of seasonal forecasts, such as those for ENSO (Considine, 2000).

Weather derivative contracts are sometimes transacted as call[7] or put[8] options (Mathews, 2009). The rapidly growing nature of the weather derivative

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[6] Historical burn analysis is the simplest type of historical analysis of a weather index and is based simply on the historical empirical index data (with no attempt to fit the data to a distribution or account for other physical or statistical features to the data).

[7] For example, in weather derivative terminology, a call option for heating degree days would give the purchaser a payout from the provider at a specified number of degree days (the provider assuming the winter would be relatively mild (relatively few HDD) and the investor assuming the winter would be relatively cold (more HDD)).

[8] As above, a put option on a heating degree day weather derivative contract would give the purchaser the largest payout for a small number of HDD with the payout decreasing with more HDD (the purchaser assuming the winter would be relatively mild and the provider assuming the winter would be relatively severe).

market is potentially encouraging with respect to the global insurance burden from weather related catastrophes. Parametric and/or physically based weather derivative contracts also bear some conceptual similarity to the same types of cat bonds and weather index insurance. There is the potential for lessons learned in one arena and contract design ideas in one arena to be adopted in other areas.

2.9. Single Year versus Multi-Year Contracts: One of the structural challenges to insurance in a changing climate context is the issue of the length of contract. Individual clients who repurchase weather related insurance each year may be subject to price volatility due to both supply and demand issues and the changing weather risks (assuming some of this risk can be captured by seasonal forecasting and integrated into the pricing of the contract). If the insurer cannot integrate forecast information into pricing such contracts and the client can make decisions about purchasing after a seasonal forecast is issued, this scenario may lead to adverse selection. However, in scenarios where skillful seasonal forecasts can be integrated into pricing considerations, it can be advantageous from the perspective of the client to consider a multi-year contract at fixed cost to have the benefit of comparative stability. At the same time, it can also be a challenge to commit multiple years' worth of resources to paying premiums. From the insurer's perspective, the benefit of a multi-year contract over a single year contract is the commitment of premiums for multiple years. The downside is the limited flexibility that the insurer has in re-pricing the contract if the forecast risk or the capital balance changes dramatically. Research conducted in the US from a web-based experiment on this issue in relation to property insurance found that there was a fairly strong preference for two year over one year contracts, even when there was a 5-10% loading cost for the 2 year contract (Kunreuther and Michel-Kerjan, 2012). This empirical work is also supported by a theoretical study suggesting that the option of multi-year insurance is generally preferable, will tend to lead to higher rates of insurance participation and that equilibrium prices will be a product of the risk aversion of the different individuals (Kleindorfer et al., 2012).

In the broader discourse about the economic value of seasonal forecasting, some research suggests that for statistically unsophisticated users who make the decision to use or not use forecasts in an iterative, conditioned fashion, additional knowledge of forecast information may actually be most useful for forecasts of intermediate skill (Millner, 2009). This concept may also apply to some degree to participation rates in index insurance. Participation in single year contracts contingent on contract performance may lead to cessation of index insurance after a non-payout (akin to a type 2 error[9]). However, this reaction to the adverse event may cause a farmer to then miss out on a payout the following year. Multi-year contract design may help to minimize or reduce this problem.

2.10. Index Insurance; Motivation: The foregoing review of various forms of insurance and financial instruments to help manage weather related risks

[9] Here I am using a "non-payout" to refer to a situation in which there is an adverse agricultural impact, but there is no payout because the index value does not reach the threshold. This is similar to the statistical concept of the type 2 error in which the null hypothesis (no payout) is not rejected, but it should have been.

highlights some of the challenges for and opportunities for the broad arena of weather and climate risk management in the "developed" world. In shifting the focus now to the "developing" world, it is important to be mindful of some of the lessons learned; the need to shift away from actuarial models based on assumptions of statistical stationarity, the need to approach the issue of subsidization with cautious awareness of unintended and unwelcome consequences and the awareness of more technical details of parametric contract design from the weather derivative and cat bond markets.

However, in the context of the "developing" world, there is a far smaller insurance industry and a far shorter period of market based financial climate risk management, although the market is growing quite rapidly. Since 2000, microinsurance in the developing world has grown to a client base of around 135 million policy holders, which only constitutes about 5% of the potential market, but in many regions, annual insurance adoption increases are on the order of 10%/year (Lloyd's, 2014). Attempts to bring about market driven "solutions" may be met with skepticism because of the painful legacy of colonialism and the detrimental effects of postcolonial power dynamics (Da Costa, 2013; Dercon et al., 2011). In stark contrast to the developed world where only a few percent of the total population is engaged in agriculture and the agriculture tends to be highly productive and to produce surpluses that can be sold on the global market on a regular basis, many nations and sub-regions within the developing world have some 70+% involvement in (predominantly subsistence) agriculture, and more than half the population of the developing world as a whole is engaged in agriculture (Livingston et al., 2011). Consequently, while for many people in the developed world, adverse weather conditions are often little more than an inconvenience except in the most extreme cases, for many in the developing world, more modestly "adverse" weather can still make a difference between life and death or between a meager living and destitution. In developing, primarily subsistence economies, surplus food production is often episodic at best (while deficits of food production are a potential episodic threat) and there is far greater direct exposure to climate related risks.

Consequently, many farmers in the developing world tend to make risk averse decisions, fearing (understandably) that the next major climate shock could plunge them into destitution (Yesuf and Bluffstone, 2009). Sadly, risk-averse decision making in this context can often perpetuate a position of economic disadvantage and contribute to a "poverty trap" by keeping yields too low to accrue savings during the better times (Sachs et al., 2004). Weather-related index insurance is perceived as a potential partial solution to some of these challenges. In particular, weather index insurance is seen to hold the potential to enable insured farmers to take risks that they would be otherwise unable to take, and thereby benefit from higher risk, higher potential yield decisions when weather conditions are comparatively favorable which can then lead to savings and a gradual escape from the "poverty trap" (Mobarak and Rosenzweig, 2012; De Nicola et al., 2011). While index insurance premiums do cut into already meager capital, the benefits of reducing the risk of the poverty trap and changing the farmer's paradigm have led to a demonstrated increase in yields in a number of projects (Hellmuth et al., 2009; Barnett et al., 2008; Fuchs and Wolff, 2011).

Two other major perceived advantages of index insurance in a developing world context are the potential speed of payout to the client population (as compared to traditional loss-based insurance where each claim must be verified) and the avoidance of moral hazard[10] (assuming no one can tamper with the index itself). However, it is important to acknowledge that index insurance is not a panacea and that it should be used in conjunction with other adaptation mechanisms. Furthermore, clear communication regarding the limitations of index insurance is essential (Hellmuth et al., 2009).

History and overview of practices*:* While being a relatively novel form of insurance (weather/climate related index insurance in the developing world didn't start in a significant way until the 21st century), there are now many weather and climate related index insurance projects have been pursued in a wide range of contexts throughout the world (Hellmuth et al., 2009; Giannini et al., 2009; Osgood et al., 2010). While the majority of the work in this arena is focused on the developing world, there are also weather index insurance contracts offered for various risks in economies in transition and middle-income countries. There has been some discussion of the potential for index insurance in the developed world

[10] In insurance terminology, moral hazard refers to situations in which the insured client actually benefits disproportionately from an insurance policy (does not bear a fair price for the insured risk), thereby incentivizing risky or destructive behavior (such as a farmer intentionally destroying crops during adverse weather to acquire an insurance payout). Section 1.5 discusses how heavy subsidization of flood insurance can encourage overdevelopment in flood prone areas; which is an example of moral hazard.

as well (Mafoua and Turvey, 2003). Weather index insurance contracts have been designed to address drought risk, flood risk, cold event risk, and have been designed to function in a manner complementary to development and disaster relief efforts (Hellmuth et al., 2009; Dick et al. 2010).

At a broad, international level, the interest in index insurance has led to several multilateral, international partnerships. In the framework of international climate negotiation, the UNFCCC Bali Action Plan of 2007 created an avenue through which index insurance was considered seriously as an important expanding arena of market based adaptation at the following UNFCCC COP in Poznan, Poland, 2008. At the Poznan COP, the Munich Climate Insurance Initiative (MCII) argued for the creation of a two-tiered approach to expanding on the use of climate index insurance in the global adaptation portfolio: the Climate Insurance Pool (CIP) and the Climate Insurance Assistance Facility (CIAF). The former was intended to absorb a pre-defined proportion of high level risks of disaster losses from vulnerable non-Annex I countries, while the latter was intended to provide technical and other layers of support to help manage middle layers of risk for the same countries. Since its conceptual development, the World Bank has helped to create specific regional CIP and CIAF funds (MCII submission to Bali Action Plan, 2008).

Also in 2008, with a grant from the Bill and Melinda Gates Foundation, the International Fund for Agriculture and Development (IFAD) and the World Food Program (WFP) partnered in creating the Weather Risk Management

Facility (WRMF). The WRMF has supported pilot projects in China and Ethiopia and done research into best practices around the world (Dick et al., 2010).

In 2009, the Global Index Insurance Facility (GIIF) was created as a multi-donor trust fund financed by the EU, Japan, the Netherlands, the International Finance Corporation and the World Bank. The GIIF also receives technical guidance from Swiss Re. To date, through the GIIF, over 600,000 clients (farmers, pastoralists and microentrepeneurs) have been insured for a total insurance portfolio of 119 million USD. As of 2013, total payouts totaled just shy of 10 million USD and about 90% of those insured have a loan or credit linked to the insurance (Galludec et al., 2014; International Finance Corporation).

One of the broader concerns about index insurance in the developing world is the affordability for extremely poor farmers. In light of this reality, there is arguably, somewhat more of a case for direct government subsidy, at least initially to get markets started (Hellmuth et al., 2009). Government and/or third party involvement has often been a feature of many index insurance pilot projects (Ward et al., 2008) and as mentioned above, many index insurance contracts are linked to loans or credit. There is still some measure of concern that if a large index insurance market (well beyond the pilot phase) receives a great deal of government subsidy, there may be market distortions to the price and other unintended and undesirable consequences (even if moral hazard is reduced). Consequently, bundling of index insurance with microcredit and/or agricultural loans is generally considered to be a preferable approach (Hellmuth et al., 2009). Credit linked index insurance is also considered to be important for scaling up

(Skees, 2007; Carter et al., 2010). Furthermore, some index insurance contracts have been designed on the basis of labor or surplus production as a means of payment (Hellmuth et al., 2009).

Prior to the abovementioned international collaborations, there have been a multitude of collaborations, pilot projects larger scale index insurance efforts in many parts of the world over the last roughly decade and a half. Arguably, drought index insurance contracts are particularly popular, both because there is a high level of vulnerability associated with drought and because droughts tend to be relatively spatially coherent risks over large areas. Drought insurance contracts have been used to help alleviate food shortages at a national level in Ethiopia (WFP project), at a more local level in Malawi (Bagazonzya and Kloeppinger-Todd, 2007), Ethiopia (Osgood et al., 2010), in Central America (Giannini et al., 2009), India (BASIX) (Bagazonzya and Kloeppinger-Todd, 2007), China (Balzer and Hess, 2009) and many other regions (Hellmuth et al., 2009). The WFP project in Ethiopia in 2006 did not experience a payout. But weak rains in 2009 triggered payouts in the WFP project (supported by Axa Re) (Balzer and Hess, 2010) and in the HARITA project (supported by many partners, but principally Oxfam America, the Rockefeller Foundation and NOAA) (Osgood et al., 2010). The drought index insurance in Malawi had been linked to agricultural loans and had been based on three different trigger rainfall levels at different times of the growing season (Hellmuth et al., 2009).

In the Caribbean, interest in index insurance has been focused on disaster (earthquake and hurricane) relief, leading to the creation of the Caribbean

Catastrophe Risk Insurance Facility (CCRIF), the world's first multinational risk pool in 2007. The CCRIF benefits from a number of risk spreading ventures aimed at reducing primarily disaster risks from hurricanes and earthquakes (but also drought and excess rainfall). This year, the World Bank is offering its first cat bond for hurricane protection to the CCRIF (CCRIF). There has also been a flood index insurance contract along the Mekong River in Vietnam that was intended to protect rice farmers from early floods, with the contract being based on upstream river gauge heights (Hellmuth et al., 2009). Among the other projects reviewed in (Hellmuth et al., 2009) was a government funded disaster relief project that was conceived and implemented in Mexico, a federally subsidized area yield index insurance project in Brazil and a livestock mortality based insurance project for Mongolia (which actually tended to more strongly correlated with cold winters). Livestock insurance has also emerged more recently in East Africa (Index Based Livestock Insurance). One of the largest and earliest providers of index insurance is the Indian microfinance and livelihood promotion institution BASIX, which started disbursing index insurance shortly after 2000 and has a client base in the hundreds of thousands (Hellmuth et al., 2009).

One particularly successful project with which the International Research Institute for Climate and Society (IRI) was involved was a relatively localized project in the Tigray region of northern Ethiopia. This project was a response to an engagement on the part of Oxfam America and the UN WFP, building on the prior work of the Horn of Africa Risk Transfer Adaptation (HARITA) project (Osgood et al., 2010). This Tigray based index insurance project scaled up very rapidly, insuring only 200 households in 2009 and over 13,000 in 2011. Stakeholder interaction and simulation games revealed that many of the villagers were inclined to choose high premium, high frequency of payout insurance contracts. This challenges the premise that the very poor universally prefer low cost, low indemnification insurance (Norton et al., 2014). In 2011 and 2012, there were sizable payouts and survey research suggests that overall satisfaction levels were high (World Bank Case Study, 2013). The findings of the research in Tigray are similar to the findings of a study that examined the demand for index based livestock insurance in northern Kenya which found that the poorest subpopulations tended to have an interest in (and a purchasing behavior favoring) high premium, high coverage contracts, whereas those who were somewhat better off, but at risk of falling into a poverty trap were more likely to be sensitive in their preferences to subtleties of the insurance price (Chantarat et al., 2013).

Among other projects in Africa with which IRI has been involved, there was a pilot drought insurance project in the UN Millennium Villages Project in 2007 and 2008 (Ward et al., 2008) based largely on the NDVI – a satellite based measure of vegetation greenness. This approach was seen as a complement to or a substitute for meteorological rain gauge data (Ward et al., 2008; Ceccato et al., 2008).

Specifically in West Africa, in 2009, a pre-feasibility assessment was carried out to explore the prospect of insuring cotton farmers in Mali on the basis of rain gauge data or satellite data. The results were not promising for rain gauge data, but slightly less discouraging for satellite based indices (Hartell and Skees, 2009). A feasibility assessment of the potential for index insurance in Senegal was carried out by a World Bank Team in 2009, finding that there is very limited experience with agricultural insurance in the country and limited legal basis for implementation of index insurance (Mahul and Toure, 2009). Since this time, a national agricultural insurance company of Senegal has arisen (Compagnie Nationale d'Assurance Agricole du Senegal (CNAAS)) with partnerships with the government of Senegal, Swiss Re and several regional reinsurance companies (Sen Re, CICA Re and Aveni Re). CNAAS now offers several insurance products for cattle, crops, weather index insurance and even navigational insurance for artisanal fishing (CNAAS).

In the last several years, pilot projects in four West African countries (Burkina Faso, Mali, Benin and Senegal) have emerged as a result of collaboration between the International Finance Corporation, Swiss Re, multiple primary insurers, PlaNet Guarantee and the Dutch company EARS, which uses nuanced satellite measures of vegetation to serve various client needs. The Benin project started in 2013 and insures 1100 clients (maize and cotton farmers) against drought risk using a weather satellite based index with a total portfolio of ~134,000 USD. The Senegal project began in 2012, insuring ~4000 clients (maize and groundnut farmers) against drought risk using a weather station based index with a total portfolio of ~450,000 USD. The Burkina Faso project started in 2011 and insures ~8300 clients (maize and cotton farmers) against drought risk using satellite based and area yield indices and has a total portfolio of about ~670,000 USD. Finally, the Mali project also started in 2011 and insures ~17,500 clients (maize farmers) against drought risk using a satellite based index with a total portfolio of about 2.5 million USD (International Finance Corporation, Planet Guarantee, 2014).

Challenges and Downsides to Index Insurance: Beyond noting that index insurance is not a panacea to all climate related agricultural risks, that there are limitations to what index insurance can address and that there is a level of historically rooted mistrust in the unfamiliar, it is important to note other potential downsides of index insurance. Perhaps most obviously, if index insurance is not regulated properly and the insurer charges usuriously high premiums, index insurance could become a vehicle for the expropriation of wealth from the poor to the wealthy. While there is relatively evidence so far that index insurance has been used in this way to further the exploitation of the poor, it is certainly possible that this could become an issue in the future.

Even if index insurance is broadly seen by the clients to be “successful” as a concept, its implementation may be politically charged if it is offered to certain populations but not to others. Newly emerging asymmetries of access could result leading to new asymmetries in vulnerability. Such asymmetries may take some time to emerge, as might the potential benefits of index insurance. The spatial, temporal and social patterns of “winners” and “losers” would likely be quite complex and heterogeneous.

There is also the issue of opportunity cost; i.e. how else could the insurance premium be used (even if the index insurance is priced in an “affordable” way). It’s possible that for a sizable proportion of the insured, the accrued downside of the premium outweighs the utility benefits of the payouts when they occur. There is a potential for index insurance to lead to increased vulnerability and exposure to market risks (Peterson, 2012). At a larger level, questions arise regarding the relationship of the state to the insured client population. If an index insurance project were implemented by a state but were framed in a compulsory, restrictive manner that limited the choices of individual farmers, this could lead to unintended, problematic consequences for portions of the client population that might be forced into buying insurance they could not really afford. To that end, it is important for implemented index insurance projects to have a keen understanding of the diversity of economic circumstances of the client base and to offer enough flexibility. Another fear may be that over-reliance or emphasis on index insurance may lead to governments not doing enough in the way of funding and work towards complementary climate risk management. At the broadest level, there are critiques of efficacy of market-based, capitalist approaches to climate risk management and adaptation. The narrative is along the lines that such market-based approaches will tend to reproduce and deepen pre-existing socioeconomic divides without necessarily reducing the drivers of climate change (Wainwright, 2012; Adger 2003).

Theory: While the foregoing overview of index insurance in practice has focused largely on agriculture, there is also some potential to use index insurance contracts to help manage hydro-climate risks to water supply with indices based on reservoir levels (Brown and Carriquiry, 2007; Ward et al., 2012). However, it is important to consider some theoretical issues related to index insurance. First, beyond whatever choices are made with regard to the type of risk to insure or the type of index to use as the basis for contract or the level of coverage to seek, there are multiple potential contract designs. Figure 1.3 shows four simple forms of contract design for a drought index insurance contract: the single step function, the two-step function and two modified linear gradient functions. The use of gradient functions has been somewhat common in practice (World Bank, 2011). In the example of Figure 1.3, consider the climatological rainfall in a particular season to be 35”. None of the contracts pay for rainfall>30”. The simple step function pays out $20 for all seasons with rainfall below 30”. The two step function pays only $10 for 30”>rainfall>20” and $40 for rainfall <20”. Gradient function 1 pays an additional $2 for every inch below 30” until 15”, where it reaches a maximum payout of $30. Gradient function 2 pays $10 for a 30” season and an additional $1 for every inch below 30” until 10”, where it reaches a maximum payout of $30. Theoretically, one could envision many other potential contract designs; three or four step functions, mixed step/gradient functions, non-linear gradient functions, etc..

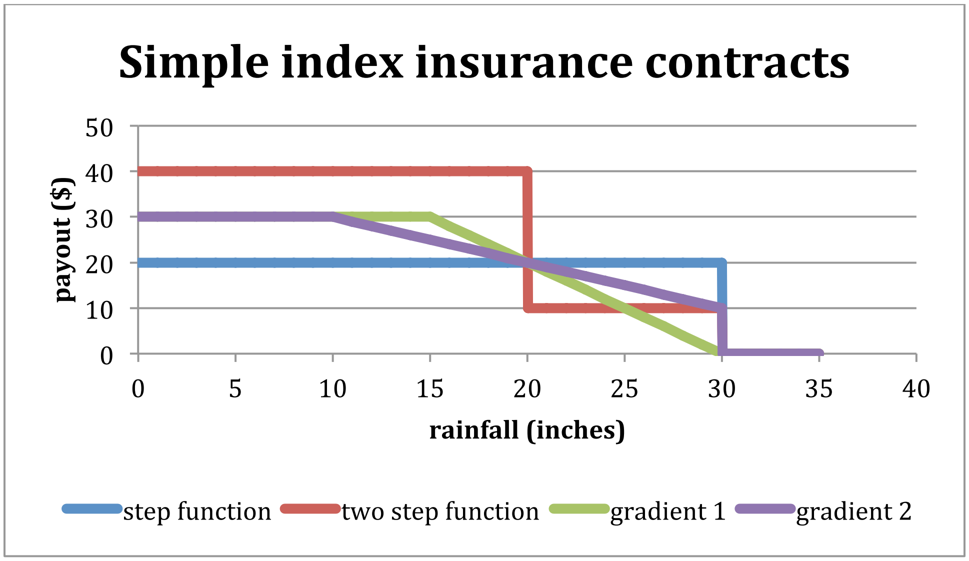

Figure 1.3: Schematic diagram of the payout functions of several different potential drought index insurance contract designs.

In practice, many (although not all) index insurance contracts are based on one of these relatively simple models. In practice, gradient functions usually are bounded in their payouts (as above) to prevent the insurance company from having runaway costs in very extreme scenarios. In practice, there are times when there are multiple triggers at different times in the growing season (because most crops have different water requirements at different stages of their development) or a requirement for multiple triggers to be met simultaneously in order to improve visibility and reliability (Hellmuth et al., 2009). Clearly, one can envision that a flood contract or an excess rainfall contract would have a complementary pattern, but the strike level would be above the climatological rain or climatological streamflow.

Preferences for different contract types will depend on the variability of the climate system, the knowledge of the farmers regarding the climate system and the sensitivity of crop production to different levels of adversity (in the above case, drought). If, in the above example, the farmers understand the regional climate variability well and the crops are highly sensitive to rainfall fluctuations, let us consider three scenarios; low rainfall variability (p(r)<25” is small and p(r)<20” is trivially small), intermediate rainfall variability (p(r)<25” is a modest concern and p(r)<20” is small), and large variability (p(r)<20” is a modest concern). In the first, the simple step function that pays out $20 for any deficit below 30” may be preferable. In the second, gradient function 2 may be preferable, as it pays out almost as much as the step function for 30”>rainfall>20” and more than the step function for lower values of rainfall. In the third case of high variability, the two-step function or the gradient 1 function may be preferable because of the higher payout levels at 20” and 15” respectively.

Without knowing the climatological history of this hypothetical scenario, it would not be possible to price these contracts, but depending on the size of the variance and the nature of the distribution of rainfall, it is quite possible that all four contracts could be comparable in cost (even if the abovementioned preferences are exercised). From a client perspective, gradient functions have obvious appeal as the scale of the payment increases in proportion to the scale of the extreme event (at least within certain bounds). From a conceptual standpoint, the simplicity of a step function is attractive, and understanding future price behavior of a step function contract requires modeling only the frequency of future extreme events (not the severity). Consequently, the contract design considered throughout will be the simple step function.

However, regardless of the nature of the payout function, the actuarially fair premium[11] of any drought index insurance contract would be given by the equation:

$$P_d = \int_0^{rstrike} p(r)y(r)dr \tag{2.1}$$

where P_d is the premium for the drought contract, p(r) is the probability of a given amount of rainfall and y(r) is the payout for that given amount of rainfall and r_{strike} is the strike or threshold level (in the above case, 30”). Note that the variable “r” in this generalized case doesn’t have to be rainfall, per se; it could be NDVI, area yield, gauge height, reservoir level, etc.. The important conceptual point is that the contract is triggered when the index falls below the strike level. By analogy, a flood index insurance contract under the same general constraints (no administrative or “loading” costs) would have the general form:

$$P_f = \int_{rstrike}^{\infty} p(r)y(r)dr \tag{2.2}$$

where P_f is the premium for the flood contract. As above “r” could be rainfall, streamflow, gauge height, etc.; the important concept is that the strike level is above the climatological mean and the insurance contract is designed to pay out when the index exceeds the strike level. In a number of ways, insuring against flood risk is a more complex challenge than insuring against drought risk and may require a larger scale of implementation (Hellmuth et al., 2009). For river flooding (as opposed to excess rainfall), there is the additional technical challenge

[11] In the insurance literature, an “actuarially fair” premium is a premium at which there is no expected profit or loss to the insurer: i.e. the annual premium exactly equals the annual expected payout. In practice, non-subsidized premiums are almost always higher than the actuarially fair price for three principle reasons; the business need to make a profit, administrative costs, and the “loading costs” associated with uncertainty.

of understanding the timing and intensity of upstream rainfall and the river hydrology. For flood related or excess rainfall related index insurance contracts especially, there is a strong need on the part of the insurer to make sure that the payout function "y(r)" is bounded in a meaningful way. While a river can run dry or a season's rains can fail completely, there is not necessarily a physical theoretical upper bound to rainfall or streamflow. This could imply runaway costs to the insurer in such an event.

For a simple step function, the equations above would further simplify to

$$P = Lp \tag{2.3}$$

where L is the total liability insured and p is the probability of payout.

Clearly, these equations are never satisfied in the real world, as there are administrative and logistical costs with administering any index insurance contract. Furthermore, uncertainty about the climate system and concern (on the part of the insurer) of a run of extreme events in quick succession will add to the insurer's capital holding needs; a cost which may then be passed on (at least in part) to the client.

This being said, from the client's perspective, the biggest concerns are likely to be two-fold:

Will the insurance have a large basis risk[12]? (i.e. will the insurance pay out when there is a severe loss?)

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[12] Basis risk is a term in the economics and insurance literature to describe imperfect hedging where the hedge (in this case the index on which the insurance contract is based) does not perfectly capture the farmer's risk and there is some probability of a devastating loss for which there is no payout.

Will the insurance have a large bias over time? (i.e. will (and to what degree will) the insurance overcharge relative to the actuarial cost over time?)

In addition to concerns about temporal basis risk, there is also some measure of concern about the issue of spatial basis risk[13] (Norton et al., 2012). On the insurance design front, shortness and/or incompleteness of historical climate and or agricultural data can often be a constraint on the quantification of index insurance pricing. At least with regard to the climate index, one potential way to address this challenge is the use of paleo-climate records to gain more refined understanding of the behavior of hypothetical index insurance contracts. Limited or incomplete climate data may offer the insurer a poor understanding of the value at risk and the distribution of climate events. In one study, use of extended climate records from tree ring analysis over 700 years has informed a theoretical retrospective analysis of potential index insurance contracts for a number of agriculturally productive areas in Asia and North America. Use of this paleo-climate data is shown to reduce uncertainty related costs, better constrain the value at risk and the distribution of climate events and even help inform contract performance in non-stationary climate regimes (Bell et al., 2013).

Ambiguity regarding the climate system and the performance of a contract over time can also be a considerable challenge to index insurance implementation. Many insurers can be characterized as ambiguity averse and may be tempted to pass costs along to the client population (Clarke, 2007). Ambiguity aversion on the part of the client can also play a role in reducing the utility of an index

[13] Spatial basis risk refers to the potential failure of a regional index to capture local vulnerabilities adequately, while temporal basis risk refers to the mismatch of index and vulnerability over time.

insurance contract and can lead to limited participation, even in the case of a well-designed contract (Bryan, 2010). Uncertainties about future climate risks can be compounded by multi-decadal variability. Even if the mean, variance and other statistical parameters of a distribution are well constrained by historical record, a region prone to multi-decadal variability may have an elevated risk of frequent threshold crossing extreme events (and therefore the associated index insurance payouts) (Siebert and Ward, 2011). While a climate region that has minimal decadal variability may require a relatively short length of record to reliably characterize the mean, variance, and other shape parameters of the index distribution, the presence of pronounced multi-decadal variability often compels a longer length of record. This can be pursued by examining the paleo-climate record (Bell et al., 2013) or by statistical simulation approaches (Siebert and Ward 2011, 2013). There may also be some role for informing index insurance with physical models in addition to statistical models (Hellmuth et al., 2009). But it is clear that there is a contextual need, in the presence of a non-stationarity and climate uncertainty to develop flexible mechanisms for applying index insurance in the presence of a changing climate (Collier et al., 2009; Greene et al., 2008).

Another potential challenge is that of predictability in the climate system. Many regions, especially in the tropical developing world have seasonal predictability that can be linked to major climatic oscillations like El Nino-Southern Oscillation (ENSO) (Ropelewski and Halpert, 1987). The first successful prediction of ENSO was made in the mid-1980s (Cane et al., 1986) and much progress in ENSO research has been made using the Cane-Zebiak model and more recent refinements. While many lingering questions remain in the arena of ENSO research, the better part of 30 years of experience have shown that seasonal forecasting can be quite skillful. Depending on the timing of the forecast and the terms of the index insurance purchase and pricing, this may or may not be an insurmountable challenge.

If the insurance contract is priced and transacted before there is reliable forecast information available, the reality of forecast will have little bearing on the execution of the contract for that season (although there may be regrets for either client or insurer if the forecast turns out to heavily weight the odds in one direction or another). If the insurance contract is priced before a reliable forecast can be made, but the client can purchase the contract after a reliable forecast, this situation will introduce adverse selection, as there will be a tendency for participation rates to be correlated with forecast risk. If the forecast is made before the index insurance contract is priced and the forecast can be integrated into the pricing, but the client population has limited or no knowledge of the forecast, adverse selection risks may be reduced, but the client's participation may be largely based on the cost of the premium in absolute terms (rather than the degree to which the price is fair, given the expected risk). If the forecast is made before the index insurance contract is priced and the client population has knowledge of the seasonal forecast, there may still be issues with adverse selection to a degree, but they may be manageable if pricing adjustments are communicated in a clear way and there is still a perception that the pricing is fair (Carriquiry and Osgood, 2012). To this effect, a study was conducted creating hypothetical index insurance contracts based on bundled agricultural loans that were responsive to ENSO forecasts in Malawi. The size of the agricultural loan (which would in turn enable differential purchasing of seeds and fertilizer) would vary in response to the ENSO forecast. In the case of an El Nino, there was an elevated risk of drought induced crop failure and the agricultural loan would shrink, the farmers would buy fewer inputs, thereby reducing financial exposure, whereas during La Nina conditions, there was a suppressed risk of drought induced crop failure, the agricultural loan would increase and the farmers would buy more inputs to take advantage of the forecasted better conditions. This approach, based on a premise of symmetric knowledge of a skillful forecast, and the integration of the forecast into the insurance pricing was found to be beneficial in reducing some of the challenges associated with forecast skill. Lessons from this theoretical study could be applied (with various modifications) in practice (Osgood et al., 2008).

More generally, there is a need with weather related insurance industry to engage a diverse portfolio of clients including those who have negatively correlated risks (Hellmuth et al., 2009). This is particularly important for large reinsurers who wish to engage in multiple projects in ENSO sensitive regions. However, insuring against negatively correlated risks is arguably a wise approach at a smaller scale and can promote the sustainability and viability of an index insurance project that might otherwise be imperiled by default risk.

Specific Regional Challenges and Opportunities: In addition to the abovementioned index insurance projects implemented in the last three years in Mali, Burkina Faso, Benin and Senegal, there have also been theoretical studies of the potential for index insurance in this region. A theoretical study of more than 3000 potential drought insurance contracts (based on local rainfall data) across 30 districts in Burkina Faso for a 21 year period of analysis for five crops (cotton, millet, sorghum, maize, and groundnut) found that such index insurance contracts could provide significant economic efficiency – particularly for the driest parts of the country, and particularly for the crops with the highest yield variability and weather related correlation (maize and groundnut) (Berg et al., 2009). A study focused on insuring millet production against drought risk in southwest Niger found that localized data was very important to the success of potential index insurance contracts. The study also found that index insurance contracts based on simulated sowing date would perform comparably or better than those based on observed sowing date and that the measured benefit tends to be greater for those using fertilizer (and that index insurance may actually enable the expansion of the use of fertilizer) (Leblois et al., 2011).

In the proposed case study in the following chapters, there is a focus on national, rather than district level data, despite the findings of the above literature expressing preference for use of more localized data (an admitted limitation of limited field research). In the following chapters, the bundling of the potential index insurance with credit or agricultural loans is not specifically described, but given this literature review of practice, there does seem to be a good motivation for the practice of designing such insurance in a credit-linked way.

With reference to the need to address negatively correlated risks, an index insurance product could be targeted simultaneously to drought risk for dryland subsistence millet farmers (who are often removed from the cash economy) and flood risk for river centered, irrigated rice farmers (who tend to be somewhat better off and who tend to experience less variability in their production). The premise behind such a framework is that the risk would spread between floods and droughts, the likelihood that both populations would need a payout at the same time or in quick succession would be low because of the anti-correlation of the events (personal conversation, Dr. Katiella Mai Moussa). Clearly, even this type of approach is not perfect, as there is a non-trivial risk of a quick succession of drought and flooding. In the early months of 2010, a heat wave and drought caused a widespread famine in much of the region (this was still underway during my research visit) and in August and September, heavy local rains and perhaps a more impervious landscape led to record flooding in the middle Niger Basin. Chapter 3 will deal more extensively with regional history, climate, and adaptation practices. Chapter 4 will describe the index insurance framework of this case study in more depth, but the many lessons of this literature review should be considered and engaged in depth in any implementation project.

References

-AIR WorldWide Report, (2013). The Coastline at Risk: 2013 Update to the Estimated Insured Value of U.S. Coastal Properties.
-Adger, W. N. (2003). Social Capital, Collective Action and Adaptation to Climate Change. *Economic Geography, 79,* 387-404.
-Anderson, D. R., (2003). Global Warming/Climate Change: Implications for the Risk Management and Insurance Industry. *CPCU eJournal.*
-Balzer, N. and U. Hess, (2009). Climate Change and Weather Risk Management: Evidence From Index-Based Insurance Schemes in China and Ethiopia. Chapter in WFP Report.
-Bagazonzya, H. K., and R. Kloeppinger-Todd, (2007). Experiences in Index-Based Weather Insurance for Agriculture: Lessons Learnt from Malawi & India. World Bank Presentation.
-Barnett, B., C. Barrett, and J. Skees (2008). Poverty Traps and Index-Based Risk Transfer Products. *World Development, 36,* 1766-1785.
-Bell, A., D. Osgood, B. Cook, K. Anchukaitis, G. McCarney, A. Greene, B. Buckley, E. Cook, (2013). Paleoclimate histories improve access and sustainability in index insurance programs. *Global Environmental Change*, *23,* 774-781.
-Berg, A., P. Quirion, and B. Sultan, (2009). Weather-Index Drought Insurance in Burkina Faso: Assessment of its Potential Interest to Farmers. *Weather Climate and Society, 1,* 71-84.
-Berz, G. A., (1999). Catastrophes and Climate Change: Concerns and Possible Countermeasures of the Insurance Industry. *Mitigation and Adaptation Strategies for Global Change*, *4,* 283-293. -Bienert, S., (2014). Extreme Weather Events and Property Values: Assessing New Investment Frameworks for the Decades Ahead. *A ULI Europe Policy & Practice Committee Report.*
-Bouwer, L., (2011). Have Disaster Losses Increased due to Anthropogenic Climate Change? *Bulletin of the American Meteorological Society, 92,* 39-46.
-Brockett, P., L. Golden, C. Yang and H. Zou, (2008). Addressing Credit and Basis Risk Arising From Hedging Weather-related Risk with Weather Derivatives. ASTIN International Actuarial Association Conference, Manchester UK.
-Brown, C. and M. Carriquiry, (2007). Managing hydroclimatological risk to water supply with option contracts and reservoir index insurance. *Water Resources Research*, *43,* W11423.
-Bryan, G., (2010). Ambiguity and Insurance. Job Market Paper.
-Burby, R., (2006). Hurricane Katrina and the Paradoxes of Government Disaster Policy: Bringing About Wise Government Decisions for Hazardous Areas. *The Annals of the American Academy of Political and Social Science, 604,* 171-191.
-Burby, R. (2001). Flood insurance and floodplain management: the US experience. *Global Environmental Change Part B: Environmental Hazards 3,* 111–122.
-Cane, M., S. Zebiak, and S. Dolan, (1986). Experimental Forecasts of El Nino, *Nature*, *321,* 827-832.
-Carriquiry, M., and D. Osgood, (2012). Index Insurance, Probabilistic Climate Forecasts, and Production. *Journal of Risk Insurance*, *79,* 287-300.
-Carter, M., L. Cheng, and A. Sarris, (2010). The impact of interlinked index insurance and credit contracts on financial market deepening and small farm productivity. UC Davis Working Paper.
-Ceccato P., M. Brown, C. Funk, C. Small, E. Holthaus, A. Siebert, and N. Ward (2008). Remote Sensing Vegetation. Paper presented at a workshop on 'Technical Issues in Index Insurance', held at IRI, Palisades, New York.

-Chantarat, S., A. Mude, C. B. Barrett and M. R. Carter, (2013). Designing Index-Based Livestock Insurance for Managing Asset Risk in Northern Kenya. *Journal of Risk and Insurance, 80,* 205-237.
-Christensen, J.H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R.K., Kwon, W.-T., Laprise, R., Magaña Rueda, V., Mearns, L., Menéndez, C.G., Räisänen, J., Rinke, A., Sarr, A.,and Whetton, P. (2007). Regional climate projections. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (eds.), Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge, United Kingdom and New York, NY, USA: *Cambridge University, Press.*
-Clarke, D., (2007). Ambiguity Aversion and Insurance. Oxford M. Phil Dissertation.
-Cleetus, R., (2013). Overwhelming Risk: Rethinking Flood Insurance in a World of Rising Seas. Union of Concerned Scientists report.
-Collier, B., J. Skees and B. Barnett, (2009). Weather Index Insurance and Climate Change: Opportunities and Challenges in Lower Income Countries. *The Geneva Papers, 34,* 401-424.
-Collier, P., (2008). "The Politics of Hunger: How Illusion and Greed Fan the Food Crisis", *Foreign Affairs online publication*.
-Considine, G., (2000). Introduction to Weather Derivatives, Aquila Energy.
-Da Costa, D., (2013). The 'rule of experts' in making a dynamic micro-insurance industry in India. *Journal of Peasant Studies, 40,* 845-865.
-Davies, K. (ed.), T. Male, A. (author), (2014). Mutually Insured Destruction: How Unchecked Crop Insurance Subsidies Harm the Environment. *Defenders of Wildlife White Paper.*
-de Nicola, F., R. V. Hill, M. Carter, R. Choularton, J. Hansen and D. Osgood, (2011). Index Insurance for Managing Climate Related Agricultural Risk: Toward a Strategic Research Agenda, *International Food Policy Research Institute workshop report.*
-Dercon, S., J. W. Gunning, and A. Zeitlin, (2011). The demand for insurance under limited credibility: Evidence from Kenya. *International Development Conference, DIAL.*
-Dick, W., A. Stoppa, J. Anderson, E. Coleman, and F. Rispoli, (2010). Weather Index-based Insurance in Agricultural Development: A Technical Guide. IFAD/WFP report.
-Dlugolecki, A., (2007). The Cost of Extreme Events in 2030. A Report for the UNFCCC.
-Easterling, D., J. Evans, P. Groisman, T. Karl, K. Kunkel, and P. Ambenje, (2000). Observed Variability and Trends in Extreme Climate Events: A Brief Review. *Bulletin of the American Meteorological Society, 81,* 417-425.
-Field, C. B., and Coauthors, Eds., (2012). Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Summary for Policy- makers. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change, 19 pp.
-Fuchs, A. and H. Wolff, (2011). Concept and Unintended Consequences of Weather Index Insurance: Case of Mexico. *American Journal of Agricultural Economics, 93,* 505-511.
-Garman, M., C. Blanco and R. Erickson, (2000). Weather Derivatives: Instruments and Pricing Issues. Financial Engineering Associates.
-GAO, (2013). Flood Insurance: Implications of Changing Coverage Limits and Expanding Coverage. Report to Congressional Committees
-GAO, (2007). Climate Change: Financial Risks to Federal and Private Insurers in Coming Decades are Potentially Significant. Report to the Department of Homeland Security, US Senate.

-GAO, (2002). Catastrophe Insurance Risks: The Role of Risk-Linked Securities and Factors Affecting Their Use. Report to the Committee on Financial Services, House of Representatives

-Galludec, G., F. Assah, and S. Panajyan, (2014). Global Index Insurance Facility: Expanding Access to Index-based Insurance in Developing Countries. GIIF factsheet.

-Giannini, A., J. Hansen, E. Holthaus, A. Ines, Y. Kaheil, K. Karnauskas, M. McLaurin, D. Osgood, A. Robertson, K. Shirley and M. Vicarelli, (2009). Designing Index-Based Weather Insurance for Farmers in Central America. Final Report to the World Bank Commodity Risk Management Group.

-Greene, A. M., A. Giannini, and S. E. Zebiak, (2009). Drought Return Times in the Sahel: A Question of Attribution. *Geophysical Research Letters, 36,* L12701.

-Hartell, J. and J. Skees, (2009). Pre-Feasibility Analysis: Index Based Weather Risk Transfer in Mali. Save the Children Foundation.

-Held, I. and B. Soden, (2006). Robust Responses of the Hydrological Cycle to Global Warming. *Journal of Climate, 19,* 5686-5699.

-Hellmuth M.E., Osgood D.E., Hess U., Moorhead A. and Bhojwani H. (eds) (2009). Index insurance and climate risk: Prospects for development and disaster management. Climate and Society No. 2. International Research Institute for Climate and Society (IRI), Columbia University, New York, USA.

-Herweijer, C., N. Ranger and R. Ward, (2009). Adaptation to Climate Change: Threats and Opportunities for the Insurance Industry. *The Geneva Papers on Risk and Insurance*, *34,* 360-380.

-Huntington, T., (2006). Evidence for intensification of the global water cycle: Review and synthesis. *Journal of Hydrology*, *319,* 83-95.

-Jewson, S., A. Brix and C. Ziehmann (2005). "Weather Derivatives Valuation: The Meteorological, Statistical, Financial and Mathematical Foundations". Cambridge, UK, Cambridge University Press.

-Karl, K. (ed. In chief), L. Bevere, L. Mueller (authors), (2014). Sigma no. 1, Natural catastrophes and man-made disasters in 2013: large losses from floods and hail; Haiyan hits the Philippines. Swiss Re report.

-Karl, K. (ed. In chief), L. Bevere, T. Seiler, P. Zimmerli and H. Feyen (authors), (2013). Sigma no. 2, Natural catastrophes and man-made disasters in 2012: A year of extreme weather events in the US. Swiss Re report.

-Kapphan, I., P. Calanca, and A. Holzkaemper, (2011). Climate Change, Weather Insurance Design and Hedging Effectiveness. Institute for Environmental Decisions (IED) Working Paper 17.

-Katz, R. W., and B. G. Brown, (1992). Extreme events in a changing climate: Variability is more important than averages. *Climatic Change, 21,* 289–302.

-Kharin, V. V., Zwiers, F. W., X. Zhang, and G. C. Hegerl, (2007). Changes in Temperature and Precipitation Extremes in the IPCC Ensemble of Global Coupled Model Simulations, *Journal of Climate, 20,* 1420-1444.

-Kleindorfer, P., H. Kunreuther, and C. Ou-Yang, (2012). Single-year and multi-year insurance policies in a competitive market. *Journal of Risk and Uncertainty*, *45,* 51-78.

-Kunkel, K.E., M. Palecki, L. Ensor, D. Easterling, K.G. Hubbard, D. Robinson, & K. Redmond (2009). Trends in twentieth-century US extreme snowfall seasons. *Journal of Climate*, *22,* 6204-6216.

-Kunreuther, H. and E. Michel-Kerjan, (2012). Demand for Multi-Year Insurance: Experimental Evidence, self-published, Center for Risk Management and Decision Processes. The Wharton School, University of Pennsylvania.

-Lalonde, D. and P. Karsenti, (2008). So you want to Issue a Cat Bond. AIR report.

-Leblois. A. P Quirion, A. Alhassane, S. Traore, (2013). Weather Index Drought Insurance: An Ex-Ante Evaluation for Millet Growers in Niger. *Environmental and Resource Economics, 57,* 527-551.
-Leichenko, R., K. O'Brien and W. Solecki, (2010). Climate Change and the Global Financial Crisis: A Case of Double Exposure. *Annals of the Association of American Geographers, 100,* 963-972.
-Leichenko R. M., and K. L. O'Brien, (2008). Environmental Change and Globalization: Double Exposures. *Oxford University Press*, Oxford and New York.
-Lewis, M. (2007). In Nature's Casino. New York Times, August 26.
-Livingston, G., S. Schonberger, and S. Delaney, (2011). SubSaharan Africa: The State of Smallholders in Agriculture. IFAD report, Conference on New Directions for Smallholder Agriculture
-Lloyd's, (2014). Insurance in Developing Countries: Exploring Opportunities in Microinsurance. 360 Risk Insight report.
-Lobell, D., and Field, C. (2007). Global scale climate-crop yield relationships and the impacts of recent warming. *Environmental Research Letters, 2,* 014002.
-Mafoua, E. K., and C. G. Turvey (2003). Weather Insurance to Protect Specialty Crops against costs of Irrigation in Drought Years. American Agricultural Economics Meeting, Montreal, QC.
-Mahul, O., and E. H. A. Toure (lead authors), (2009). Index-Based Crop Insurance in Senegal: Promoting Access to Agricultural Insurance for Small Farmers. World Bank Report.
-Mann, R., and K. Green, (2013). Spotlight on Catastrophe Bonds. Schroders, UK Strategic Solutions.
-Mathews, J. (2009). Dog Days and Degree Days, CME Group.
-McHale, C. and S. Leurig, September, (2012). Stormy Future For U.S. Property/Casualty Insurers: the Growing Costs and Risks of Extreme Weather Events. A Ceres Report.
-McLeman, R. and Smit, B. (2006), Vulnerability to climate change hazards and risks: crop and flood insurance. *Canadian Geographer, 50,* 217-26.
-Meehl, G. A., T. Karl, D. R. Easterling, S. Changnon, R. Pielke Jr., D. Changnon, J. Evans, P. V. Groisman, T. R. Knutson, K. E. Kunkel, L. O. Mearns, C. Parmesan, R. Pulwarty, T. Root, R. T. Sylves, P. Whetton, and F. Zwiers, (2000). And Introduction to Trends in Weather and Climate Events ; Observations, Socioeconomic Impacts, Terrestrial Ecological Impacts, and Model Projections. *Bulletin of the American Meteorological Society, 81,* 413-416.
-Meehl, G. A., Tebaldi, C., (2004). More Intense, More Frequent, and Longer Lasting Heat Waves in the 21st Century, *Science*, *305,* 994-997.
-Michaels, D., D. Malmquist, A. Knap and A. Close, (1997). Climate Science and Insurance Risk. *Nature*, *389,* 225-227.
-Michel-Kerjan, E., and H. Kunreuther, (2011). Redesigning Flood Insurance, *Science, 333*, 408-409.
-Mills, E. (2009)a. From Risk to Opportunity: Insurer Responses to Climate Change. A Ceres Report.
-Mills, E. (2009)b. A global review of insurance industry responses to climate change. *The Geneva Papers, 34,* 323-59.
-Mills, E. (2007). Synergisms between climate change mitigation and adaptation: an insurance perspective. *Mitigation and Adaptation Strategies for Global Change, 12,* 809-842.
-Mills, E. (2005). Insurance in a climate of change. *Science 309,* 1040-1043.

-Millner, A. (2009). What is the True Value of Forecasts? *Weather, Climate and Society*, *1,* 22-37.
-Min, S. K., X. Zhang, F. Zweirs, and G. Hegerl, (2011). Human contribution to more intense precipitation extremes. *Nature*, *470,* 378-381.
-Mitchell, J., (2003). European River Floods in a Changing World. *Risk Analysis, 23,* 567-574.
-Mobarak, A. M., and M. Rosenzweig, (2012). Informal Risk Sharing, Index Insurance and Risk Taking in Developing Countries. American Economic Association Annual Meeting.
-Muller-Furstenberger, G., and I. Schumacher (2009). Uncertainty and Insurance in Endogenous Climate Change. Ecole Polytechnique Working Paper.
-New, M., B. Hewitson, D. B. Stephenson, A. Tsiga, A. Kruger, A. Manhique, Bernard Gomez, C. A. S. Coelho, D. N. Masisi, E. Kululanga, E. Mbambalala, F. Adesina, H. Saleh, J. Kanyanga, J. Adosi, L. Bulane, L. Fortunata, M. L. Mdoka, and R. Lajoie, (2006). Evidence of trends in daily climate extremes over southern and west Africa, *Journal of Geophysical Research, 111,* D14102.
-Niehorster, F., M. Aichinger, R. Murnane, N. Ranger, S. Surminski, (2013). Warming of the Oceans and Implications for the (Re)insurance Industry. A Geneva Association Report.
-Norton, M., Osgood, D., M Madajewicz, E. Holthaus, N. Peterson, R. Diro, C. Mullaly, T. L. Teh, and M. Gebremichael, (2014). Evidence of Demand for Index Insurance: Experimental Games and Commercial Transactions in Ethiopia. *The Journal of Development Studies*, *50,* 630-648.
-Norton, M., Turvey, C., and Osgood, D. (2012). Quantifying spatial basis risk for weather index insurance. *Journal of Risk Finance, 14,* 20-34.
-Osgood, D. E., J. Chen, T. Dinku, E. Holthaus, B. Lyon, M. Madajewicz, C. Mullaly, M. Norton, A. Pascualini, S. Pant, N. Peterson, R. Saavedra, J. Sharoff, K. E. Shirley, C. Small, S. Stiffel, T.-L. Teh, (2010). HARITA IRI Report to Oxfam America.
-Osgood, D., P. Suarez, J. Hansen, M. Carriquiry, and A. Mishra, (2008). Integrating Seasonal Forecasts and Insurance for Adaptation among Subsistence Farmers: The Case of Malawi. World Bank Policy Research Working Paper 4651.
-Perroy, L., (2005). Impacts of Climate Change on Financial Institutions' Medium to Long Term Assets and Liabilities, presented to the Staple Inn Actuarial Society. MSc degree at the Department of Environmental Science and Technology, Imperial College, London.
-Peterson, N. (2012). Developing Climate Adaptation: The Intersection of Climate Research and Development Programmes in Index Insurance. *Development and Change, 43,* 557-584.
-RMS Report, (2005). Hurricane Katrina: Profile of a Super Cat; Lessons and Implications for Catastrophe Risk Management.
-Robison, P., (2007). Hedge Funds Pluck Money from Air in $19 billion Weather Gamble. Bloomberg News, August 2.
-Ropelewski, C. and M. Halpert, (1987). Global and Regional Scale Precipitation Patterns Associated with ENSO. *Monthly Weather Review, 115,* 1606-1626.
-Rosenzweig, C., G. Casassa, D.J. Karoly, A. Imeson, C. Liu, A. Menzel, S. Rawlins, T.L. Root, B. Seguin, P. Tryjanowski, (2007). Assessment of observed changes and responses in natural and managed systems. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 79-131.

-Sachs, J., J. MacArthur, G. Schmidt-Traub, M. Kruk, C. Bahadur, M. Faye and G. McCord, (2004). Ending Africa's Poverty Trap. *Brookings Papers on Economic Activity*, *I,* 117-240.
-Sarewitz, D. R. Pielke Jr. and M. Keykhah, (2003). Vulnerability and Risk: Some Thoughts from a Political and Policy Perspective. *Risk Analysis, 23,* 805-810.
-Serra, T., B. Goodwin, and A. Featherstone, (2003). Modeling Changes in the US Demand for Crop Insurance During the 1990s. Annual meeting of the American Agricultural Economics Association.
-Shaik, S., K. Coble, T. Knight, A. Baquet, and G. Patrick, (2008). Crop Revenue and Yield Insurance Demand: A Subjective Probability Approach. *Journal of Agricultural and Applied Economics, 40,* 757-766.
-Siebert, A., and N. Ward, (2011). Future Occurrence of Threshold-Crossing Seasonal Rainfall Totals: Methodology and Application to Sites in Africa. *Journal of Applied Meteorology and Climatology, 50,* 560-578.
-Siebert, A., and M. N. Ward, (2013). Exploring the Frequency of Hydroclimate Extremes on the River Niger Using Historical Data Analysis and Monte Carlo Methods. *African Geographical Review,* online publication.
-Sierra, K., T. Roberts, M. de Nevers, C. Langley and C. Smith, (2013). First Steps Toward a Quality of Climate Finance Scorecard (QUODA-CF): Creating a Comparative Index to Assess International Climate Finance Contributions. Center for Global Economy and Development, A Brookings Institution paper.
-Skees, J., (2007). Challenges for Use of Index-Based Weather Insurance in Lower Income Countries. A GlobalAgRisk publication.
-Smith, V., and J. W. Glauber, (2012). Agricultural Insurance in Developed Countries: Where Have We Been and Where Are We Going? *Applied Economic Perspectives and Policy, 34,* 363-390.
-Smolka, A., (2006). Natural disasters and the challenge of extreme events: risk management from an insurance perspective. *Philosophical Transactions of the Royal Society A*, *364,* 2147-2165.
-Stohs, S., and J. LaFrance, (2003). A Learning Rule for Updating the Distribution of Crop Yields over Space and Time. University of California agricultural and resource economics seminar lecture.
-Tebaldi C., K. Hayhoe, J. Arblaster and G. Meehl, (2006). Going to the Extremes: An Intercomparison of Model Simulated Historical and Future Changes in Extreme Events. *Climatic Change, 79,* 185-211.
-Trenberth, K.E., P.D. Jones, P. Ambenje, R. Bojariu, D. Easterling, A. Klein Tank, D. Parker, F. Rahimzadeh, J.A. Renwick, M. Rusticucci, B. Soden and P. Zhai, (2007). Observations: Surface and Atmospheric Climate Change. In: *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
-Thomas, A. and R. Leichenko, (2011). Adaptation through insurance: lessons from the NFIP. *International Journal of Climate Change Strategies and Management, 3,* 250-263.
-Valverde, L. J. and M. W. Andrews, (2006). Global Climate Change and Extreme Weather: An Exploration of Scientific Uncertainty and the Economics of Insurance. Insurance Information Institute Working Paper.
-van Aalst, M., (2006). The impacts of climate change on the risk of natural disasters. *Disasters*, *30,* 5-18.

-Wainwright, J. (2010). Climate Change, Capitalism and the Challenge of Transdisciplinarity. *Annals of the Association of American Geographers, 100,* 983-991.
-Ward, M. N., E. M. Holthaus, A. Siebert, and D. Osgood, (2008). Index Insurance for Drought in the Millennium Villages Project, *American Meteorological Society Conference*, 20th Conference of Climate Variability and Change, P1.9.
-Ward, M. N., Brown, C., Baroang, K., & Kaheil, Y. (2012). Reservoir performance and dynamic management under plausible assumptions of future climate over seasons to decades. *Climatic Change, 18,* 307–320.
-Warner, K., N. Ranger, S. Surminski, M. Arnold, J. Linnerooth-Bayer, E. Michel-Kerjan, P. Kovacs, C. Herweijer, (2009). Adaptation to Climate Change: Linking Disaster Risk Reduction and Insurance. A publication managed by United Nations International Strategy for Disaster Reduction Secretariat (UNISDR).
-Wender, M., (2011). Goodbye Family Farms and Hello Agribusiness: The Story of How Agricultural Policy is Destroying the Family Farm and the Environment. *Villanova Environmental Law Journal*, *22(1),* Article 6.
-Wisner, B., P. Blaikie, T. Cannon and I. Davis, (2004). At Risk: Natural Hazards, People's Vulnerability and Disasters. 2nd edition, *Routledge,* New York.
-World Bank report, (2011). Weather Index Insurance For Agriculture: Guidance for Development Practitioners. Agriculture and Rural Development Discussion Paper 50.
-World Bank, (2013). Ethiopia: Using a Social Safety Net to Deliver Disaster Insurance to the Poor. Case Study.
-Yesuf, M., and R. Bluffstone, (2009). Poverty, Risk Aversion, and Path Dependence in Low-Income Countries: Experimental Evidence from Ethiopia. *American Journal of Agricultural Economics*, *91,* 1022-1037.
-Zeigler, A., J. Sheffield, E. Maurer, B. Nijssen, E. Wood, D. Lettenmaier, (2003). Detection of Intensification in Global- and Continental-Scale Hydrological Cycles:Temporal Scale of Evaluation, *Journal of Climate*, *16,* 535-547.

Websites

-AccuWeather; What Storm Damage Does Your Home Insurance Cover? (March 24th, 2010). Retrieved from http://www.accuweather.com/en/weather-news/what-storm-damage-does-your-ho/26548
-The Caribbean Catastrophe Risk Insurance Facility. (n.d.). Retrieved from http://www.ccrif.org
-Companie Nationale D'Assurance Agricole du Senegal (CNAAS) (n.d.). Retrieved from http://www.cnaas.sn/produits.php
-2013 Farm Subsidy Database; Environmental Working Group. (2013). Retrieved from http://farm.ewg.org
-Fielding, J., (2007). Environmental Injustice or Just the Lie of the Land: an Investigation of the Socio-Economic Class of Those at Risk from Flooding in England and Wales. *Sociological Research Online, 12*, http://www.socresonline.org.uk/12/4/4.html
–Hallegatte, S., J. C. Hourcade, (2006). Why economic growth dynamics matter in assessing climate change damages: illustration on extreme events. https://halshs.archives-ouvertes.fr/halshs-00009339.
-Index Based Livestock Insurance. (n.d.). Retrieved from http://livestockinsurance.wordpress.com
-Insurance Information Institute Hurricane and Windstorm Deductibles. (November 2014). Retrieved from http://www.iii.org/issue-update/hurricane-and-windstorm-deductibles
-International Finance Corporation Home. (n.d.). Retrieved from http://www.ifc.org/wps/wcm/connect/corp_ext_content/ifc_external_corporate_site/home

-International Finance Corporation; PlaNet Guarantee (2014). Retrieved from http://www.ifc.org/wps/wcm/connect/industry_ext_content/ifc_external_corporate_site/industries/financial+markets/retail+finance/insurance/planet+guarantee

-Major, D. C., R. Leichenko, K. Johnson, and M. Linkin, (2013). Projecting Future Coastal Flooding Damages with Climate Change. *Review of Environment, Energy and Economics (Re3)*. http://dx.doi.org/10.7711/feemre3.2013.09.002

-Mendelsohn, R., K. Emanuel, S. Chonabayashi, (2011). The Impact of Climate Change on Global Tropical Storm Damages. World Bank. https://openknowledge.worldbank.org/handle/10986/3638

-Munich Climate Insurance Initiative submission to Bali Action Plan, entitled "Insurance Instruments for Adapting to Climate Risks", September 2008. Retrieved from http://unfccc.int/resource/docs/2008/smsn/ngo/033.pdf.

-Munich Re Climate Insurance Initiative (n.d.). Retrieved from http://www.munichre.com/en/group/focus/climate-change/strategic-approach/leading-initiatives/mcii/index.html

-Risk Management Monitor, The 50 Largest Reinsurers (September 2011). Retrieved from http://www.riskmanagementmonitor.com/the-50-largest-reinsurers/.

-Smith, R., (2003). Statistics of Extremes with Applications in Environment, Insurance and Finance. http://www.stat.unc.edu/postscript/rs/semstatrls.ps

-UNEP Finance Initiative (n.d.). Retrieved from http://www.unepfi.org/about/statements/ii/

Chapter 3: Regional History, Economy and Adaptation Practices

In order to lay the framework for discussion of index insurance as a meaningful climate risk management tool in the West African Sahel, there is some need to understand the region's human history, economy and adaptation practices. Clearly many books can and have been written on these subjects. The purpose in this chapter is to give a relatively brief overview.

3.1. An Overview of pre-Colonial History: Human habitation in the West African Sahel can be traced back to at least 5000 years BCE. Unlike in many areas of early human habitation where archaeological evidence suggests that plant domestication predated animal domestication, the opposite seems to be true for the pre-history of the West African Sahel (Kahlheber and Neumann, 2007). As far as the archaeological record is able to elucidate, foraging and hunting were the dominant forms of livelihood during the first several millennia of human habitation in the region during a climatic period known as the African Humid Period. Paleoclimatic evidence suggests that this humid period came to a relatively abrupt end around 3500 BCE (deMenocal et al., 2000), culminating in a severe dry spell around 2500 AD (Guo et al., 2000) which forced human migration southward. It was in the context of this more arid period that the need for a more sedentary, cultivation oriented life began. Sorghum and pearl millet were among the first plant crops to be cultivated in the region and remain critical components of regional agriculture today (Kahlheber and Neumann, 2007). From the region's prehistory to the modern day, there has been tremendous diversity of language and culture and there are multiple hundreds of languages spoken and distinct ethnicities in the region today.

In the middle to later part of the Common Era, several large kingdoms rose to power between the 8th century CE and the French colonial period in the 19th century CE. The first of these kingdoms was the Kingdom of Ghana, centered in modern day Senegal, Mauritania and Mali, reaching dominance from the mid 700s to late 1000s CE. Figure 3.1 is a map depicting the domain of this ancient kingdom. This kingdom grew wealthy on trade of gold, ivory and salt, domesticated the camel and was considerably influenced by Islam and the Muslim conquest of Northern Africa (Muhammad, 2005; Levtzion and Spaulding, 2003). The kingdom of Ghana collapsed when sacked by the Almoravid movement in the 1070s (Levtzion and Spaulding, 2003). After this, several brief kingdoms followed, notably the Sosso, which briefly conquered the Mandinka kingdoms of modern Mali (Levtzion and Spaulding, 2003).

Figure 3.1: Map of the Kingdom of Ghana. (Maps of Ghana and the Swahili Coast)

After 1235 CE, the Mali Empire came to dominate much of the region, extending from the Atlantic coasts of modern Senegal and Mauritania into Guinea, Mali, and along the River Niger to Niger. Figure 3.2 is a map depicting the geographic domain of the Mali Empire. The Mali Empire was known for its great wealth and became a great center not only for trade, but also for learning and scholarship, including in mathematics, literature, astronomy and art. The city of Timbuktu in particular rose to prominence as a cultural center (Piga, 2003; Ki-Zerbo, 1997). The Mali Empire had many vassal states, but starting in the late 1300s began to lose control of many of the vassal states in the Northern and Eastern regions to the growing Songhai Empire. During this period after the 1300s, there was also a reduction of trans-Sahara trade and a shift of focus to trade along the Atlantic coast.

Figure 3.2: Map of the Mali Empire. (Heilbrunn Timeline of Art History. The Empires of the Western Sudan)

The Songhai Empire rose to regional dominance in the mid 1400s to late 1500s and came to claim much of modern Mali, Burkina Faso, Niger, and parts of modern Senegal, Guinea, Benin and Nigeria. Figure 3.3 is a map depicting the geographic extent of the Songhai empire. During the height empire, almost the entire course of the Niger River (except for the lower reaches in humid Nigeria) was under Songhai control, making it one of the largest Islamic empires in history (Muhammad, 2005). The city of Gao in the eastern part of modern Mali was the capital and seat of power, although Timbuktu maintained much of the cultural significance it had had under the Mali empire. The Songhai empire economy was based primarily on a clan system in which a person's lineage would determine his/her trade (Olson, 1979). In the late 1500s, invaders from the Saadi dynasty of modern Morocco sacked Gao, Timbuktu and Djenne, unseating the Songhai Empire's power (Muhammad, 2005). However, ruling such a vast territory quickly proved too challenging for the Saadi dynasty and the region became fragmented once again.

Figure 3.3: Map of the Songhai Empire. (The Songhay Empire 1493-1528)

In the east, near Lake Chad, in modern Niger, Nigeria, Cameroon and Chad, the Kanem-Bornu state (which had been in existence since the 9th century CE) rose to greater prominence following the fall of the Songhai empire and the Saadi dynasty (Zakari, 1985; Oliver and Atmore, 2005). Further west, various Hausa kingdoms rose to power and at times tried to consolidate power, but were frequently vulnerable to attack (Hogben and Kirk-Greene, 1966).

In 1809, the Fulani War led to the creation, under Usman dan Fodio of the Sokoto caliphate, an Islamic state (Hill et al., 2008). At its largest extent, the Sokoto caliphate extended from the eastern border of modern Burkina to modern Cameroon and included much of Niger and Nigeria. Figure 3.4 is a map depicting the geographic extent of the Sokoto caliphate. Ethnically, most of its inhabitants were Hausa, Fulani (although the empire also extended into Yorubaland in western Nigeria) (Falola, 2009a). The early rulers of the Sokoto caliphate abolished systems of hereditary succession in favor of leadership being appointed by virtue of Islamic scholarship and moral virtue (Chafe, 1994). The governance structure of the caliphate was that of multiple smaller (largely autonomous) emirates pledging allegiance to the sultan of Sokoto (Burnham, 1994). This sometimes led to internal clashes and conflicts. All land in the empire was considered owned by the whole community, although the sultan or individual emirs could allocate land to individuals or families (Swindell, 1986). Exchanges were largely monetized and by this point, agriculture had diversified a fair amount, including cotton, indigo, grain, rice, tobacco and onion (Lovejoy, 1978).

Islamic scholarship was an important port of the caliphate since its founding (Falola, 2009a).

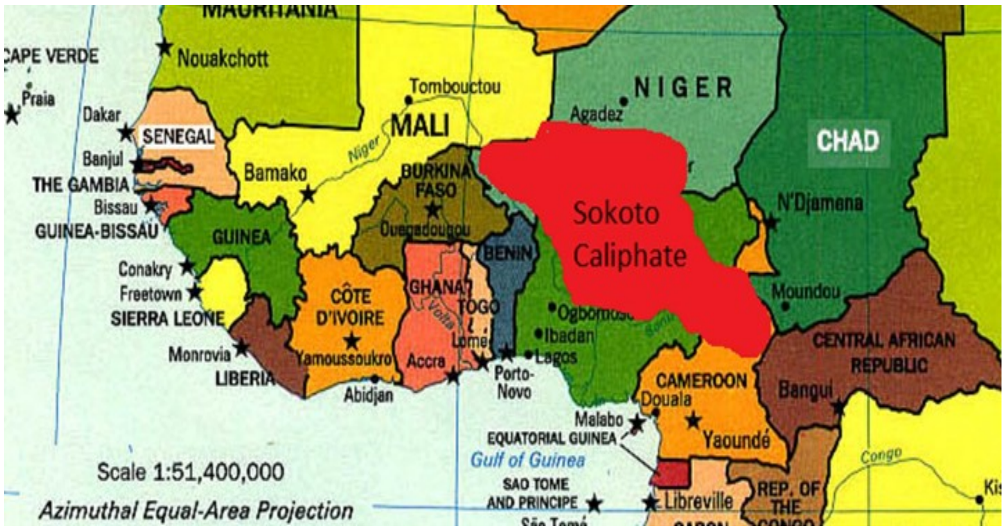

Figure 3.4: Map of the Sokoto Caliphate. (Nairaland Forum)

In the late 19th century, both the British and French had been taking a colonial interest in the Sokoto caliphate and West Africa more generally. British forces were able to exploit division within the Sokoto caliphate to their advantage and ultimately gained control of the Sokoto caliphate in 1903 (Falola, 2009b).

The earlier empires of the pre-colonial period, particularly the Songhai, did engage in slave trade and many of the slaves traded in early African empires were Europeans (Olson, 1979). However, from the 1600s to the colonial period, one of the major defining practices of the global economy was the Atlantic slave trade. While many Africans were "acquired" as slaves by kidnapping and raids at gunpoint, many African kings and local political leaders were willing to sell criminals and members of other ethnicities into slavery (Obadina, 2000). Between the mid-1600s and 1900 an estimated 10 million enslaved Africans ended up in the New World, over half of whom were traded in ports between modern Nigeria and Senegal. An estimated additional 2 million died on route to the New World (Lovejoy, 2000). Clearly, the horrific legacy of slavery took a terrible toll on both individuals and cultures. Slave trade was so widespread that parts of modern Togo, Benin, Nigeria and Ghana were known as the “Slave Coast”.

3.2. Regional Colonial History: Starting in the late 19th century, various European powers began to commandeer large portions of West Africa under the colonial “Scramble for Africa”. The two most powerful forces in West African colonization were the British and the French. This being said, other European colonial powers (Germany and Portugal) did play a more minor role. The modern nation of Cameroon had been a German colony from 1884 to the end of WWI, when the British and the French claimed different parts of its territory (Haupt, 1984). Modern Togo had been a German protectorate from 1884 to the end of WWI and was then taken by the French (History of Togo). Modern Guinea Bissau was a Portuguese colony (History of Guinea Bissau). Nigeria, Ghana, Sierra Leone and the Gambia were all British colonies. But the most geographically expansive colonization campaign in the region was under the French. Under colonial French rule, “French West Africa” or “Afrique Occidentale Francaise” was established as a federation of eight colonial territories: Senegal, Mauritania, Guinea (formerly French Guinea), Mali (formerly French Sudan), Cote D’Ivoire, Burkina Faso (formerly upper Volta), Niger, Benin (formerly Dahomey). The French also had colonial holdings in Northwest Africa (modern Morocco, Algeria and Tunisia), and central Africa (modern Chad, Central African Republic, Gabon and People's Republic of the Congo). French colonial rule from the late 1800s to WWII was extremely restrictive and West Africans under this rule were not considered French citizens, but rather "French subjects": meaning they did not have the rights to own property, due process, travel internationally, dissent, or vote. The sole geographic exception to this were some small areas within what is modern Senegal in which citizens were treated as French citizens and were able to participate in French political life (Aldrich, 1996; Manning, 1998). Figure 3.5 is a map depicting European colonial rule of Africa in the late 19th century.

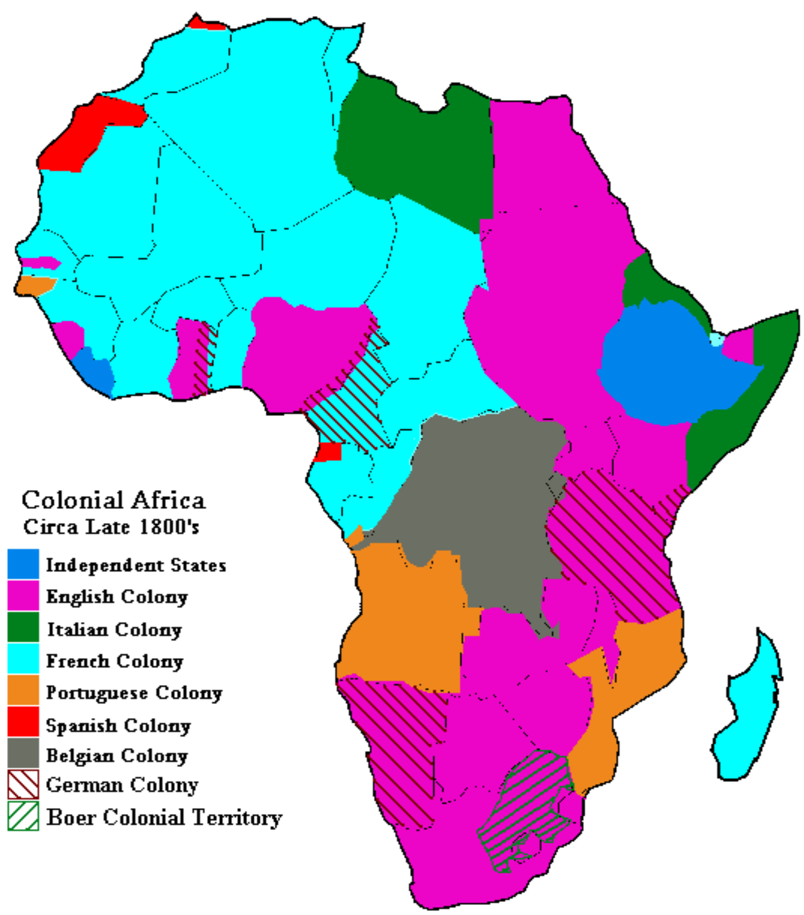

Figure 3.5: Map of the European Colonization of Africa circa late 1800s. (Empathos National Library; Colonial Africa)

In order to coalesce power and administration during this period, the French transferred all political power pertaining to the "governance" of French colonial West Africa west of Gabon to a single Governor General in Senegal (Klein, 2007). French lieutenant governors who would report to the Governor General in Dakar were appointed to administer the individual colonies of French West Africa. Within each colony, there were French "commandants de cerle" who would administer small collections of villages. Only at the most local, village specific level (beneath the level of the "cercle") were there African village chiefs (who themselves were selected by the French for their loyalty to French purposes and subject to removal by the French) (Conklin, 1998).

While the French had been less deeply involved in the Atlantic slave trade than their counterparts in Britain and Portugal, French exploitation of the native populations of their colonies often involved slave labor (Ali Dinar). During the French colonial period, there was also exploitation through taxation. While the production of groundnuts and cotton was encouraged, much of the proceeds of the sale of these cash crops went directly to the France. This was somewhat at odds with the legacy of British African colonial rule, where there was somewhat more autonomy in governance and some of the wealth acquired in the colony accrued to an African middle class (Ali Dinar).

Geographically, the borders of Cote D'Ivoire, Benin and Guinea were the first to take their contemporary shape. Mali, Burkina Faso and Niger, being interior landlocked areas were not delineated as separate administrative areas until 1925. Then, for much of the 1930s, modern Burkina Faso was bifurcated into two parts – the northern part being absorbed into the administration of Mali and the southern part being absorbed into the administration of Cote D'Ivoire (WHKMLA, 2005).

In 1940, with the fall of France to Nazi Germany and the failed attempt on the part of the Allies to regain Dakar for the Free French, much of French West Africa became part of the Nazi colonial empire through the administration of Vichy France until the Allied landings in North Africa in 1942. Quite understandably, there was a great deal of anger and resentment directed towards the French, which had been building from the early stages of the colonial period.

At the end of WWII, in 1945, the French government began a process of extending more limited rights to the colonies. For the first time, several seats in French Parliament were granted to West African "subjects". In 1946, a new law granted some limited citizenship rights to natives of the African colonies. 1946 also brought the election of local representatives in each territory. In 1956, the "Loi Cadre" brought universal suffrage to the French colonies and made the African colonies a part of the French union. In 1958, the legal structure changed again, and the colonies became "protectorates " in the "French community". In 1960, a further revision of the French constitution, the failure of the French-Indochina War, and conflict in Algeria enabled most of the former colonies to unilaterally change their own constitutions and to declare independence (Manning, 1998; Chafer, 2002).

Some loose multi-state coalitions existed briefly after this push for independence: Senegal and Mali formed the "Mali federation" and Niger, Burkina

Faso, Benin and Cote D'Ivoire formed the Sahel-Benin Union. But each of these coalitions was short lived, and by 1961 each modern Sahelian West African nation was both independent from France and from each other and engaged in autonomous governance (Chafer, 2002).

Clearly, the repressive nature of French colonial rule had a profound impact on the region's political and economic development during the colonial period and after. Arguably that legacy of exploitation is a significant part of the reason for the region's extreme poverty today as the actions of the colonial power can be viewed as an appropriation of African labor productivity in the service of the colonial empire. Furthermore, as there was very little European settlement in French West Africa (as compared to British colonial South Africa for example), there was also comparatively little development by the colonizers of physical infrastructure (Huillery, 2009).

While there are "different perspectives" on the legacy of colonialism and the true impacts of colonization on the post-colonial period, the critical geographic and philosophical traditions of Western scholarship and much of the African post-colonial scholarship paints a decidedly negative picture of the colonizing forces. Terms like "subaltern", coined by philosopher and theoretician Gayatri Spivak and "Orientalism", coined by Edward Said describe the psychology of "othering" and subordination used to rationalize colonialism in the past and imperialism in the present. Many African scholars and politicians in both British and French West Africa, including (but certainly not limited to) Chinua Achebe, Djibo Bakary, Hamani Diori, Cheikh Anta Diop, Joseph Ki-Zerbo, Nazi

Boni, Aoua Keita, Adame ba Konare and many others have written and spoken very critically of the devastating impacts of colonization and its enduring hegemonic legacy.

3.3. Regional post-Colonial History: Following independence from France in 1960, the nations of Mali, Burkina Faso and Niger, along with the other former colonies of French West Africa set out on a process of democratization. However, this endeavor was complicated, in part by the profound ethnic and linguistic and livelihood diversity of the respective countries. As mentioned previously, the West African Sahel is home to a tremendous diversity of culture and language and the colonial borders of French administration tended to reflect geographic convenience in the interests of the French rather than a true understanding of the ethnic diversity of the region.

Mali: At the time of Malian independence in 1960, the estimated population was around 4 million and the first president was Modibo Keïta, an advocate of African socialism (Library of Congress, 2005). His policies focused on nationalization of economic resources and he established a one-party state. Following progressive economic decline, in 1968, Keita’s power was toppled in a bloodless military coup led by Moussa Traoré. The military led government of Moussa Traoré held onto political power for more than two decades but faced multiple challenges (Library of Congress, 2005). While there was an attempt on the part of Traoré to reform the economy, devastating droughts in the early 1970s, which led to widespread famine, and multiple episodes of political unrest demanding multi-party democracy threatened Traoré's power (Loyn, 2005). In the late stages of his rule, Traoré allowed some limited political liberalization, but would not allow full-fledged multi-party democracy. In the 1980s, many of the economic policies aimed at satisfying the demands of the International Monetary Fund, but within Mali, the net effect tended to be the benefit of already wealthy and the further impoverishment of the poor. In 1990, cohesive opposition movements began to form, but the political situation was complicated by the return of many Tuaregs[14] to northern Mali. Peaceful student protests against the prevailing economic policies were violently suppressed in 1991 (Library of Congress, 2005).

Anti-government revolutionary protests in March of 1991 ultimately led to a coup (especially when many members of the military decided to join the cause of democracy and no longer follow the orders of Traoré), a transitional government and a new constitution. In 1992, the first multi-party democratic election resulted in the presidency of historian and geographer Alpha Konaré. Konaré was re-elected for a second term in 1997 (Library of Congress, 2005). His terms were noted for the restoration of democracy, the decentralization of the government and his handling of the Tuareg "Rebellion" and the civil war of the early 1990s. Corruption was still a significant problem during his presidency.

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[14] The Tuareg people are a Berber ethnic group, who live a nomadic, pastoralist life primarily in the Sahara Desert or on the very fringes of the Sahel. Tuareg peoples inhabit parts of Mali, Niger, Burkina Faso, Algeria, Libya, Morocco and Tunisia. Because their lifestyle is nomadic, and so heavily exposed to drought risk, they have at times been in conflict with the "settled" populations of the abovementioned countries. Many Tuaregs have felt that in the wake of the dissolution of French colonial rule, there should have been a separate Tuareg state and that the central governments of the nations in which they live don't really appreciate their needs. These tensions have led to several "rebellions" and separatist movements throughout the region's postcolonial history.

In 2002, retired general Amadou Touré, who had led the military revolt against Traoré 11 years earlier was elected president. He also served two terms and his presidency was sometimes viewed as atypical because he did not belong to a defined political party and built a governing coalition from many political parties. In spite of sluggish economic development, some problems with corruption and various ethnic tensions, the presidential administrations of Konaré and Touré are generally regarded as periods of relative political and social stability (USAID Africa: Mali).

Early in 2012, this period of comparative calm came to a rather dramatic end when several insurgent groups began fighting against the Malian government for greater autonomy of northern Mali. Among the groups fighting was a Tuareg separatist group (Mouvement National pour la Libération de l'Azawad (MNLA)) and an Islamist Tuareg group Ansar Dine. The insurgency quickly led to capture of the Northern Malian cities of Kidal, Gao and Timbuktu (Ahmed and Callimachi, 2012). Shortly thereafter, the Islamist group Ansar Dine and other Islamist groups including the Movement for Oneness and Jihad in West Africa (MOJWA) and Al Qaida in the Islamic Maghreb (AQIM) which had joined MNLA in fighting against the Malian government, claimed the territorial gains against Mali as their own in an effort to advance their own objectives (BBC, June 2012). Elements within the Malian military were disappointed with the Touré government's handling of the crisis in Northern Mali and carried out a non-violent coup d'etat in February and March of 2012 (This Day Live, March 2012). The US Air Force air-dropped supplies to assist the Malian military during the early months of this conflict (News 24, March 2012). By July of 2012, the Islamists had gained control of much of Northern Mali from the Tuaregs (Nossiter, 2012).

The Malian government and the regional coalition Economic Community of West African States (ECOWAS) appealed to the French and more broadly to the international community for military assistance in dealing with the crisis in the north in the autumn of 2012 and in early 2013, French and African Union military forces joined in the fight to regain control of northern Mali. In response to the tensions between the objectives of the Tuaregs and the Islamists, in January of 2013, the MNLA realigned with the Malian government in exchange for more autonomous control over the states of Northern Mali (Al Arabiya, January 2013). After several months of fighting in which Malian, French, African Union and Tuareg forces combined to fight the Islamist elements in northern Mali, much of northern Mali was regained. In June of 2013, a peace accord was struck between the government of Mali and the MNLA (BBC, June 2013). Three months later, the latter backed out after government forces opened fire on unarmed protesters (Al Jazeera, November 2013). Tensions continue to the present, although the intensity of the fighting, violence and bloodshed over the last year is significantly less than during the initial phase of the conflict in 2012. The presidency of Mali also changed hands an additional time since 2012; from March of 2012 to September 2013, the interim president was Dioncounda Traoré and in September 2013, Ibrahim Boubakar Keita was elected (Diallo and Diarra, 2013).

Burkina Faso: Formerly the Republic of Upper Volta, Burkina Faso was given its contemporary name in 1984 by then president Thomas Sankara. "Volta" refers to the Volta River system, which drains to the Gulf of Guinea through Ghana. The upper reaches and headwaters of the three main tributaries (the Black, Red and White Volta) are in Burkina Faso and much of the country is in the Volta river drainage basin.

In 1960, after independence from France, the first national elections involving universal suffrage were held and Maurice Yaméogo was elected the nation's first president. Yameogo banned all political parties except his own, provoking a great deal of unrest. In 1966, the military intervened and he was deposed in a coup d'etat. (Lefaso.net, 2009). The coup d'etat resulted in the dissolution of the National assembly and military rule under Lt. Col. Sangoulé Lamizana for four years. In 1970, Upper Volta ratified a new constitution that established a four-year transition period towards complete civilian rule. Lamizana retained power even into the later 1970s as president of mixed civilian military governments. (Lefaso.net, 2005). In 1977, a new constitution was written and in 1978, Lamizana was re-elected. However, following challenges with powerful trade unions, in 1980, Lamizana's government was overthrown in a bloodless coup by the forces of Colonel Saye Zerbo. In so doing, Zerbo eradicated the 1977 constitution. In 1982, following its own struggles with the nation's powerful trade unions, Zerbo's government was overthrown by the forces of Major Dr. Jean Baptiste Ouedraogo and the Council of Popular Salvation (All Africa; Jean Baptise Ouedraogo).

Factional infighting developed between moderates in the CSP and other elements led by Captain Thomas Sankara and in August of 1983, yet another coup d'etat brought Sankara to power. Sankara was a pan-Africanist, Marxist (he was an admirer of Fidel Castro) and emphatically anti-imperial in his philosophy. The translation of "Burkina Faso" is "land of the upright/honest people". Sankara refused Western aid from the International Monetary Fund and the World Bank and focused on promoting agricultural self-sufficiency and widespread campaign of vaccinations against common diseases; meningitis, yellow fever and measles (Omar, 2007). Part of his government's plans also included planting millions of trees to stall the progress of desertification (California Newsreel, Thomas Sankara: The Upright Man). He also promoted agricultural development by redistributing land to the poor and by engaging in an ambitious rail and road network. His policies were also progressive on matters of gender and education promoting the expansion of schools and outlawing forced marriage, polygamy and female genital mutilation. While his policies were quite progressive and is widely regarded favorably by many of Burkina Faso's poor population, his rule was rather authoritarian and resulted in the banning of unions and free press. His populist agenda ran counter to a variety of entrenched interests within the country and internationally (Bounkoungou, 2007).

In 1987, a French backed coup d'etat ended his rule (and his life through assassination) and Blaise Compaoré became the new president. Early in his career, Compaoré was actually considered friends with Sankara and he (Compaoré) played an active role in the coups d'etat against Zerbo and

Ouedraogo in the early 1980s. Compaoré described the killing of Sankara as an accident but the circumstances were never properly investigated (Kasuka, 2011).

This being said, he described his policies and those of his ruling party (the Congress for Democracy and Progress (CDP)) as a “rectification” of Sankara’s populist progressive Marxism. He reversed many of the policies of Sankara and returned the country back to the fold of the International Monetary Fund. One of his arguments was that Sankara’s policies had compromised the relationships between Burkina Faso and France and Cote D’Ivoire (Kasuka, 2011).

Some limited democratic reforms were introduced in 1990. In 1991, Compaoré was re-elected in a sham election where the main opposition parties boycotted the election. He was re-elected in 1998. In 2000, a constitutional amendment was put into place limiting a president to two terms. However, in 2005, he ran (and won) again, arguing that the constitutional amendment should not be applied retroactively (IRINNews, August 2005). He was then re-elected again in 2010.

In late October 2014, after having been in power for 27 years, when Compaoré dissolved the government in order to make a constitutional amendment to try to extend his rule yet further, violent protests ensued and Compaoré decided to step down from power. At present, the interim leader for the transitional government is Lt. Colonel Isaac Zida. Despite the controversies surrounding Compaoré’s nearly three-decade rule, his government has played an important role in mediating regional tensions; including the 2010-2011 Ivorian crisis and the 2012 Northern Mali conflict (Chilson, 2012).

Niger: In 1960, at the time of Niger's independence from France, Hamani Diori was the first president. He had been the head of the counsel of Ministers of the Republic from 1958 to 1960. For the first 14 years of Niger's independence, Niger had a single party civilian government with Hamani Diori as president (Decalo, 1990). While Diori gained international respect as a spokesman for African affairs and his arbitration in conflicts involving other countries, his domestic administration was plagued with larger problems and there were several coup attempts during his administration. In 1974, a combination of severe drought and accusations of rampant corruption led to the coup of the Diori regime. In 1974, military forces under the direction of Col. Seyni Kountché took power after the coup and Kountche was the president until his death in 1987 (Decalo, 1997). While one of the first actions of Kountché's rule was to seek to address the food crisis caused by the drought, his rule was quite autocratic and all political parties were banned. One of Kountche's policies during this period of drought was to prohibit urban residents from housing or sheltering non-kin who had left more drought vulnerable areas (Alidou, 2005). Like his predecessor, Kountche's aversion to political dissent led to multiple coup attempts. However, during this time, there was economic growth and infrastructure expanded. The economic growth of the 1970s and 1980s was also facilitated by a growing international demand for uranium (Decalo, 1997).

Kountche's rule was followed, in 1987 by the rule of his chief of staff, Colonel Ali Saibou. In 1989, a new constitution was adopted and new presidential elections were held and Saibou was re-elected. While Saibou made attempts to normalize political relations and liberalize some of the policies of his predecessor, there was still a widespread demand for a true multi-party democracy. The Saibou regime acquiesced to these demands at the end of 1990s and organized a national conference in 1991 to begin an era of multi-party democracy. The national conference formed a transitional government, proposed a new constitution and put a number of new institutions into place including the right to freedom of press. New presidential elections didn't take place until 1993 when, in the nation's first multiparty democratic elections, Mahamane Ousmane was elected. Ousmane's presidency was politically turbulent, and short-lived although it did result, in 1995 with a peace accord between the central government and Tuareg groups. There were in particular tensions between Ousmane and his Prime Minister Hama Amadou (Ibrahim and Souley, 1996).

Frustration with political gridlock led to a coup d'etat, carried out by the forces of Ibrahim Baré Mainassara in 1996 (Ibrahim and Souley, 1996). Elections were held later that year and Ousmane was allowed to run as a candidate, but Mainassara won the vote in a highly controversial election (African Elections Database; Elections in Niger). His presidency was somewhat in line with a rise in Islamic fundamentalism and his economic policies engaged the International Monetary Fund but the country subsequently struggled under the burden of debt (BBC, April 1999). In 1998 and 1999 there were increasing protests about his legitimacy and in 1999, Mainassara was ambushed and killed by soldiers as he was trying to flee the country (BBC, September 1999).

The coup leader, Daouda Wanke succeeded Mainassara as temporary head of state until elections later that year, which resulted in the election of Mamadou Tandja. Mamadou Tandja was president of Niger from 1999 to 2010. Debt accrued in earlier administrations and limited economic growth made international donor support quite limited. In an effort to promote economic development Tandja's administration took some (rather unpopular) measures to limit government spending, including reducing educational grants and limited military pay which led to a mutiny (BBC, September 1999). Despite growing unpopularity in his first term, Tandja was re-elected in 2004, although he again came under sharp criticism for his handling of the 2005 drought and famine, claiming that there was no food crisis (BBC, September 2005).

While Tandja had initially signaled a willingness to step down from power at the end of his second term in 2009, as the election drew nearer and his allies advocated he stay, he dissolved the government and tried to force a new constitution, which would have abolished a two term limit (Massalitchi, 2009).

Consequently, in February of 2010, a coup d'etat organized by the Supreme Council for the Restoration of Democracy deposed Tandja from power. Lt. General Salou Djibou was the coup organizer and interim leader. New presidential elections were held in January 2011 and the new (and current) president of Niger is Mahamadou Issoufou. Issoufou had been a prominent candidate in several of Niger's prior presidential elections. But already, in late 2013, large-scale protests have been highly critical of his inability to alleviate chronic challenges of food insecurity and economic development (Al Jazeera, December 2013).

3.4. Regional Economy, Demographics and Culture: These three nations share many economic similarities, while simultaneously embodying tremendous cultural diversity. There is a very pronounced regional north to south precipitation gradient, which has a deep impact on vegetation cover as shown in Figure 3.6. This, in turn has a deep impact on the geography of farming and pastoral practice and places constraints on population density as shown in Figure 3.7. The majority of the region's population lives in the southern/southwestern portions of the respective nations.

Figure 3.6: Satellite map of contemporary West Africa. (The Onyx Express; Preserving our Culture, our Legacy)

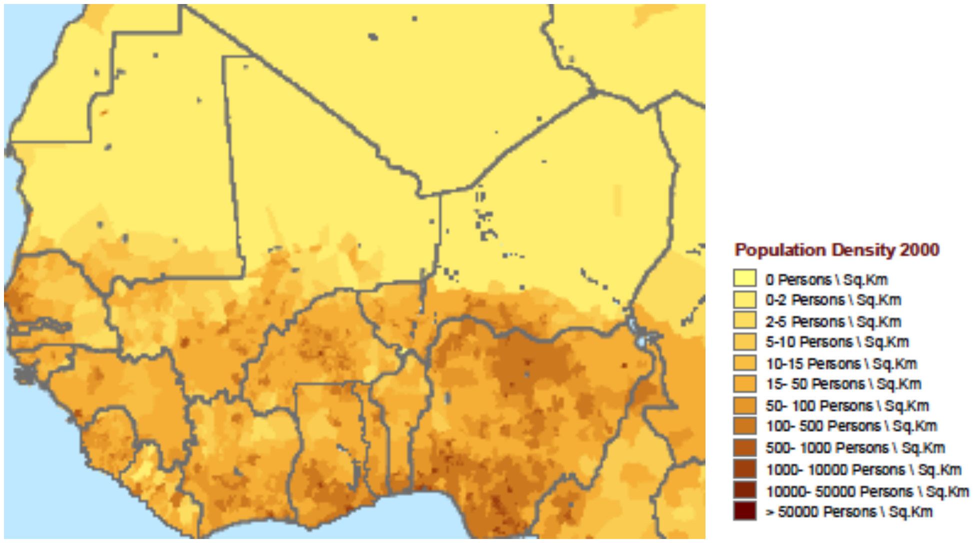


Figure 3.7: Population density map of West Africa (2000). (Poverty Mapping, SEDAC, CIESIN)

Mali: Mali's population has increased significantly since independence from the French in 1960, reaching around 16 million today (from around 4 million in 1960). Most of the nation's population is rural, but according to the 2009 census, roughly 1.8 million people live in the capital city of Bamako and there are seven other cities with over 100,000 inhabitants. While Mali has a relatively short life expectancy (in the low 50s), the observed very rapid population growth is a product of a very demographically young population (median age is around 16) (CIA, 2009). The government takes the form of a semi-presidential republic with both a president and a prime minister. Roughly half of the population lives on less than 1.25 USD/day and the aggregate per capita GDP (in purchasing power parity) is around 1100 USD/year). Roughly half of the population is of the Mande ethnicity. The Fula are the largest minority ethnic group at around 17% of the population, followed by the Voltaic (Senufo and Bwa) and the Tuareg and other smaller minorities (Library of Congress, 2005). Roughly 90% of the population is

Muslim, although a majority of the Muslim population is non-denominational. The most common vernacular language is Bambara. However, in addition to Arabic and the colonial French, there are 13 other native languages that have national language status and several dozen other languages (Library of Congress, 2005).

Mali’s key industry is agriculture. Cotton is its most valuable export crop, but the majority of farmers are engaged in farming subsistence crops or lower value cash crops. Millet, rice, maize, groundnuts, and various vegetables, along with livestock rearing constitute the livelihoods of most Malians. Roughly 80% of the Malian workforce works in agriculture and the majority of the balance works in the service sector. Gold, livestock and agriculture amount to 80% of Mali’s export economy (Carpenter, 2007; CIA, 2009).

Burkina Faso: Like Mali, the population of Burkina Faso has increased significantly since independence from the French in 1960 (around 4.5 million), to around 17 million today. Like Mali, the majority of the population is rural, but the capital and largest city of Ouagadougou is home to around 1.7 million inhabitants. The second largest city, Bobo Dioulasso has over a half million inhabitants, but no other Burkina cities exceed a population of 100,000. Life expectancy and median age in Burkina Faso are quite similar to Mali. A comparable proportion of the nation’s inhabitants live on less than 1.25 USD/day although the aggregate per capita income is a little higher than Mali (around 1700 USD/year in purchasing power parity terms) (International Monetary Fund, 2014). Roughly half of the population is of the Mossi ethnicity. The Fula are the largest minority ethnic group at around 10% of the population, followed by a number of other smaller minorities. Tuaregs comprise only about 3% of the Burkinabe population. According to a 2006 government census, about 60% of the population is Muslim, around 25% are Christian and most of the rest follow traditional belief systems. The three “recognized languages” of Burkina Faso (other than French) are Moore, Mandinka and Bambara. However, Burkina Faso is home to roughly 70 languages (Lewis, 2009).

The economy is also quite similar to that of Mali – roughly 80% of the population is engaged in agriculture and/or raising livestock. Millet, maize, rice, cotton, peanuts (groundnuts) and sorghum are the most central crops. Mineral resources include gold, copper, iron, manganese, phosphates, and tin (Profile – Burkina Faso). The service sector is still rather underdeveloped, although some utilities have performed quite well.

Niger: Niger’s population has grown even faster than that of Mali or Burkina Faso, and according to many sources (UN, CIA and World Bank estimates) has the highest national fertility rate in the world (Mali being second). In 1960, the population was around 3.5 million people and is almost 18 million today. Like Mali and Burkina Faso, the population is largely rural. The capital and largest city of Niamey has experienced rapid population growth in the last decade and a half and is now estimated to have a population on the order of 1.5 million. Zinder, Maradi, Agadez and Tahoua also have populations in excess of 100,000 residents.

Life expectancy and median age in Niger are quite similar to Mali and Burkina Faso. A comparable proportion of the nation's inhabitants live on less than 1.25 USD/day although the aggregate per capita income is lower than for Mali or Burkina Faso (around 800 USD/year in purchasing power parity terms). Roughly half of the population is of the Hausa ethnicity. The Zarma, Tuareg and Fula are the largest minority ethnic groups at around 20%, 10% and 10% of the population, respectively. Roughly 99% of Niger's population is Muslim. In addition to French and Arabic, the "national languages" of Niger are Hausa, Fulfulde, Gourmanchema, Kanuri, Zarma and Tamasheq. Niger is home to over a dozen languages (Ethnologue; Niger).

The economy is also quite similar to that of Mali and Burkina Faso – roughly 80% of the population is engaged in agriculture and/or raising livestock. Millet, cowpeas, cassava, rice, cotton, peanuts (groundnuts) and sorghum are the most central crops. The most profitable mineral resource in Niger has been uranium, primarily found in the north of the country and recently oil exploration has begun and oil is a new export (All Africa, November 2011). The service sector is still rather underdeveloped and as with Burkina Faso and Mali, Niger is a recipient of international donor aid for development.

The extreme poverty of the region is accompanied not only by very high fertility rates and short life expectancy, but also by a range of other correlated socioeconomic risks including high rates of infant mortality, relatively limited literacy rates, limited access to health care, and elevated risks of food insecurity.

A number of mapping studies show correlated indices of poverty at the national and subnational level (Poverty Mapping, SEDAC, CIESIN).

3.5. Climate Vulnerability as a Social and Gendered Construct: It is clear from the prior discussion of the region's political history and economy that drought risk poses a significant challenge to the people of the West African Sahel. While not perceived as being as large a threat to regional livelihoods, flooding risks hold the potential for significant future economic losses and displacement (Tarhule, 2005; Tschakert et al., 2010).

In the preceding sections of this chapter, the discussion of the region's political history has focused largely on political and military history; a space generally dominated by male (and often relatively wealthy) actors. However, the discourse on vulnerability to climate extremes is also a socially constructed and gendered discourse. Many asymmetries exist within the society of the West African Sahel. Among those asymmetries is the issue of gender equity. While the broad cultural and religious overtone of the region is patriarchal and rather restrictive of women's liberties, there are multiple embodied realities of gender relations in the Sahel, ranging from the most conservative "secluded" lives to emergent more "modern" sensibilities (Alidou, 2005; Schroeder, 1986). In particular, regional gender norms generally have historically had a particularly negative impact on women's climate related vulnerability; through reduced earning potential, reduced ownership rights, reduced access to education, disproportionate suffering in the context of seasonal hardships and several other economic disadvantages (Schroeder, 1986).

During agriculturally difficult times, men will often leave rural villages to go to cities or mines in search of work. This labor migration can also be a challenge to community sustainability and while a sense of community is somewhat pervasive as a cultural norm, increased livelihood stress tends to lead to more individuated behavior and some intra-communal and intra-household conflict often along gender lines (Chetima and Borlaug, 2008). It is very clear from both regional literature and a broader discourse on vulnerability that there are often deep gendered differences in vulnerabilities within societies. In going forward constructively, adaptation measures must be attentive to these issues and seek to reduce gender inequity and engage feminist perspectives (in both climate vulnerability discourse and more generally in the construction of an understanding of the region's history and collective experience) (Busia, 2005; Tall et al., 2014; Nath and Behera, 2011).

Gender related challenges and drought vulnerabilities are also a product of globalization as well as regional culture (Alidou, 2005), thereby feeding into a broader discourse of double exposure (Leichenko and O'Brien, 2008). While much of the literature on climate-linked vulnerability focuses on exposure to climate risks at a relatively large scale of spatial and political aggregation, there is also scholarship the delineates a finer structure of vulnerability, adaptive capacity, social welfare, and pre-existing conditions (Paavola and Adger, 2006). At times, the very structures that create certain vulnerabilities and differentiated access to resources (such as markets for agricultural goods) are often also perceived as the best hope of alleviating poverty and addressing underlying development concerns (Shipton, 1990).

To that end, arguably well-intentioned development initiatives can wind up exploiting pre-existing divisions either across class lines or gender lines. One study shows how initiatives to promote land reclamation[15], while in principle a good idea with a clear community benefit may prompt the overturning of existing land tenure practices along certain social, cultural or gendered lines. Specifically, in the Gambia, female market gardeners had helped ease the economic impact of persistent drought conditions, only to have their resources taken by male lineage heads and community leaders through donor generated agroforestry and soil and water management projects (Schroeder, 1997).

Participatory methods can more directly assess the perception of risks on the part of vulnerable populations. One such study in Senegal queried rural villagers on their respective perceptions of their own livelihood vulnerability. Results were analyzed on the basis of gender. Bad health and lack of money were perceived as the greatest threat to life and livelihood in the region. Female respondents tended to the above participatory study in rural Senegal tended to be more concerned about health issues, poor village level infrastructure and lack of access to capital/job training than their male counterparts (Tschakert, 2007). While these concerns are not necessarily climate dependent, clearly, climate variability and change can also have profound impacts on health. Much of the

[15] land reclamation in this sense is a process by which degraded soil is renewed or rehabilitated through practices designed to reverse the damage of the earlier degradation

Sahel is part of Africa's "meningitis belt" and is also vulnerable to epidemic or endemic malaria transmission (Thomson et al., 2004; Lafferty, 2009). More broadly, adaptive capacity, resilience and vulnerability at the individual level are heavily dependent on mobility, regional institutional strength, monetary, and social capital (Nath and Behera, 2011).

3.6.Vulnerability and Adaptation to Drought (overview): There are several conceptual definitions of drought that are commonly used including meteorological, hydrological, agricultural, and socioeconomic. Meteorological drought is generally defined in terms of rainfall deficit or through a combination of rainfall and temperature metrics. Hydrological drought is generally defined in terms of surface and/or subsurface water supply (streamflow, water table, reservoir levels, etc.). Agricultural drought connects the hydroclimatic forcing to agricultural impact focusing on soil moisture at critical times in a crop's growing cycle. Socioeconomic droughts are generally defined as situations in which the demand for a commodity exceeds the supply because of a water deficit (National Drought Mitigation Center).

Environmental and human geographers have explored the impact of drought and land degradation on different portions of the West African economy and have explored both the environmental and social causes for such impacts, often through the context of political ecology and political economy. Discourse on drought vulnerability relates back even to the colonial era. A detailed historical study of the political economy and political ecology of food production in the northern Nigerian Sahel suggests that during the pre-colonial period, practices were somewhat more adaptive to regional climate shocks than during the colonial and later times. This study argues that the commoditization of food production and the diversion of agricultural resources towards cash crop production led indirectly to significant Marxian challenges. During the droughts of the late 20th century, per capita food production declined, producing a need to supplement the subsistence economy with purchased grain, which was itself impacted by drought and consequently subject to price fluctuations, feeding back on the average citizen and often creating an intensification of indebtedness and poverty (Watts, 1983).

On multi-year time scales, desertification[16] is a related issue that also has received much attention in the literature on the West African Sahel. One of the early theorists of Sahelian desertification was the notable meteorologist Jule Charney. The meteorological argument behind the narrative of Sahelian desertification is that with the removal of vegetation cover, the surface albedo of the landscape increases. This increased albedo then causes more radiative cooling aloft, leading to upper level atmospheric subsidence and a consequent retrenchment (and potential expansion) of arid conditions (Charney, 1975; Xue and Shukla, 1993). In these early theoretical studies, the magnitude of the impact was quite significant, implying that the region's climate was highly sensitive to changes in vegetation cover (either by natural means or by changes in cultivation practices). While this conceptual model of desertification is meteorologically

[16] Desertification is defined as the process of the encroachment of the desert landscape on formerly non-desert environments. While the process is often accelerated by drought, other (often human) factors, such as overgrazing and various other types of land use change are intimately connected with the process of desertification.

sound, overemphasis on this particular mechanism at times led to the assumption (later proven largely incorrect) that the Sahelian drought of the late 20th century was caused largely by land degradation (Brooks, 2006). It has been shown in the more recent past that much of the variability of Sahelian rainfall can be more properly linked to patterns of tropical ocean temperatures and the temporal variability of the temperature gradient between the Sahelian interior and the tropical oceans (Giannini et al., 2003). Nevertheless, on a local scale, vegetation feedbacks on rainfall and land degradation can be important issues.

The companion issues of land degradation and desertification are intertwined with both the discourse of drought and rural livelihood vulnerability. In the tradition of Charney's hypothesis, some quantitative research in environmental geography has suggested that desertification is the result of a biophysical feedback mechanism that is inherently unstable and may lead to persistence of degradation following relatively small environmental forcings (Phillips, 1993; Charney et al., 1977), thereby potentially confounding the prospects for vulnerability reduction if even relatively small changes are made to reduce vegetation cover. However, other studies show that even in the height of the late twentieth century drought, when regional rainfall was some 30% lower than it had been in the 1950s and 1960s, the margin of the Sahara desert did not shift southward considerably and there had been no substantive systematic reduction in water use efficiency of the vegetation cover in the Sahel in the 1980s and 1990s (Nicholson et al., 1998; Prince et al., 1998).

Efforts to understand the extent of soil erosion have often proven problematic because of data constraints. A local political ecology approach may help to elucidate some of the linkages between soil health and the natural and social environment. Fieldwork in Niger in the 1990s showed that erosion is correlated with factors such as male migration, suggesting that households with access to non-farm income may facilitate soil erosion indirectly (Warren et al., 2001). Furthermore, farmer concerns tended to focus on losses of soil's productive capacity, rather than absolute erosion rates (Warren et al. 2003).

There have been multiple policies over the course of the region's history aimed at trying to encourage more resilience and sustainable practice. One of the most significant recent international efforts to combat desertification and to encourage more resilient and sustainable land use has been Africa's Great Green Wall project, sponsored by the UNDP Global Environmental Facility (GEF). In principle, this "green wall" will be, at completion around 9-10 miles wide and stretch over 4000 miles long from the Atlantic coast of Senegal to the Red Sea coast of Djibouti. The proposed vegetation cover is intended to help stabilize soils and fight desertification. In theory, this project should also create at least a small-scale favorable biophysical feedback on the climate system that encourages more rain (more vegetation => lower albedo, more water storage in plants => greater potential for convective motion and more water available through transpiration) (The Great Green Wall Initiative; GEF).

In 2010, 11 countries of the Sahel and Sahara signed a convention to create the Great Green Wall Agency and the PanAfrican Agency of the Great

Green Wall (PAGGW). The project is financed by the GEF Trust fund, the Least Developed Countries Fund (LCDF), and is backed by many other regional and international organizations including REDD+, the World Bank, various other UN agencies, and various African organizations. The goal of the GGW Agency is to strengthen and harmonize existing regional efforts to combat desertification (The Great Green Wall Initiative; GEF). While there are already regional projects underway undertaken by smaller scale agencies, the language of the GGW Agency and the PAGGW is aspirational. One local project under the initiative has led to planting trees in some 50,000 acres of land in Senegal (Science Alert, July 2014).

Drought vulnerability and adaptation for farming communities: The rainy season is relatively short, especially for the more arid zones further north. Consequently, growing seasons are also relatively brief for most crops and in most sub-regions within these three nations. Planting dates are contingent on rainfall and soil moisture conditions being favorable and local practice for assessing planting date often involves hand testing soil moisture (anecdotal information, multiple experts, 2010 field study). Growing seasons are somewhat longer for areas further south and for irrigated cultivation areas along the River Niger, its inland delta and other important regional rivers. As mentioned above, multiple crops are grown throughout the region including millet, maize, cassava, sorghum, rice, peanut, cowpeas and cotton. While cotton, peanut and some surplus markets of the other food staples do constitute a significant portion of the cash economy, the subsistence economy is primarily dominated by millet.

In comparison to other crops, millet is relatively drought and heat tolerant (it is a C4 crop), grows quickly and has a high nutritional value, being fairly rich in macronutrients, minerals and total caloric intake. Consequently, a 2002 study estimated that some three quarters of the caloric intake of the semi-arid tropics of Africa came from millet. The most dominant sub-type is pearl millet, with finger millet being second (Olibana, 2002). Despite its drought tolerance, millet along with the other regional staple crops are nevertheless quite responsive to variations in seasonal rainfall.

Throughout the region, one of the common adaptive practices is “zai” farming, in which small holes are dug in the soil and crops are planted in the holes rather than in rows on open fields (Reij et al., 2009; Barbier et al., 2009). While this process can be labor intensive, it offers several advantages: closer access of the crop’s roots system to soil moisture the water table, less probability of erosion, enhanced water recovery after rainfall, partial shading of the crop, and improving soil fertility. Figure 3.8 depicts zai farming.

Zai techniques improve soil fertility

Figure 3.8: Photo of Zai farming techniques. Reij et al., 2009

Another traditional approach to drought risk management is stone line contour or “bund” farming in which stones are arranged in lines along contours to limit runoff and erosion and store surface water for agricultural cultivation. Stone line contour farming is well adapted to relatively shallow slopes, has been widely adapted in Burkina Faso, Niger and Mali (Barbier et al., 2009). Figure 3.9 depicts a stone line field. There have also been efforts over the last two decades in Niger to replant trees on agricultural lands (Reij et al. 2009).

Figure 3.9: Photo of the use of stone line contour farming. Note the lush green vegetation on the upslope (right) side of the stone line – this is where water tends to collect. (FAO Corporate Document Repository).

In terms of the global discourse on climate change, it is also worth noting that enhanced vegetative cover also acts as a carbon sink; thereby contributing to climate change mitigation as well as local adaptation. The above strategies and others have a long and rich regional history and local knowledge should be carefully integrated in adaptation proposals and practice (Nyong et al., 2007). There can be disconnects between the objectives of many well-intentioned agricultural researchers seeking to help subsistence farmers and farmers themselves (the former often encouraging maximization of yields during average seasons and the latter being risk averse against the threat of large losses due to drought). Nevertheless, some practices, such as low density planting, use of manure as fertilizer, and cultivation of both early and late maturing varieties in the same season help to both bolster average yields and reduce risk of loss. Practices that increase average yields but do not reduce loss risk include high-density cultivation with inorganic fertilizer use, monoculture of early maturing varieties and incorporating inorganic fertilizer in very poor soils (DeRouw, 2004). The soil of the Sahel is quite heterogeneous in its productive potential (Ben Mohamed et al., 2012). While challenges of soil fertility are critical to agricultural productivity, this arena clearly requires adaptations other than weather index insurance.

Local adaptive practices also include substantial intercropping and some selective breeding, but genetic cultivar resilience for millet and sorghum crops in the face of climate constraints can be enhanced through farmer-expert interactions. One such initiative managed through the Institute for Crop Research in the Semi-Arid Tropics (ICRISAT) sought to provide farmers with greater genetic diversity and a stronger crop population buffering capacity. Traits pursued in this research included flooding tolerance, seedling heat tolerance, and phosphorus efficiency (Haussman et al., 2012).

Individual agricultural intensification in the region can be described as “climbing a ladder” from initially labor intensive techniques that require little if any capital outlay (such as zai farming), to the increased use of fertilizers, and use of more sophisticated crop varieties to an ultimate transition to a cash crop cultivation, and agroforestry (Aune and Bationo, 2008). Conceptually, it should be noted that index insurance could potentially lead to intensification of cultivation and without the proper management and soil conservation practices, this could lead to depletion of soil nutrients and other unintended negative consequences which are not directly climate related but that could have significant effects on crop performance.

Modeling studies have shown the benefit of added moisture to crop yields and the detriment experienced by additional heat stress (Boubacar, 2010; Ben Mohamed et al. 2002). In a multi-component historical analysis of millet production in Niger, tropical Atlantic SST and JAS rainfall are found to be the two leading predictors of millet production. This study then simulates hypothetical millet production for 2025 subject to both increasing temperature and declining rainfall assumptions and significant reductions in production (~13%) result (Ben Mohamed et al., 2012). However, there are large acknowledged uncertainties to how regional practices may evolve. Some recent research indicates that there is a substantial "yield gap". It is estimated that current yield rates may be as low as 1/3 of potential yield rates with proper management and generous application of fertilizer. This being said, a log-linear modeling approach was taken in this study to model the impacts of temperature and precipitation changes on potential millet and sorghum yields in the Niger River Basin and significant vulnerabilities were found. Sorghum is found to be more sensitive to declining precipitation than millet a 2°C rise in regional temperature and a 10% reduction in regional rainfall (considered the likely "worst case scenario" for the region) is modeled to lead to something like a 40-60% reduction in the crop yield. While these losses in productive capacity can be counteracted to some degree or even overcome with better management practices and increased use of fertilizer, the region's rapid population growth clearly makes the vulnerability very urgent (Tarhule and Akumaga, 2014). The broader projected vulnerability of cereal crop production in Africa to climate forcing is shown in Figure 3.10.

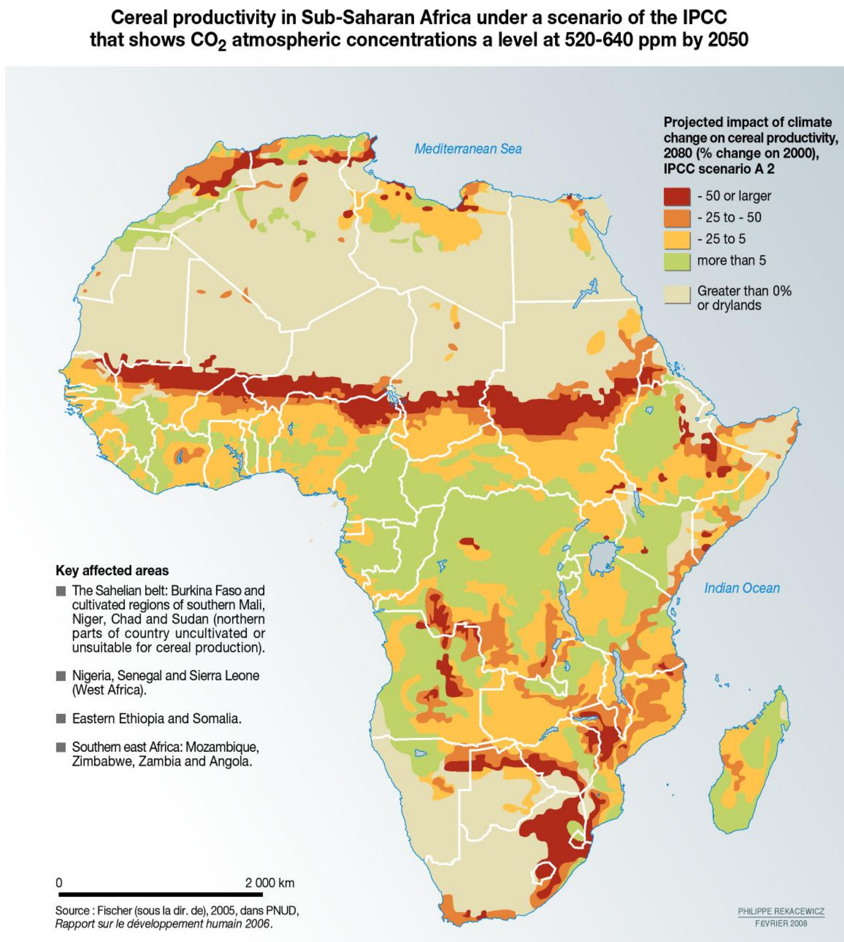


Figure 3.10: Projected changes to cereal crop productivity in sub-Saharan Africa by 2080 (relative to 2000) in a scenario with atmospheric CO_2 concentration between 520 and 640 ppmv by 2050. Note the very negative projected impact for much of the Sahel and much of the semi-arid lands across Africa; from Tarhule and Akumaga, 2014; original source – Fischer 2005

Drought vulnerability and adaptation for pastoral communities: Even though a greater proportion of the population of the West African Sahel is engaged in agriculture than pastoralism (and there is a considerable proportion of the population engaged in both agriculture and livestock cultivation in a settled small holder farm setting), much has been written about the impact of drought on pastoral communities and livelihoods because of the precarious and itinerate nature of this lifestyle and its exceptional vulnerability to water availability and pasture conditions (Watts, 1983; Thebaud and Batterbury, 2001). Because a pastoralist lifestyle requires geographic mobility and grazing, their practices have often borne the brunt of the criticism for land degradation. Significant challenges to securing reliable water and pastureland are embodied in the multiple and complex activities required to sustain reliable access to such resources (Thebaud and Batterbury, 2001). However, migration of pastoral herders is not necessarily a simple response to drought and can depend on many other environmental, economic and political factors (Bassett and Turner, 2007).

The dry period of the late twentieth century has induced a shift in the composition of domestic livestock in the west African Sahel, with smaller stock (sheep and goats) becoming more prominent in the overall livestock composition of the region (relative to cattle) (Turner, 1999). Part of this shift is attributed to environmental causality, with cattle needing more extensive and healthier pastureland than small stock. This biological need drove a north to south migration by many pastoralists with large cattle proportions during the drier periods of the late twentieth century. However, this shift in livestock composition is also partially explained by class, gender and cultural influences as well: pastoralists tend to acquire sheep and goats before developing cattle stock, so poorer male pastoralists and female pastoralists tend to own larger proportions of small stock, while wealthier male pastoralists tend to own larger proportions of cattle. During this period, there has been a demographic shift in the drier regions of the Sahel leading poorer male pastoralists and female pastoralists to embody a larger proportion of the total pastoralist community (Turner, 1999).

The impact of livestock markets on the political economy and ecology of a region is a story of the multifaceted impact of the “social embeddedness” of such markets. While much of the current discourse on development focuses on the role of markets as a mechanism for stimulating local investment and increasing the economic and environmental security of smallholder farmers, patterns of differential access to livestock markets as well as differential levels of livelihood vulnerability often tend to reinforce each other with poorer pastoralists being less able to sell their livestock at a favorable price and more vulnerable to both price volatility and environmentally induced shortfalls. These biases in access and pricing are often the product of social biases along lines of class and gender (Turner and Williams, 2002).

Drought related interactions between farming and pastoral communities: Another critical livelihood and cultural issue is the interaction between pastoral and agricultural communities. As for communities or individuals who have a mixed agricultural/pastoral livelihood, there has been some speculation regarding the role of livestock and some speculation has arisen that livestock can help to serve as a “buffer stock”, by functioning as a “liquid asset” that can be used to smooth out drought induced shocks to agricultural yields. However, this theory regarding the role of livestock in mixed livelihood settings is controversial and one study found this conclusion to be largely false with economic gains from livestock sales addressing a small portion of drought-induced crop losses in a field study in Burkina Faso in the early 1980s (Fafchamps et al., 1998). Another study showed that in two communities in western Niger, while some attempt has been made to hedge the risk from dwindling crop yields through the use of livestock, livestock populations and grazing areas in this study region have also declined leading to increased livelihood vulnerability (Chetima and Borlaug, 2008).

Drought induced migration of cattle and pastoral communities in the context of Niger is also a more widespread consequence of the late twentieth century droughts and has induced conflict between pastoral and agricultural communities (Thebaud and Batterbury, 2001). Following the droughts of the early 1970s, large numbers of Fulani pastoralists migrated from a drier climatology in Mali and Burkina Faso into the northern regions of the Ivory Coast. While this migration and its concomitant increase in national beef production was welcomed by the Ivorian government, it was bitterly opposed by the agricultural Senufo peasants of the region who then had to contend with greatly increased competition for resources and issues with livestock who would graze their crops (Bassett, 1988).

Many efforts to reconcile such competing demands on natural resources by the government of Niger have resulted in violence and conflict between different ethnic groups. Many of the larger aid organizations appear sufficiently daunted by the challenges of addressing pastoral livelihoods that aid is declining for pastoral regions. In Eastern Niger, a very dry region even by Sahelian standards, the regional dry period of the 1970s and 1980s compelled many pastoralists to switch from livestock to camel herding and conflicts over well and borehole access arose between competing ethnic groups (Thebaud and Batterbury, 2001). Governmental involvement in water allocation issues in the pastoral context has tended to seek to "sedentarize" pastoral populations in a particular place, to try to privatize pastoral economies and to treat pastoral populations with a certain degree of prejudice. To examine the impact of such efforts to "sedentarize" pastoral populations, one study done in the Gourma region of Mali suggests that grazing and browsing practices that are confined to narrower regions tend to induce larger detrimental impacts to the ecosystem by creating overgrazing pressures (Hiernaux, 1996). While there is pressure on the federal governments of the Sahelian states to break away from these trends and to adopt a more culturally sensitive and decentralized approach to these issues, institutional inertia and under-representation of pastoral peoples in official government capacities compromises this objective (Thebaud and Batterbury, 2001).

3.7. Vulnerability and Adaptation to Floods: While drought risk is the more dominant regional livelihood concern regional floods from heavy rainfall and high streamflows also create a significant livelihood concern. A historical study of newspaper accounts of flooding in Niger found that between 1970 and 2000, flooding events rendered almost 30,000 people homeless (Tarhule, 2005). As Mali, Niger and Burkina Faso are all inland countries, there is concern only related to freshwater flooding. Flooding events can cause significant displacement and infrastructure damage in cities and can damage agricultural yields through submersion or pest infestation.

At a broad level, there is comparatively little attention paid to flooding risk (relative to drought risk) in the Sahel, but many anecdotal accounts of property damage, ensuing homelessness and other complicated entanglements of vulnerability suggest that a "drought and desertification" narrative should be replaced with a "climate extremes" narrative that addresses both drought and flooding risks (Tschakert et al., 2010; Tarhule, 2005). One of the worst regional famines of the 20th century was initiated by widespread flooding in the early 1950s. The excessive rainfall compromised the millet crop (causing rot) and led to grain price volatility and ensuing conflicts between farming and pastoral communities. Despite this particular flood induced famine, and pest invasion related losses (which are often also a product of wet conditions) the general correlation between millet (and most regional dryland crops) and rainfall is still quite strongly positive (Grolle, 1997).

Clearly, flooding risks are most severe along the major riverbanks, lakeshores and in hollows. In addition to whatever urban and rainfed agricultural populations are located along or near such areas, most of the region's irrigated crop cultivation also occurs in areas vulnerable to flooding. In particular, irrigated rice cultivation is an important component of the region's economy. While irrigated rice crops are vulnerable to drought risk and relatively flood tolerant, truly uncontrolled flooding can be damaging to rice yields (Wassman and Dobermann, 2007). Rice crops can also be sensitive to soil salinization and to very high temperatures. One study found that low temperatures (even those typical of winter nights in the Sahel (~10C) could lead to spikelet sterility

(Dinkuhn et al., 1995). As such, the dependence of the irrigated rice crop on climate risks is more complex than the relationship between millet yields and rainfall.

Both irrigation and flooding also bring with them the expansion of standing pools of water, which are a well-known requirement for mosquito breeding and hence a significant factor in malaria transmission (Dolo et al. 2004). Increased flooding risks may be accompanied by elevated risks of malaria transmission. While there are well-understood adaptations to dealing with malaria transmission (use of bednets, insecticide spraying campaigns), approaches to dealing with the more direct consequences of flood risk are more varied. Individual or community based structural adaptations, such as construction of gutters, ditches and raised storage containers to manage excess water flow, adjusted farming practice, pursuit of alternative economic activities, and pursuit of social capital are among the adaptive strategies employed in the wake of flooding (Tschakert et al. 2010). There is some evidence that land use practices are changing the region's runoff coefficient, potentially leading to a higher likelihood of river flooding with a given level of rainfall (Amogu et al. 2010; Descroix et al., 2012).

3.8. Recent Events: Unusually high temperatures in April of 2010 led to a high rate of death from heat related illnesses. Other news stories confirm this account, but one quote from the July 2010 research trip was "pendant Avril, à cause de chaleur, ils mangaient des feuilles", "in April, because of the heat, they ate leaves" (anecdotal information from my driver, Moussa; referring to people living in the city of Niamey - such desperation was also widely documented in the countryside). Another anecdotal account estimated that death rates approached 70 fatalities per day in the capital city of Niamey during the height of the heat wave (2010 population around 1.2 million) (anecdotal account, Dr. Leonard N. Njau). For point of comparison, this is almost three times the global average mortality rate (7.9/1000/year) (CIA World Factbook).

A famine emerged over the course of 2010 and was estimated to affect a large proportion of the population although the estimates vary - some estimates are as high as 80% of the population of 12 million people (Hirsch, 2010) but other estimates, in this case made by the WFP are more conservative and on the order of half the population (BBC; August 2014). The precise balance of root causes of this famine are somewhat difficult to assess - part of it was related to poor harvest from 2009 due to drought and part of it was related to the heat stress early in 2010. The 2010 famine drove many Nigeriens south to Nigeria and downstream dam releases in Nigeria have led to flooding and displacement in Nigeria as well (BBC). Part of the 2010 famine was also attributable to rising food prices - as harvests fell by roughly a third, food prices themselves rose by about a third (BBC). Another local challenge is that there are some individual traders have been hoarding food - buying it cheaply from farmers at harvest time and selling it back at largely inflated prices during the course of this crisis (BBC, August 2010). Part is attributable to agricultural policy (news sources) and part of this famine may be attributed to corruption and delays in transmitting food aid to vulnerable areas from the airport (anecdotal information). While estimates on the total number of food insecure vary, the more conservative estimates place the figure around half the population this year.

Later in 2010, virtually unprecedented flooding took place along the Niger River, adding yet more trauma to a region already under great stress. This flooding caused displacement and homelessness for around 100,000 people (BBC, October 2010). Another source puts the figure of displaced persons closer to 200,000 people (Voice of America, August 2010). According to streamflow records obtained from the Niger Basin Authority, the average monthly streamflow in August and September were both higher than for any other year in the period since 1950. The streamflow climatology for July was the third highest in that same length of record and for August, the streamflow climatology was four standard deviations above the mean. The July-October streamflows of 2012 and 2013 also had extremely high streamflows in Niger, with 2012 being the highest. The flooding of 2012 led to the displacement of more than 400,000 people across the Sahel (UN OCHA report, 2012). The rainy season of 2013 also led to widespread flooding and very high streamflow levels in Niamey, which again led to widespread displacement (Diallo, 2013).

Burkina Faso and Mali have faced similar regional challenges, although the political situation and the hunger situation in 2010 was not as challenging. Burkina Faso was actually able to offer Niger 5,000 tons of cereals in April to help fight their famine in 2010 (World Food Program, April 2010). FEWS net did not report very dramatic food shortages in Burkina Faso or Mali in 2010 (Famine

Early Warning Systems Network). While the regional climate conditions were regional, differences in politics and structure are largely attributable for the differences in experienced hunger.

However, in 2012, the Sahel food crisis was more widespread and had significant impacts on Burkina Faso and Mali as well as Niger. The 2012 food crisis was a product of drought, food price volatility and the political conflict in northern Mali among other factors (World Food Program, June 2012). The current situation (autumn of 2014) is somewhat more favorable for food security (FEWS Net; West Africa) and there have not been major floods this season.

3.9. Climate Vulnerability, International Development and Aid: The broader discourse on development aid often points to the environmental pressures of the Sahel exacerbating already stark deficiencies of capital (Batterbury and Warren, 2001; Bassett and Bi Zueli, 2000). Arguably, this development aid discourse, in casting the Sahel as a region of perennial victimization by environmental challenges and capital deficiencies carries an overtone of environmental determinism that may not be quite appropriate. While this master narrative clearly does have some salience and while environmentally induced economic strains are a very real burden on the region, a more detailed analysis reveals a finer structure to livelihood and environmental sustainability in the region (Batterbury and Warren, 2001).

There are a number of "best practices" for climate services gained from experience. Among them are bridging gaps through enabling institutional frameworks, tailoring climate information to a usable format at a local scale, giving farmers an adequate voice, salience through integration of local and scientific knowledge, face to face dialogue to communicate seasonal information, engagement of diverse communication channels and sensitivity to socioeconomic and gendered issues of equity (Tall et al., 2014).

The agricultural and pastoral livelihoods typical of the Sahel are highly sensitive to the timing, intensity, spatial and temporal distribution of rainfall with famine being a common regional consequence of drought. Throughout subSaharan Africa, drought risk is found to be the most significant climate impact on economic growth (Brown et al., 2008). Addressing drought related risks is also a significant component of the work done by humanitarian and development organizations in the region: including International Development Research Council (IDRC), United Nations Development Program (UNDP), United Nations High Commission on Human Rights (UNHCR), World Food Program, Oxfam, International Red Cross/Red Crescent, Drylands Development Centre, United States Agency for International Development (USAID).

Although the hazards of misguided development initiatives should be acknowledged, the challenges of development, environmental restoration and adaptation to climate change are still all pressing practical concerns for the people of the West African Sahel and for the humanitarian aid and international development communities. These drought related challenges for the West African Sahel region also must be interpreted against the backdrop of the trend towards urbanization in western Africa both within and to the south of the Sahel region and a wide array of complex political, economic and cultural forces acting on and within the region (Olukoshi, 2001). However, there still remains considerable disagreement and complexity in assessing the most appropriate strategies to achieve long-term development and drought resilience (Batterbury and Warren, 2001).

The challenges of fostering improved drought resilience can be viewed through the lens of adaptation to existing climate change and can potentially serve as a lesson for adaptation to future climate changes. The period from 1968-1990 was marked with a gradually increasing capacity to prevent famine in the West African Sahel region through improved early warning systems and better mobilization and coordination of donor and food aid resources. However, differing approaches to reducing the underlying vulnerability are still often plagued by the ideological differences of their respective advocates. Broadly, one group of proposed adjustments focuses on technological improvements and improvements in seed varieties, irrigation and other increased yield agricultural and land use practices. Another group, almost in ideological opposition seeks to focus on agroforestry and a scaling back of intensive cultivation of the landscape to achieve a more sustainable future (Kates, 2000). In a development context, a heterodox merging of technological and sustainability innovations and considerations is likely to be important for long-term success.

One of the important development innovations has been the Famine Early Warning System (FEWS) program, which uses satellite data to monitor drought conditions, food prices, changing demographic patterns and evidence of crop failure in order to anticipate ensuing famines (Famine Early Warning Systems Network). Innovations in seed varieties and the efforts of a wide assortment of international, regional, national and subnational initiatives have been brought to bear in order to combat the effects of drought and to address the challenges of development in the region. One recent project that has taken an interdisciplinary, cross-sectoral approach to development is the UN sponsored Millennium Villages Project. Conceived in 2004 as a partnership between the UNDP, Columbia University's Earth Institute and Millennium Promise, the Millennium Villages Project is dedicated to helping specific villages in the developing world achieve the Millennium Development Goals through multi-sectoral investments in agriculture, water management, health, education, and infrastructure. The project has already shown remarkable success by many metrics (Sanchez et al., 2007).

It will be essential for future development projects in the region to engage multiple sectors in a sustainable way, avoid simplistic narratives of environmental determinism, learn from best practices and local knowledge and integrate an understanding of climate vulnerability into development initiatives. Index insurance could potentially be complementary to many of these efforts, but could also be detrimental in some circumstances, especially if insurance rates are high enough that the enterprise becomes a vehicle for extraction of wealth from the poor.

References

-Ahmed, B. and Callimachi, R., (2012). Islamic Extremists attack Timuktu in north Mali. Associated Press.
-Aldrich, R., (1996). Greater France: A history of French Overseas Expansion. Palgrave MacMillan.
-Alidou, O., (2005). Engaging Modernity: Muslim Women and the Politics of Agency in Postcolonial Niger. University of Wisconsin Press.
-Amogu, O., L. Descroix, K. AS. Yero, E. LeBreton, I. Mamadou, A. Ali, T. Vischel, J.C. Bader, I. B. Moussa, E. Gautier, S. Boubkraoui and P. Belleudy, (2010). Increasing River Flows in the Sahel?, *Water, 2,* 170-199.
-Aune, J., Bationo, A. (2008). Agricultural intensification in the Sahel – The ladder approach. *Agricultural Systems, 98,* 119-125.
-Barbier, B. Yacouba, H., Karambiri, H., Zorome, M., Some, B. (2009). Human Vulnerability and Climate Vulnerability in the Sahel: Farmers' Adaptation Strategies in Northern Burkina Faso. *Environmental Management, 43,* 790-803.
-Bassett, T. J., (1988). The Political Ecology of Peasant-Herder Conflicts in the Northern Ivory Coast. *Annals of the Association of American Geographers*, *78,* 453-472.
-Bassett, T. J., and K. Bi Zueli, (2000). Environmental Discourses and the Ivorian Savanna. *Annals of the Association of American Geographers, 90,* 67-95.
-Bassett, T. J. and M. D. Turner, (2007). Sudden Shift or Migratory Drift? Fulbe Herd Movements to the Sudano-Guinean Region of West Africa. *Human Ecology, 35,* 33-49.
-Batterbury, S.,and A. Warren, (2001). The African Sahel 25 years after the great drought: assessing progress and moving towards new agendas and approaches. *Global Environmental Change, 11,* 1-8.
-Ben Mohamed, A., van Duivenbooden, N., and Abdoussallam, S., (2002). Impact of Climate Change on Agricultural Production in the Sahel – Part 1. Methodological Approach and Cast Study for Millet in Niger. *Climatic Change, 54,* 327-348.
-Bounkoungou, M., (2007). Burkina Faso salutes "Africa's Che" Thomas Sankara. Reuters.
-Brooks, N. (2006). Climate Change, Drought and Pastoralism in the Sahel. Discussion on the World Initiative on Sustainable Pastoralism.
-Brown, C., Meeks, R., Hunu, K., and Yu, W. (2008). Hydroclimatic Risk to Economic Growth in SubSaharan Africa. IRI Technical Report.
-Boubacar, I. (2010). The Effects of Drought on Crop Yields and Yield Variability in the Sahel. Southern Agricultural Economics Association Meeting.
-Burnham, P. and M. Last (1994). From Pastoralist to Politician: The Problem of a Fulbe "Aristocracy". *Cahiers d'Études Africaines, 34,* 313–357.
-Busia, A. (Series editor) (2005). Women Writing Africa: West Africa and the Sahel. Feminist Press, CUNY.
-Carpenter, C. (2007). World and its Peoples: Middle East, Western Asia and Northern Africa, Marshall Cavendish Corporation.
-Chafe, Kabiru Sulaiman (1994). Challenges to the Hegemony of the Sokoto Caliphate: A Preliminary Examination. *Paideuma, 40,* 99–109.
-Chafer, T., (2002). The End of Empire in French West Africa: France's Successful Decolonization. Oxford.
-Charney, J. G. (1975). Dynamics of deserts and drought in the Sahel. *Quarterly Journal of the Royal Meteorological Society, 101,* 193–202.
-Charney, J., Quirk, W.J., Chow, S.-H., Kornfeld, J., (1977). A comparative study of the effects of albedo change on drought in semi-arid regions. *Journal of Atmospheric Science, 34,* 1366–1385.
-Chétima, M. M. K. and N. Borlaug, (2008). Vulnerability to Drought and Food Insecurity in the Sahel: Preliminary Findings from 25 years of human and livestock population dynamics in Western Niger, Research Brief, LEAP, University of California, Davis.

-Chilson, P. (2012). Burkina Faso: A Small West African Country Struggles to Bring Peace to Mali. Pulitzer Center on Crisis Reporting.
-CIA, (2009). Mali. World Factbook.
-Conklin, A. (1998). A Mission to Civilize: the Republican Idea of Empire in France and West Africa 1895–1930. Stanford University Press.
-Conway, D., Persechino, A., Ardoin-Bardin, S., Hamandawana, H., Dieulin, C. and Mahe, G. (2008). Rainfall and water resources variability in Sub-Saharan Africa during the 20th century. *Tyndall Center Working Paper 119.*
-Decalo, S., (1997). Historical Dictionary of the Niger (3rd ed.). Scarecrow Press.
-Decalo, S. (1990). Coups and Army Rule in Africa. Yale University Press.
-deMenocal, P., J. Ortiz, T. Guilderson, J. Adkins, M. Sarnthein, L. Baker, and M. Yarusinsky, (2000). Abrupt onset and termination of the African Humid Period: rapid climate responses to gradual insolation forcing. *Quaternary Science Reviews*, *19,* 347-361.
-Derouw, A. (2004). Improving yields and reducing risks in pearl millet farming in the African Sahel. *Agricultural Systems, 81,* 73-93.
-Descroix, L., Genthon, P., Amogu, O., Rajot, J. L, Vandervaere, J. P., Sighomnou, D. (2012). The highest Red flood of the Niger River ever recorded in Niamey: climate change or land use change?" Poster session 8A, Water Resources Quantification and Management and Floods and Extreme Events, AMMA Conference, Toulouse, France.
-Diallo, M. (2013). Flooding in the Sahel leaves thousands of families facing uncertain futures. International Federation of Red Cross and Red Crescent Societies.
-Diallo, T., and A. Diarra, (2013). Turnout low in second round of Mali's legislative election. Reuters.
-Dinkuhn, M., Sow, A., Samb, A., Diack, S., and Asch, F., (1995). Climatic Determinants of Irrigated Rice Performance in the Sahel – I. Photothermal and Microclimatic Responses of Flowering, *Agricultural Systems, 48,* 385-410.
- Dolo, G., Briet, O., Dao, A., Traoré, S., Bouare, M., Sogoba, N., Niare, O., Bagayogo, M., Sangare, D., Teuscher, T., and Toure, Y., (2004). Malaria transmission in relation to rice cultivation in the irrigated Sahel of Mali. *Acta Tropica, 89,* 147-159.
-Fafchamps, M., C. Udry, K. Czukas, (1998). Drought and Saving in Africa: Are Livestock a Buffer Stock? *Journal of Development Economics*, *55,* 273-306.
-Falola, T., (2009). Historical Dictionary of Nigeria. Lanham, Md: Scarecrow Press.
-Falola, T., (2009). Colonialism and Violence in Nigeria. Bloomington, IN: Indiana University Press.
-Favreau, G., Cappelaere, B.,Massuel, S., Leblanc, M., Boucher,M., Boulain, N. and Leduc, C. (2009). Land clearing, climate variability, and water resources increase in Semiarid Southwest Niger: a review. *Water Resources Research 45*, W00A16.
-Foley, J. A., M. T. Coe, M. Scheffer, and G. Wang, (2003). Regime Shifts in the Sahara and Sahel: Interactions between Ecological and Climatic Systems in Northern Africa. *Ecosystems, 6,* 524-539.
-Giannini, A., R. Saravanan, and P. Chang (2003). Ocean Forcing of Sahel Rainfall on Interannual to Interdecadal Time Scales, *Science, 302,* 1027- 1030.
-Grolle, J. (1997). Heavy rainfall, famine, and cultural response in the West African Sahel: the 'Muda' of 1953-54. *GeoJournal, 43,* 205-214.
-Guo, Z., N. Petit-Maire, and S. Kropelin, (2000). Holocene non-orbital climatic events in present-day arid areas of northern Africa and China. *Global and Planetary Change, 26,* 97-103.
-Haupt, W., (1984). Germany's Overseas Protectorates 1884–1918. Friedberg: Podzun-Pallus Verlag.
-Haussman, B., Rattunde, H. Rattunde, E., Traore, P. vom Bocke, K., Parzies, H., (2012). Breeding Strategies for Adaptation of Pearl Millet and Sorghum to Climate Variability and Change in West Africa. *Journal of Agronomy and Crop Science, 198,* 327-339.

-Herman, A., V. B. Kumar, P .A. Arkin, and J.V. Kousky, (1997). Objectively Determined 10- Day African Rainfall Estimates Created for Famine Early Warning Systems. *International Journal of Remote Sensing, 18,* 2147-2159.

-Hiernaux, P., (1996). The Crisis of Sahelian Pastoralism: Ecological or Economic? Network Paper 39a, Overseas Development Institute, Pastoral Development Network.

-Hill, B. D., Buckler, J., Ebrey, P. B., Beck, R. B., & Crowston, C. H. (2008). A History of World Societies, Volume C: From 1775 to Present (Vol. 3). Macmillan.

-Hogben, S. J. and A. Kirk-Greene, (1966). The Emirates of Northern Nigeria: A Preliminary Survey of Their Historical Traditions. Oxford University Press.

-Huillery, E. (2009). History matters: The long-term impact of colonial public investments in French West Africa. *American Economic Journal: Applied Economics*, *1,* 176-215.

-Ibrahim, J. and Souley, A. (1998). The Rise to Power of an Opposition Party: the MNSD in Niger Republic, in "The Politics of opposition in contemporary Africa" (edited by A. Olukoshi).

-International Monetary Fund, (2014). Burkina Faso.

-Kahlheber, S., and K. Neumann, (2007). The Development of Plant Cultivation in Semi-Arid West Africa, in "Rethinking Agriculture: Archaeological and Ethnoarchaeological Perspectives", T. Denham, J. Iriarte, and L. Vrydaghs (eds.), Left Coast Press, Walnut Creek, CA.

-Kasuka, B. (ed.) (2011). African leaders. CreateSpace independent publishing.

-Kates, R. W., (2000). Cautionary Tales: Adaptation and the Global Poor. *Climatic Change*, *45,* 5-17.

-Ki-Zerbo, J., (1997). UNESCO General History of Africa, Vol. IV, Abridged Edition: Africa from the Twelfth to the Sixteenth Century. University of California Press.

-Klein, M. (2007). France's African Colonies. In T. Benjamin (Ed.) Encyclopedia of Western Colonialism since 1450. 2, 490. Detroit: Macmillan Reference USA.

-Lafferty, K. (2009). The ecology of climate change and infectious diseases. *Ecology, 90,* 888-900.

-Levtzion, N., and J. Spaulding, (2003). Medieval West Africa: Views From Arab Scholars and Merchants. Princeton NJ: Markus Wiener

-Lewis, P. (2009). Ethnologue: Languages of the World, 16th edition.

-Library of Congress, (2005). Country Profile: Mali.

-Lovejoy, P. (1978). Plantations in the Economy of the Sokoto Caliphate. *The Journal of African History, 19,* 341–368.

-Lovejoy, P. (2000). Transformations in Slavery. Cambridge University Press.

-Manning, P., (1998). Francophone Sub-Saharan Africa, 1880–1995. Cambridge University Press.

-Loyn, D. (2005). Mali's nomads face famine. BBC.

-Massalitchi, A. (2009). Niger's Tandja Dissolves Parliament. Reuters.

-Nath, P., and Behera, B. (2011). A critical review of impact of and adaptation to climate change in developed and developing economies. *Environment, Development and Sustainability, 13,* 141-162.

-Nossiter, A., (2012). Jihadists' fierce justice drives thousands to flee Mali. New York Times.

-Nyong, A., Adesina, F., Osman Elasha, E. (2007). The value of indigenous knowledge in climate change mitigation and adaptation strategies in the African Sahel. *Mitigation and Adaptation Strategies for Global Change. 12,* 787-797.

-Obilana, A. (2002). Overview: Importance of Millets in Africa. ICRISAT working paper.

-Oliver, R., and A. Atmore, (2005). Africa Since 1800, Fifth Edition. Cambridge University Press.

-Olson, J., (1979). The Ethnic Dimension in American History. New York: St. Martin's Press, Inc..

-Olukoshi, A., (2001). West Africa's Political Economy in the Next Millennium: Retrospect and Prospect. *CODESRIA and OXFAM Monograph series ISBN 2-86978-104-0*.

-Omar, F. (2007). Commemorating Thomas Sankara. Group for Research and Initiative for the Liberation of Africa.

-Paavola, J., Adger, W.N., (2006). Fair adaptation to climate change. *Ecological Economics, 56,* 594–609.

-Phillips, J. D., (1993). Biophysical Feedbacks and the Risks of Desertification, *Annals of the Association of American Geographers, 83,* 630-640.

-Piga, A., (2003). Islam et villes en Afrique au sud du Sahara: Entre soufisme et fondamentalisme. KARTHALA Editions, Paris, France.

-Prince, S. de Coulston, E., Kravitz, L. (1998). Evidence from rain use efficiencies does not indicate extensive Sahelian desertification. *Global Change Biology, 4,* 359-374.

-Reij, C., Tappan, G., and Smale, M. (2009). Agroenvironmental transformation in the Sahel: another kind of "Green" Revolution. IFPRI working paper.

-Rudolf, J. (2010). Food Crisis Worsens in West Africa. New York Times

-Sanchez, P., C. Palm, J. Sachs, G. Denning, R. Flor, R. Harawa, B. Jama, T. Kiflemariam, B. Konecky, R. Kozar, E. Lelerai, A. Malik, V. Modi, P. Mutuo, A. Niang, H. Okoth, F. Place, S. E. Sachs, A. Said, D. Siriri, A. Teklehaimanot, K. Wang, J. Wangila, and C. Zamba, (2007). The African Millennium Villages. *Proceedings of the National Academy of Science, 104,* 16775-16780.

-Schroeder, R. A., (1997). Re-Claiming" Land in the Gambia: Gendered Property Rights and Environmental Intervention. *Annals of the Association of American Geographers, 87,* 487-508.

-Schroeder, R., (1986). Gender Vulnerability to Drought: A Case Study of the Hausa Social Environment. *Natural Hazard Research*, Working Paper 58.

-Shipton, P., (1990). African Famines and Food Security: Anthropological Perspectives. *Annual Review of Anthropology, 19,* 353-394.

-Swindell, K., (1986). Population and Agriculture in the Sokoto-Rima Basin of North-West Nigeria: A Study of Political Intervention, Adaptation and Change, 1800-1980. *Cahiers d'Études Africaines, 26,* 75–111.

-Tall, A., J. Hansen, A. Jay, B. Campbell, J. Kinyangi, P. K. Aggarwal and R. Zougmoré, (2014). Scaling up climate services for farmers: Mission Possible. Learning from good practice in Africa and South Asia. CCAFS Report No. 13. Copenhagen: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).

-Tarhule, Aondover (2005). Damaging rainfall and flooding: the other Sahel hazards. *Climatic Change 72,* 355–377.

-Tarhule, A. and Akumaga, U., (2014). Climate Change Impacts on Rain-Fed Agriculture and Crop Yields in the Niger Basin. *Climate Risk Management Session, AAG annual meeting.*

-Thébaud, B. and S. Batterbury, (2001). Sahel Pastoralists: Opportunism, Struggle, Conflict and Negotiation. A Case Study from Eastern Niger. *Global Environmental Change*, *11,* 69-78.

-Thomson, M., Connor, S., Ward, M. N., Molyneux, D. (2004). Impact of Climate Variability on Infectious Disease in West Africa. *EcoHealth, 1,* 138-150.

-Tschakert, P., Sagoe, R., Ofori-Darko, G., Codjoe, S. N. (2010). Floods in the Sahel: an analysis of anomalies, memory, and anticipatory learning. *Climatic Change, 103,* 471-502.

-Tschakert, P. (2007). Views from the vulnerable: Understanding climatic and other stressors in the Sahel. *Global Environmental Change, 17,* 381-396.

-Tucker, C. J., J. E. Pinzon, M. E. Brown, D. A. Slayback, E. W. Pak, R. Mahoney, E. F. Vermote, and N. E. Saleous, (2005). An Extended AVHRR 8-km NDVI Data Set Compatible with MODIS and SPOT Vegetation NDVI Data. *International Journal of Remote Sensing,* submitted.

-Turner, M. D. (1999). Merging Local and Regional Analyses of Land Use Change: The Case of Livestock in the Sahel, *Annals of the Association of American Geographers, 89,* 191-219.

-Turner, M. D. and T. O. Williams, (2002). Livestock Market Dynamics and Local Vulnerabilities in the Sahel. *World Development, 30,* 683-705.

-Warren, A., S. Batterbury, and H. Osbahr, (2001). Soil Erosion in the West African Sahel: A Review and an Application of a "Local Political Ecology" in South West Niger. *Global Environmental Change*, *11,* 79-95.
-Warren, A., Osbahr, H., Batterbury, S., & Chappell, A. (2003). Indigenous views of soil erosion at Fandou Béri, southwestern Niger. *Geoderma*, *111*, 439-456
-Wassmann, R., and Dobermann, A., (2007). Climate Change Adaptation through Rice Production in Regions with High Poverty Levels. *Semi Arid Tropics EJournal.*
-Watts, M., (1983). Hazards and Crisis: A Political Economy of Drought and Famine in Northern Nigeria. *Antipode, 15,* 24-34.
-Xue, Y., and J. Shukla, (1993). The Influence of Land Surface Properties on Sahel Climate. *Journal of Climate, 6*, 2232-2245.
-Zakari, M., (1985). Contribution à l'histoire des populations du sud-est nigérien, Niamey.

Websites
-African Elections Database; Elections in Niger (n.d.). Retrieved from http://africanelections.tripod.com/ne.html
-Al Arabiya News, Jan. 2013. "Tuareg rebels ready to help French forces in Mali". Retrieved from http://english.alarabiya.net/articles/2013/01/14/260337.html.
-Ali Dinar, A., French in West Africa. (n.d.). Retrieved from http://www.africa.upenn.edu/K-12/French_16178.html
-Al Jazeera; Mali's Tuareg fighters end ceasefire. (November 2013). Retrieved from http://www.aljazeera.com/news/africa/2013/11/mali-tuareg-fighters-end-ceasefire-201311309323467 3103.html
-Al Jazeera; Thousands protest against Niger's president. (December 2013). Retrieved from http://www.aljazeera.com/news/africa/2013/12/niger-protest-2013122818045873463.html
-All Africa, (n.d.). "Jean-Baptiste Ouedraogo". Retrieved from http://fr.myafrica.allafrica.com/view/people/main/id/07V7P9PybUchTCKr.html.
-All Africa; Niger: As Refinery Opens, Niger Joins Club of Oil Producers, (November 2011). Retrieved from http://www.allafrica.com/stories/201111301248.html
-BBC, (September, 1999). "1999: President of Niger 'killed in ambush'". Retrieved from http://news.bbc.co.uk/onthisday/hi/dates/stories/april/9/newsid_2463000/2463927.stm
-BBC, (September 2005). "Niger leader denies hunger claims". Retrieved from http://news.bbc.co.uk/2/hi/africa/4133374.stm
-BBC News | Africa | April 1999. President Mainassara: A profile. (n.d.). Retrieved from http://newsvote.bbc.co.uk/2/hi/africa/315840.stm
-BBC; Niger River floods destroying homes and crops. (2010, October 8). Retrieved from http://www.bbc.co.uk/news/world-africa-10929144
-BBC; Niger hunger 'worse than 2005' (2010, August 14). Retrieved from http://www.bbc.co.uk/news/world-africa-10976093
-BBC; Niger food hoarding 'puts children at risk' (2010, August 21). Retrieved from http://www.bbc.co.uk/news/world-africa-11045959
-BBC; Guinea-Bissau profile. (n.d.). Retrieved from http://www.bbc.com/news/world-africa-13443186
-BBC; Togo profile. (n.d.). Retrieved from http://www.bbc.com/news/world-africa-14106781
-BBC; Islamists seize key town in Mali. (June 2012). Retrieved from http://www.bbc.com/news/world-africa-18610618
-BBC; Mali signs peace deal with Tuareg. (June 2013). Retrieved from http://www.bbc.com/news/world-africa-22961519
-California Newsreel - THOMAS SANKARA: THE UPRIGHT MAN. (n.d.). Retrieved from http://newsreel.org/nav/title.asp?tc=CN0205
-Empathos National Library; Colonial Africa. (n.d.). Retrieved from http://www.empathosnationenterprises.com/Consulate/EN-Library/Black-Studies/afcolony.html

-Ethnologue; Niger. (n.d.). Retrieved from http://www.ethnologue.com/country/NE/languages
-Famine Early Warning Systems Network. (n.d.). Retrieved from http://www.fews.net
-Famine Early Warning Systems Network. West Africa (n.d.). Retrieved from http://www.fews.net/west-africa
-FAO Corporate Document Repository (n.d.). Retrieved from http://www.fao.org/docrep/006/y3951e/y3951e05.htm
-Heilbrunn Timeline of Art History. The Empires of the Western Sudan; Mali Empire (n.d.). Retrieved from http://www.metmuseum.org/toah/hd/mali/hd_mali.htm
-Hirsch, A. 2010. Niger's markets are full yet famine shadows the dusty roads. The Guardian. Retrieved from http://www.guardian.co.uk/world/2010/aug/01/niger-famine-food-crisis
-History of Guinea-Bissau. (n.d.). Retrieved from http://www.historyworld.net/wrldhis/PlainTextHistories.asp?historyid=ad46
-History of Togo. (n.d.). Retrieved from http://www.historyworld.net/wrldhis/PlainTextHistories.asp?historyid=ad42
-IRINNews BURKINA FASO: Compaore's decision to bid for re-election raises opposition hackles. (August 2005). Retrieved from http://www.irinnews.org/report/55816/burkina-faso-compaore-s-decision-to-bid-for-re-election-raises-opposition-hackles
-Lefaso.net. L'actualite du Burkina sur Internet. Retrieved from http://www.lefaso.net
-Map of Ghana and the Swahili Coast. (n.d.). Retrieved from http://www.ghanaswahili.weebly.com/maps.html
- Muhammad, K.. African Kingdoms - Kingdoms of Ancient African History,. (October 2005). Retrieved from http://www.africankingdoms.com
-National Drought Mitigation Center; Types of Drought. (n.d.). Retrieved from http://www.drought.unl.edu/DroughtBasics/TypesofDrought.aspx
-Nairaland Forum. Map of the Sokoto Caliphate (n.d.). Retrieved from http://www.nairaland.com/1874957/map-sokoto-caliphate
-News 24; Malian forces battle Tuareg rebels. (March 2012). Retrieved from http://www.news24.com/Africa/News/Malian-forces-battle-Tuareg-rebels-20120304
-Obadina, T., (2000). Slave trade as root to African Crisis. (n.d.). Retrieved from http://www.afbis.com/analysis/slave.htm
-Profile - Burkina Faso. (n.d.). Retrieved from http://www.inadev.org/profile_-_burkina_faso.htm
-Poverty Mapping. SocioEconomic Data and Applications Center. (n.d.). Retrieved from http://sedac.ciesin.columbia.edu/data/collection/povmap
-Science Alert; Africa builds 'Great Green Wall' of trees to improve farmlands. (July 2014). Retrieved from http://www.sciencealert.com/news/20142407-25916.html
-The Great Green Wall Initiative | Global Environment Facility. (n.d.). Retrieved from http://www.thegef.org/gef/great-green-wall
-The Onyx Express; Preserving Our Culture, Our Legacy. (n.d.). Retrieved from http://www.onyxexpress.org/2014/02/19/preserving-our-culture-our-legacy/#sthash.n324uRwg.dpbs
-The Songhai Empire 1493-1528. (n.d.). Retrieved from http://www.zonu.com/detail-en/2010-01-05-11636/The-Songhai-Empire-1493-1528.html
-This Day Live; Mali Army Claims Upper Hand over Rebels Amid Coup Disarray (March 2012). Retrieved from http://www.thisdaylive.com/articles/mali-army-claims-upper-hand-over-rebels-amid-coup-disarray/112262/
-UN OCHA report http://www.unocha.org/top-stories/all-stories/niger-heavy-rains-and-floods-force-more-400000-people-their-homes, 2012.
-UN World Food Program. Sahel Crisis: 8 questions answered (June 2012). Retrieved from http://www.wfp.org/stories/sahel-crisis-8-questions-answered
USAID Africa: Mali. (n.d.). Retrieved from https://web.archive.org/web/20101111133055/http://www.usaid.gov/locations/sub-saharan_africa/countries/mali/

-Voice of America UN: Floods in Niger Displace 200,000. (August 2010). Retrieved from http://www.voanews.com/content/un-floods-in-niger-displace-200000-101762283/155686.html
-World Food Programme Fighting Hunger Worldwide. Burkina Faso offers Niger 5000 tons of cereals to help fight famine (April 2010). Retrieved from http://www.wfp.org/content/burkina-faso-offers-niger-5000-tons-cereals-help-fight-famine
WHKMLA: Historical Atlas, French West Africa Page. (March 2005). Retrieved from http://www.zum.de/whkmla/histatlas/westafrica/haxfrwa.html

Chapter 4: Regional Climate, Index Selection and Contract Design

4.1. Regional Climatology: West Africa has a very pronounced zonal rainfall gradient, with regions further south being wetter and regions further north being drier. As discussed in section 3.4, this has a significant impact on where people live within Niger, Mali and Burkina Faso, and population densities tend to follow the rainfall gradient. There is also a more modest climatological meridional rainfall gradient with regions further west tending to be slightly wetter than regions further east at the same latitude. A regional rainfall climatology map for 1979-2009 is shown in Figure 4.1 below from the Global Precipitation Climatology Project (Adler et al., 2003; Huffman et al., 2009).

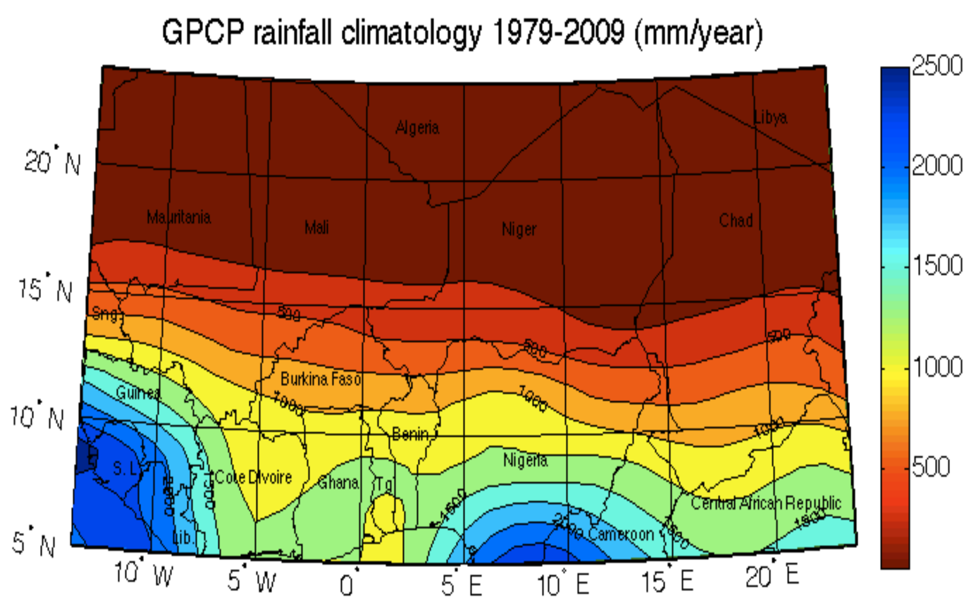


Figure 4.1: Adapted from GPCP data.

Only far SW Burkina Faso and SW Mali receive a climatological rainfall in excess of one meter. Within the three nations of this study, regions south of the

500 mm isohyet include roughly 90% of Burkina Faso, a third of Mali and only a small fraction of Niger. The Sahel is commonly considered to be the transition zone from the truly arid Sahara Desert to the North and the more humid environments of central Africa and the coast of the Gulf of Guinea. The exact boundaries of the Sahel are somewhat subject to interpretation and are commonly defined in terms of isohyets. However, the Sahel can be thought of as extending in the west from Senegal to Sudan and Ethiopia in the East.

In terms of seasonality, the weather in the Sahel is quite hot all year round, with a uni-modal rainy season in the boreal summer, whereas areas to the south transition to bimodal rainfall regimes, peaking in boreal spring and boreal fall. Daytime high temperature variability in the Sahel is relatively minimal, but bimodal with the hottest periods in March-May and a secondary peak in September-November. The monthly average daytime high temperatures across the region are rarely below 30°C (86°F), even during boreal winter and can be in excess of 42°C (108°F) in the more arid sub-regions in the March-May season. While heat waves can take regional temperatures above 45°C (113°F), truly extreme heat waves with temperatures in excess of 50°C (122°F) are rare, if not unprecedented in the region.

The rainfall during the June-October period tends to suppress the temperature slightly and there is some cooling during boreal winter (although this is more noticeable for nighttime lows than daytime highs). The rainy season peaks in the month of August, with July and September receiving lesser but still substantial rainfall. Climatological rainfall in May, June and October is generally less substantial and can be virtually absent in the more arid regions further north. For May, June and October to be devoid of rainfall is unusual, but precipitation from November to April is extremely limited and rare. Figures 4.2 a, b, c, d and e are the climographs for Bamako, Mali, Gao, Mali, Ouagadougou, Burkina Faso, Niamey, Niger, and Agadez, Niger, respectively.

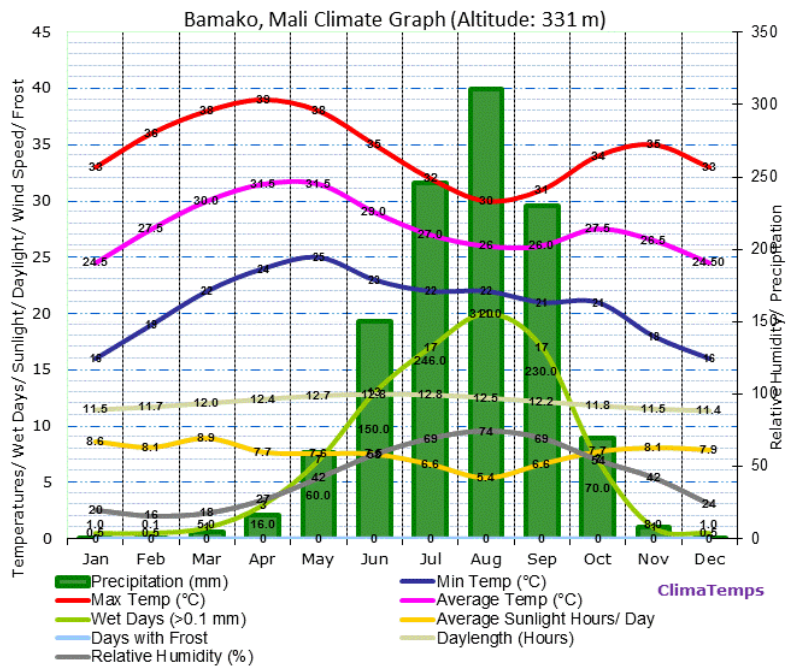


Figure 4.2a: Bamako, Mali climograph (Bamako Climate Graphs) (12.65N, 8W)

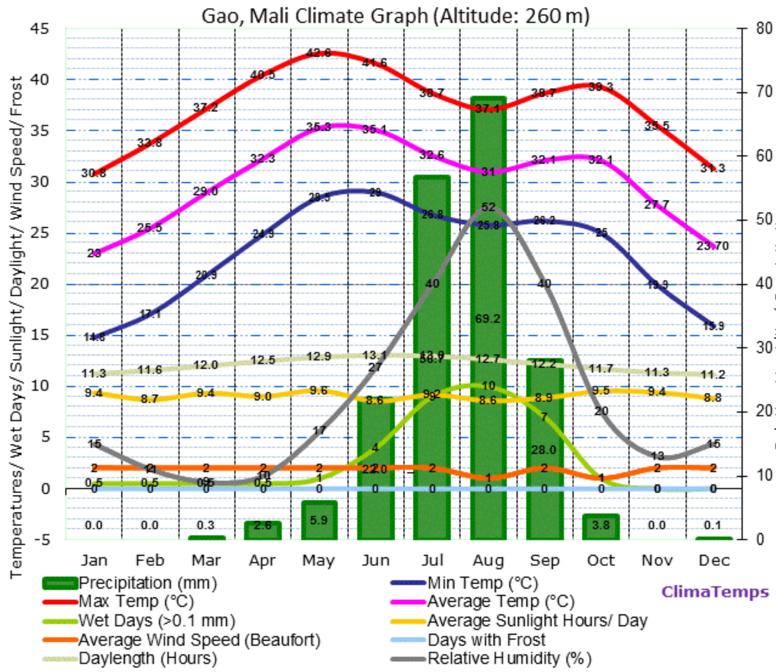


Figure 4.2b: Gao, Mali climograph. (Gao, Mali Climate Graphs) (16.27N, 0.05W)

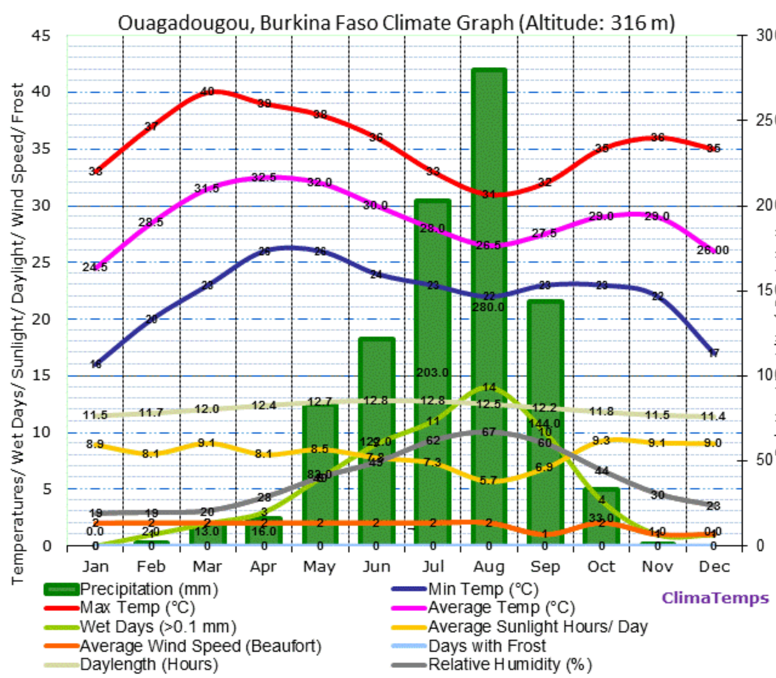


Figure 4.2c: Ouagadougou, Burkina Faso climograph. (Ouagadougou Climate Graphs) (12.35N, 1.54W)

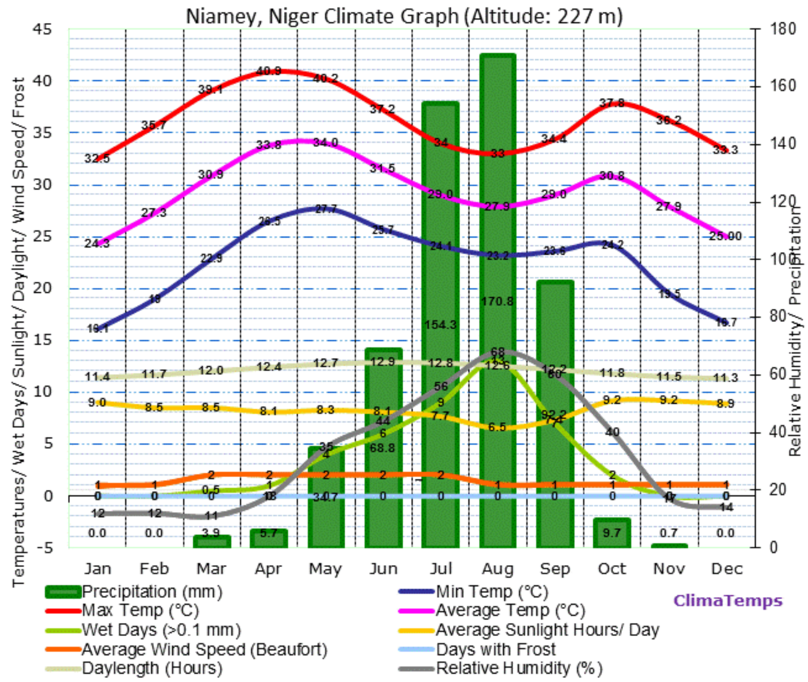


Figure 4.2d: Niamey, Niger climograph. (Niamey, Niger Climate Graphs) (13.52N, 2.1E)

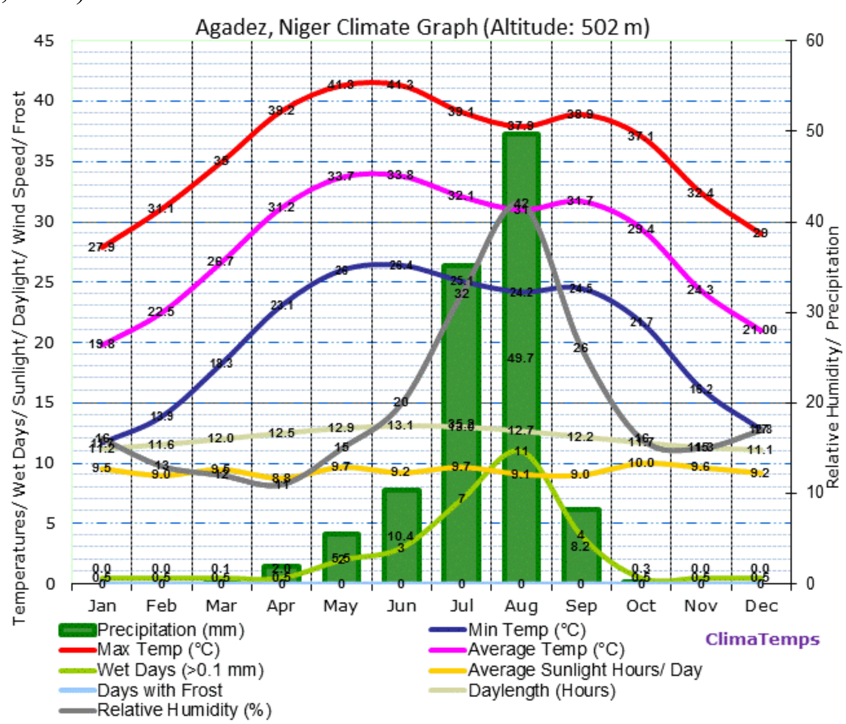


Figure 4.2e: Agadez, Niger climograph. (Agadez Climate Graphs) (16.96N, 7.98E)

The climatological rainfall for the arid cities of Gao and Agadez (both north of 16N) is considerably less than the climatological rainfall for the three capital cities (south of 14N). This is a product of both lower monthly rainfall climatologies and shorter effective rainy seasons (limited rainfall in June and September and almost none from October to May in these cities). Unsurprisingly, the pattern of relative humidity and the number of wet days tracks the development and termination of the rainy season in each city. In all five cities, August is the rainiest month, and the month in which the rainfall induced cooling was most pronounced. In all five cities, July is the second rainiest month, but the proportional rainfall contributions of the different months to the total annual rainfall varies by city.

The capital cities, and other comparably southerly locations experience stronger rainfall-associated temperature suppression during the rainy season (with Bamako and Ouagadougou experiencing their coolest average daytime high temperatures in August). In these more humid subregions, the temperature difference between the daytime high and nighttime low also decreases notably during the rainy season because of cloud cover (and suppressed radiative cooling during the rainy season), whereas for the arid regions of Gao and Agadez, diurnal temperature contrast does not change dramatically between the seasons. Gao and Agadez reach higher climatological temperatures in the March-May period than do the more humid regions further south, but Agadez experiences cooler average temperatures and nighttime temperatures during boreal winter (perhaps in part due to elevation, as well as latitude).

4.2. Regional Climate History: While there is some evidence for changes in the region's temperatures in the 20th century (New et al., 2006) consistent with an overall pattern of regional warming, the region has historically faced far larger temporal changes in precipitation and hydro-climatology.

Paleoclimate studies have shown that on geological time scales, significant fluctuations in average annual rainfall have occurred repeatedly in West Africa and that drought, desertification and "regime shift" between different climate states have been part of the long-term history of the region (Foley et al. 2003). On paleoclimate time scales, the Sahel and Sahara have seen profound changes in regional precipitation. The Sahel was drier than present between 1000–2700 years ago, but shortly after the Last Glacial Maximum, it was considerably wetter (Beyerle et al., 2003; deMenocal et al. 2000). Some of these transitions were quite abrupt and were forced by a combination of orbital forcing, and the complex interaction of land surface, ocean and atmospheric forcing (Gasse, 2000).

This part of Africa is also prone to large decadal and multi-decadal fluctuations in precipitation. In the relatively recent past, over the later portion of the 20th century and into the early 21st century, Sahelian rainfall has declined from a relatively wet period in the 1950s and 1960s to a drier period in the late 1970s, 1980s and early 1990s (Biasutti et al. 2008; Nicholson, 2005, Nicholson, 1980; Ndiaye et al., 2011; Mohino et al. 2011). As discussed in Chapter 3, the drought conditions of the 1970s and 1980s caused widespread famine and hardship throughout the region. More recently, however, meteorological records have shown somewhat of a rebound in precipitation from the late 1990s into the first decade of the 21st century (Giannini et al., 2008; Lebel and Ali, 2009; Greene et al., 2009; Nicholson, 2013). This recovery of the rains has been spatially heterogeneous with the western Sahel experience less proportional increase in rainfall than the central Sahel (Nicholson, 2005; Lebel and Ali, 2009). Figure 4.3 shows an aggregated all-Sahel rainfall time series from 1950-2011.

Generally, changes in streamflow have tracked changes in rainfall, (although with some measure of temporal lag discussed more in Chapter 5). As discussed in Chapter 3, some of the recent river floods in the region have been quite extreme and have at times occurred without proportionally anomalous precipitation (Amogu et al., 2010; Descroix et al., 2012). This issue is explored in more depth in Chapter 5.

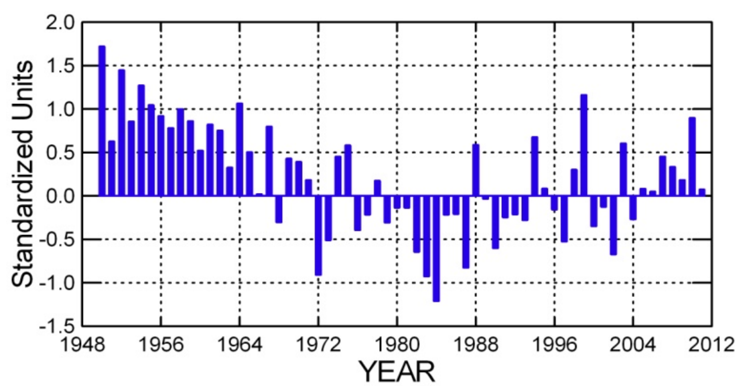


Figure 4.3: Sahel Rainfall 1950-2011. Sahel Rainfall 1950–2011. Each bar indicates the mean standardized seasonal (July–September) rainfall anomaly in each year 1950–2011 (i.e. for year i, we calculate the number of SDs each station is above/below its 1961–1990 normal, and then take the average of these values across all stations to give the mean standardized anomaly for year i)). The station data for this analysis are taken from the Global Historical Climate Network in the domain 10N–20N, 20W–30E. (data described in (Lawrimore et al., 2011), this index discussed in (Ward et al., 2012)). In the eastern Sahel, some stations near 20N are extremely climatologically dry, so a station is required to have a climatological July–September rainfall of at least 100 mm in order to qualify for inclusion in the analysis.

This drier period of the 1970s, 80s and early 90s had a roughly 30% lower average rainfall than the 1950s and 1960s (Nicholson, 2005). Despite the wetting trend of the recent past, the mean rainfall over the last 20 years is clearly not back to what it had been in the 1950s and 1960s. Changes to mean streamflow were even larger (~40%) and are discussed in more depth in Chapter 5. By visual inspection of the time series in Figure 4.3, it is also evident that the variance in the dry period of the 1970s-1990s and the "re-greening" period of the early 21st century is larger than the variance during the 1950s and 1960s. These observations of the regional change in rainfall mean and variability are complemented by similar changes to the region's streamflow, as discussed in more depth in Chapter 5.

Observational studies of regional rainfall from meteorological stations have been complemented by a number of in situ measurements (soil moisture content, evapotranspiration rate, etc.) and in the satellite era, with remotely sensed meteorological data. Examples include NOAA Climate Prediction Center's (CPC) Morphed rainfall data (CMORPH) (Joyce et al. 2004), CPC Rainfall Estimate (RFE) (Herman et al. 1997), Africa Rainfall Climatology (ARC) (Love et al. 2004), Normalized Difference Vegetation Index (NDVI) (Tucker et al. 2005), and Enhanced Vegetation Index (EVI) (Huete et al. 2002). Other products have been developed to integrate and interpolate station meteorological data to a climate model scale grid, including the Climate Anomaly Monitoring System (CAMS) (Ropelewski et al. 1985) and reanalysis[17] data (Kalnay et al. 1996)).

4.3 Regional Climate Dynamics (seasonal): On seasonal time scales, the west African monsoon (also known as the Southwest African monsoon) is brought about by a strong surface temperature and pressure gradient between the land surface in the west African Sahel and the Sahara (comparatively high temperature and low surface pressure) and the Gulf of Guinea (comparatively low temperature and high surface pressure) during the northern hemisphere summer months. The development of the surface thermally induced low pressure center over the Sahel and Sahara gradient drives a strong onshore wind from the Gulf of Guinea into the core of west Africa, where the advected moisture laiden air is heated by the high surface temperatures, rises, cools and drops its moisture in the form of convective precipitation (Nicholson, 2000; Sultan et al. 2003b). During other periods of the year, this temperature/pressure gradient between the interior of North Africa and the Gulf of Guinea disappears and the zonal center of rising air moves further south, causing a reversal of winds and the dry season in the semi-arid Sahel.

The center of rising, convective motion described above is part of the Intertropical Convergence Zone (ITCZ) and its seasonal zonal oscillation is responsible for the pattern of uni-modal precipitation in the region and the ITCZ makes its furthest northward advance during the July-September season. More southerly latitudes closer to the coast of Guinea tend to have longer uni-modal

[17] Reanalysis is a type of climatology data that incorporates station data, where available into dynamical climate models through data assimilation techniques in order to produce fields of climate information on an interpolated grid.

rainy seasons or bimodal rainy seasons (Trzaska, 2008). A schematic illustration of the surface wind fields in January and July are shown in Figure 4.4.

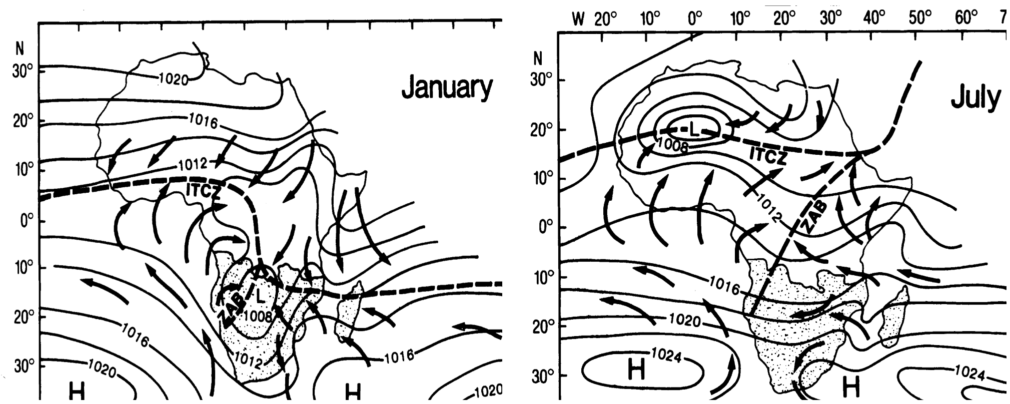


Figure 4.4: Diagram of surface wind and pressure patterns in West Africa in January and July. from Trzaska (2008)

As the moist air from the Gulf of Guinea flow north/northeast to the ITCZ and rises, storm systems are then advected from east to west by prevailing winds and influenced by the African easterly jet (AEJ) (at low levels ~3km) and the tropical easterly jet (TEJ) (at high levels ~15km). These atmospheric jet streams form as a result of the seasonal gradients of heating and geopotential height[18] at different levels in the atmosphere, although the African Easterly Jet is quite sensitive to surface vegetation feedbacks (Cook, 1999). The tropical easterly jet is part of a more global process extending all the way to southeast Asia, whereas the African Easterly Jet is more localized and its sensitivity to local land surface feedbacks can imply that strong AEJ development can suppress precipitation in the West

[18] Geopotential height is a meteorological term used to denote the height of an isobaric (equal pressure) surface above global mean sea level.

African Sahel (Cook, 1999). A schematic diagram of the vertical-meridional cross section of the monsoon dynamics is shown in Figure 4.5.

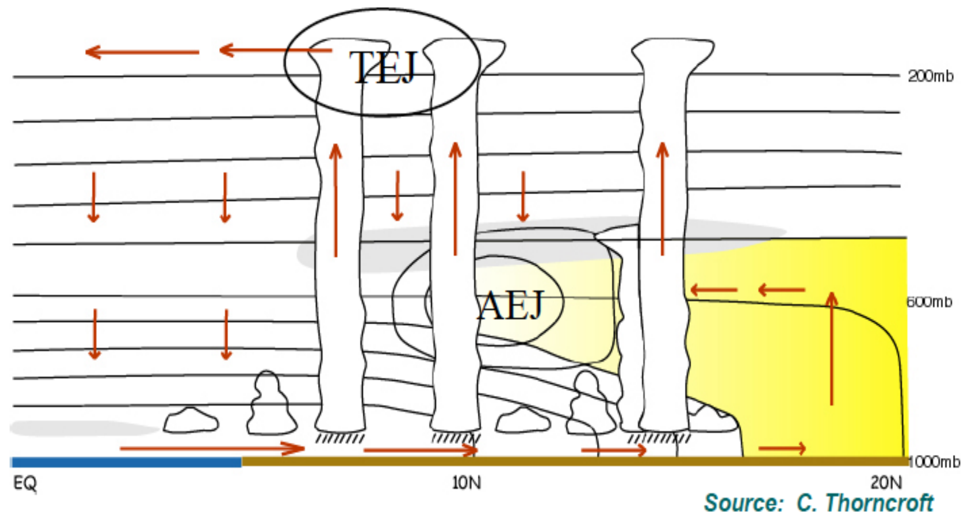


Figure 4.5: Schematic diagram of atmospheric circulation in West Africa from the equator to 20N and from the surface to 200mb. from Trzaska, 2008

On an intraseasonal time scale, the variability of West African Sahelian rainfall can be attributed to differences in the frequency of convective storms moving from east to west across the African continent during the core of the monsoon season (Lebel et al. 2003).

The topic of monsoon onset also has a significant impact on the agricultural sector and on livelihood impacts more generally because the timing of the rains and the temporal distribution of rainfall within a season will impact planting date decisions and will place constraints on crop growth. The statistical onset of the monsoon in the West African Sahel is somewhat more variable than the termination (Sultan et al., 2003a). There is also evidence to suggest that in some monsoon seasons, there may be a period of weeks without rain after the first storm before the "core" of the monsoon returns – in effect a sort of "stutter" to the onset of the rainy season (Sultan et al. 2003a,b; Siebert et al. 2008). Within the season, there is some evidence that dry years in the recent past (last 20 years or so) have experienced increased frequency of dry spells within the season (Salack et al., 2011). These realities of the intraseasonal variability create additional challenges to regional livelihoods as these features of the climate system leads to uncertainty in the optimal planting time and can add to subsistence farmers' climate risk exposure.

Dynamics of interannual variability: On inter-annual time scales, heavy rainfall seasons in the Sahel tend to be correlated with strong inter-hemispheric sea surface temperature gradients in the tropical Atlantic. When the temperature and pressure gradients between the southern and/or equatorial tropical Atlantic and the Sahel interior are particularly pronounced during the summer monsoon, stronger onshore winds tend to be stimulated, thereby increasing the advection of moisture laden air onto the continent. The reverse is true when the temperature and pressure gradients are relatively weak. This so-called "Atlantic dipole" has a powerful effect on regional rainfall, sometimes leading to pronounced hydroclimate extremes (Camberlin et al., 2001; Rodriguez-Fonseca et al., 2011; Nnamchi and Li, 2011; Ward, 1998). There is a close relationship between the Atlantic dipole and the "Atlantic Nino" phenomenon, whereby warm sea surface temperature (SST) anomalies develop in the Gulf of Guinea. This warm phase of the Atlantic dipole or "Atlantic Nino" tends to enhance precipitation along the Gulf of Guinea coast and suppress precipitation in the Sahel (Nnamchi and Li, 2011). This being said, historically, sea surface temperature variability in the tropical Atlantic is generally less pronounced than in the Pacific because the energetics of the Bjerknes feedback[19] occurs on seasonal time scales in the Atlantic, as opposed to interannual time scales in the Pacific (Burls et al., 2011).

Sahelian rainfall anomalies are also known to have a modest negative correlation with ENSO conditions due to a coupled ocean-atmosphere teleconnection between the tropical Pacific SST field and the tropical Atlantic SST field. During El Nino (warm) events, the peak tropical Atlantic SST field tends to be displaced to the north, but the Walker circulation also extends eastward, leading to subsidence over tropical Africa. During La Nina events, the peak tropical Atlantic SST field tends to be displaced to the south, but there is Walker related divergence from the eastern tropical Pacific which contributes to enhanced low level moisture flux into the Sahel. Consequently, there tends to be somewhat of an association between El Nino events and drought in the Sahel, whereas heavy rains tend to be associated with La Nina conditions (Joly and Voldoire, 2009). However, this ENSO related correlation is not nearly as pronounced as in many other regions of the world (Ropelewski and Halpert, 1987).

Dynamics of decadal/multidecadal variability: As Figure 4.3 indicates, the region is quite prone to variability on decadal/multi-decadal time scales. Much of this shift of rainfall patterns has been attributed to changing patterns of sea surface temperatures – primarily in the tropical Atlantic Ocean with the Atlantic

[19] In oceanography and atmospheric science, the Bjerknes feedback is the positive feedback mechanism between SST gradients and the wind field induced by the associated pressure gradients.

Multidecadal Oscillation (AMO)[20] (Zhang and Delworth 2006, Giannini et al. 2003). However, forecasting future precipitation changes has proven difficult as the dynamics of the AMO are not fully understood and global climate change is a confounding factor that impacts both the land and sea surface temperatures. The AMO index is generally based on north Atlantic SSTs and the figure 4.6 below shows the AMO on the basis of detrended SSTs from NOAA.

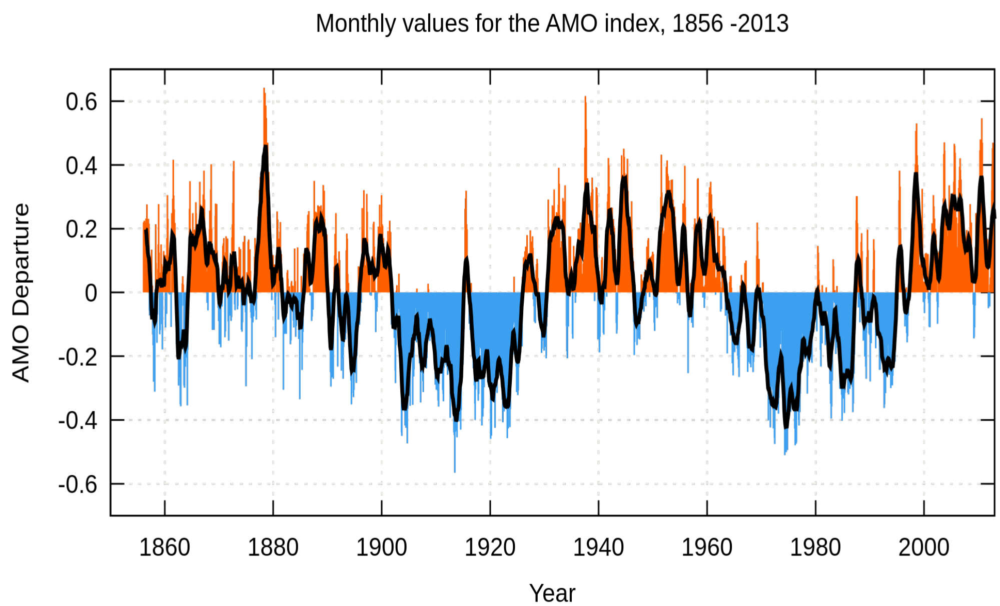


Figure 4.6: Monthly anomalies of the AMO index from 1856-2013. Black line is a 12 month moving average. (ESRL, NOAA)

It's clearly evident that the "negative phase" of the AMO in the 1970s, 80s and early 90s coincides with the Sahelian dry period depicted Figure 4.3, while the wet periods of the 1950s/60s and the most recent 20 years are coincident with a positive AMO phase. The literature also discusses how the AMO phase tends to positively correlate with Sahelian precipitation (i.e. when the tropical Atlantic as a

[20] The Atlantic Multidecadal Oscillation is a mode of variability occurring in the north Atlantic Ocean which has its principle expression in the sea surface temperature field.

whole is warm, Sahelian precipitation tends to be elevated) (Giannini et al., 2003; Knight et al., 2006).

There is also significant variability of the Niger River streamflow on these time scales and correlation between Niger River streamflow and AMO phase (Conway et al., 2008; Paturel et al., 2003). Paleoclimatic evidence suggests that the positive correlation between Sahelian rainfall anomaly and AMO anomaly has been persistent over much of recorded history (Shanahan et al., 2006). Even though tropical Atlantic SSTs play a critical role in shaping Sahelian rainfall on long-term time scales, there are also more subtle influences regarding the comparative strength of SST anomalies in the tropical Atlantic and other tropical ocean basins (Giannini et al., 2013; Wenhaji, 2013).

Both interannual and multi-decadal variations in the region's rainfall have been related to near-global scale patterns of sea surface temperature variation (Lamb 1978, Folland et al. 1986, Janicot 1992, Ward 1998, Giannini et al 2003, Biasutti et al 2008).

Future modeling challenges: Numerous global and regional scale climate models have been examined to explore the pattern of multidecadal variability in the region in the past and in future simulations (Vanvyve et al., 2008; Biasutti et al. 2008). Projections of natural modes of climate variation on decadal to multi-decadal timescales (such as the Atlantic Multi-decadal Oscillation) are the subject of active predictability evaluation (Meehl et al., 2009), although levels of skill are currently considered modest[21]. Clearly, systemic global change will be a major issue for future understandings of regional dynamics (Solomon et al. 2007).

There are several conceptual challenges to modeling rainfall and hydroclimatic future scenarios in the Sahel. Currently, our long-term understanding of the Atlantic Multidecadal Oscillation is limited – in part by the shortness of instrumental record. Furthermore, the interaction between the AMO and patterns of global climate change are uncertain.

As interannual variability is shaped by both a modest ENSO teleconnection and sensitivity to the tropical SST gradient in the Atlantic, modeling the interannual variability is somewhat more complex than in some of the other regions. Again, there is also still uncertainty in the ENSO literature and the literature on Atlantic variability regarding how systemic climate change may impact these oscillations.

Furthermore, in climate change simulations, there are competing dynamic factors: the interior of Northern Africa, (i.e. the Sahel and Sahara) is expected to warm rather substantially, while the Gulf of Guinea is also expected to warm somewhat more modestly (Christensen et al., 2007). The strength of the West African monsoon rainfall is a function of how much water is evaporated, the threshold water vapor concentration for precipitation and the strength of the monsoonal moisture flux. If the temperature in the interior of Northwest Africa rises by two or more degrees C and the land-ocean temperature gradient grows as

[21] More progress has been made on developing seasonal predictions (a few months ahead) based on sea surface temperature connections to West Africa rainfall (e.g., see Ndiaye et al. 2011 and references therein). Such developments provide additional prospects for River Niger risk management, which are beyond the scope of this paper.

a function of climate change (as implied by most IPCC modeling studies under moderate to intensive emission scenarios), this will stimulate enhanced evaporation and monsoonal moisture flux. However, the elevated Sahelian/Saharan temperatures in a climate change scenario may increase the threshold water vapor concentration for precipitation. Furthermore, monsoon strength will be partly contingent on the strength and variability of the African Easterly Jet (Cook, 1999).

On interannual time scales, moisture flux into the Sahel depends in part on the global tropical pattern of SSTs (Giannini et al., 2013). Another factor to consider in modeling the future of the West African Monsoon and related hydroclimate extremes is the role of biophysical feedbacks. Expanded plant cover in the Sahel will tend to encourage greater precipitation through enhanced transpiration, whereas diminished plant cover will facilitate desertification. Some modeling studies suggest that there may be multiple stable equilibria to this type of regional biophysical feedback (Wang and Eltahir, 2000). Vegetative changes may also feed back dynamically on the strength of the African Easterly Jet.

As a consequence of these and other competing factors and complex dynamics, there is disagreement among global climate modeling (GCM) studies of the West African Monsoon regarding the sign of the anticipated precipitation anomaly in an altered climate (Biasutti et al., 2008; Solomon et al., 2007). Much of this uncertainty depends on fine details of the parameterization of the convective West African monsoon process and the role of ocean forcing (Giannini et al. 2008).

4.4 Index Data (overview): The central technical challenge to index insurance is designing a proper index. Ideally a proper index is well correlated with target impact variables (in this case agricultural data) and performs well at capturing historical anomalies (as derived by some measure of skill in the historical record). To acquire some guidance on this challenge, during a research trip to Niamey, Niger in July of 2010, Dr. Katiella Mai Moussa, the national project coordinator for the UNDP GEF, suggested a bundled contract that served both a population of dryland subsistence farmers and a population of irrigated farmers (who tend to be wealthier). Dr. Moussa was generally skeptical about the idea of index insurance because of the perceived costs involved, but thought the bundling idea could potentially work. The idea of targeting negatively correlated risks to lower default risk has been discussed elsewhere in the literature on index insurance (Hellmuth et al., 2009).

Agricultural data: As discussed in Chapter 3, the dominant staple crop through much of this region (Niger, Mali and Burkina Faso) is millet (FAO). Rice is also grown in a variety of environments, including under irrigated cultivation near the Niger River and its tributaries. While high quality high spatial resolution, temporally complete data regarding agricultural yields in this region is an acknowledged challenge (Carletto et al., 2013), there is, however, publicly available district (province) level data for each of these cultivars through the countrySTAT resource. The length of record for this higher resolution data for

Niger is relatively short, starting only in 2000. For Burkina Faso and Mali, this district level agricultural data is available starting in 1984.

However, at a national level, area harvested, yield, production and various other statistics are available for millet and irrigated rice in these three countries through the Food and Agricultural Organization's statistics division (FAOSTAT). Data for area harvested, yield and production were acquired for millet, rice and cotton for Niger, Burkina Faso and Mali. These records are temporally comprehensive in the late 20th/early 21st century and run from 1961 to 2011 with no gaps. Given the temporal completeness of these national scale data, they will serve as the focal point of this analysis.

These data are strongly trended over time (particularly the area harvested and production data), probably in large part because of the very significant population growth over the last 50 years discussed in Chapter 3. One can make an intuitive argument that the yield of an agricultural variable is more strongly related to a climate variable than the area harvested, although this contention is debatable. Clearly, climate factors have a direct impact on agricultural productivity, but so do various other factors, such as crop variety, soil conditions (with regard to nutrient fertility), soil moisture, pests, fertilizer usage, etc.. Area harvested and production (which is the product of area harvested*yield) are arguably a product of population and policy shifts along with climatic, soil and other factors. However, climate risks still have an important impact on choices individual farmers make regarding how much land to harvest. Under an adverse climate, planting and harvesting a large area of crop will be a wasted investment

(Yesuf and Bluffstone, 2009). In light of the above reflections, the de-trended millet and rice production values will serve as the focus of this index insurance contract design. The de-trended millet production for the three countries is shown in Figure 4.7 below.

It is visually evident that the dry period of the 1970s and 1980s experienced generally suppressed millet production relative to the early period, when adjusted for the trend induced by population. Similarly, the "re-greening" period in the late 1990s and 2000s seems to experience enhanced millet production. The variability of the de-trended millet production also seems to increase dramatically after the mid-1980s. This could be a consequence of climate factors, shifting cultivation practices and/or population growth and dynamics, or some combination of multiple factors.

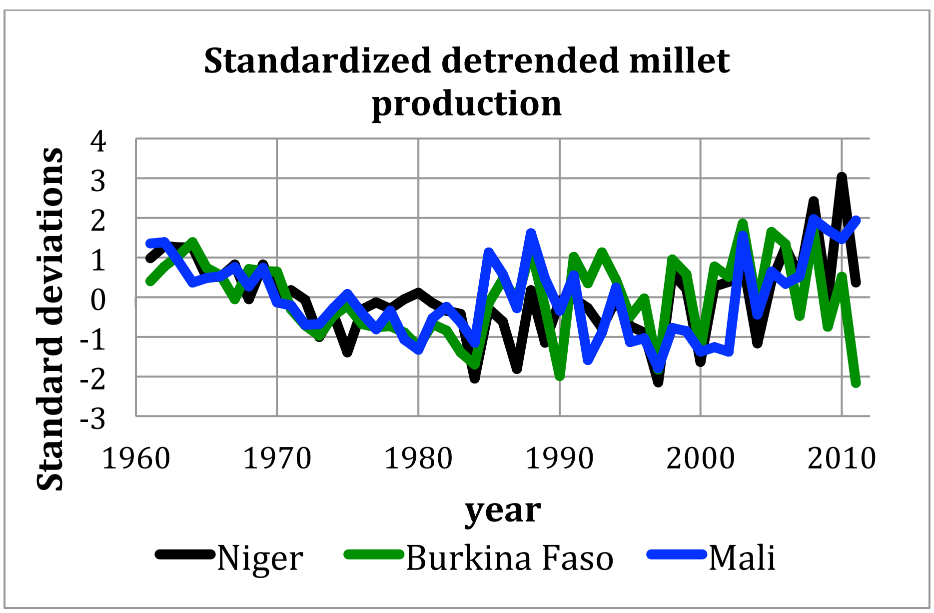


Figure 4.7: Graph of the millet production data for Niger, Burkina Faso and Mali, made by removing the linear trend in the data and standardizing the resulting anomalies. Original data source; FAO

Meteorological data: In this index analysis selection process, several rainfall estimates were considered. One rainfall index is the gauge based Global Historical Climate Network (GHCN) (Vose et al., 1992). Over 20,000 rain gauge and/or meteorological stations throughout world are involved in this network. However, the data itself is somewhat inconsistent than the other considered rainfall metrics. While still generally reported at a monthly time scale, GHCN data is more likely to have missing values or incomplete records. However, GHCN data goes back much further than the other data. For my analysis here data gathering is restricted to 1950 to the present.

Another station based rainfall data set employed here is the NOAA NCEP CPC Precipitation Over Land dataset (PRECL). These data are reported monthly on a 2.5 degree horizontal grid from 1948 to 2012 (Chen et al., 2002). These data come originally from gauge stations (many of which were part of the GHCN program) and interpolated to a 2.5 degree grid. Again, with both the GHCN and PRECL data, the main rainy season July-September was the focus.

Another such index is the satellite based Global Precipitation Climatology Project (GPCP) derived from measurements taken from NASA satellites since 1979 at a monthly time resolution and a 2.5 degree spatial resolution (Adler et al., 2003, Huffman et al., 2009). For the Index analysis, the July-September rainfall was used.

Hydrologic data: Streamflow values for the flood months for Koulikoro, Mali, Dire, Mali and Niamey Niger were explored as potential indices. These data were acquired during the abovementioned research trip to Niamey, Niger in July, 2010 – more specifically to the Niger Basin Authority and were provided courtesy of Mr. Ibrahim Olomoda. The data are continuous from 1950 to 2009.

Vegetation data: The vegetation index known as NDVI (Normalized Vegetation Difference Index) was considered from the USGS Africa Data Dissemination Service (Tucker et al. 2005). This dataset runs from 1981 to 2004 in dekads (increments of 10 days) at an 8 km resolution. There is also a more contemporary iteration of this dataset beginning in 2004 and running to 2010. For the purposes of this analysis, these data were aggregated to a coarser array to more closely resemble the other potential index variables. NDVI data was acquired over an area spanning the three nations of Niger, Mali and Burkina Faso during the dekads of July, August, September and October.

ENSO data: Furthermore, the NINO extended indices of tropical Pacific sea surface temperature were also considered (Kaplan et al., 1998; Reynolds et al., 2002). Specifically, the monthly values of NINO regions 1+2, 3, 3.4 and 4 from 1950 to the present were explored as potential indices.

4.5. Correlation Analysis: The first step in analyzing these data is to do basic correlation analyses. For this, I use the standard Pearson correlation. As mentioned above, because of the strongly trended nature of most of the agricultural data, the correlations reported here are generally with the de-trended agricultural time series unless otherwise noted. There are 18 agricultural variables in this analysis: millet area harvested, yield and production, rice area harvested, yield and production for each of the three nations: Niger, Burkina Faso and Mali.

Agricultural data at different scales: A correlation analysis of the national level production data from FAOSTAT and the aggregated district (subnational) data from countrySTAT shows the following results in Table 4.1. CountrySTAT data were available from 1984-2011 for Burkina Faso and Mali. As there are 27 years of overlap, the threshold for two sided statistical significance at the 95^{th}%ile is 0.37. Given the shortness of the subnational data for Niger, this analysis was only done for Burkina Faso and Mali. **Bolded values** indicate statistically significant positive correlations, while ***<u>bold, italicized underlined values</u>*** indicate statistically significant negative correlations (this will be true for all other tables in Chapter 4). This correlation table uses the raw (non-detrended) national scale area harvested, yield and production from FAOSTAT.

Correlation coefficient	Aggregated Burkina millet production	Aggregated Burkina rice production	Aggregated Mali millet production	Aggregated Mali rice production
National area harvested	**0.774**	**0.966**	**0.771**	**0.934**
National yield	**0.916**	0.261	0.342	**0.846**
National production	**0.99**	**0.988**	**1**	**0.999**

Table 4-1: Correlation table relating the national scale millet and rice area harvested, yield and production (from FAOstat) to the aggregated millet and rice production data (from Countrystat). CountryStat data was available for all the provinces of Burkina Faso and Mali from the mid 1980s to 2011. The aggregation method was a simple summation of the production data from each of the provinces' production. The exceptionally high correlations between the aggregated CountryStat production data and the national production data from FAO indicate that these two datasets are quite consistent (as would be expected).

As we can clearly see from this table, the correlation between the aggregated countrySTAT data and the FAO national data for production is almost perfect. In most cases, (with the exception of millet in Burkina Faso), the correlation between area planted at the national level and the aggregated countrySTAT production is higher than the correlation between the latter and national level yield data.

Correlation Analysis between Agriculture data and other Potential Indices: In this analysis, correlations were calculated between the observed rainfall, streamflow and NDVI indices and the detrended national scale agricultural data from the FAO.

GHCN: GHCN rainfall data had to be carefully selected on the basis of completeness of station record. GHCN data was downloaded for May through October, but the initial focal point of this analysis was the July-September period. JAS aggregations were calculated and completeness of record was evaluated on the basis of one of two criteria: if from 1970-2000, there were at least 25 years of JAS rainfall or if from 1950- 2012, there were at least 47 years of JAS rainfall (~75% complete) the station was included in the index. If neither of these conditions were met, the station would not be included in the index. In reality, most stations that met one condition also met the other. The JAS precipitation was then standardized by station and each JAS seasonal total was normalized to that station's mean and variance. A station-based index was constructed for each nation that averaged the normalized anomalies into one national index. The national index for Niger includes 15 stations, for Mali includes 21 and for Burkina Faso, only 7. Furthermore, a year-by-year adjustment was made to account for the fact that different years included different numbers of stations: this is described in (Ward, 1994).

In the resulting correlation analysis, there is a 51-year overlap between the GHCN data and the FAO data (from 1961-2011), so the threshold for 2-sided statistical significance at the 95th%ile is +/-0.277. The correlation results are shown in Table 4-2 below.

Pearson correlation	Niger GHCN index	Burkina Faso GHCN index	Mali GHCN index
millet area	**0.39**	**0.436**	0.273
millet yield	**0.533**	**0.444**	0.244
millet production	**0.48**	**0.616**	**0.493**
rice area	-0.168	**0.285**	**0.394**
rice yield	-0.017	-0.086	**0.462**
rice production	-0.084	**0.313**	**0.426**

Table 4-2: Table of Pearson correlation values between the millet and rice area harvested, yield and production and the JAS aggregated GHCN rainfall indices for Niger, Burkina Faso and Mali. Bolded values are statistically significant.

As we can see, millet production has a significant positive correlation with the GHCN indices for all three nations. Millet yield and area also have robust correlations for Niger and Burkina Faso. The correlation between rice statistics and the GHCN indices varies by country, being weakly negative for Niger, while attaining significant positive correlation for Burkina Faso and Mali. This is partially due to more extensive rice cultivation in both Burkina Faso and Mali than in Niger. This may include more non-irrigated rice cultivation, for those nations, which may be more vulnerable to drought risk.

NOAA Precipitation over Land (PRECL): The NOAA Precipitation over Land dataset also shows a strong correlation with agricultural variables in the region, particularly millet. The advantage to using this type of dataset over the GHCN is the consistency of record. Individual stations may not report data in certain years and the national level GHCN indices mentioned each experience a marked decline in station coverage around the late 1990s. On balance, when the correlation analysis was done, the GPCP gridded rainfall dataset did not have the same level of significant correlation as the PRECL. So the results for the most promising PRECL correlation analyses are shown in Figures 4.8a, b, and c below. Again, the PRECL dataset runs from 1948 to the present, so there is a 51-year overlap (1961-2011) with the agricultural data from FAO. Hence the threshold for significance is +/-0.277. The maps below show the correlation of the gridded NOAA PRECL precipitation with the de-trended millet production for Niger, Burkina Faso and Mali.

These maps truncate in latitude at 8.75N and 16.25N. The downloaded data spanned a larger range (6.25 to 23.75N and 13.75W to 28.75 E), but for the sake of focusing on the region that is most critical, correlations have been calculated over a more restricted area. While this northern map boundary cuts off the northern part of Mali and Niger, these regions are essentially desert as can be seen in Figure 3.1 and are north of the 250 mm isohyet. In such arid environments crop agriculture is limited and a pastoral lifestyle or other economic activities (such as mining in northern Niger) tend to be more dominant. As with the other maps, the correlation values were calculated on a 2.5 degree grid and then interpolated using spline interpolation for intermediate points.

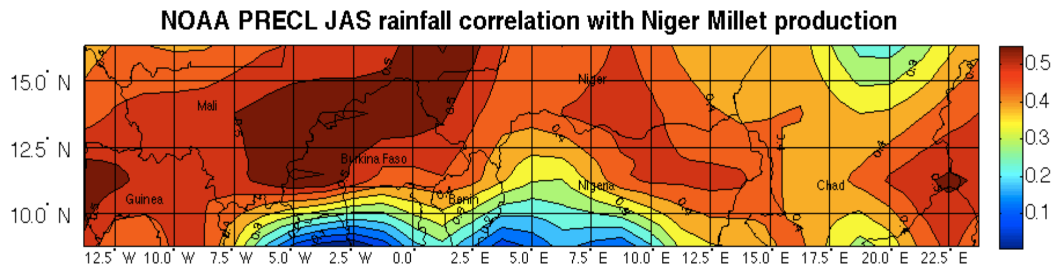


Figure 4.8a: Correlation map between the NOAA PRECL JAS rainfall and de-trended, standardized Niger millet production.

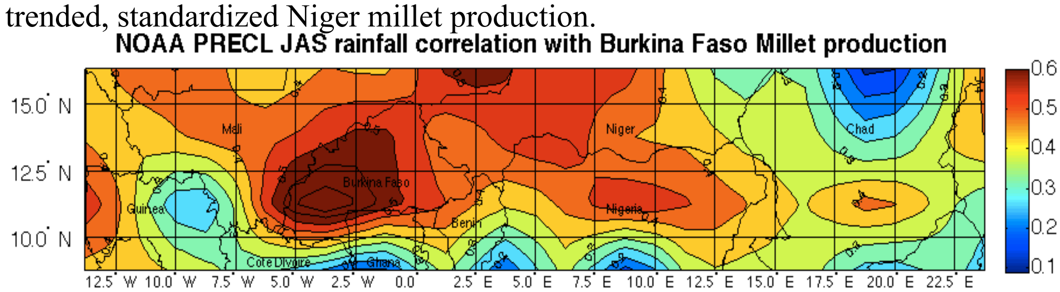


Figure 4.8b: Correlation map between the NOAA PRECL JAS rainfall and de-trended, standardized Burkina Faso millet production.

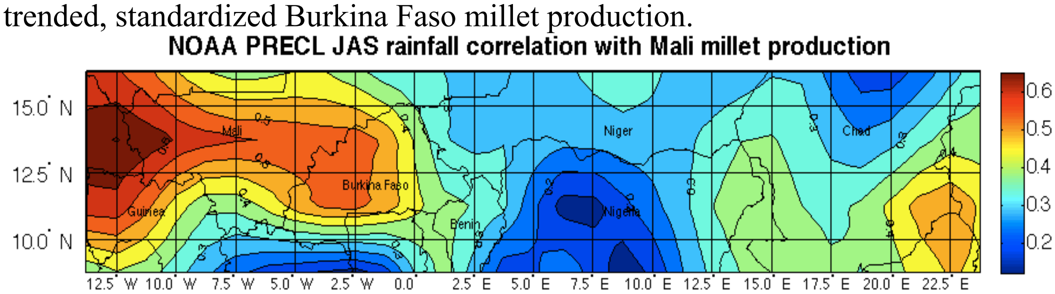


Figure 4.8c: Correlation map between the NOAA PRECL JAS rainfall and de-trended, standardized Mali millet production.

We can see quite clearly that these indices perform very well over the appropriate countries. All of southern Niger achieves statistical significance for the correlation between PRECL JAS and Niger millet production. All of Burkina Faso achieves statistical significance for the correlation between PRECL JAS and Burkina Faso millet production with the peak correlation located in western and central Burkina Faso. All of southern and western Mali achieves statistical significance between PRECL JAS and Mali millet production.

GPCP: The correlation between the GPCP and the agricultural indices is not quite as strong as that between the agricultural indices and the PRECL dataset, so the PRECL is considered preferable.

Streamflow: Monthly aggregated streamflow data from the Niger Basin Authority was also analyzed in reference to the agricultural data. Here, the overlap is 49 years from 1961-2009. Consequently, the threshold correlation for 2-sided 95% significance is +/-0.283. Correlations between flood month streamflow and the various agricultural variables are shown in Tables 4-3. As the climatological streamflow in Dire in November and December are close in value, results for shown for both. A similar logic is used for Niamey, given that December and January are the peak flood months for Niamey.

For the millet crop, a similar story emerges: enhanced streamflow correlates well with millet production in each of the three nations. For the rice crop, in Niger, there is a statistically significant negative correlation between the rice crop and streamflow. The strongest negative correlation is between the Niamey December streamflow and the Niger national rice production. The correlation between Niamey December streamflow and regional rainfall is explored in more depth in this Chapter and statistical simulations of future potential flood recurrence are explored in Chapter 5.

		Koulikoro Sep.	Dire Nov.	Dire Dec.	Niamey Dec.	Niamey Jan+1[22]
Niger	millet area	**0.439**	**0.409**	**0.483**	**0.341**	**0.379**
	millet yield	**0.452**	**0.423**	**0.419**	**0.486**	0.195
	millet production	**0.520**	**0.517**	**0.524**	**0.534**	**0.318**
	rice area	***-0.437***	***-0.449***	***-0.477***	***-0.527***	***-0.418***
	rice yield	***-0.286***	-0.243	-0.262	-0.223	***-0.317***
	rice production	***-0.505***	***-0.534***	***-0.550***	***-0.571***	***-0.534***
Burkina Faso	millet area	-0.012	0.012	0.012	-0.046	-0.248
	millet yield	0.254	**0.304**	**0.324**	**0.314**	0.152
	millet production	0.257	**0.306**	**0.319**	**0.296**	0.039
	rice area	**0.735**	**0.643**	**0.677**	**0.650**	**0.716**
	rice yield	-0.273	-0.267	-0.213	***-0.325***	***-0.359***
	rice production	**0.642**	**0.583**	**0.636**	**0.584**	**0.626**
Mali	millet area	0.186	0.077	0.159	0.101	0.052
	millet yield	0.192	0.242	0.176	0.255	-0.118
	millet production	**0.352**	**0.297**	**0.318**	**0.346**	0.016
	rice area	**0.605**	**0.509**	**0.558**	**0.542**	**0.595**
	rice yield	**0.471**	**0.544**	**0.603**	**0.542**	**0.351**
	rice production	**0.650**	**0.612**	**0.666**	**0.641**	**0.612**

Table 4-3: Table of Pearson correlation values between agricultural variables from FAOSTAT (at the national level) and monthly streamflow for specified gauge stations and months. Statistically significant positive correlations are shown in **bold.** Statistically significant negative correlations are shown in ***bold underline italics.***

NDVI: The correlation between the NDVIg dataset and the agricultural yield from 1981-2004 was calculated on a coarsened grid. The 8 km spatial resolution

[22] January+1 here means the January after the year of the agricultural yield value. We expect good rainfall in year x to lead to good harvests in the same year (September/October) and high streamflow in the flood season for Niamey – December/January.

raw data was degraded to roughly 2.5 degrees to be in concert with the other analysis. This degradation was achieved by simply taking an area average of a 31x31 cell box (about 250 km). Given that there are 24 years of record with this dataset, the threshold correlation for two sided 95% significance is +/- 0.409. The results of the NDVI correlations are shown in Figures 4.9a-d below.

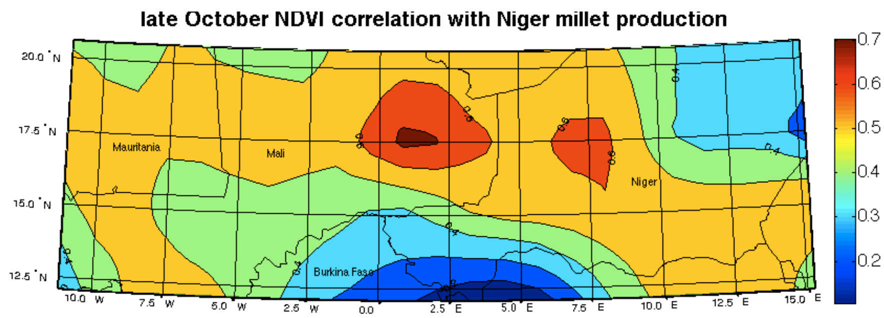


Figure 4.9a: Correlation of late October NDVI with de-trended, standardized Niger millet production.

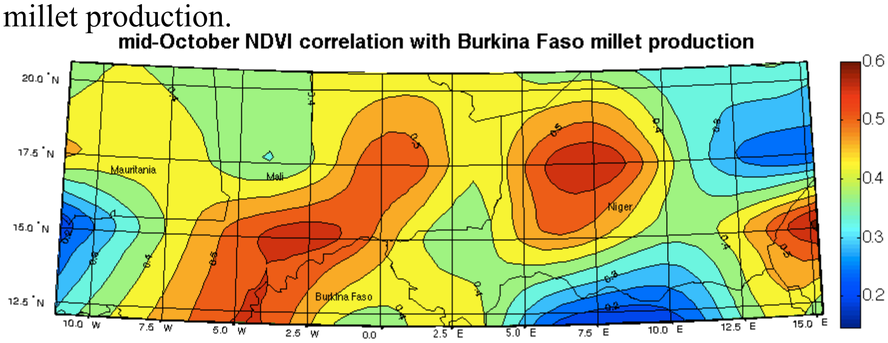


Figure 4.9b: Correlation of mid October NDVI with de-trended, standardized Burkina Faso millet production.

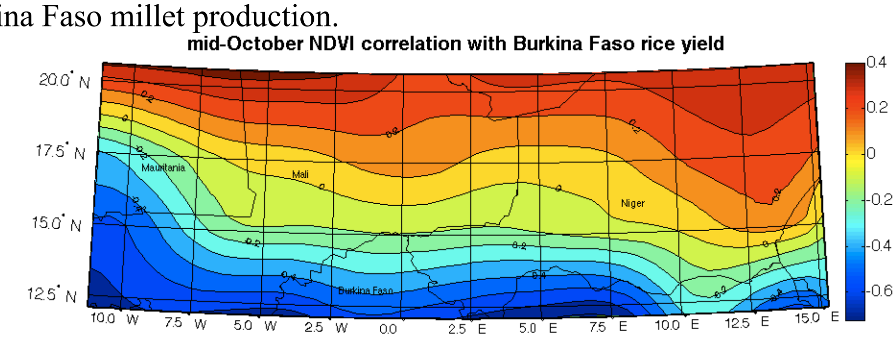


Figure 4.9c: Correlation of mid October NDVI with Burkina Faso rice yield.

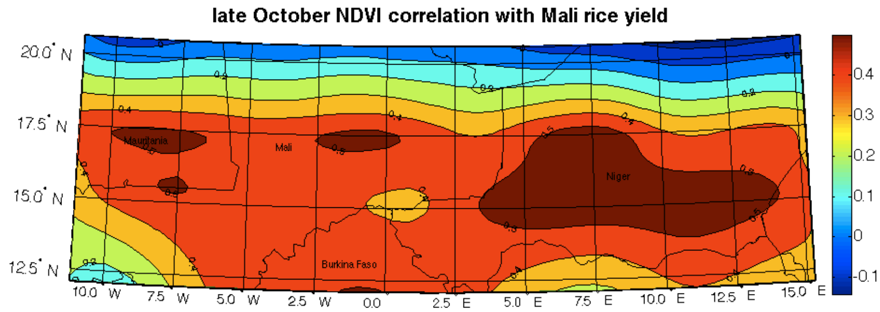


Figure 4.9d: Correlation of late October NDVI with Mali rice yield.

These particular periods and correlations were shown because they had relatively high correlations. As we can clearly see from the above analysis, the late October NDVI has significant positive correlations with Niger millet production and with Mali rice yield, while the mid-October NDVI has significant positive correlation with Burkina millet production and negative correlation with Burkina Faso rice yield. However, while many of these correlation values are statistically significant, the average positive correlation values are not as large as those for the NOAA PRECL, so on balance, the NOAA PRECL is considered a superior index for drought risk for millet farmers. Furthermore, the average negative correlation values were not as negative as that between the Niamey December streamflow and the Niger rice crop.

ENSO Indices: While a correlation analysis was done between the various agricultural variables and the different NINO indices for NINO regions 1+2, 3, 3.4 and 4, relatively little statistically significant correlation was found between these variables, particularly for the NINO 3 and 3.4 indices. For NINO 1+2, the April-July indices show some statistically significant negative correlation with millet yield in Burkina Faso, the December index shows some significant negative correlation with Mali rice yield and production and the March and April indices show a significant negative correlation to Mali millet production. The NINO 3 index in March and April also shows some significant negative correlation with Mali millet production. The NINO 3.4 April and May indices also show significant negative correlation with Mali millet production. For the NINO 4 indices, there are significant positive correlations with July, August and September and December and Niger rice production. There are also significant negative correlations for June-September and December-February indices and the rice production in Burkina Faso. The July index also shows a significant negative correlation with millet yield in Mali. As there are 51 years of data overlap between the ENSO indices and the agricultural data (1961-2011), the threshold for statistical significance is +/- 0.277. The table 4-4 below shows the resulting correlation analysis – only statistically significant results are shown.

As mentioned earlier, ENSO state and regional precipitation tend to be negatively correlated (i.e. La Nina tends to be correlated with wetter conditions and El Nino tends to be correlated with drier conditions). However, this correlation is rather weak as the mechanism of rainfall in the West African Sahel has a rather remote teleconnection to the tropical Pacific (Ropelewski and Halpert, 1987).

	Niger rice	Burkina Faso millet	Burkina Faso rice	Mali millet	Mali rice
January			-0.293p***		
February			-0.297p***		
March				-0.299p*, -0.331p	
April		-0.3y		-0.284p**, -0.279p*, -0.308p	
May		-0.304y		-0.287p**	
June		-0.365y	-0.283p***		
July	0.288p***	-0.316y	-0.306p***	-0.291y***	
August	0.315p***		-0.35p***		
September	0.322p***		-0.358p***		
December	0.298p***		-0.293p***		-0.28y, -0.283p
December-1			-0.282p***		

Table 4-4: Table of Pearson correlation values between the agricultural data and different ENSO indices. Only statistically significant results are shown. If the number is followed by y, the agricultural variable is yield, whereas if the number is followed by a p, the agricultural variable is production. If no stars follow the number the ENSO index is NINO 1+2. For *, **, and ***, the ENSO domains are NINO 3, NINO 3.4 and NINO 4 respectively. Dec -1 refers to the correlation between the December NINO index and the agricultural production or yield in the following year (i.e. how skillful was December 1980 NINO index at predicting agricultural yield and production in 1981).

Correlation between Hydrology and Rainfall: An important feature to understand about this region is the connection between the regional rainfall and streamflow. The flood month streamflow on the Niger River acts somewhat as a regional integration of area rainfall over the season. Flood months vary depending on the point in the river's course. Streamflow data taken from Koulikoro, Mali is meant to be indicative of the upper Niger basin and the peak flow month is September. The Dire, Mali station represents the inland delta region of Mali and both November and December have roughly equal high climatological flow.

Niamey Niger is representative of the middle Niger basin and December and January have roughly equal high flows.

Figures 4.10a-e below show the correlation maps of Niamey December streamflow with GPCP rainfall for JFM, AMJ, JAS, OND and the whole year. GPCP data for this analysis extends from 1979 to 2009, so there are 31 years of record implying that the threshold for 2-sided 95% confidence is a correlation of +/-0.358. The correlation structure for the JFM and AMJ seasons is somewhat chaotic. Unsurprisingly, there is more widespread positive correlation for the JAS season. Geographically, the strongest regional correlation is in the latitude band 10 to 15N, especially during JAS and for the whole year (which is dominated by JAS rainfall). However, one persistent feature is the significant positive correlation between rainfall in the Guinea highlands and the Niamey streamflow (roughly 7 to 12 N and 7 to 12 W) even during the non-JAS seasons and Niamey streamflow. As the Guinea highlands are the headwaters of the Niger River, this is to be expected on some level.

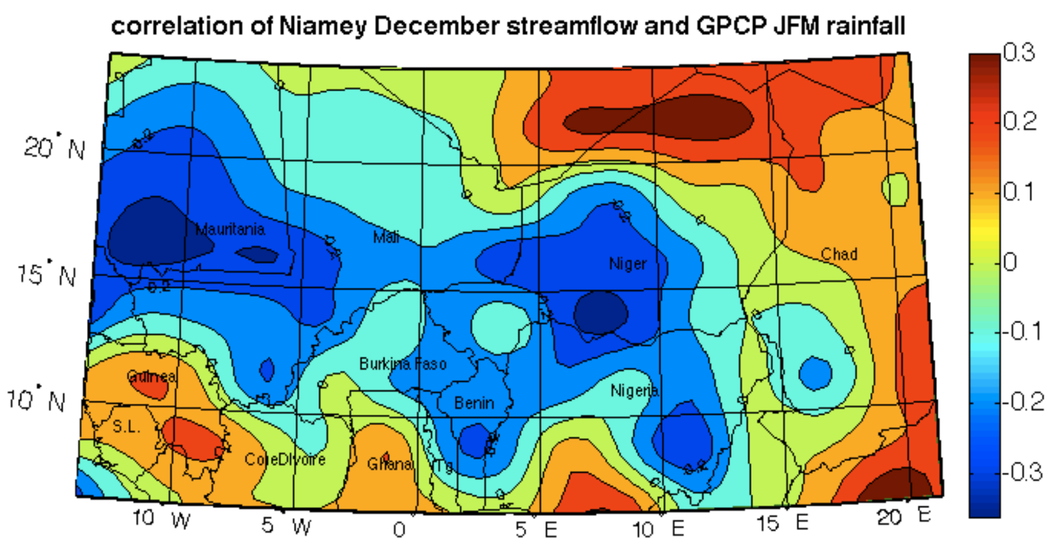


Figure 4.10a: Correlation of Niamey December streamflow with GPCP JFM rainfall.

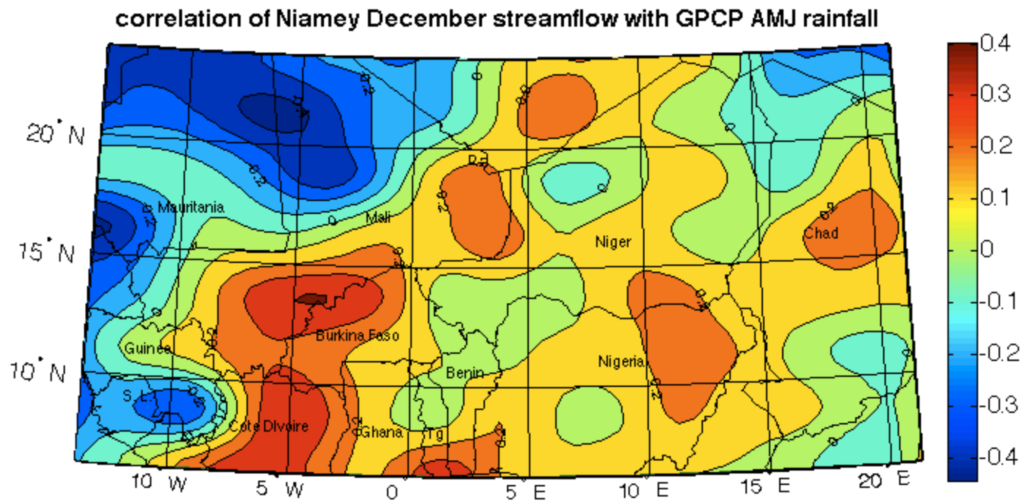


Figure 4.10b: Correlation of Niamey December streamflow with GPCP AMJ rainfall.

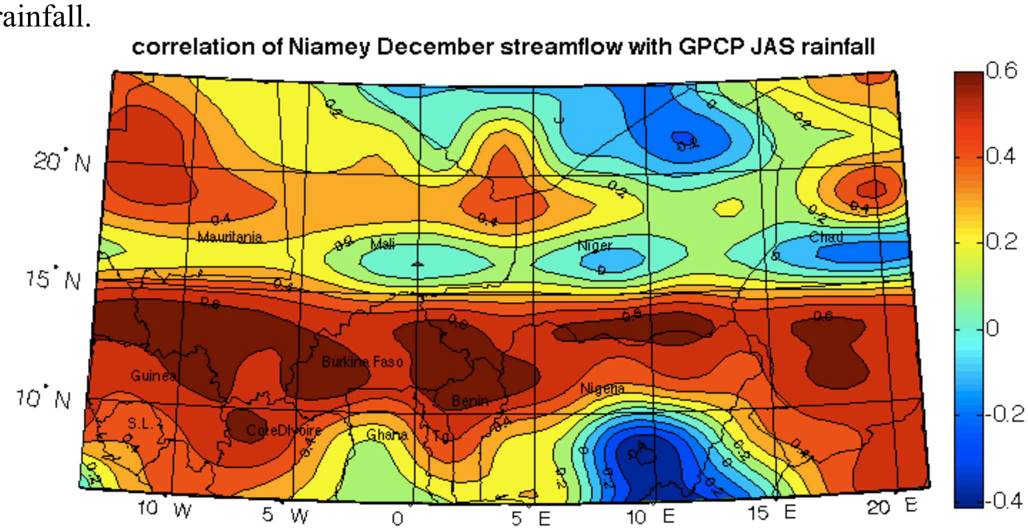


Figure 4.10c: Correlation of Niamey December streamflow with GPCP JAS rainfall.

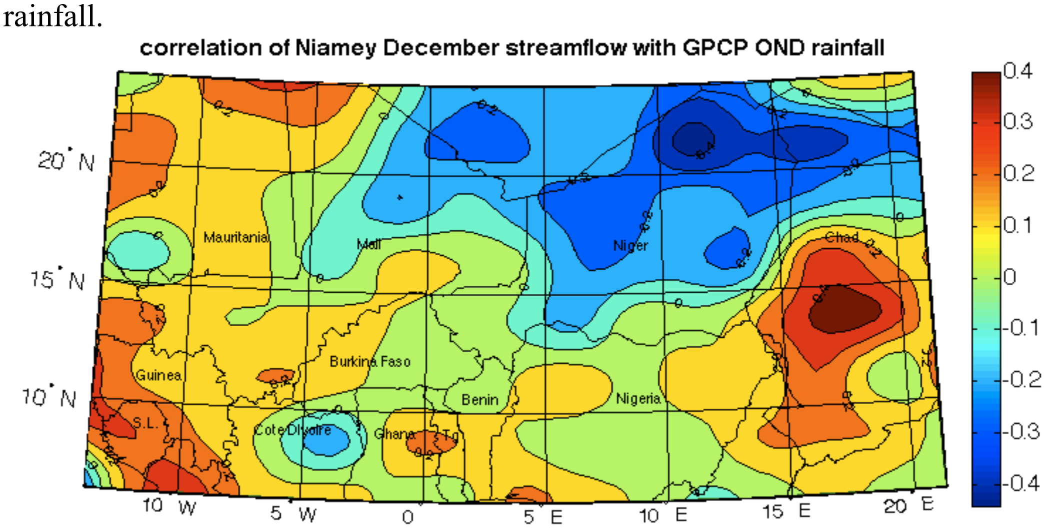


Figure 4.10d: Correlation of Niamey December streamflow with GPCP OND rainfall.

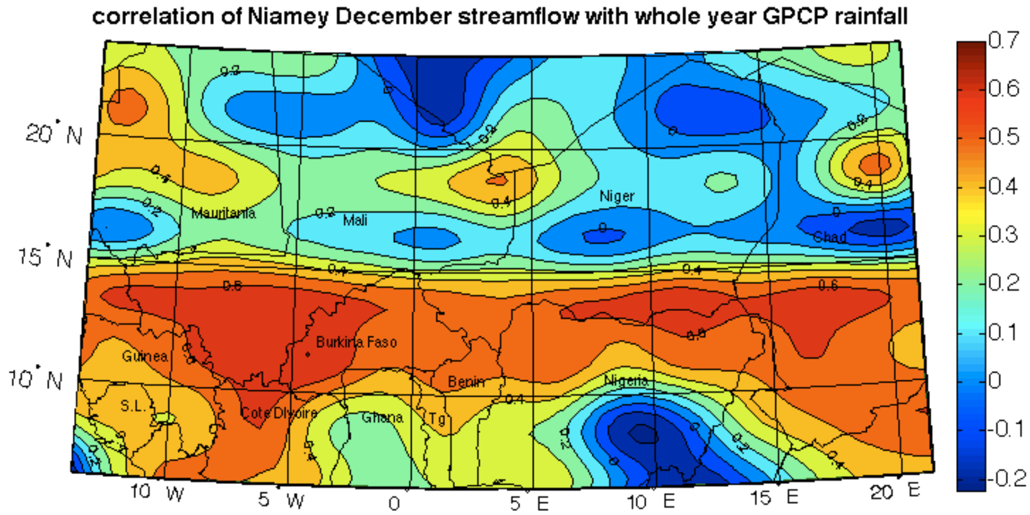


Figure 4.10e: Correlation of Niamey December streamflow with GPCP whole year rainfall.

4.6. Gerrity Skill Score: In addition to raw correlation analysis, another useful tool for assessing the skill of an index insurance contract is the Gerrity skill score (GSS) (Gerrity, 1992). This is a categorical score parameter which measures how well a given index performs at capturing the values in each of multiple categories. A perfectly skillful index that does not make any mistakes has a GSS of 1 and an index with no skill at all would have a GSS of 0. Negative GSS scores are possible for indices that perform worse than random guessing. In general, correlation strength and GSS tend to be correlated, but some indices with a relatively low correlation may have a high GSS and vice versa.

The first step in the process of assessing the GSS is to assess the parameter a, defined here by equation 4.1

$$a_q = \frac{1 - \sum_{r=1}^{q} p_r}{\sum_{r=1}^{q} p_r} \qquad (4.1)$$

where p represents probability, r and q are both index values. For the simplest index insurance contract design, with only two states of the world (exceeding the threshold and not exceeding the threshold), q can either be 1 (exceeding the threshold) or 2 (not exceeding the threshold). So, for example, if we create a contract with a single threshold and a flat payout of a fixed amount, no matter by how much the threshold is exceeded, and we are looking at the 10^{th}%ile drought, then a_1=(1-0.1)/0.1 = 9 and a_2 = (1-0.1-0.9)/(0.1+0.9) = 0.

The next step is to calculate the "skill matrix" whose elements are described by equations 4.2 and 4.3 for diagonal and off-diagonal entries respectively.

$$s_{ii} = \frac{1}{\kappa}\left(\sum_{q=1}^{i-1} a_q^{-1} + \sum_{q=i}^{\kappa} a_q\right) \tag{4.2}$$

$$s_{ij} = \frac{1}{\kappa}\left(\sum_{q=1}^{i-1} a_q^{-1} - (j-i) + \sum_{q=j}^{\kappa} a_q\right) \tag{4.3}$$

where κ is the number of categories – 1. As equation 4.3 is written, there is an assumption that j>i. For i<j, $s_{ij} = s_{ji}$. In the simplest index insurance case, with two states of the world (threshold exceeding and non-threshold exceeding), κ=1. κ is equal to the number of categories minus 1. When i=1, the first term in Equations 4.2 and 4.3 vanish. When i> κ, the last terms in equations 4.2 and 4.3 vanish. So in our simple example above, $s_{11} = a_1$=9, s_{22} =1/a_1 = 1/9, and s_{21}=s_{12}=-1.

The Gerrity skill score is then calculated as

$$GSS = \Sigma p_{ij} s_{ij} \tag{4.4}$$

where the p_{ij} are the probabilities of each ij pair.

It should be noted here that it is mathematically possible, if one constructs a GSS on the basis of a theoretical rather than observed probability, to attain a GSS higher than 1. If, for example one has 50 year overlapping records between the agricultural index and the insurance index and the threshold is for a theoretical 1 in 10 event, but the impact variable (here the agricultural production) has 7 events that cross that threshold and the index insurance performs perfectly, correctly identifying all 7 threshold crossing events and all 43 non-threshold crossing events, the GSS would then be (9*7+0.1111*43)/50 = 1.3555. There are two ways around this problem: a) construct the index on observed rather than theoretical probabilities or b) normalize the results by the "perfect contract" with the observed number of threshold crossing events in the agricultural index. These two methods will lead to slightly different results, but the basic picture will remain the same.

This is a qualitative, value-laden statement, but a GSS of 0.3 is somewhat skillful and an adjusted GSS of 0.5 is strong and robust. Clearly, GSS values of 0.7, 0.8 and higher are very robust and strongly indicative of a beneficial contract. Ultimately, index insurance contracts must be negotiated by stakeholder engagement as well as expert contract design. But as general idea, a GSS value of 0.3 is probably strong enough to offer some benefit in many situations, provided the correlation is also strong and a GSS value in the vicinity of or exceeding 0.5 would likely make an index insurance contract quite beneficial unless the relationship between the region's climate and agricultural yield undergoes major future changes.

One potential critique of the GSS is that as constructed, it places an equal penalty on both types of conceptual "mistakes" a contract can make because $s_{ij}=s_{ji}$. What this means mathematically is that a false payout and a failure to pay in the case of a low yield year (basis risk) are viewed with equal penalty from the standpoint of the GSS. Clearly, these different events have very different practical consequences and would be perceived differently by the parties to the index insurance. A false payout would generally be welcomed by the target client population but would be unwelcome by the insurer. A failure to pay in the case of a low yield year would be a reason for the client population to be mistrustful of the contract, while simultaneously easing concerns about viability and solvency in the perspective of the insurer.

This is another qualitative, value-laden statement, but the ideal "imperfect" index insurance contract has as many or slightly more false payouts than failures to pay. If the failure to pay rate exceeds the false payout rate, the stakeholders may never get on board because of mistrust. If the false payout rate exceeds the failure to pay rate by too much, the contract's solvency will be threatened.

For the sake of simplicity and analysis in this dissertation, simple, step function contracts will be the emphasis of the analysis. As an initial step, the 1 in 10 recurrence statistic is considered. Some fieldwork evidence from a pilot project in Ethiopia suggests that when premiums are scaled appropriately, even very poor farmers may often prefer contracts that cost more but payout more, rather than less frequently (Norton et al., 2014).

The GSS lends itself well as a tool to analyze step function contracts, but is less well equipped to address gradient functions and other more complex contract designs. If there is a continuously varying payment when the index crosses the strike threshold, one may prefer to analyze the problem by means of a continuous, rather than discrete skill estimate, such as the linear error in probability space (LEPS) (Ward and Folland, 1991).

Table 4-5 below shows the calculated Gerrity scores for a simple one step contract with a theoretical 1 in 10 threshold crossing frequency for relevant GHCN and streamflow indices (only GSS in excess of 0.3 are shown).

*The potential Niger rice production contract based on Niamey December streamflow is based on a negative correlative relationship – i.e. the contract is triggered when the Niamey December streamflow reaches the 90th percentile or higher. The Mali millet yield contract is based on a positive correlative relationship between Dire November streamflow and the Mali millet yield data.

	Niger millet production	Burkina Faso millet production	Mali millet yield	Niger rice production
GHCN	0.557	0.756		
streamflow			0.395	0.352*
correct payouts	3	4	3	2
false payouts	2	2	5	3
failures to pay	2	1	3	3

Table 4-5: The top two lines show Gerrity skill score, bottom three lines show the number of correct payouts, false payouts and failures to pay in the historical record. For the GHCN, there are 51 years of overlap with the agricultural data (1961-2011). For the streamflow data, there are 49 years of overlap (1961-2009).

The GHCN and agricultural data overlap for 51 years and the streamflow and agricultural data overlap for 49 years. Because the streamflow data in this analysis demonstrates a strongly multidecadal character, this analysis was calculated on the basis of the GSS from the anomalous streamflow off of the 9 year running average.

These above potential indices have the advantage of having roughly as many or slightly more false payouts to failures to pay. Thus, in addition to having a high GSS, they also have a relatively high desirability for both insurer and client on the basis of the historical record.

As discussed earlier, the correlation strength between the agricultural variables and the other potential indices (GPCP rainfall, NDVI and ENSO indices) is somewhat more limited. Consequently, Gerrity scores were calculated for the NOAA PRECL dataset, but not the others.

When the Gerrity score of the NOAA PRECL dataset was mapped over the spatial domain mentioned above, the Gerrity scores were quite heterogeneous - often with significant positive Gerrity scores adjacent to negative or insignificant Gerrity scores. To help address this problem, the NOAA PRECL dataset was then aggregated at a national level. The gridboxes at 13.75N, 1.25E to 13.75E, along with the gridboxes at 16.25N, 6.25E to 13.75E constitute the "Niger" index. The gridboxes at 11.25N, 3.75W to 1.25E and the gridbox 13.75, 1.25W constitute the "Burkina Faso" index. The gridboxes at 16.25N, 3.75W to 3.75E, at 13.75N from 11.25W to 3.75W and at 11.25 from 8.75W to 6.25W constitute the "Mali" index.

The Gerrity analysis of these country-wide index insurance contracts (for millet yield and production) is shown in Table 4-6. The GSS for the Mali index was quite low and is therefore not included.

Gerrity score with NOAA PRECL	Niger	Burkina Faso
Millet yield	0.473	0.485
Correct payouts	3	2
False payouts	1	6
Failures to pay	3	1
Millet production	0.379	0.49
Correct payouts	2	3
False payouts	1	5
Failures to pay	3	2

Table 4-6: The first and fifth lines showing Gerrity skill score, for millet yield and millet production, respectively. The other lines show the number of correct payouts, false payouts and failures to pay in the historical record. For the GHCN, there are 51 years of overlap with the agricultural data (1961-2011). For the streamflow data, there are 49 years of overlap (1961-2009).

It should be noted that while these GSS's are fairly good, the relatively high number of failures to pay in the Niger index cases and the very high rate of false payout in the Burkina indices may make these particular contracts less desirable.

4.7 Conclusions Regarding Index Selection: In light of all the above analyses, there are several promising indices for Niger and Burkina millet production: GHCN, and aggregated NOAA PRECL in particular. GPCP rainfall is not as promising and nor regional NDVI. Many of the streamflow variables could also function as potential indices for the Niger and Burkina millet production, but this is not really necessary in light of the success with the other metrics. There is some potential for a streamflow-based contract for Mali millet yield using the November streamflow values from Dire and for a negatively correlated streamflow-based contract for Niger rice production using December streamflow values from Niamey (both calculated off the residuals from a 9 year running mean). The NDVI also shows some promise as a potential basis for contract in late October for the Niger and Burkina millet production and in mid-October for the Mali rice yield (positive correlation) and the Burkina rice yield (negative correlation).

The ENSO indices showed limited potential, but a Mali millet production contract could potentially be written on the basis of March or April NINO indices in NINO boxes 1-3.4. Burkina Faso rice production, millet yield and Niger rice production also showed some correlation with various ENSO indices. Most of these contracts would be negatively correlated to their respective NINO indices, with the exception of Niger rice production. This is consistent with our larger picture – the slight negative correlation between Sahelian rainfall and ENSO indices (or positive correlation between Sahelian rainfall and SOI) would then imply that agricultural variables that are negatively correlated with rainfall (Niger rice production) should have a correlation of the opposite sense with ENSO indices, while agricultural variables that are positively correlated with rainfall (most of the other indices) should have a negative correlation with ENSO indices.

References

-Adler, R. F., G. J. Huffman, A. Chang, R. Ferraro, P. Xie, J. Janowiak, B. Rudolf, U. Schneider, S. Curtis, D. Bolvin, A. Gruber, J. Susskind, P. Arkin, E. J. Nelkin, (2003). The Version-2 Global Precipitation Climatology Project (GPCP) Monthly Precipitation Analysis (1979-Present). *Journal of Hydrometeorology, 4,* 1147-1167.

-Amogu, O., Descroix, L., Yero, K. AS., LeBreton, E., Mamadou, I., Ali, A., Vischel, T., Bader, J.C., Moussa, I. B., Gautier, E., Boubkraoui, S. and Belleudy, P. (2010). Increasing river flows in the Sahel? *Water 2,* 170–199.

-Beyerle, U., Rueedi, J., Leuenberger, M., Aeschbach-Hertig, W., Peeters, F., Kipfer, R. and Dodo, A. (2003). Evidence for periods of wetter and cooler climate in the Sahel between 6 and 40 kyr BP derived from groundwater. *Geophysical Research Letters 30,* GL016310.

-Biasutti, M., I. M. Held, A. H. Sobel, and A. Giannini, (2008). SST Forcings and Sahel Rainfall Variability in Simulations of the Twentieth and Twenty-First Centuries. *Journal of Climate, 21,* 3471-3486.

-Burls, N., C. Reason, P. Penven, and S. G. Philander, (2011). Similarities between the tropical Atlantic seasonal cycle and ENSO: An energetics perspective. *Journal of Geophysical Research*, *16,* C11010.

-Camberlin, P., Janicot, S. and Poccard, I. (2001). Seasonality and atmospheric dynamics of the teleconnection between African rainfall and tropical sea surface temperature: Atlantic vs. ENSO. *International Journal of Climatology 21,* 973–1005.

-Carletto, C., Jolliffe, D., and Banerjee, R., (2013). The Emperor has no Data! Agricultural Statistics in SubSaharan Africa, online publication.

-Chen, M., P. Xie, J. E. Janowiak, and P. A. Arkin, (2002). Global Land Precipitation: A 50-yr Monthly Analysis Based on Gauge Observations. *Journal of Hydrometeorology*, *3,* 249-266

-Christensen, J.H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R.K., Kwon, W.-T., Laprise, R., Magaña Rueda, V., Mearns, L., Menéndez, C.G., Räisänen, J., Rinke, A., Sarr, A.,and Whetton, P. (2007). Regional climate projections. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (eds.), Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge, United Kingdom and New York, NY, USA: *Cambridge University, Press*.

-Cook, K., (1999). Generation of the African Easterly Jet and Its Role in Determining West African Precipitation. *Journal of Climate, 12,* 1165-1184.

-deMenocal, P., J. Ortiz, T. Guilderson, J. Adkins, M. Sarnthein, L. Baker, and M. Yarusinsky, (2000). Abrupt onset and termination of the African Humid Period: rapid climate responses to gradual insolation forcing. *Quaternary Science Reviews, 19,* 347-361.

-Gandin, L. and A. Murphy (1992). Equitable Skill Scores for Categorical Forecasts**,** *Monthly Weather Review*, *120,* 361-370.

-Gasse, F., (2000). Hydrological changes in the African tropics since the Last Glacial Maximum. *Quaternary Science Reviews, 19*, 189-211.

-Gerrity, J. Jr., (1992). A Note on Gandin and Murphy's Equitable Skill Score**.** *Monthly Weather Review*, *120,* 2709-2712.

-Giannini, A., Salack, S., Lodoun, T., Ali, A., Gaye, A. and Ndiaye, O. (2013). A unifying view of climate change in the Sahel linking intra-seasonal, interannual and longer time scales. *Environmental Research Letters 8,* 024010.

-Giannini, A., M. Biasutti, and M. M. Verstraete (2008). A Climate Model-Based Review of Drought in the Sahel: Desertification, the Re-Greening and Climate Change. *Global and Planetary Change, 64,* 119-128.
-Giannini, A., R. Saravanan, and P. Chang (2003). Ocean Forcing of Sahel Rainfall on Interannual to Interdecadal Time Scales. *Science, 302,* 1027- 1030.
-Greene, A.M., L. Goddard, N. Ward, A. Siebert, E. Holthaus, M. Hellmuth, and W. Baethgen, (2008). Climate change, one decade at a time. Paper presented at a workshop on 'Technical Issues in Index Insurance', held 7–8 October 2008 at IRI, Columbia University, New York.
-Hellmuth, M. E., D. E. Osgood, U. Hess, A. Moorhead, and H. Bhojwani, Eds., (2009). Index Insurance and Climate Risk: Prospects for Development and Disaster Management. Climate and Society Series, Vol. 2, International Research Institute for Climate and Society, 112 pp.
-Huete, A., K.Didan, T.Miura, E.P.Rodriguez, X.Gao, L.G. Ferreira (2002). Overview of the Radiometric and Biophysical Performance of the MODIS Vegetation Indices. *Remote Sensing of Environment, 83,* 195-213.
-Huffman, G. J., R. F. Adler, D. T. Bolvin, G. Gu, (2009). Improving the global precipitation record: GPCP Version 2.1. *Geophysical Research Letters, 36*, L17808, doi;10.1029/2009GL040000.
-Joly, M. and Voldoire, A. (2009). Influence of ENSO on the West African Monsoon: temporal aspects and atmospheric processes. *Journal of Climate, 22*, 3193–3210.
-Joyce, R. J., J. E. Janowiak, P. A. Arkin, and P. Xie, (2004). CMORPH: A method that produces global precipitation estimates from passive microwave and infrared data at high spatial and temporal resolution. *Journal of Hydrometeorology, 5,* 487-503.
-Kalnay, E., Kanamitsu M, Kistler R, Colins W and 18 others (1996). The NCEP/NCAR 40-years reanalyses project. *Bulletin of the American Meteorological Society, 77*, 437–471.
-Kaplan, A., M. Cane, Y. Kushnir, A. Clement, M. Blumenthal, and B. Rajagopalan (1998). Analyses of global sea surface temperature 1856-1991. *Journal of Geophysical Research, 103,* 18,567-18,589.
-Knight, J., Folland, C. and Scaife, A. (2006). Climate impacts of the Atlantic multidecadal oscillation. *Geophysical Research Letters, 33*, L17706.
-Lamb, P. J., (1978). Large-scale Tropical Atlantic surface circulation patterns associated with Subsaharan weather anomalies. *Tellus, 30,* 240-251.
-Lawrimore, J., Menne, M., Gleason, B., Williams, C., Wuertz, D., Vose, R., & Rennie, J. (2011).
An overview of the global historical climatology network monthly mean temperature data set, version 3. *Journal of Geophysical Research Atmospheres, 116*, D19121.
-Lebel, T. and Ali, A. (2009). Recent trends in the central and Western Sahel rainfall regime (1990–2007). *Journal of Hydrology, 375*, 52–64.
-Lebel T., A. Diedhiou and H. Laurent (2003). Seasonal Cycle and Interannual Variability of the Sahelian rainfall at Hydrological Scales, *Journal of Geophysical Research*, *108,* doi:10.1029/2001JD001580, 8389-8350.
-Love, T. B., V. Kumar, P. Xie, and W. Thiaw, (2004). A 20-Year Daily Africa Precipitation Climatology Using Satellite and Gauge Data. *AMS Conference on Applied Climatology.*
-Mohino E., Janicot, S. and Bader, J. (2011). Sahel rainfall and decadal to multi-decadal sea surface temperature variability. *Climate Dynamics, 37*, 419–440.
-Nicholson, S. (2005). On the question of the "recovery" of the rains in the West African Sahel. *Journal of Arid Environments, 63*, 615–641.

-Nicholson, S. and Selato, J. (2000). The influence of La Nina on African rainfall. *International Journal of Climatology, 20,* 1761–1776.
-Nicholson, S. E., C. J. Tucker and M. B. Ba, (1998). Desertification, Drought and Surface Vegetation: an Example from the West African Sahel. *Bulletin of the American Meteorological Society, 79,* 815-829.
-Nnamchi, H. and Li, J., (2011). Influence of the South Atlantic Ocean Dipole on West African Summer Precipitation. *Journal of Climate, 24,* 1184-1197.
-Norton, M., D. Osgood, M Madajewicz, E. Holthaus, N. Peterson, R. Diro, C. Mullally, T.L. Teh, and M. Gebremichael, (2014). Evidence of Demand for Index Insurance: Experimental Games and Commercial Transactions in Ethiopia. *Journal of Development Studies, 50,* 630-648.
-Paturel, J., Ouedraogo, M., Servat, E., Mahe, G., Dezetter, A., Boyer, J.F. (2003). The concept of rainfall and streamflow normals in West and Central Africa in a context of climatic variability. *Hydrological Sciences, 48,* 125–137.
-Phillips, J. D., (1993). Biophysical Feedbacks and the Risks of Desertification, *Annals of the Association of American Geographers, 83,* 630-640.
-Rodriguez-Fonseca, B., Janicot, S., Mohino, E., Losada, T., Bader, J., Caminade, C., Chauvin, F., Fontaine, B., Garcia-Serrano, J., Gervois, S., Joly, M., Polo, I., Ruti, P., Roucou, P. and Voldoire, A. (2011). Interannual and Decadal SST-forced Responses of the West African Monsoon. *Atmospheric Science Letters, 12,* 67–74.
-Ropelewski, C. F. and Halpert, M. S. (1987). Global and regional scale precipitation patterns associated with ENSO. *Monthly Weather Review, 115*, 1606–1626.
-Ropelewski, C.F., J.E. Janowiak, and M.S. Halpert, (1985). The analysis and display of real time surface climate data. *Monthly Weather Review, 113,* 1101-1106.
-Salack, S., Muller, B., Gaye, A. Rain-based factors of high agricultural impacts over Senegal. Part I: integration of local to sub-regional trends and variability. *Theoretical Applied Climatology 106,* 1-22.
-Shanahan, T., Overpeck, J., Wheeler, C. W., Beck, J.W., Pigati, J., Talbot, M., Scholz, C., Peck, J. and King, J. (2006). Paleoclimatic variations in West Africa from a record of late Pleistocene and Holocene lake level stands of Lake Bosumtwi, Ghana. *Palaeogeography, Palaeoclimatology, Palaeoecology, 242,* 287–302.
-Siebert, A. and Ward, M. N. (2013). Exploring the frequency of hydroclimate extremes on the Niger River using historical data analysis and Monte Carlo methods. *African Geographical Review,* online publication.
-Siebert, A., M. N. Ward, O. Ndiaye, and P. Kangah (2008). Statistical Characterization of the Dry Spell Risk during the West African Monsoon from Meteorological Station Data. *American Meteorological Society Conference*, 20th Conference of Climate Variability and Change, P1.11.
-Solomon, S., Qin, D., Manning, M., Marquis, M., Averyt, K., Tignor, M. M. B., Miller Jr., H. L. and Chen, Z. (eds) (2007). Climate change 2007: the physical science basis. Cambridge, UK and New York, NY, USA: *Cambridge University Press.*
-Sultan B., S. Janicot and A. Diedhiou, (2003)a. The West African Monsoon Dynamics. Part I: Documentation of Intraseasonal Variability. *Journal of Climate, 16,* 3389-3406.
-Sultan B., and S. Janicot, (2003)b. The West African Monsoon Dynamics. Part II: The ‘‘Preonset’’ and ‘‘Onset’’ of the Summer Monsoon. *Journal of Climate, 16,* 3407-3427.
-Trzaska, S. (2008). Variability and Predictability of African Monsoon. Presentation at the Abdus Salam International Centre for Theoretical Physics
-Tucker, C. J., J. E. Pinzon, M. E. Brown, D. A. Slayback, E. W. Pak, R. Mahoney, E. F. Vermote, and N. El Saleous (2005). An Extended AVHRR 8-km NDVI Data Set Compatible with MODIS and SPOT Vegetation NDVI Data. *International Journal of Remote Sensing, 26,* 4485-4498.

-Reynolds, R.W., N.A. Rayner, T.M. Smith, D.C. Stokes, and W. Wang, (2002). An Improved In Situ and Satellite SST Analysis for Climate. *Journal of Climate, 15,* 1609-1625.
-Ropelewski, C. and M. Halpert, (1987). Global and Regional Scale Precipitation Patterns Associated with ENSO. *Monthly Weather Review, 115,* 1606-1626.
-Vanvyve, E., N. Hall, C Messager, S. Leroux, and J.P. Ypersele (2008). Internal variability in a Regional Climate Model over West Africa. *Climate Dynamics, 30,* 191-202.
-Vose, R. S., Richard L. Schmoyer, Peter M. Steurer, Thomas C. Peterson, Richard Heim, Thomas R. Karl, and J. Eischeid, (1992). The Global Historical Climatology Network: long-term monthly temperature, precipitation, sea level pressure, and station pressure data. ORNL/CDIAC-53, NDP-041. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee.
-Wang, G., Eltahir, E., Foley, J., Pollard, D., Levis, S. (2004). Decadal variability of rainfall in the Sahel: results from the coupled GENESIS-IBIS atmosphere-biosphere model. *Climate Dynamics, 22,* 625–637.
-Ward, M. N., and Folland, C., (1991). Prediction of Seasonal Rainfall in the north Nordeste of Brazil using eigenvectors of sea-surface temperature. *International Journal of Climatology, 11,* 711-743.
-Ward, 1994 dissertation
-Ward, M. N., E. M. Holthaus, A. Siebert, and D. Osgood, (2008). Index Insurance for Drought in the Millennium Villages Project. *American Meteorological Society Conference*, 20th Conference of Climate Variability and Change, P1.9.
-Ward M. N., Siebert, A., & Ndiaye, O. (2012). Decadal to multi-decadal variation in Sahel rainfall since 1950 and associated changes in the frequency of threshold-crossing seasonal rainfall totals. 4th African Monsoon Multidisciplinary Analysis International Conference, Book of abstracts (pp. 277–278). Toulouse, France.
-Ward, M. N. (1998). Diagnosis and short-lead time prediction of summer rainfall in tropical north africa at interannual and multidecadal timescales. *Journal of Climate, 11*, 3167–3191.
-Wenhaji, C. (2013). Variability of the West-African climate explained by sea surface temperature biases in the CMCC's climate model. Presentation at the International Research Institute for Climate and Society.
-Yesuf, M., and R. Bluffstone, (2009). Poverty, Risk Aversion, and Path Dependence in Low-Income Countries: Experimental Evidence from Ethiopia. *American Journal of Agricultural Economics, 91,* 1022-1037.
-Zhang, R., Delworth, T. L. (2006). Impact of Atlantic multidecadal oscillations on India/Sahel rainfall and Atlantic hurricanes. *Geophysical Research Letters 33,* L17712.

Websites

-Agadez, Niger Climate Graphs. (n.d.). Retrieved from http://www.agadez.climatemps.com/graph.php
-Bamako Climate & Temperature. (n.d.). Retrieved from http://www.bamako.climatemps.com
-CountrySTAT. (n.d.). Retrieved from http://www.countrystat.org
-Earth System Research Laboratory, NOAA, AMO index values (n.d.). Retrieved from http://www.cdc.noaa.gov/Correlation/amon.us.long.data
-Faostat.org. (n.d.). Retrieved December 9, 2014, from http://www.faostat.org
-Gao, Mali Climate Graphs. (n.d.). Retrieved from http://www.gao.climatemps.com/graph.php

-Niamey, Niger Climate Graphs. (n.d.). Retrieved from http://www.niamey.climatemps.com/graph.php

-Ouagadougou Climate & Temperature. (n.d.). Retrieved from http://www.burkina-faso.climatemps.com

-Population, total. (n.d.). Retrieved from http://data.worldbank.org/indicator/SP.POP.TOTL

-World Population Prospects, the 2012 Revision. (n.d.). Retrieved from http://esa.un.org/unpd/wpp/index.htm

Chapter 5: Niger River Data Analysis

5.1. Overview of Regional Hydrology: The River Niger provides vital water, fisheries and agricultural resources for millions of people in nine nations in sub-Saharan West Africa. It is arguably the most important surface water source in the West African Sahel, but is classified as a river system strongly impacted by dams and channel fragmentation (Nilsson et al., 2005). The resources of the River Niger are managed by the multinational Niger River Basin Authority, which focuses primarily on water and hydroelectric management, but has a role to play in many other sectors as well. Much of the region's agriculture is not irrigated, but there are portions that are. Clearly, allocation rules along this multinational waterway have to be designed carefully with an awareness of the potential implications of climate change and multi-decadal variability. One feature of the River Niger hydrology is the large inland delta region in central Mali.

The river rises in the Guinean highlands, flowing northeast through Mali towards the fringe of the Sahara desert, before turning south, flowing into Niger and ultimately flowing into Nigeria, reaching its delta at the Gulf of Guinea. The Niger Basin Authority divides the river into four major sub-catchments, depicted in Figure 5.1: the upper Niger, Niger inland delta, middle Niger and lower Niger regions. The inland delta region is a seasonally flooded wetland region that can provide significant agricultural yields during years of plentiful water, but is also a region of strong evaporative losses. The fluctuations of this inland delta have important implications for the region's water resources. Niamey, Niger, Dire and

Koulikoro, Mali are gauge stations used in this analysis and are representative of the middle basin, inland delta and upper basin respectively. Each catchment has its own hydrological characteristics.

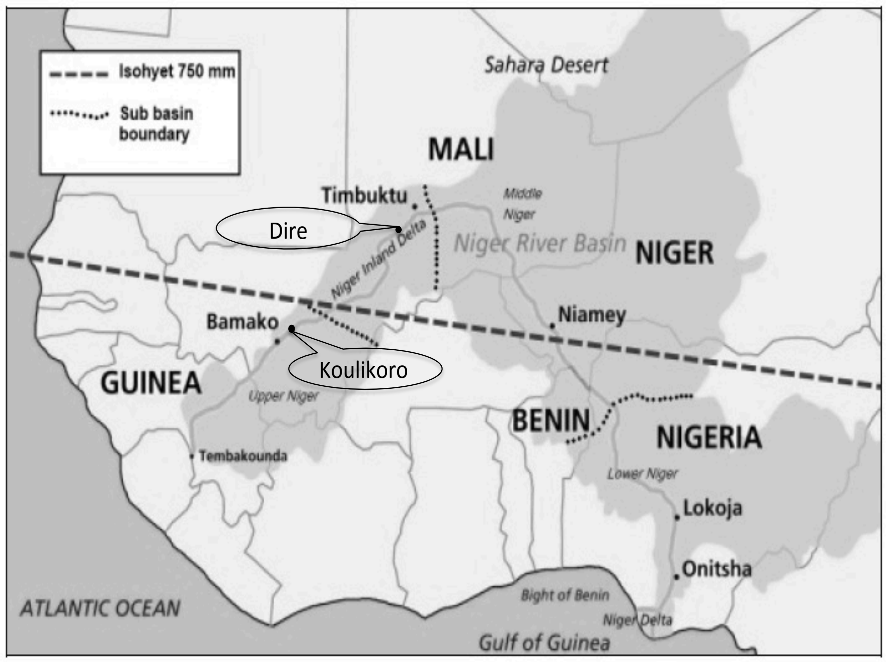


Figure 5.1: The Niger River basin, with sub-basins (Lower Niger, Middle Niger, Inland Delta and Upper Niger), and the locations of Koulikoro and Dire Mali delineated; adapted from KfW report 2010

Throughout the region, the River Niger's waters are used to support a wide range of economic activities including a wide range of irrigated agriculture (predominantly rice and millet), flood recession agriculture, livestock cultivation, fisheries and trade (Diarra, et al., 2004, Beukering, et al. 2005).

Clearly both extreme high and low flow conditions pose challenges to these various enterprises and associated lives and livelihoods. For the last several years, the Niger Basin Authority has been in the implementation phase of a Hydrological Cycle Observing Systems (HYCOS) project. This project was developed by the World Meteorological Organization and is being supported by the French agencies: French Agency for Development (FAD) and Institute de Recherce pour le Developpment (IRD) and the African Water Facility (AWF). Among its charges, this project helps to inform the management decisions that the Niger Basin Authority makes. Better information on the future frequency of extreme streamflow events may prove useful for such endeavors (Niger HYCOS Project Document, 2006; Hellmuth et al., 2009).

This chapter offers a historical overview of the regional hydro-climatology from Niger Basin Authority streamflow data (dating back to 1950) in section 5.2, and explores the potential frequency of high and low flow events in the near term future (next 30 years) in sections 5.3 and 5.4. In the future, explicit simulations from global climate models representing both natural MDV and GC may be added into the method. At this point, our primary motivation is to assess the sensitivity of Niger River extremes to specified assumptions about the magnitude of MDV and GC. More details of the method are in (Siebert and Ward, 2011), where simulations were undertaken drawing on historical statistics of rainfall variability in Africa. In our simulation method, natural multi-decadal variability (MDV) is represented as a stochastic process (assuming variations of a specified magnitude), while systematic GC is represented by an assumed linear trend over the near-term timeframe that we consider (2010-2040). In addition to statistically representing MDV and GC, interannual variability is also stochastically imposed and informed by statistical properties found in the historical record. As is noted in more detail in section 5.2, one of the additional factors that must be considered for

River Niger flow is the possible impact of changes in the hydrologic system, such as through changes in the run-off coefficient. As runoff coefficient increases, the probability of a flood for a given level of precipitation tends to increase. While certain types of land cover change may induce an increase in runoff coefficient, there is also some observational evidence that in some parts of the Sahel, conversion of savanna to cropland has led to an increase in groundwater storage, a phenomenon sometimes termed "the Sahelian paradox" (Favreau et al., 2009). The simulations performed in this chapter are confined to assessing implications of changes in the climate system forcing on the hydrology, while recognizing other aspects need to be considered as well for a full assessment of future risks in the River Niger system.

The broader purpose of this research is to inform climate risk management activities, as extreme events of high and low flows are likely to create an especially disproportionate impact on the local population's livelihood outcomes. In particular, as discussed in chapter 4, the simulation of high flows relates to the frequency of payouts for flood insurance for irrigated rice farmers along the Niger River. Better information on the future frequency of extreme streamflow events may also prove useful for other regional risk management activities (Hellmuth et al., 2009; Niger HYCOS Project Document, 2006).

Prior studies of this river basin have also drawn on streamflow data from the Niger Basin Authority including from Niamey, Dire and Koulikoro (Abrate et al. 2010, Amogu et al., 2010, and Descroix et al. 2009) leading to general conclusions about the period of relatively high flows during the Sahel wet regime (approximately 1950-1969, hereafter P1), relatively low flows during the Sahel dry regime (approximately 1970-93, hereafter P2) and more recently, the moderate recovery of flows and rainfall (approximately 1994-2009, hereafter P3), as well as providing a number of additional perspectives, such as the possible impacts of changes in run-off coefficients.

This chapter aims to contribute further in two general areas. Firstly, characterization of the historical variability is here addressed at times of year especially relevant for society (flood month, and maximum flow during July-September when the system shows some short timescale response to rainfall), and also, we provide a perspective of changes not just in the mean flow, but also in terms of the distribution of flows in each epoch. Secondly, this chapter aims to contribute by providing an approach and some initial results for estimating plausible future flow scenarios, with a particular focus on the frequency of threshold crossing flow events (TCEs) and the implication of TCE frequency for index insurance pricing. These Monte Carlo simulations can be considered as complementary information to that which may be achieved by primary physical and dynamical modeling approaches, drawing directly on General Circulation Model climate model scenario output, or regional model downscaled output, to inform hydrological interpretations including through driving spatially distributed and physically based hydrological models.

Hydrological Data: The hydrological data for this study were provided by the Niger Basin Authority in Niamey, Niger and were acquired during a research trip undertaken in July 2010. Discussions with experts suggested the observed streamflow variations are primarily reflections of climate and hydrology, with changes in streamflow management of secondary relevance. Therefore, interpretations in this paper are confined to climate and hydrology, though some management impacts in the data cannot be ruled out. Daily streamflow values for 1950-2009 were provided for three stations: Koulikoro, Mali in the upper basin, Dire, Mali in the inland delta region and Niamey, Niger in the middle basin (station locations are depicted in Figure 5.1). These data are continuous (i.e. there are no missing values) and were aggregated into 5-day, monthly, seasonal and annual values. Most results presented here are for the flood month values. The Niger Basin Authority uses data from these particular stations in monthly bulletins regarding the state of flow on the River Niger and these stations are considered to be representative of their respective sub-catchments. The streamflow data from the Niger Basin Authority is a recognized resource for research into the region's hydroclimatology (Descroix et al., 2009; Amogu et a., 2010).

Section 5.2 will explore the nature of streamflow fluctuation, including analysis of the mean, the standard deviation, and the skew of the different stations during the different epochs. Further, some analysis of the 1 in 10 high flow and the 1 in 10 low flow will be conducted. The findings in sections 5.2 then inform the statistical simulations of plausible near-term (2010-2040) scenarios (sections 5.3 and 5.4), evaluating implications for changes in TCE frequency and index insurance price. While a regional rainfall climatology map was shown in Chapter

4, a more specific rainfall climatology map for the Niger Basin is shown in Figure 5.2 below.

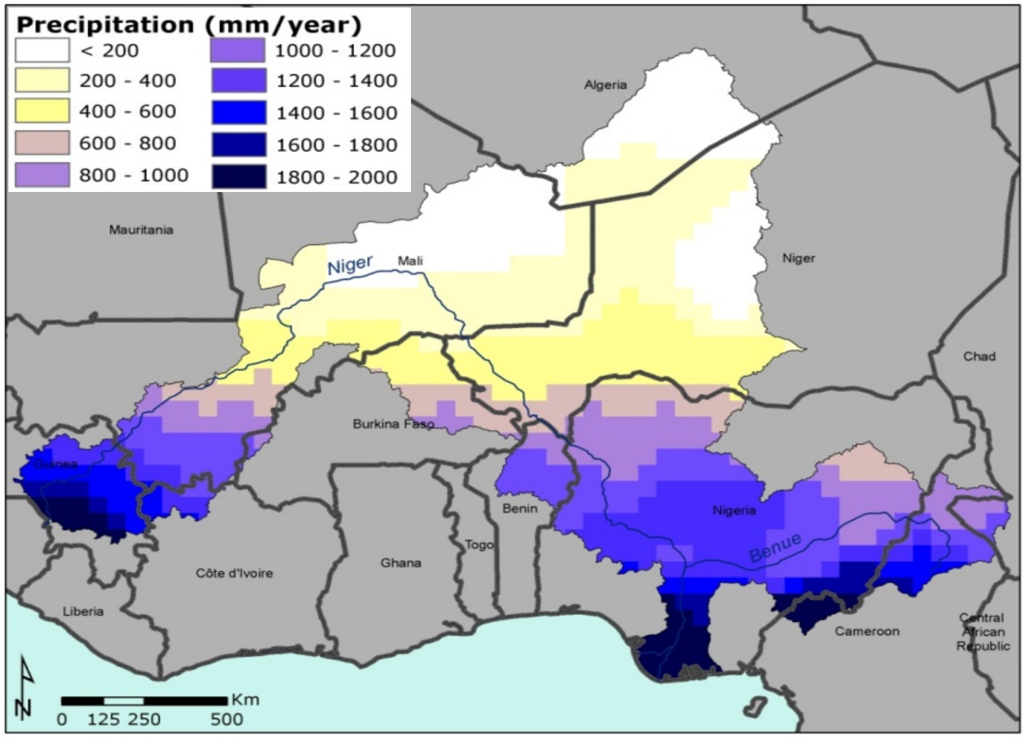


Figure 5.2: Average annual precipitation in the Niger River drainage basin; from Tarhule and Akumaga, 2014

5.2. Historical Hydrological Analysis (Introduction): Figures 5.3, 5.4 and 5.5 display the climatology and time series of annual average streamflow for Koulikoro, Dire, and Niamey, respectively. It is evident from the streamflow climatologies that Koulikoro has a climatologically higher streamflow than either Dire or Niamey. While the isohyet maps shown in 5.2 implies that Koulikoro is only modestly wetter in rainfall climatology than Niamey, and that Dire is markedly drier than either Niamey or Koulikoro, the path of the river from the humid Guinean highlands through the semi-arid to arid Sahelian conditions contributes to this reduction of flow from the upper to middle portions of the basin. It is also clear that the timing of the highest flow varies depending on the position of the hydrological station along the river's course: the month of peak streamflow for Koulikoro (closest to the largest source of precipitation in the Guinea highlands) is around September (towards the end of the monsoon rains), while the months of peak streamflow for Dire are November and December and the months of peak streamflow for Niamey are December and January.

Furthermore, the described timing of the reduction of streamflow in concert with the reduction of rains in the P1 to P2 transition is visually clear from the three figures below, as is a modest recovery of streamflow in concert with the recovery of the rains in the P2 to P3 transition. It should be noted that the driest years in the Sahel in terms of rainfall were in the early to mid-1980s. By contrast, the minimum of the streamflow in each of the three figures below is in the mid 1980s to the mid-1990s.

Mean Characteristics: Table 5-1 shows the mean of the streamflows at the three stations during the whole time series and the three periods: P1, P2 and P3. It is important to have in mind that the estimates of these sub-period means (as well as the subsequent statistics presented) are subject to considerable uncertainty, and this needs to be integrated into interpretation of the results. Several analyses and calculations have been made to provide insight into the uncertainty. One source of uncertainty to check is the extent to which the exact choice of period boundary may artificially inflate the period differences.

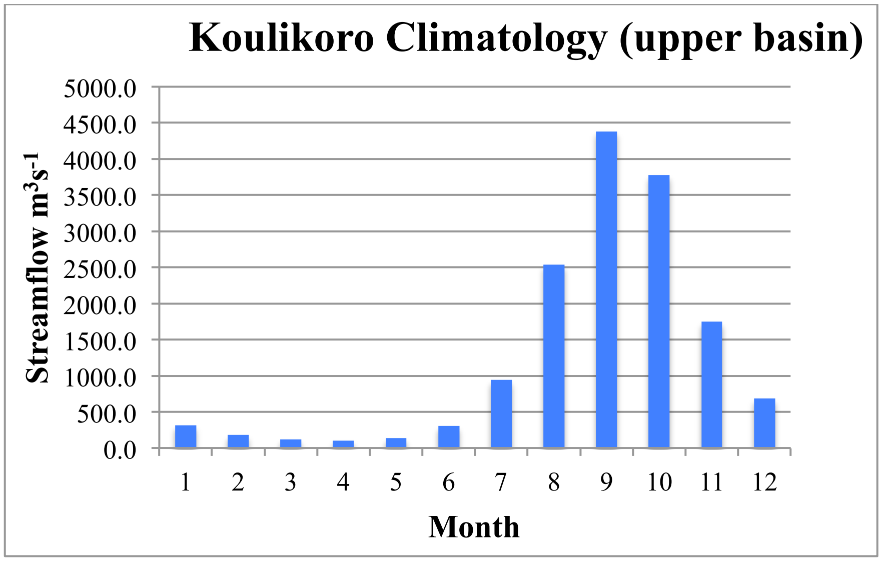


Figure 5.3a: Koulikoro monthly streamflow climatology based on the monthly aggregated daily streamflow values (calculated from the monthly aggregated daily streamflow values from the Niger Basin Authority).

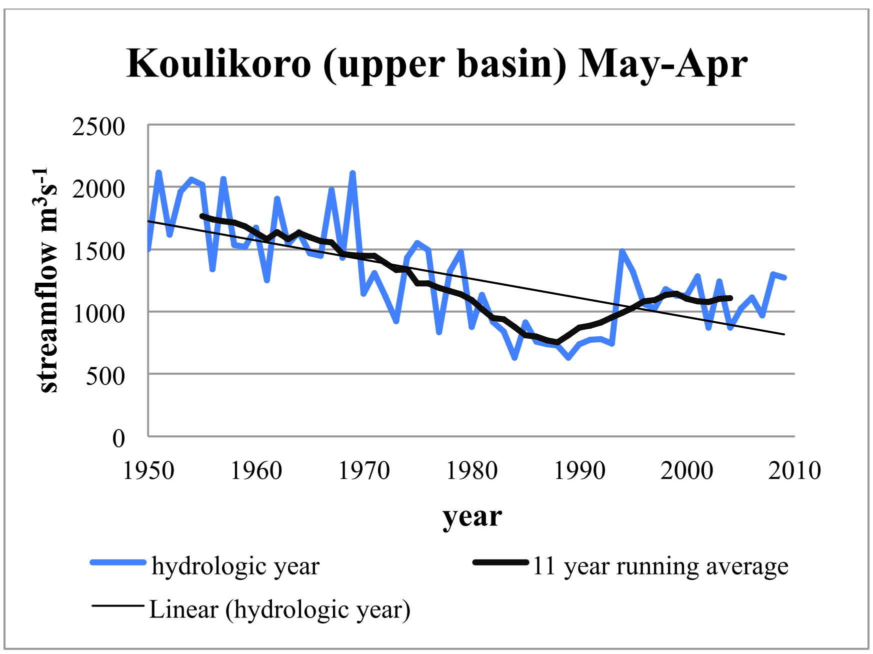


Figure 5.3b: Koulikoro streamflow timeseries from 1950-2009 (calculated from the monthly aggregated daily streamflow values from the Niger Basin Authority).

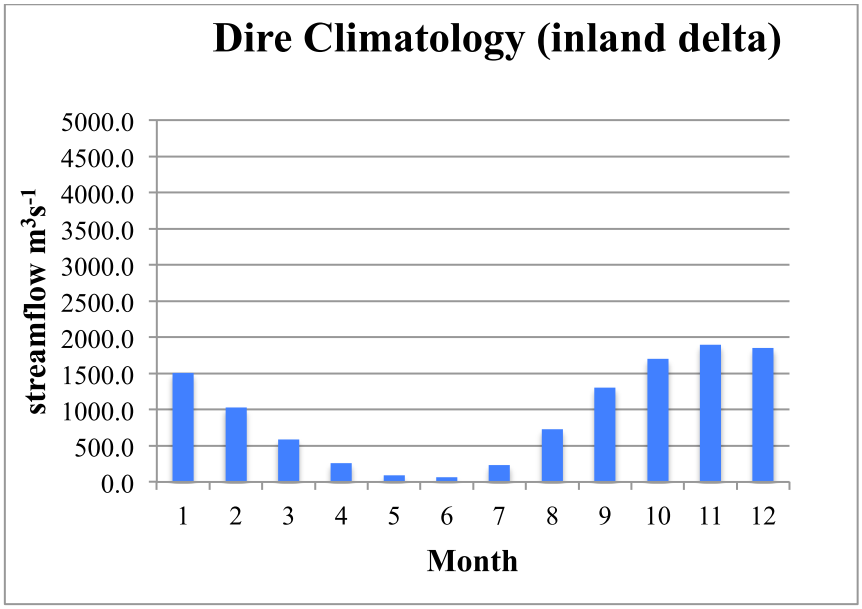


Figure 5.4a: Dire monthly streamflow climatology based on the monthly aggregated daily streamflow values (calculated from the monthly aggregated daily streamflow values from the Niger Basin Authority).

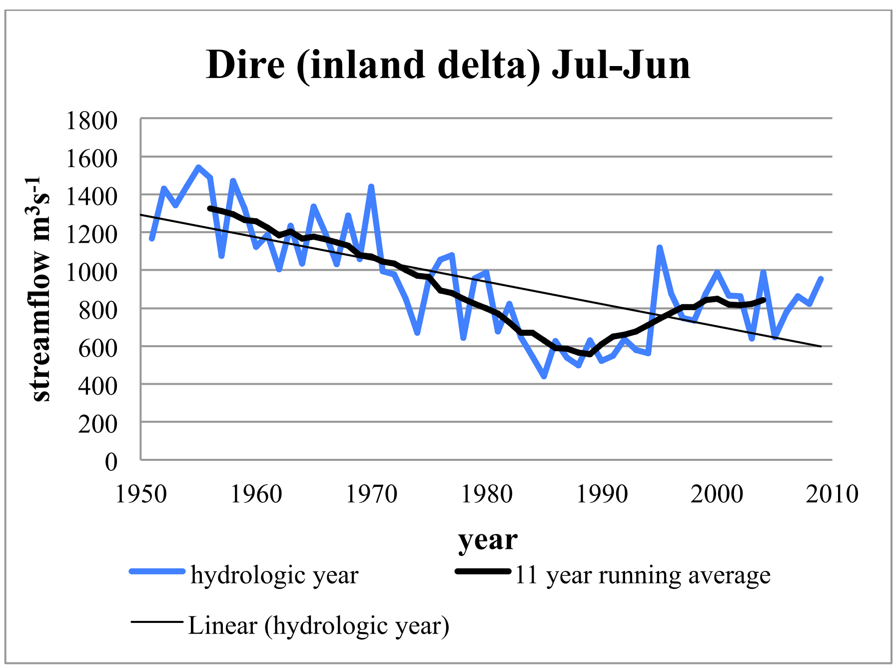


Figure 5.4b: Dire streamflow timeseries from 1950-2009 (calculated from the monthly aggregated daily streamflow values from the Niger Basin Authority).

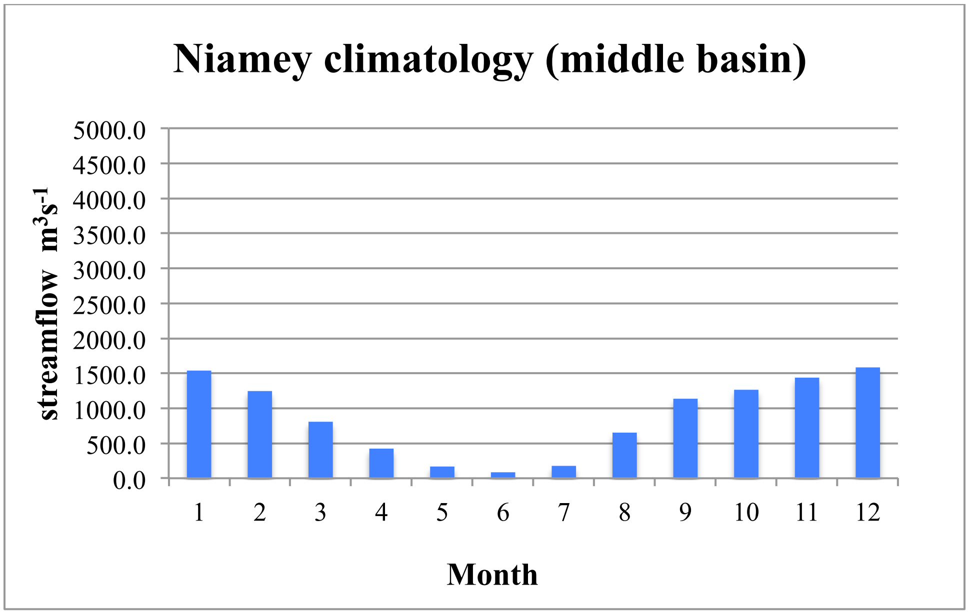


Figure 5.5a: Niamey monthly streamflow climatology based on the monthly aggregated daily streamflow values (calculated from the monthly aggregated daily streamflow values from the Niger Basin Authority).

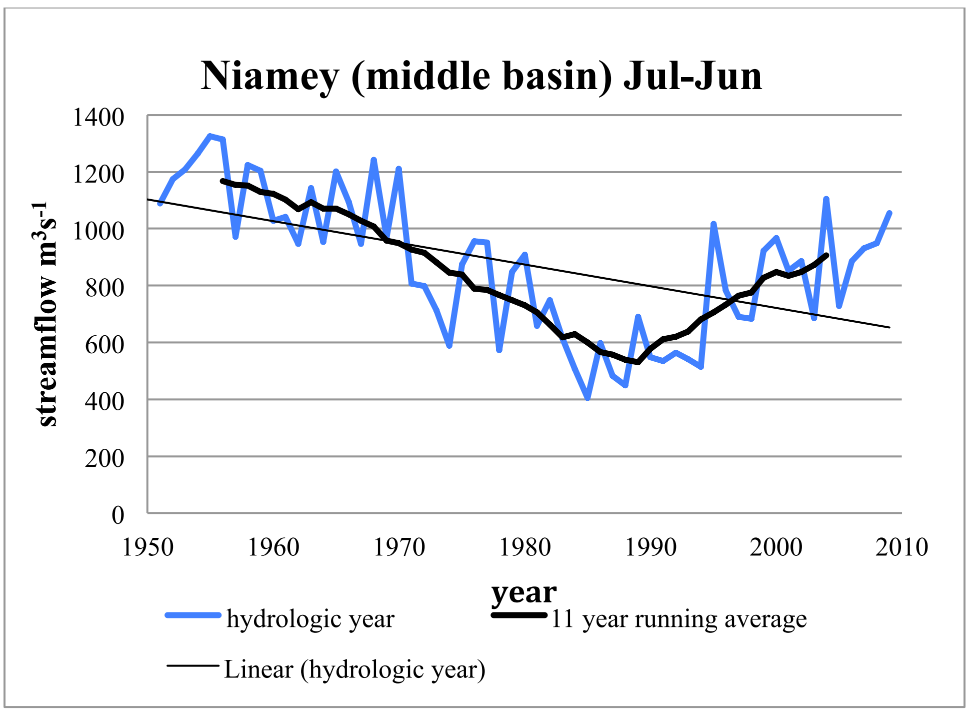


Figure 5.5b: Niamey streamflow timeseries from 1950-2009 (calculated from the monthly aggregated daily streamflow values from the Niger Basin Authority).

This has been tested by performing a Monte Carlo simulation that permitted the period boundaries to vary randomly by up to +/- 3 years. Results showed the mean differences apparent in Table 5-1 are much larger than the uncertainty due to shifting period boundaries in this way, even for the recovery from P2 to P3, the magnitude of recovery was generally 2 to 4 times the standard deviation that resulted from shifting the period boundaries. Another source of uncertainty is simply the shortness of record in each period. For at least approximate guidance, the standard error on each estimate is calculated assuming full degrees of freedom (n-1, where is the number of years in the given period).

When thinking about the mean changes across epochs, one may note that from an impacts perspective, it is not relevant whether changes are related to a specific time-series process. Therefore, assuming full degrees of freedom for standard error estimates for the epoch statistics (mean, standard deviation and percentiles), essentially providing a basis for assessing how surprising the epoch differences are when compared to random realizations of the values in the series. More explicitly, to assess the extent to which mean changes were larger than a random realization of the actual values observed in the historical record, a Monte Carlo test was performed to assess the rank of the observed change, within the ranking of the changes that results from randomly rearranging the historical period values. In all cases mean change from P2 to P1 was larger than any of the 500 realizations. For P2 to P3, only the hydrological year change at Dire failed to be close to or greater than the 95%ile of ranked values (see further discussion of Dire hydrological year below).

The focus of Table 5-1 and the historical analysis included is on the mean flow for the flood month (i.e. month of highest flow) at each station (taken as September for Koulikoro, November for Dire and January for Niamey). An analysis was also made of the "hydrologic year", but is generally not shown in the results. For the purposes here, when it is referred to, the hydrologic year is May to April for Koulikoro and July to June for Dire and Niamey. Using a calendar year approach would yield unintended smoothing by including information on two rainy seasons (since Jan-May mostly represents rainfall observed in the previous calendar year).

Streamflow m^3s^{-1}	Koulikoro	Dire	Niamey
1950-2009 mean flood month	4382±323	1899±73	1540±114
P1 mean flood month	5524±351	2125±60	1899±57
P2 mean flood month	3593±470	1723±132	1269±213
P3 mean flood month	4134±375	1897±81	1545±142

Table 5-1: Mean streamflow during the different epochs (P1 = 1950-69, P2=1970-93, P3=1994-2009). Confidence intervals are computed at a 95% significance level on the basis of the standard error of the mean equation SE = $s/n^{1/2}$. So the interval is 1.96*SE.

In comparing the stations, Koulikoro clearly has the highest flow, and Niamey is slightly lower in average flow than Dire. When comparing the different time periods, a strong decline in streamflow is clearly visible during the P1 to P2 transition – that is of the order of 30% of the streamflow for the flood month (although this decrease is somewhat reduced in the case of Dire). We can also see that the increase in streamflow in the P2 to P3 transition is smaller (about 15%) than the reduction of streamflow in the P1 to P2 transition (although the increase is smaller in Dire and larger in Niamey). The transitions between the epochs for Dire seem to be a bit more muted than the transitions for the other stations. Although the flood month increase from P2 to P3 is still clearly larger than the SE estimates in Table 5-1, the result for the hydrologic year (not shown) is not statistically significant. By virtue of this station being situated in the inland delta region of Mali, the local soil/landscape conditions may contribute to an especially long "memory" in the streamflow signal (Diarra et al. 2004).

Autocorrelation Characteristics: One way of exploring the strength of multi-decadal variability (i.e., slowly evolving natural oscillations) in a regional climate record is by examining the one-year autocorrelation (the strength of the statistical relationship between the anomaly of one year to the next). A higher autocorrelation value tends to indicate stronger multi-decadal variability. As can be seen in Table 5-2, the lag one-year autocorrelation for these three hydrological stations is quite high – from 0.6-0.73. Furthermore, the lag one-year autocorrelations for the monthly averaged streamflow during the peak flood months is also quite high.

However, it should be noted that a high raw lag-1 autocorrelation value may be somewhat misleading. In the presence of a strong trend in the data, the raw autocorrelation value will pick up on the trend without necessarily representing a true process of low-frequency fluctuation. In the data analyzed here, the P1 period is sufficiently wetter than the P3 period that there is a significant downward trend in the 1950-2009 record, despite the partial recovery of rainfall and streamflow in the P2 to P3 transition. The autocorrelation of the de-trended time series assumes that the trend is driven entirely by GC (i.e., none of the trend is due to chance alignment of the slowly evolving natural MDV oscillations). Furthermore, in the hydrologic data included, there are statistically significant autocorrelations at longer lag times. As such, the autocorrelation at lag-1 year of the de-trended time series is considered a lower limit estimate of the magnitude of MDV in the historical record.

Table 5-2 shows the raw lag-1 autocorrelation values and the lag-1 autocorrelation values of the de-trended time series for both the hydrologic years and for the flood months.

Station	Koulikoro	Dire	Niamey
Hydrologic year lag autocorrelation 1950-2009	0.41/0.6/0.74 (0.04/0.29/0.51)	0.58/0.73/0.83 (0.26/0.48/0.65)	0.54/0.7/0.81 (0.37/0.57/0.72)
Flood month lag autocorrelation 1950-2009	0.33/0.54/0.7 (0.07/0.32/0.53)	0.43/0.62/0.76 (0.31/0.52/0.68)	0.58/0.73/0.83 (0.5/0.67/0.79)

Table 5-2: Station autocorrelations (values in parenthesis are from detrended time series). The A/B/C format in which values are presented denote the lower limit, expected value, and upper limit respectively of the lag one year autocorrelations. These confidence intervals are calculated at the 95% level from the following equations:
CI = tanh(z_L),tanh(z_U)), where $z_L = z - Z_{\frac{1+p}{2}}/\sqrt{n-3}$, $z_U = z + Z_{\frac{1+p}{2}}/\sqrt{n-3}$, where $z = 0.5ln\left(\frac{1+r}{1-r}\right)$ from Fisher's z-transformation and $Z_{\frac{1+p}{2}}/\sqrt{n-3}$ is the critical value taken from the normal distribution, n is the number of years and r is the lag-1 year autocorrelation (von Storch and Zwiers, 1999).

As the dataset is 60 years long, the threshold of significance for a 2 sided significance test for 0 correlation is 0.255**.** The lag-1 autocorrelation for all three stations is statistically significant.

Standard Deviation and Variance Characteristics: Another crucial element to the understanding of the region's hydrology and sensitivity to extremes of streamflow is the exploration of the standard deviation and other measures of variance. In addition to computing the standard deviation, another useful statistic is the coefficient of variation (COV), which is defined as the ratio of the standard deviation/mean. Furthermore, for risk management applications, specific empirical thresholds of high or low streamflow are useful. In this study, we consider the 90%ile and 10%ile flows (i.e. the 1 in 10-year high flows and 1 in 10-year low flows). Figures 5.6 and 5.7 show the standard deviation and $90^{\%ile}$ and 10%ile flows for the different stations for the respective flood month flows.

If one examines the raw standard deviation values, P2 appears to have the largest variability of the three periods by a large margin. One significant factor for this conclusion is that while the magnitude of the streamflow transition is quite large, the rate of streamflow transition between the different epochs is slower than the rate of change of the rainfall. Consequently, some of the observed enhancement of the variability during the dry period is an artifact of a downward trend in streamflow during the first portion of P2.

To address this problem, we must look at the corrected standard deviations in Figure 5.6, which are based on the residuals from an 11-year running mean for the whole time series and for P1, P2 and P3. This simple box-car filter approach has limitations, but the purpose of this analysis is to address a "truer" estimate of the variance of the interannual streamflow values, leaving aside the period shifts and the strong multi-decadal signal. The standard deviations calculated from the residuals off the 11-year running mean do not show as clear a relationship between climatological mean streamflow and standard deviation as with the uncorrected standard deviation, although there is still some general enhancement of standard deviation during P2 for flood month at Dire and Niamey (and the increase is outside the SE range shown on Figure 5.6).

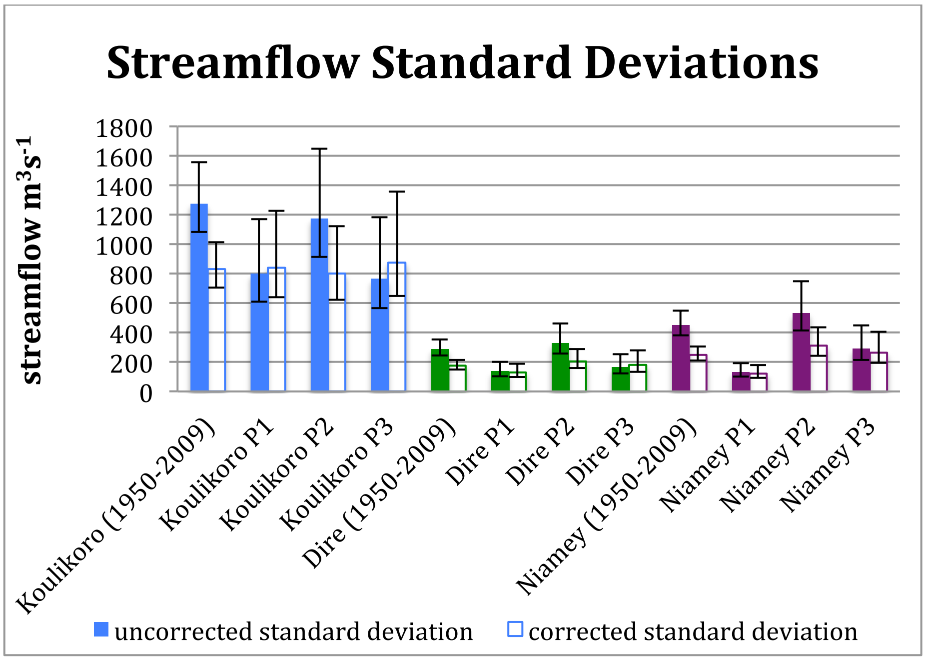


Figure 5.6: Streamflow standard deviations for Koulikoro, Dire and Niamey for the whole 1950-2009 period, P1, P2 and P3. The filled bars (left side of each pair) signify the uncorrected standard deviation, computed purely on the basis of the raw empirical data. The unfilled bars (right side of each pair) signify the corrected standard deviation, computed on the basis of the deviations from an 11-year running mean. The error bars are computed on the basis of the following equation for the confidence interval of the variance: $(n-1)s^2/\ X^2_{(\text{limit},\ n-1)}$ where n is the number of years and s is the sample standard deviation and the X^2 denotes the chi-square statistic. As this is a chi-square based metric, the lower and upper limits are not symmetric about the expected value of the SD. These confidence intervals are for a two sided 95% confidence interval.

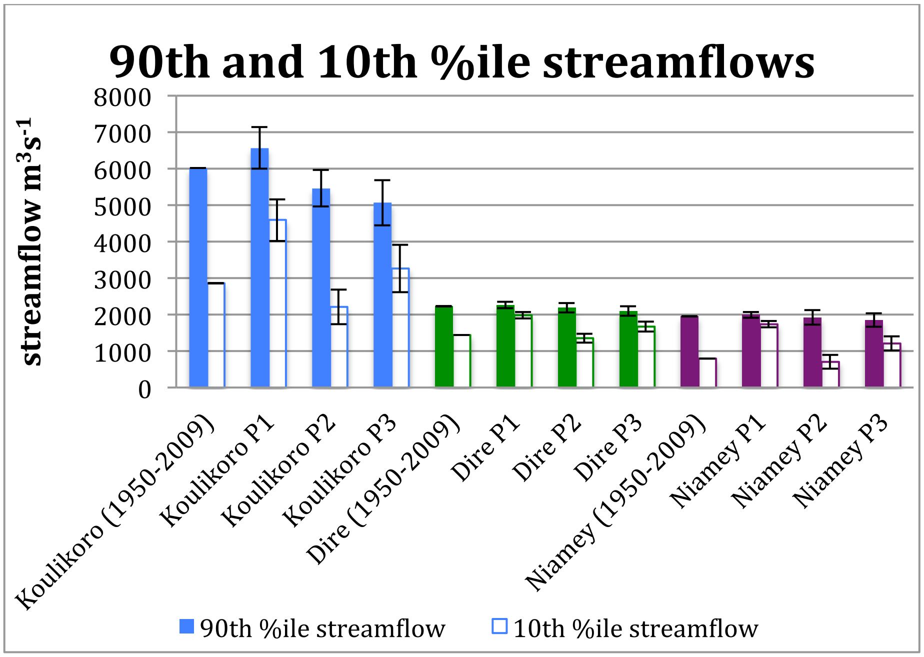


Figure 5.7: 90th percentile and 10th percentile thresholds for the different station/epoch combinations. The filled bars (left side of each pair) denote the 90th %ile streamflow and the unfilled bars (right side of each pair) denote the 10th %ile streamflow. Confidence intervals for 90th and 10th percentiles are computed by Monte Carlo simulation using the epoch means, SDs and associated standard errors. These confidence intervals are symmetric about the respective expected values and are for a two sided 95% confidence interval.

This result is in contrast to the general tendency of rainfall data over land to show an increase in standard deviation with an increase of climatological mean precipitation, thereby experiencing a peak in the wet tropics (Adler et al., 2012). Overall, the observations about the modest but generally consistent Niger streamflow variance response to the mean change are also corroborated by other supporting literature (Paturel et al., 2003) and may be connected to the issue of groundwater storage.

First of all, during a dry regime, it can be argued that the water table would fall, making the region more susceptible to low flows and reduced base flows. However, drier soil may have reduced infiltration capacity, thereby leading to a high runoff coefficient during the years of P2 that were relatively wet, thereby still leading to relatively high flows and maintaining substantial interannual variance. However, more thorough, comprehensive study of these aspects of the regional surface and subsurface hydrology is still needed before relative weight can be attributed to the various mechanisms. For example, some studies suggest that throughout the later half of the 20th century and into the early 21st, the water table, at least in some regions (such as the SW of Niger) has been rising, in part as a result of land use changes that have increased the runoff coefficient, causing water to pool in hollows and drain to the subsurface more readily over time (Favreau et al., 2002). Various studies document an increasing runoff coefficient in the late 20th and early 21st century that may contribute to an increase in variance in streamflow (Amogu et al. 2010, Descroix et al., 2009).

Figure 5.6 shows some patterns that relate to the multi-decadal variation of precipitation regime, such as the tendency for a general increase of the SD during P2, (dry period) relative to P1 and P3 (wet periods). However, the results should also be interpreted in terms of possible systematic trends over the whole period (possibly related to land use changes). Such overall tendencies have spatial heterogeneity. Koulikoro tends to have a generally static or downward trend in the standard deviation over the three epochs, whereas Niamey and Dire tend to have more of an upward trend in SD (and COV – not shown) across the epochs.

We also observe that the value of the low flow threshold is much more sensitive to the regional precipitation regime than is the high flow threshold. This is clearly evident in both the flood month (Figure 5.7) and hydrologic year analysis (not shown). Indeed, the 90th%ile changes are close to or within the SE ranges in Figure 5.6. In contrast, the 10th%ile changes are well outside the SE range estimation, and show clear response to the epochs, with reduction during P2 and increase in P3 (though still lower than in P1). This greater sensitivity of the 10th%ile can be considered consistent with the slight increase in streamflow variance during P2. It is also notable that the 90th%ile is actually lower for P3 than P2 (though not outside the SE range). As alluded to in the discussion of SD changes, these findings may be partly attributed to changes in Sahel-wide runoff coefficient (Amogu et al., 2010).

Specific aspects of July-September hydrological data: By contrast to the data regarding the peak flood month, the July to September streamflow in the middle Niger basin and inland delta regions are strongly associated with local monsoon rains (while the peak flood months represent an integration of rainfall over the upstream basin over time). Consequently, the statistical characteristics of the peak 5-day streamflow value during July-September (Table 5-3) tends to more directly mirror the statistical character of the local rains – i.e. during the wet periods (P1 and P3), there is a larger variance in the streamflow and all skew values are positive, with the dry period (P2) having a larger positive skew that is statistically significant at the 5% level (see further discussion of the skew). A further interesting point to note is that while the lag-1 year autocorrelation for the flood month is positive, the lag-1 year autocorrelation for this July-September 5-day peak flow value period is negative. Although these autocorrelation values are weakly statistically significant at best, the negative sign may show a link between the quasi-biennial oscillation and the monsoon rains as documented elsewhere in the literature (Kafando et al., 2011).

Streamflow	Average	SD	Lag-1 autocorrelation	Skew
1950-2010	1304±74	251/296/360	0.06±0.23	0.83±0.65
P1	1362±103	179/236/345	-0.33±0.39	0.45±0.76
P2	1126±84	162/209/293	-0.21±0.36	1.65±0.79
P3	1487±159	249/335/510	-0.09±0.41	0.41±1.06

Table 5-3: Peak 5-day July to September Niamey streamflow statistics: mean, standard deviation, autocorrelation and skew. Uncertainty is presented as in Table 5-2 and Figure 5.6.

In addition to the above analysis, streamflow values for July-September 2010 were also provided for Niamey, as this season had exceptionally high streamflow values. July average streamflow for 2010 was the third highest in the 61 years of data, and August and September streamflow values were both records. Follow on research into this event suggests that although the seasonal rains were above average in the monsoon of 2010, the rainfall was not so exceptional as to clearly explain the exceptional flooding and high river levels in the middle basin. This hydrological event in 2010 can also be partly attributed to a larger runoff coefficient than in previous flooding events (Descroix et al., 2012). Furthermore, the rainy season of 2012 has also led to extensive flooding displacing more than 400,000 people (UN OCHA report, 2012). The rainy season of 2013 also led to widespread flooding and very high streamflow levels in Niamey, which again led to widespread displacement (Diallo, 2013). This is part of a broader trend towards higher runoff coefficients associated with land use changes in the Sahel (Amogu et al., 2010). Figures 5.8 show the hydrographs for the three stations. Figures 5.8 a and b in particular show how unusually high the streamflow values for Niamey were during the July-October periods of 2010, 2012 and 2013; in each case reaching above 2000 m^3s^{-1} and exceeding the streamflow during the "climatological" peak flood month of January. Figure 5.8 c and d show the streamflow for Koulikoro and Dire for the 2012/2013 and 2013/2014 seasons.

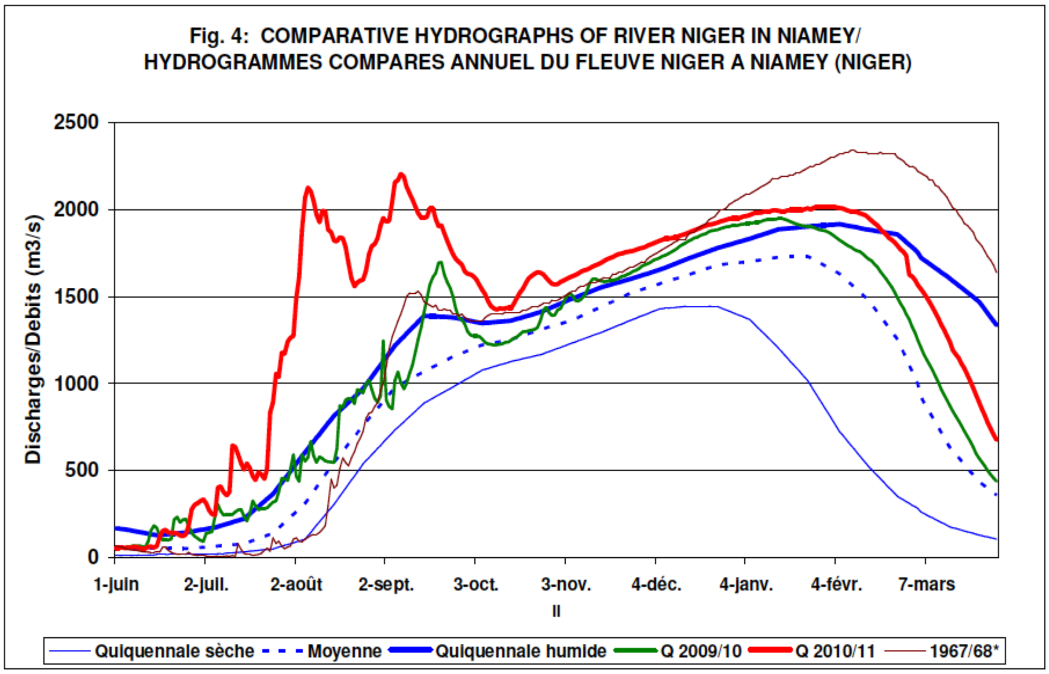


Figure 5.8a: Niamey hydrograph from March 2011 Niger Basin Authority bulletin. Streamflow for 2010/2011 is depicted in red.

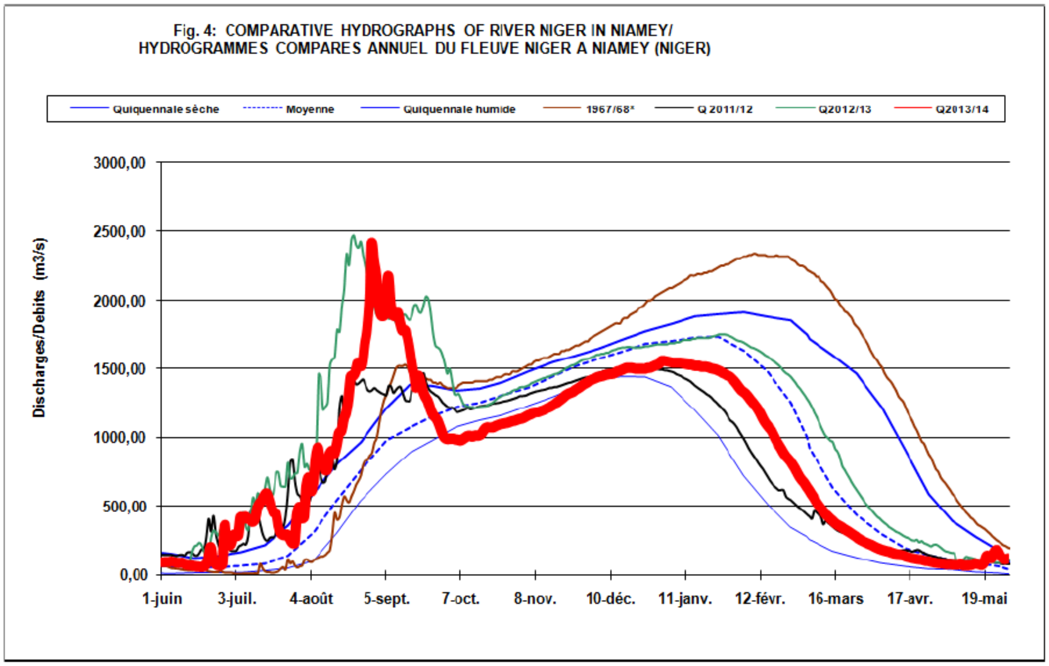


Figure 5.8b: Niamey hydrograph from May 2014 Niger Basin Authority bulletin. Streamflow for 2013/2014 is depicted in red and for 2012/2013 is depicted in green.

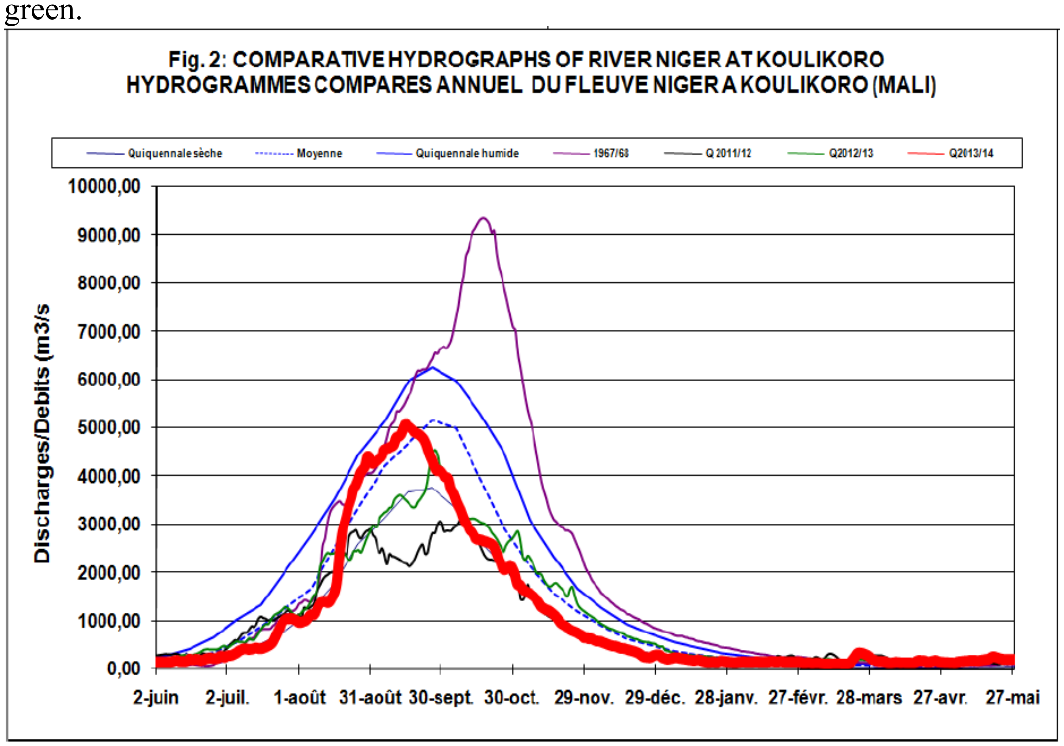


Figure 5.8c: Koulikoro hydrograph from May 2014 Niger Basin Authority bulletin. Streamflow for 2013/2014 is depicted in red and for 2012/2013 is depicted in green.

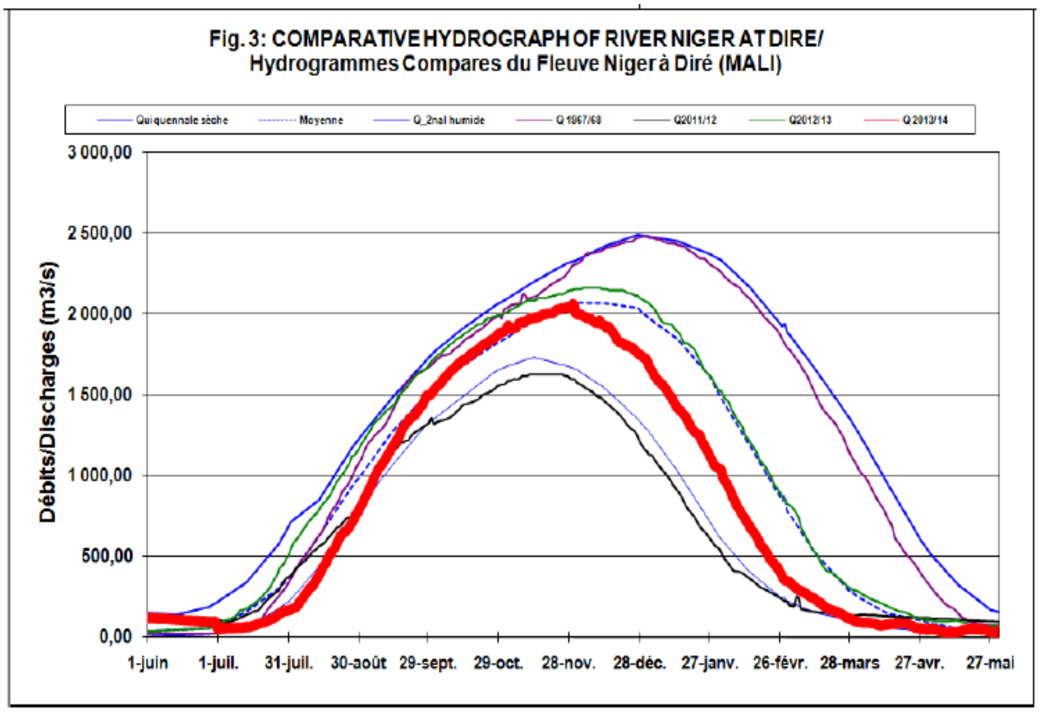


Figure 5.8d: Dire hydrograph from May 2014 Niger Basin Authority bulletin. Streamflow for 2013/2014 is depicted in red and for 2012/2013 is depicted in green.

While the streamflow values for 2010, 2012 and 2013 were quite exceptional, the regional rainfall totals were not as anomalous. This disconnect raises the possibility that future flooding events in the Sahel may be more strongly attributed to changes in the runoff coefficient than the severity of precipitation events themselves (Amogu et al., 2010; Descroix et al., 2012). If regional runoff coefficients are sensitive to human activity, then actual flooding events may have a disproportionate response to a modest rainfall forcing. This is clearly an area requiring further study.

***Skew Characteristics**:* Returning now to our flood month and hydrologic year analysis, another key statistic is the skew value or third statistical moment about the mean. Formally, the skew is given by equation 1 below.

$$Skew = \frac{n}{(n-1)(n-2)} \sum_{i=1}^{n} \left(\frac{x_i - \bar{x}}{s}\right)^3 \qquad (5.1)$$

where n is the number of data points, x is the variable of interest, i is an index value and s is the sample standard deviation. Qualitatively, the skew statistic is a measure of the degree of asymmetry of a statistical distribution. Positively skewed datasets have long tails for positive departures from the average value (eg. wealth tends to be positively skewed). Negatively skewed datasets have long tails for negative departures from the average value. An analysis of the skew for all three stations, for 1950-2009, P1, P2 and P3 was done. None of the skew values were found to be statistically significantly different from zero, when appropriate corrections were made to the sample size to account for the above-mentioned autocorrelation. If the skews had been significant, we consider that the skew values of the individual epochs are more meaningful representations of the skew of the possible streamflow outcomes in any given year than the skew value across 1950-2009, which would have an aggregating effect. There is a tendency for slightly larger skew values during the dry epoch than during the wet epochs. This is understandable in light of regional rainfall patterns that also tend to be more positively skewed in dry climatologies and/or during dry periods (Siebert and Ward, 2011, Fatichi et al., 2012). There was further a tendency for negative skew values in P3. This may be partly attributable to the observed changes in runoff coefficient through the region (Descroix et al., 2009, Amogu et al., 2010).

Discussion of the Historical Period Variance Statistics for Application in the Simulations: In the simulations (sections 5.3 and 5.4) we assume specific trends for mean streamflow at each of the stations. There remains the question of what interannual standard deviation to assume during the simulations. The results in the historical period to date suggest only modest relationships between mean flow and standard deviation. In addition, the issue is complicated by the discussion of the evolving nature of the runoff coefficient. Further work is needed to assess possible scenarios of how these surface and subsurface hydrological properties will change in the future during a changing climate (and changing land surface), and how they will impact interannual variance of streamflow. For our purposes in this paper, we will assume a constant interannual variance, and focus on the most recent period (P3) for the estimates of variance and COV that are needed in the simulations.

5.3. Simulations with no MDV: The Monte Carlo simulations in this section will contain inter-annual variability and systematic trend (introduction of MDV is reserved for section 5.4). As mentioned in section 5.2 the flood month streamflow distributions are found to have skew values not statistically different from zero. Due to the lack of a significant skew and the desire for simplicity, interannual variability is randomly sampled from a normal distribution with a mean and standard deviation as estimated in P3. Simulations are generated for 31 years, considered to be 2010-2040, representing an extension of each station's record of observations up to 2009. For all experiments, 1000 simulations were made. The simulations are used to assess the frequency of threshold crossing events in 2010-2040, under the specific assumptions about future variability and trend.

Quantile-quantile analysis of the P3 period was performed to ascertain the goodness of fit of the assumption of normality, and results did not reject normality. In Siebert and Ward (2011), interannual variability was also sampled from the skew-normal distribution, but given the skew discussion in the previous section, we do not at this point feel application of the skew-normal distribution to this streamflow problem would enhance results. For the Monte Carlo simulation, the threshold values chosen for this portion of our study are taken from the empirically derived normal distribution using the P3 flood month basic statistics as summarized in Figure 5.6. Table 5-4 below displays these critical high and low flow thresholds. They are slightly different from the empirical observed thresholds, but not drastically so (as expected given the distribution is approximately normal).

Streamflow m^3s^{-1}	Koulikoro	Dire	Niamey
Simulated high flow threshold	5114	2108	1915
Simulated low flow threshold	3154	1686	1175

Table 5-4: Thresholds for 1 in 10 high flows and low flows based on P3 statistics assuming a normal distribution.

First, simulations of the flood month values are undertaken with trend set to zero (Figure 5.9). These results can be considered as a baseline, estimating the range of possible outcomes for 2010-2040 assuming that the mean and standard deviation observed in P3 remain constant into the future. Threshold values are selected on the basis of the normal distribution derived from the P3 statistics as shown in Table 5-5.

For Figures 5.9, 5.10, 5.11 and 5.12, we depict the probability of a given number of TCEs in the period from 2010-2040. For Figure 5.9 (baseline scenario), the probabilities displayed are derived from the binomial distribution. This is the standard distributional assumption to use for categorical scenarios (threshold crossed, no threshold crossed). The probability density function of the binomial distribution is given by the equation

$$P_k = \frac{n!}{k!(n-k)!} p^k (1-p)^{n-k} \tag{5.2}$$

where P_k is the probability of k extreme events in n years. In this case, n is 31 (2010-2040), p is 0.1 (the one in ten threshold). The specific values in Figure 5.9 can be calculated by equation 5.2. In Figure 5.9 with no trend or MDV, we would expect 31/10 = 3.1 1 in 10-year threshold crossing events (the expected value of the binomial distribution is np). As we can see, this expectation is confirmed in the figure. Figure 5.9 shows 3 threshold crossings in the 31-year period being the most strongly represented result. In addition, Figure 5.9 also gives an indication of the natural range of possible outcomes in the 31-year period, for example, showing that zero 1 in 10-year events has a probability of about 0.04 (i.e. 4% of the simulations, as shown on Figure 5.9).

The baseline results are generalizable to all stations, since there is an assumed normal distribution. Next, we add a systematic trend to the random interannual variability. Now, for a given systematic trend, the change in the frequency of threshold crossing events varies across the specific station. Stations with a lower ratio of standard deviation to mean are more sensitive, and changes in threshold crossing event frequencies are larger for a given trend magnitude. As discussed in Siebert and Ward (2011), the COV statistic determines this sensitivity completely.

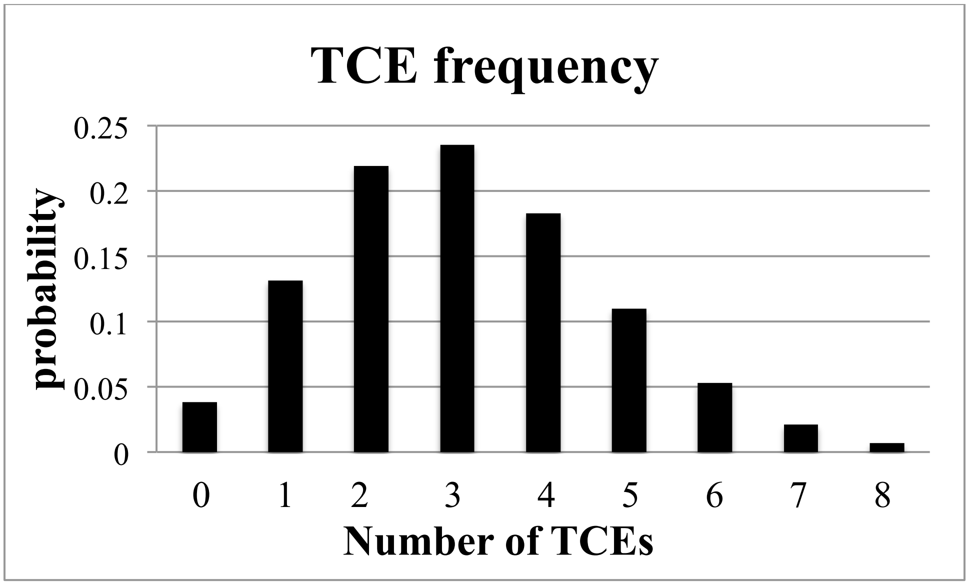


Figure 5.9: Frequency of threshold crossing extremes in the baseline analysis (no trend and no MDV). The frequencies are derived from the binomial distribution for 31 years of data, a 10% TCE frequency. This baseline simulation assumes stationary white noise and normality. The bar chart shows that, in any given 31-year period, while 3 1-in-10 year events is the most likely outcome – occurring roughly 24% of the time, there is nonetheless a small chance (about 4% probability) of 0 events, and also a small chance of getting a very large number of events This chart is applicable to all stations, with just the actual value of the implied thresholds varying according to the specific climatology at each station (see Table 5-5).

In the results presented here, we focus on the flood month statistics. Figure 5.10 displays the implications of a + and – 20% trend in the mean (flood month) streamflow during the course of the 2010-2040 period for Koulikoro or Niamey (i.e. 0 trend in 2010, 10% change in 2025 and 20% change in 2040). The P3 COV for Koulikoro is 0.186. The P3 COV for Niamey is virtually identical at 0.187, so the results in Figure 5.10 are shown as being representative of both Koulikoro and

Niamey. As is found elsewhere in climate literature small imposed changes in the mean correspond to large changes in the frequency of extreme events, even while maintaining a constant variance (Meehl et al., 2000; Kharin et al., 2007). This is also corroborated by observational studies around the world (New et al., 2006).

In Figure 5.10, the average frequency of high flows increases to 7.42 in the +20% streamflow simulation case and decreases to 1.3 in the -20% streamflow case. The same analysis was also done for low flows, but the results are not shown here, as the focus is on flooding risks for the River Niger.

Figure 5.11 displays the same types of data as do Figures 5.10, but this time for Dire, Mali in the inland delta. The P3 COV in this instance is 0.087. With this smaller coefficient of variation, we expect a stronger response to the trend (i.e. a 20% trend in the mean translates to a larger number of standard deviations of change and consequently a stronger enhancement or suppression of extreme events).

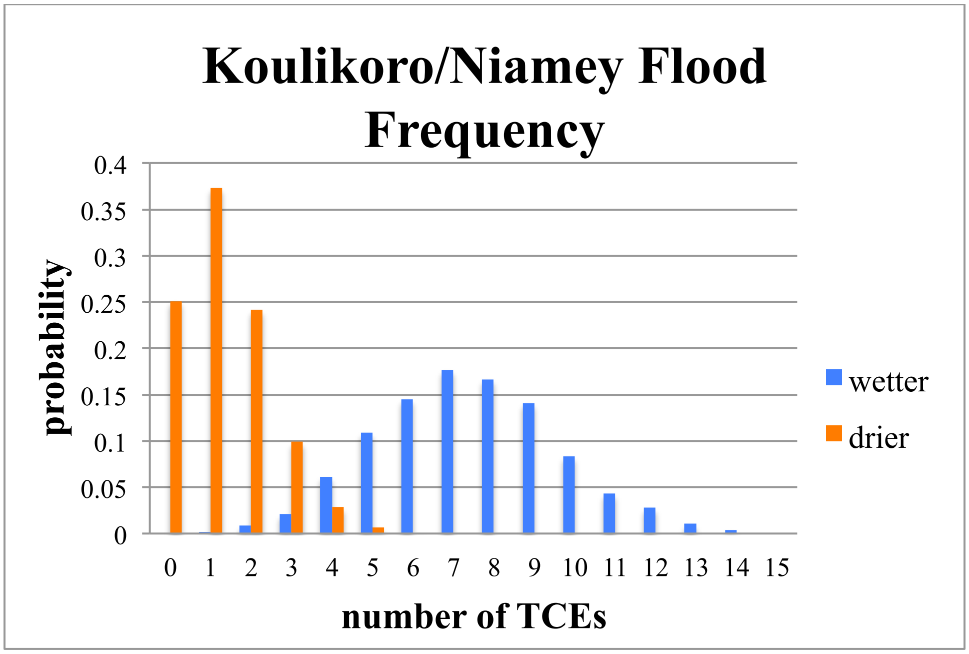


Figure 5.10: Frequency of threshold crossing extreme floods for Koulikoro under specified climate change assumptions. (Characteristics for Niamey are almost identical due to the almost identical coefficient of variation statistic). “Wetter” refers to a +20% trend in mean streamflow during 2010-2040, while “drier” refers to a -20% trend in mean streamflow during 2010-2040.

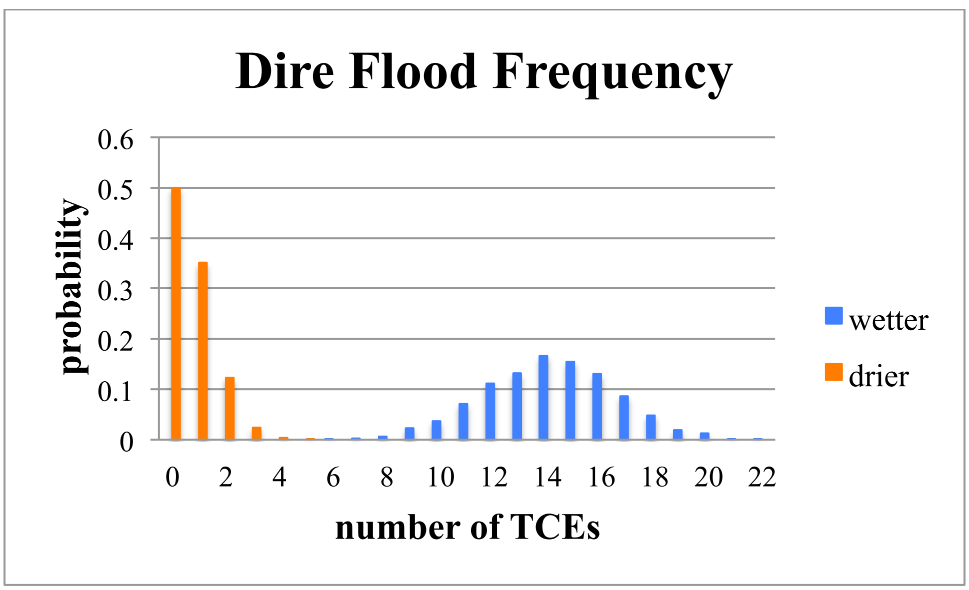


Figure 5.11: Frequency of threshold crossing extreme floods for Dire under specified climate change assumptions. “Wetter” refers to a +20% trend in mean streamflow during 2010-2040, while “drier” refers to a -20% trend in mean streamflow during 2010-2040.

In this case, because the COV is much smaller, a 20% trend in the mean streamflow corresponds to a strong change in the frequency of extreme events. Here, the average frequency of high flows increases to 14.17 in the +20% streamflow simulation case and decreases to 0.68 in the -20% streamflow simulation case. The results were reciprocal for the frequency of low flows.

It is worth recalling that in the historical record, Dire has shown smaller percent changes in streamflow during the contrasting precipitation regimes. Therefore, it is possible that for a given climatic shift in the future, the response of flow at Dire may be relatively smaller, thereby damping this apparent greater sensitivity of its threshold crossing events.

Index insurance implications of GC: As discussed in chapter 2, for a simple step function index insurance contract, the actuarially fair premium is simply P = Lp, where P is the premium, L is the total insured liability and p is the probability of threshold exceedance. Given the above analysis and discussion, the actuarial price of a potential flood index insurance contract for Niamey based on the 10% historical recurrence, would rise from 10% of insured liability to 23.9% of insured liability in the +20% mean streamflow case (TCE frequency shifting from 3.1 TCEs/31 years to 7.42 TCEs/31 years). Conversely, in the case of a 20% decline in mean streamflow, the premium would drop to 4.2% of insured liability (TCE frequency shifting from 3.1 TCEs/31 years to 1.3 TCEs/31 years).

While the above analysis suggests that a price change for a hypothetical contract in Dire, Mali would be more dramatic, as chapter 4 discussed, there is not as robust a negative correlation of rice yields and streamflow in Mali. Furthermore, the relatively muted variability of the historical time series at Dire and the unique nature of the inland delta environment may imply that index insurance would not be the most suitable adaptation for that region.

5.4. Simulations with MDV: In this section, multi-decadal variability is simulated via a lag-1 year autoregressive (AR) process. While other analyses of serially correlated time series sometimes include a moving average component as well (ARMA or ARIMA), the AR process is chosen in this study for the sake of simplicity. Analyses of these different techniques have shown that simple AR-1 and AR-2 processes can perform as well as ARMA or ARIMA models (Makridakis and Hibon, 1997). The AR process is tuned to maintain the same standard deviation as observed in the base period P3.

A baseline is shown in Figure 5.12 with a lag-1 year autocorrelation of 0.6 as compared to the prior baseline statistics with no autoregressive process. For reasons stated in section 3, this approach to modeling the MDV by using a simple AR(1) coefficient of 0.6 is considered to be a lower limit estimate of the true MDV sensitivity. It is quite clearly visible from this analysis that the frequency of extreme events has a larger spread when a multi-decadal signal is included (discussed in more detail in Siebert and Ward 2011).

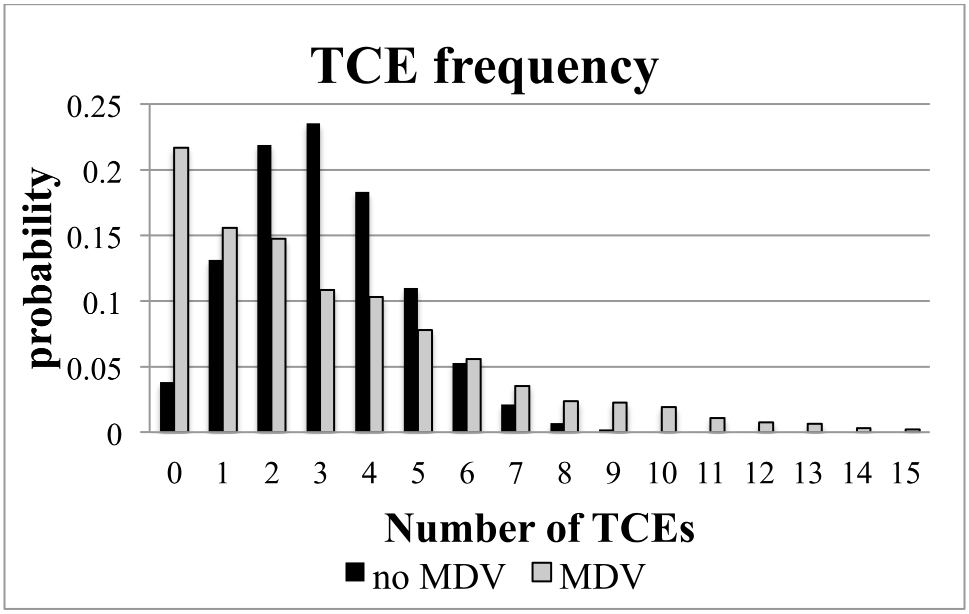


Figure 5.12: Baseline experiment revisited – with and without multidecadal variability (MDV). The simulations with MDV are computed with a lag 1-year autocorrelation of 0.6. The "no MDV" result is the same as shown in Fig. 5.7.

Index insurance implications of MDV: This increase in the probability of a very large number of extreme events (even if the expected value does not change) will have implications for the "loading" costs of index insurance, which are connected to climate uncertainty. The insurer would have an interest in passing at least part of this additional risk on to the consumer in the form of added premium cost in order to balance against the added risk of default. However, a very large increase in the price of the insurance contract to hedge against this risk would be quite unpopular and would limit interest in or viability of the insurance contract in the first place. While this is fundamentally a subtle (and somewhat political and economic) judgment call, one could imagine that for the sake of argument the "loading" cost from the climate "uncertainty risk" could be proportional to the risk of a large number of payouts in a given period (for example 10 or more payouts in a 30 year period). Equation 2.3 would then become:

$$P_d = L(p(r \leq r_{strike}) + fp(10+\text{TCEs in 30 years})) \quad (5.3)$$

where P_d is the premium, L is the liability (payout), $p(r \leq r_{strike})$ is the expected probability of threshold crossing and p(10+TCEs in 30 years) is the probability of 10 or more extreme events in a 30 years (on the basis of Monte Carlo simulation) and f is some fraction from 0 to 1 to be determined by the insurer or in negotiation between the insurer and the client. The more generalized form (analog to equation 2.1) would become

$$P_d = \int_0^{rstrike} p(r)y(r)dr + f\sum_{k=10}^{30} p(k)y(k) \quad (5.4)$$

where k is the number of TCEs in a 30 year period.

If f is too close to 1, the insurer is passing much of the uncertainty cost on to the client and this may diminish participation rates, but will help protect against default. If f is too close to 0, the premium is closer to the actuarially fair price, but the insurer faces greater financial exposure to default and collapse of the insurance if the multi-decadal variability causes a string of payout years.

Simulations of MDV+GC: The future variability of the region's streamflow will be a product of trends induced by regional and/or global climate, accompanying changes in standard deviation, further changes in land use and runoff coefficient as well as natural multi-decadal climate forcing. It is very difficult to estimate all these parameters and to combine them in a cogent mathematical framework. Future land use changes are an unknown as are future changes to runoff coefficient. The current method is exploring the implications of plausible climate fluctuations, and future work may focus on plausible assumptions about other physical factors impacting possible trends in the nature of the streamflow. Indeed, in the prior section, the mean streamflow statistics from the P3 period were imposed. While the standard deviation will change, no attempt is made to address the issue of the standard deviation change here – that analysis is left for Chapter 6.

However, this study has explored simulations in which a trend in the mean streamflow is coupled with multi-decadal variability (as simulated via the AR process discussed above). In each simulation, multi-decadal variability is stochastically generated as an AR process for 2010-2040, and a mean change is imposed in addition for the 2010-2040 period. A strong trend and strong autocorrelation are likely to result in the most significant enhancement of extreme event frequency. Again, the extreme event thresholds are as given in Table 5-4 and the P3 statistics are used for mean and standard deviation.

In the following simulations, the magnitude of multi-decadal variability is allowed to vary by adjusting the lag-1 autocorrelation in the AR process. When set to 0, it implies no MDV (i.e. white noise process). As discussed in section 5.2, values of about 0.6 may be typical of Sahel climate and some of the stations for River Niger streamflow. To explore sensitivity of threshold crossing events, we have performed experiments across the range of AR correlation from 0 to 0.8, and across the range of trends from -20% to + 20%. Rather than show bar chart figures for each experiment set (as in Figs. 5.9-5.12), the probability of 10 or more extreme events in the simulated 2010-2040 period (i.e. estimated by drawing on the Monte Carlo sample for a given combination of AR process and trend). Figure 5.10 displays the probability of 10 or more extreme events in the 2010-2040 time period as a function of AR magnitude and systematic trend. The interannual variability sampled to create Figure 5.10 is drawn from the normal distribution with the P3 COV in Koulikoro of 0.186. Again, given the similarity of this COV value to that of Niamey, the results are ostensibly the same for Niamey. Results for Dire (not shown) again show increased sensitivity due to the smaller COV.

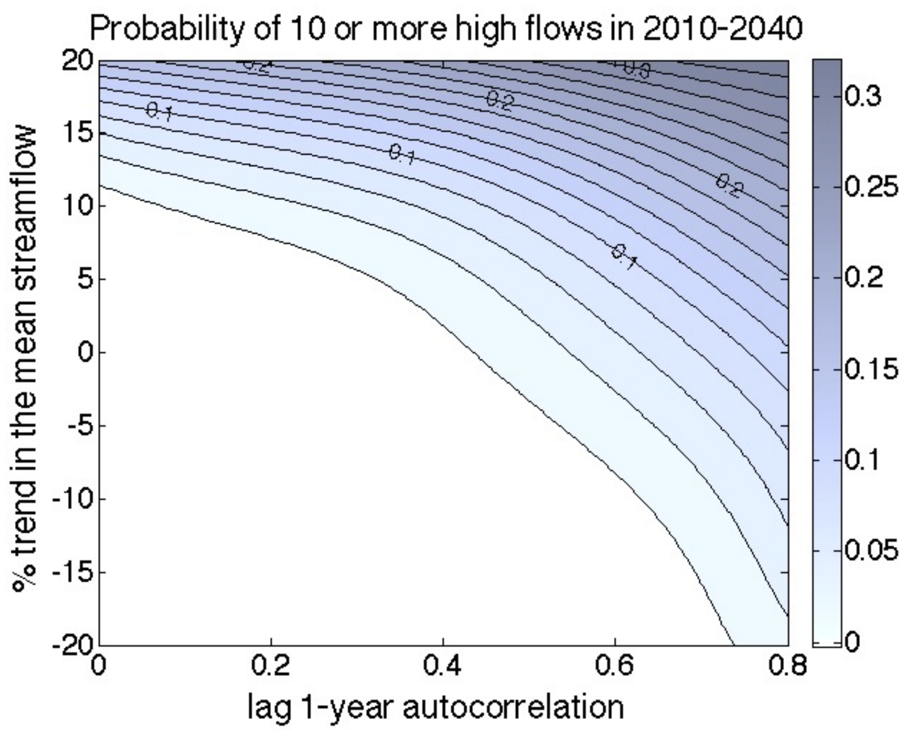


Figure 5.13: Probability of 10 or more threshold crossing high flows in 2010-2040 with specified trends in mean streamflow (y-axis) and autoregression coefficient for the MDV in the streamflow (x-axis). These results are for Koulikoro/Niamey.

As one can clearly see from Figure 5.13, the probability of 10 or more extreme events is strongly sensitive to both the mean trend and the autocorrelation strength. The observed autocorrelation values in Table 5-2 can be consulted to guide which areas of the plot are most relevant. These plots show that the peak probability of 10 or more floods is located in the top right corner for high flow events (i.e. under positive trend and high MDV magnitude). Analogous research was also done for low flow events (not shown) indicate that the peak probability of 10 or more low flow events occurs with a -20% trend in the streamflow and a strong autocorrelation. In examining Figure 5.13, we that for a trend of +20% in the mean streamflow, with 0 autocorrelation, the expected frequency of 10+ TCEs in a 30 year window is around 0.16, but for a 0.6 autocorrelation, the probability of 10+ TCEs in a 30 year window rises to around 0.3 (effectively doubling the "loading" costs on the basis of equation 5.3). For a trend of +10% in the mean streamflow, the 0 autocorrelation case has a less than 0.02 change of producing 10+ TCEs in 30 years, while the 0.6 autocorrelation case has a roughly 0.13 chance of producing 10+ TCEs (effectively quintupling the loading cost on the basis of equation 5.3).

Finally, another transformation of the basic bar-chart presentation is to calculate the spread in terms of the standard deviation or mean absolute departure from the expected number of extreme events in a given 31-year period. Such a statistic can be defined as the absolute error (ABSE):

$$ABSE = \frac{\sum_{i=1}^{n} |f_i - 3.1|}{n} \tag{5.5}$$

Such measures are particularly relevant for index insurance, since uncertainty in outcome is an important factor in determining premium price. Figure 5.14 gives an example of ABSE as a function of trend and AR process. It shows how MDV as well as global change is a very important factor in assessing viability of index insurance.

Clearly, the ABSE is strongly sensitive to both the mean trend and the autocorrelation strength. Like Figure 5.13, the maximum ABSE is in the upper right hand corner (i.e. under positive trend and high MDV magnitude) for the high flow ABSE and in the lower right hand corner (i.e. under negative trend and high MDV magnitude) for the low flow ABSE (not shown). The minimum ABSE in each case is on the left side of the figure at small MDV near zero trend. In index insurance terms, the ABSE is an indication of price uncertainty.

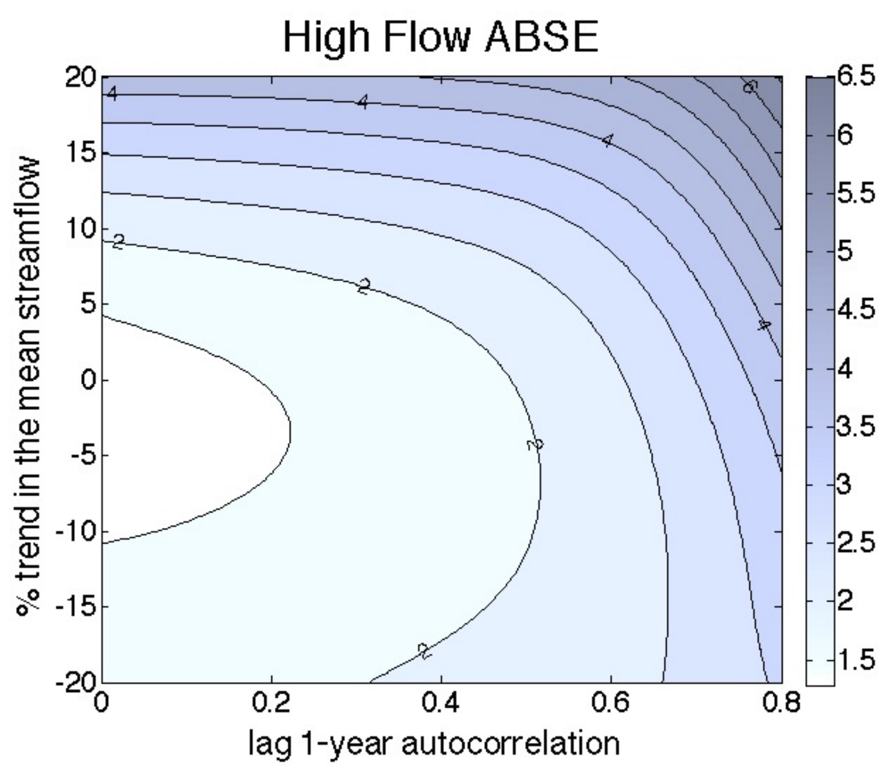


Figure 5.14: ABSE of high flows in 2010-2040 with specified trends in mean streamflow (y-axis) and autoregression coefficient for the MDV in the streamflow (x-axis). These results are for Koulikoro/Niamey.

5.5. Conclusions Regarding the Monte Carlo Analysis: The first part of this chapter has described historical variations of Niger River flow at three locations on the river's course. The data used in this study were daily streamflow data provided by the Niger Basin Authority for each of three stations for the period from 1950-2009; Koulikoro in the upper basin, Dire in the inland delta region and Niamey in the middle basin. The daily data were aggregated in monthly averages (focusing on the time series of the climatological flood month at each station) or annual averages for most of the analysis. Then, under specific assumptions about climate variation and change for the near-term, Monte Carlo simulations have been undertaken. The simulations are informed partly by the historical statistics, and partly by plausible assumptions about possible magnitudes of the impact of climate change on Niger River flow. The simulations are used to assess possible changes in the frequency of extreme flow events, which have implications for index insurance and can inform risk management strategies more broadly.

The historical streamflow data from 1950-2009 reveal that the mean flow of the epochs is generally in concert with the broader Sahel rainfall fluctuations discussed in Chapter 4 (on the basis of the Global Historical Climate Network). This paper has shown that the flood month (and JAS peak flow) also follow the same general pattern. The lag-1 autocorrelation analysis of the streamflow also shows expression of the naturally occurring multidecadal climate variability in the region. The paper has also considered aspects of the distribution of streamflow in each sub-period, a dimension of the changes that has been less studied in prior literature. Relative to rainfall, the streamflow experiences more gradual transitions between epochs, so the streamflow variance statistic in P2 appears very high. The low flow thresholds of the different epochs were noticeably more sensitive to epochal transitions than the high flow thresholds. The analysis of the residual from smoothing gives a more realistic estimate of interannual variability during P2, but is still, on balance, slightly larger than the standard deviations of P1 and P3. This tendency is the opposite of what is expected from the rainfall variance and may be related to land surface characteristics during the dry period. The increase of streamflow standard deviation during dry epochs (along with the asymmetry in threshold changes mentioned above) may be included in future Monte Carlo simulations but here, for now, the choice was made to keep constant SD into the future, for first order estimates of the sensitivity of threshold crossing event frequencies.

A brief statistical summary of the peak 5-day Niamey July-September streamflow was included, since it has some distinct aspects from annual/flood month characteristics, and is particularly relevant for livelihoods close to the river. The streamflow during this time of year responds more directly to local rainfall, so the epochal analysis mirrors more directly the character of rainfall changes: a clear positive covariance of the standard deviation with the mean and the skew values are positive (as is consistent with seasonal rainfall skew values). Within each sub-period (i.e. after effective removal of much of the low frequency variance), there is also a negative lag-1 autocorrelation, potentially indicating a signal from biennial climate fluctuation. More specifically, hydrographs from recent years in the middle Niger River basin (Niamey) show very pronounced flooding events in the JASO periods of 2010, 2012 and 2013.

Skew values are not found to be statistically significant either in the sub-periods or in the 1950-2009 range, when the sample size is appropriately adjusted for autocorrelation. In other contexts, skew may be more explicitly incorporated into Monte Carlo simulations (as introduced for rainfall in Siebert and Ward, 2011).

The Monte Carlo simulations for 2010-2040 reveal a strong sensitivity of the 1 in 10-year threshold crossing events to a 20% trend in mean streamflow. For example, a 20% positive trend in the mean streamflow leads to a more than doubling of the flood frequency for Koulikoro and Niamey and a more than quadrupling of flood frequency for Dire. These changes in the simulated extreme event frequency imply commensurate changes in the actuarial price for potential flood index insurance contracts for the middle Niger Basin.

The coefficient of variation (COV) is strongly suppressed in the inland delta (Dire), and this implies that a 20% trend in average streamflow would create a larger departure from the baseline TCE frequency. This needs more investigation, accounting for possible damping of the percent change by inland delta land surface features. The impact of the COV on extreme event frequency is documented by earlier work (Siebert and Ward, 2011) and is clearly visible in the simulations here, contrasting Dire on the one hand and Koulikoro and Niamey on the other.

Simulations that include multi-decadal variability show that the frequency of 10 or more extreme events in the 2010-2040 is shown to be sensitive to both trend and MDV. A simple heuristic conception of the "loading" costs associated with index insurance suggests that the loading costs should reflect the Monte Carlo simulated probability of a large number of extreme events. Consequently, this cost (which would be added to the actuarial premium) is highly sensitive to both trend and MDV. Furthermore, multidecadal variability increases the uncertainty of the expected frequency of extreme events, as revealed by the ABSE statistic. In both the analysis of the frequency of extreme events and the analysis of the ABSE, the results quantify how the sensitivity increases as a function of trend magnitude and MDV magnitude, and clearly motivate the need to address MDV and GC in index insurance applications and more generally in other climate risk management strategies.

Results may be interpreted for their implications with regard to the proposed flood index insurance contracts for Niger irrigated rice farmers. It is shown that the actuarial price of index insurance contracts would be highly contingent on trends in the mean streamflow and the loading costs would be dependent on both trends in the mean and the degree of the multi-decadal variability. Other application specific insights may require that the output from Monte Carlo simulations be run through other impact models. This was done for a simplified reservoir management system in Ward et al (2012b). In reference to the temporally evolving nature of the risk mentioned above, an index insurance model could be adapted to have temporally updating thresholds (as in Siebert and Ward, 2011).

When running simulations through impact models, the extent to which updated climate normals can reduce impacts and better inform strategies (Siebert and Ward, 2011; Ward et al. 2012b), is a further key area for investigation. There is a recognized need for more incorporation of land surface change into the simulations of the Niger River Basin for increased realism. Nonetheless, in this chapter, the implications of some key aspects of climate variability and change on the frequency of hydroclimate extremes for the Niger River Basin have been assessed - an important step for providing enhanced information to inform index insurance assessment and other risk management activities for the near-term (~20-40 years) time horizon.

References

-Abrate, T., P. Hubert and D. Sighomnou, (2010). A Student on the Hydrological Series of the Niger River at Koulikoro, Niamey and Lokoja Stations. *International Workshop* ADVANCES IN STATISTICAL HYDROLOGY, Taormina, Italy

-Adler, R. F., G. Gu, G. J. Huffman, (2012). Estimating Climatological Bias Errors for the Global Precipitation Climatology Project (GPCP), *Journal of Applied Meteorology and Climatology, 51,* 84-99.

-Amogu, O., L. Descroix, K. AS. Yero, E. LeBreton, I. Mamadou, A. Ali, T. Vischel, J.C. Bader, I. B. Moussa, E. Gautier, S. Boubkraoui and P. Belleudy, (2010). Increasing River Flows in the Sahel? *Water, 2,* 170-199.

-Anderson, R.L., (1941). Distribution of the serial correlation coefficients. *Annals of Mathematical Statistics, 8,* 1-13.

-Beukering, P. J. H. van, B. Kone, H. Goosen, and L. Zwarts, (2005). The Impact of Water Management on Poverty and the Environment in the Upper Niger River Basin (Mali). *Working Paper, Poverty Reduction and Environmental Management.*

-Biasutti, M., I. Held, A. Sobel, A. Giannini, (2008). SST Forcings and Sahel Rainfall Variability in Simulations of the Twentieth and Twenty-First Centuries. *Journal of Climate, 21,* 3471-3486.

-Dawdy, D.R., and Matalas, N.C., (1964). Statistical and probability analysis of hydrologic data, part III: Analysis of variance, covariance and time series, in Ven Te Chow, ed., Handbook of applied hydrology, a compendium of water-resources technology: New York, McGraw-Hill Book Company, p. 8.68-8.90.

-Descroix, L., G. Mahé, T. Lebel, G. Favreau, S. Galle, E. Gautier, J-C. Olivry, J. Albergel, O. Amogu, B. Cappelaere, R. Dessouassi, A. Diedhiou, E. Le Breton, I. Mamadou, D. Sighomnou, (2009). Spatio-Temporal Variability of Hydrological Regimes Around the Boundaries Between Sahelian and Sudanian Areas of West Africa: A Synthesis. *Journal of Hydrology, 375,* 90-102.

-Descroix, L., M. Esteves, K. Souley Y´ero, J.-L. Rajot, M. Malam Abdou, S. Boubkraoui, J. M. Lapetite, N. Dessay, I. Zin, O. Amogu, A. Bachir, I. Bouzou Moussa, E. Le Breton, and I. Mamadou, (2011). Runoff Evolution According to Land Use Change in a Small Sahelian Catchment. *Hydrology and Earth System Sciences Discussions*, *8,* 1569-1607.

-Descroix, L., P. Genthon, O. Amogu, J. L Rajot, J. P. Vandervaere, D. Sighomnou, (2012). The Highest Red Flood of the Niger River Ever Recorded in Niamey: Climate Change or Land Use Change? Poster session 8A, Water Resources Quantification and Management and Floods and Extreme Events, *AMMA Conference,* Toulouse, France.

-Diallo, M. (2013). Flooding in the Sahel leaves thousands of families facing uncertain futures. *International Federation of Red Cross and Red Crescent Societies*.

-Diarra, S., M. Kuper, and G. Mahe, (2004). Integrated Flood Plain Management Case Study, Mali: Flood Management Niger River Inland Delta. *Report; World Meteorological Organization/Global Water Partnership.*

-Eklundh, L. and M. Sjostrom, (2005). Analysing Vegetation Changes in the Sahel Using Senson Data from Landsat and NOAA. *Proceedings of International Symposium on Remote Sensing of Environment,* St. Petersburg, Russia.

-Fatichi, S., V. Y. Ivanov, E. Caporali, (2012). Investigating Interannual Variability of Precipitation at the Global Scale: Is There a Connection with Seasonality? *Journal of Climate, 25,* 5512-5523.

-Favreau, G., C. Leduc, C. Marlin, M. Dray, J.D. Taupin, M. Massault, C.L.G. LaSalle, and M. Babic, (2002). Estimate of Recharge of a Rising Water Table in Semiarid Niger from ^{3}H and ^{14}C Modeling, *Ground Water*, *40,* 144-151.

-Folland, C. K., T. N. Palmer, and D. E. Parker, (1986). Sahel Rainfall and Worldwide Sea Temperatures, 1901-85, *Nature, 320,* 602-607.
-Giannini, A., R. Saravanan, and P. Chang, (2003). Oceanic Forcing of Sahel Rainfall on Interannual to Interdecadal Time Scales. *Science, 302,* 1027-1030.
-Greene, A., A. Giannini, and S. Zebiak, (2009). Drought Return Times in the Sahel: A Question of Attribution. *Geophysical Research Letters, 36,* L12701.
-Hellmuth, M. E., D. E. Osgood, U. Hess, A. Moorhead, and H. Bhojwani, Eds., (2009). Index Insurance and Climate Risk: Prospects for Development and Disaster Management. *Climate and Society Series*, Vol. 2, International Research Institute for Climate and Society, 112 pp.
-Hermann, S., (2007). Variability of Sahelian Rainfall and its Impact on Vegetation Dynamics. *Sahel Conference,* NCAR.
-Hulme, M. (1992). Rainfall changes in Africa: 1931–1960 to 1961–1990. *International Journal of Climatology, 12,* 685–699.
-Janowiak, J., and P. Xie, (1999). CAMS-OPI: A Global Satellite-Rain Gauge Merged Product for Real-Time Precipitation Monitoring Applications, *Journal of Climate, 12,* 3335-3342.
-Janicot, S., (1992). Spatiotemporal Variability of West African Rainfall. Part II: Associated Surface and Airmass Characteristics. *Journal of Climate, 5,* 499-511.
-Kafando, P., F. Chane-Ming and M. Petitdidier, (2011). Analysis of Small Scale Waves Over the West African Area, *American Meteorological Society extended abstract*.
-Kharin, V., F. Zwiers, X. Zhang, G. Hegerl, (2007). Changes in Temperature and Precipitation Extremes in the IPCC Ensemble of Global Coupled Model Simulations. *Journal of Climate*, *20,* 1419-1444.
-Lawrimore, J., M. Menne, B. Gleason, C. Williams, D. Wuertz, R. Vose and J. Rennie, (2011). An Overview of the Global Historical Climatology Network Monthly Mean Temperature Data Set, Version 3, *Journal of Geophysical Research Atmospheres*, *116,* D19121.
-Lebel, T., and A. Ali, (2009). Recent Trends in the Central and Western Sahel Rainfall Regime (1990-2007). *Journal of Hydrology*, *375,* 52-64.
-L'Hote, Y., G. Mahe, B. Some, (2003). The 1990s rainfall in the Sahel: the Third Driest Decade Since the Beginning of the Century. *Hydrologic Sciences Journal, 48,* 493-496.
-Mahé, G., J. Paturel, E. Servat, D. Conway and A. Dezetter, (2005). The Impact of Land Use Change on Soil Water Holding Capacity and River Modeling in the Nakambe River, Burkina Faso, *Journal of Hydrology*, *300,* 33-43.
-Makridakis S. and M. Hibon (1997). ARMA models and the Box-Jenkins Methodology, *Journal of Forecasting, 16,* 147-163.
-Meehl, G. A., T. Karl, D. R. Easterling, S. Changnon, R. Pielke Jr., D. Changnon, J. Evans, P. V. Groisman, T. R. Knutson, K. E. Kunkel, L. O. Mearns, C. Parmesan, R. Pulwarty, T. Root, R. T. Sylves, P. Whetton, and F. Zwiers, (2000). An Introduction to Trends in Weather and Climate Events ; Observations, Socioeconomic Impacts, Terrestrial Ecological Impacts, and Model Projections. *Bulletin of the American Meteorological Society, 81,* 413-416.
-Meehl, G. A., L. Goddard, J. Murphy, R. J. Stouffer, G. Boer, G. Danabasoglu, K. Dixon, M. A. Giorgetta, A. M. Greene, E. Hawkins, G. Hegerl, D. Karoly, N. Keenlyside, M. Kimoto, B. Kirtman, A. Navarra, R. Pulwarty, D. Smith, D. Stammer, and T. Stockdale, (2009). Decadal Prediction: Can it be Skillful? *Bulletin of the American Meteorological Society*, *90,* 1485-1467.
-Mohino E., S. Janicot and J. Bader, (2011). Sahel Rainfall and Decadal to Multi-Decadal Sea Surface Temperature Variability. *Climate Dynamics, 37,* 419-440.

-Ndiaye, O., M. N. Ward and W. Thaw, (2011). Predictability of Seasonal Sahel Rainfall Using GCMs and Lead-Time Improvements Through the Use of a Coupled Model. *Journal of Climate*, *24,* 1931-1949.
-Nicholson, S. E., (1980). The Nature of Rainfall Fluctuations in Subtropical West Africa. *Monthly Weather Review, 108,* 473-487.
-Nicholson, S., (2005). On the Question of the "Recovery" of the Rains in the West African Sahel. *Journal of Arid Environments, 63,* 615-641.
-Nicholson, S.E., (2013). The West African Sahel: A Review of Recent Studies on the Rainfall Regime and Its Interannual Variability. *ISRN Meteorology*, *2013,* Article ID 453521, 32 pages, doi:10.1155/2013/453521.
-Nilsson, C., C. Reidy, M. Dynesius, and C. Revenga, (2005). Fragmentation and Flow Regulation of the World's Large River Systems. *Science, 308*, 405-408.
-Paturel, J. E., M. Ouedraogo, E. Servat, G. Mahe, A. Dezetter, J.F. Boyer, (2003). The Concept of Rainfall and Streamflow Normals in West and Central Africa in a Context of Climatic Variability. *Hydrological Sciences, 48,* 125-137.
-Shanahan T., J. Overpeck, C. W. Wheeler, J.W. Beck, J. Pigati, M. Talbot, C. Scholz, J. Peck, and J. King, (2006). Paleoclimatic variations in West Africa from a record of late Pleistocene and Holocene lake level stands of Lake Bosumtwi, Ghana. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *242,* 287-302.
-Siebert, A. and M. N. Ward, (2011). Future Occurrence of Threshold Crossing Seasonal Rainfall Totals: Methodology and Application to Sites in Africa. *Journal of Applied Meteorology and Climatology, 50,* 560-578.
-Shukla, J., (1995). On the Initiation and Persistence of the Sahel Drought, *Natural Climate Variability on Decade-to-Century Time Scales, National Research Council*.
-Solomon, S., D. Qin, M. Manning, M. Marquis, K. Averyt, M. M. B. Tignor, H. L. Miller Jr., and Z. Chen, Eds., (2007). Climate Change 2007: The Physical Science Basis. *Cambridge University Press*, 996 pp.
-Tabachnick, B. G., and L. S. Fidell, (1996). Using Multivariate Statistics. 3rd ed. *Harper Collins*, 880 pp.
-Tarhule, A. and Akumaga, U., (2014). Climate Change Impacts on Rain-Fed Agriculture and Crop Yields in the Niger Basin. *Climate Risk Management Session, AAG annual meeting*.
-Von Storch, H., & Zwiers, F. (1999). Statistical analysis in climate reseach. *Cambridge: Cambridge University Press*. 484 pp.
-Wang, G., E. A. B. Eltahir, J. A. Foley, D. Pollard, S. Levis, (2004). Decadal Variability of Rainfall in the Sahel: Results from the Coupled GENESIS-IBIS Atmosphere-Biosphere Model, *Climate Dynamics, 22,* 625-637.
-Ward, M. N., (1998). Diagnosis and Short-Lead Time Prediction of Summer Rainfall in Tropical North Africa at Interannual and Multidecadal Timescales, *Journal of Climate, 11,* 3167-3191.
-Ward, M. N., A. Siebert and O. Ndiaye, (2012)a. Decadal to Multi-Decadal Variation in Sahel Rainfall Since 1950 and Associated Changes in the Frequency of Threshold-Crossing Seasonal Rainfall Totals. *4th African Monsoon Multidisciplinary Analysis International Conference, Book of Abstracts, 277-278. Toulouse, France, July.*
-Ward M.N., C. Brown, K. Baroang and Y. Kaheil, (2012)b Reservoir Performance and Dynamic Management under Plausible Assumptions of Future Climate over Seasons to Decades. Climatic Change. **(DOI:** 10.1007/s10584-012-0616-0)

Websites

-KfW, Entwicklungsbank, report (2010). Adaptation to Climate Change in the Upper and Middle Niger River Basin. Retrieved from http://ccsl.iccip.net/niger_river_basin.pdf
-Niger HYCOS Project Document, (2006). Retrieved from http://www.whycos.org/whycos/projects/under-implementation/niger-hycos
-UN OCHA report (2012). Retrieved from http://www.unocha.org/top-stories/all-stories/niger-heavy-rains-and-floods-force-more-400000-people-their-homes,

Chapter 6: GCM Informed Projections of Index Insurance Behavior

6.1. Regional Climate Modeling Overview: As was shown in Chapter 4, certain observed indices of rainfall (GHCN and NOAA PRECL) correlate well with the national scale detrended millet production for Niger, Burkina Faso and Mali, and there was a robust relationship between Niamey streamflow and Niger irrigated rice production. Gerrity skill scores were particularly high for the GHCN JAS precipitation indices for Burkina Faso and Niger. However, in order to assess the potential future viability of index insurance in this region, in light of climate change, it is essential to have an understanding of how the region's hydroclimatology is projected to change.

The IPCC AR5, WGI suggests that on the basis of the CMIP5 multi-GCM comparison under RCP 4.5, "West Africa" (defined as 11.4S to 15N, 20W to 25E) is likely to have an inner-quartile range of 0-4% increase in precipitation (during JJA) and a 1.6-2.6 C increase in temperature by 2100 (relative to 1986-2005) (IPCC 2013). It should be noted that only the very northern portion of this "West Africa" domain includes the Sahel. In the context of more Sahel-specific climate modeling analyses, there is still a lack of agreement among GCM output regarding the expected sign of the precipitation change in the Sahel in the 21st century, relative to the 1986-2005 base period (IPCC 2013, Biasutti 2013). This finding is similar to earlier modeling studies of the region's rainfall (Gianinni et al. 2013, Cook and Vizy, 2006).

Part of the inherent challenge of assessing future trends in the rainfall and hydroclimatic balance of the Sahel is that there are competing dynamical mechanisms at work in the region's hydroclimatology. When the interior of North Africa gets unusually hot relative to the sea surface temperatures around the Gulf of Guinea, an enhanced pressure gradient ensues, driving stronger onshore winds during the monsoon season. Higher sea surface temperatures also facilitate more evaporation and the potential for more precipitation globally (Held and Soden, 2006), but higher ambient temperatures require a higher atmospheric water vapor concentration to trigger precipitation and can also evaporate enough surface water to reduce potential biophysical feedback (Wang and Eltahir, 2000). Furthermore, it has been shown in prior research that Sahelian rainfall trends are quite responsive to anomalies in the sea surface temperatures, not only of the tropical North Atlantic but of the other tropical ocean basins as well (Giannini et al. 2003, Gianinni et al., 2013). There is still considerable uncertainty regarding the trajectory of the Atlantic Multi-decadal Oscillation (although the current state seems to be a positive phase anomaly) (Knight et al., 2006). From the regional modeling studies, there does seem to be a robust expectation that the interior of North Africa is likely to warm more than the maritime regions around the Gulf of Guinea through much of the 21st century (Vizy et al. 2013, IPCC 2013).

A precipitation-only index is a first step to estimating climate related stresses to agriculture in the West African Sahel. Total water stress on a rain-fed millet crop would have a relationship to both precipitation and evapotranspiration (which in turn depends on temperature, ambient humidity, winds, etc.). There are different formulations of total evapotranspiration, including the Penman Monteith and Thornthwaite models of potential evapotranspiration (Penman, 1948, Monteith, 1965, Thornthwaite, 1948). There are also various drought indices, including the standardized precipitation/evaporation index (SPEI) or Hargreaves and Allen models to assess seasonal water balance (Hargreaves and Allen, 2003). These more specific conceptions of evapotranspiration and total hydrological drought tend to require multiple data parameters; sunshine intensity, temperature, winds, relative humidity, etc.. Such observational data is not always readily available in rural areas of subSaharan West Africa.

This chapter will focus on analysis of the seasonal precipitation as the potential basis for index insurance contract. GCM based evaporation data is also analyzed in order to present a larger picture of the region's hydroclimatology, but is not considered explicitly as a basis for index insurance. In a practical sense, there is an advantage to using a relatively simple index as the basis for an index insurance contract. More complicated contracts based on more sophisticated models may be more challenging to communicate effectively to a potential client population.

6.2. Model Data and Methods: The Global Climate Models used for this section of the analysis are as follows;

National Oceanic and Atmospheric Administration Geophysical Fluid Dynamics Lab

(NOAA- GFDL) CM3, 2.5 lon x 2 lat grid, (USA) (Donner et al. 2011)

National Center for Atmospheric Research (NCAR) CCSM4 r1i1p1, 1.25 lon x 0.94 lat grid, (USA) (Gent et al., 2011)

Centre National de Recherche Meteorologique (CNRM) CM5 r1i1p1, 1.41 degree grid, (France) (Voldoire et al., 2011)

National Aeronautics and Space Administration – Goddard Institute for Space Studies (NASA-GISS) model E2 H, r1i1p1, 2.5 lon x 2 lat grid, (USA) (Schmidt et al. 2006)

and the Commonwealth Scientific and Industrial Research Organization (CSIRO) MK 3.6, r1i1p1, 1.875 lon x 1.865 lat, (Australia) (Jeffrey et al., 2013)

Each of the above models were a part of the Climate Model Inter-comparison Project 5 (CMIP5) efforts in support of the IPCC AR5. From each of these models, monthly precipitation and evapotranspiration data was acquired for the historical period of 1980-2005 and for the 21st century projections on the basis of the RCP 4.5 (middle emissions) and RCP 8.5 (high emissions) scenarios. The months of July, August and September in particular were examined, as these are the core months of the rainy season for the Sahel (although the importance of October, June and even May rainfall is significant for areas in the southern Sahel and further south into more humid regions).

All Sahel Indices: The first layer of geographic analysis is to explore the behavior of Sahel wide indices. The All Sahel JAS index for each model was created by averaging the grid-box specific standardized anomalies across the Sahel domain; 10N to 20N, 15W to about 20 E.   For each index, mean values and standard deviation values were calculated on the basis of the 2060-2100 period and the 1980-2020 period. The ratios of the means and standard deviations of the two periods were calculated.

Country/Region Specific Indices: In addition to creating Sahel-wide indices, country specific indices were created using spatial subdomains. The specific details of geographical domain varied slightly from model to model as each model had different spatial resolutions. The Mali "box" is 12W to 4W and 12N to 15N. Northeastern Mali is relatively arid and infertile. Far southern Mali is wet enough that some rainfall characteristics differ from much of the rest of the Sahel. The Burkina Faso "box" is 5W to 2E, 12N to 15N. This box includes most of the country but excludes the southern portion, which again is semi-humid. The Niger "box" is 12N to 15N from the Prime Meridian to 15 E. Northern Niger, like northern Mali is too arid for high levels of agricultural productivity. The geographic domains of the respective boxes are shown in Figure 6.1.

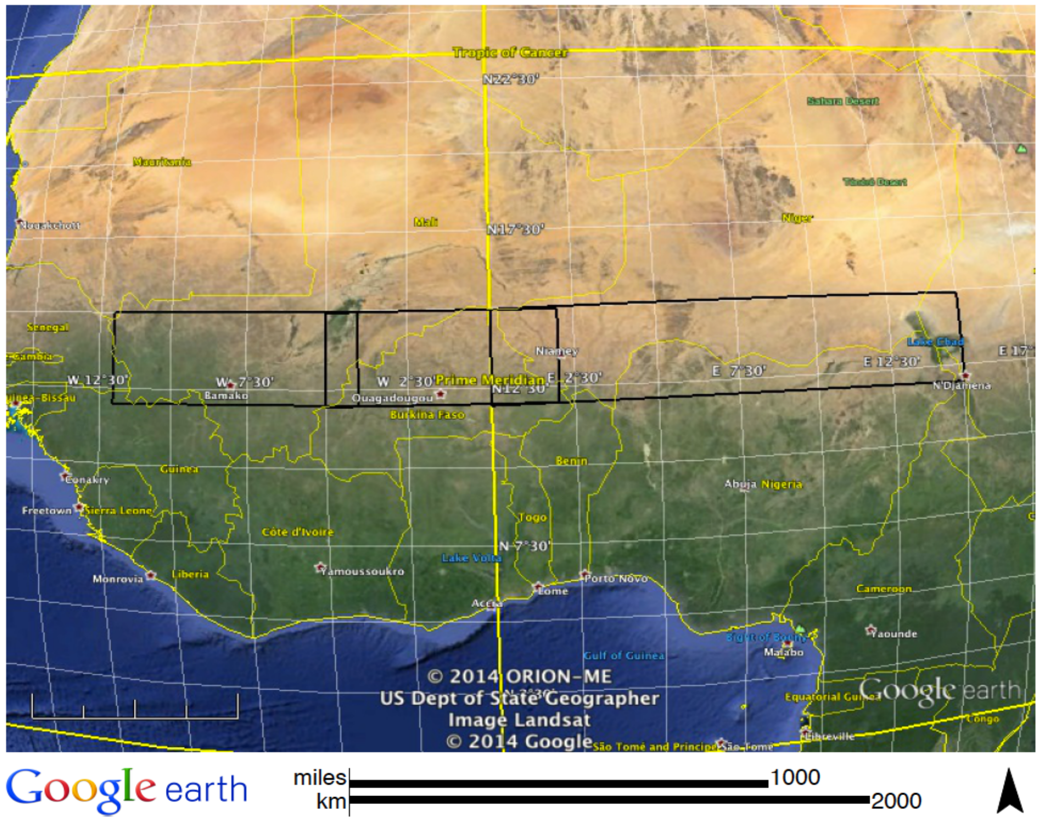


Figure 6.1: Country Specific Spatial Domains; made in Google Earth.

As was shown in Chapter 4, the streamflow in the middle Niger basin in the December/January flood months was strongly correlated to the rainfall throughout the Sahel, particularly in the JAS months, but even more specifically in the region near the headwaters of the Niger River. Figures 4.10 c and e show an area of strong correlation between Niamey December streamflow and the JAS rainfall in the domain from 10-14N and 13-4W, including southern Mali, much of eastern Guinea, parts of Burkina Faso, Senegal and Cote D'Ivoire. The rainfall in this region will serve as the basis for estimations of future flooding potential in Niger and hence for the flood related index insurance contracts for the irrigated Niger rice crop. The region is shown below. This box is shown in Figure 6.2.

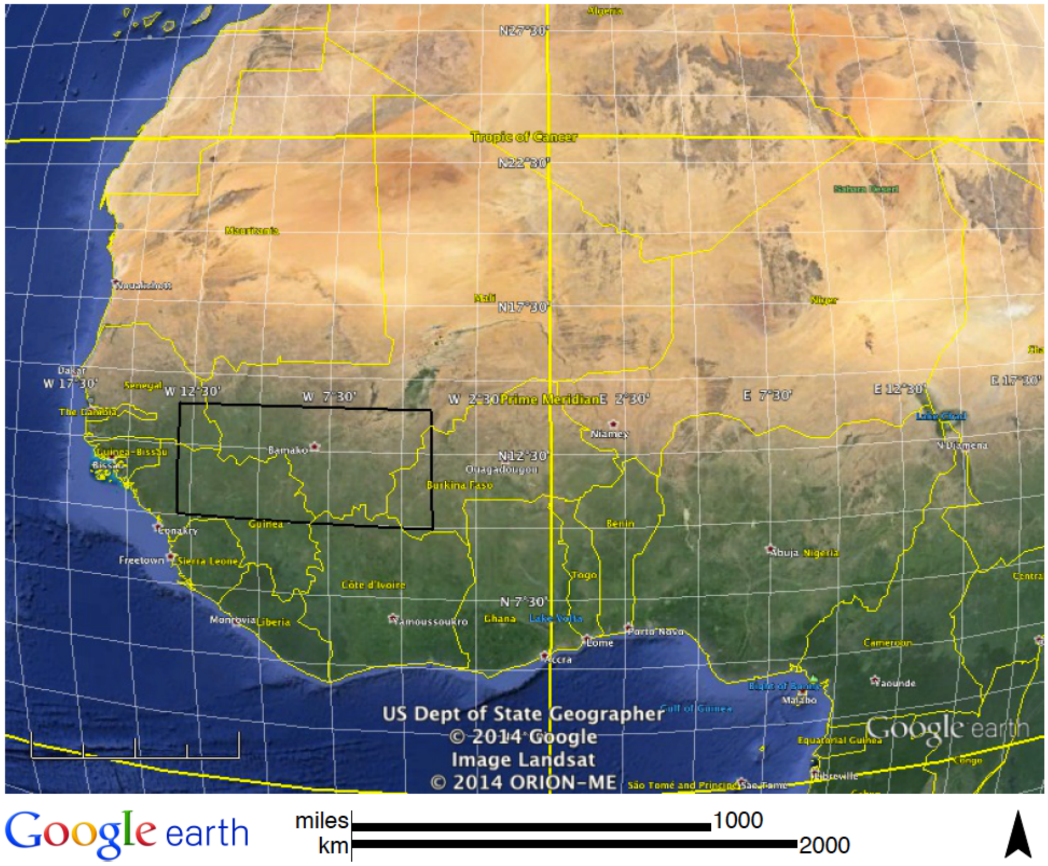


Figure 6.2: Upper Niger Basin Domain; made in Google Earth.

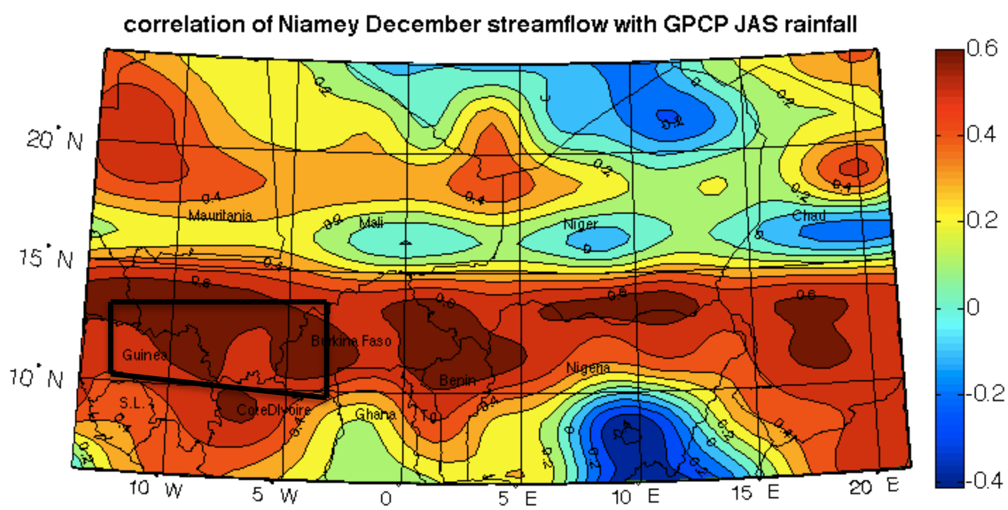


Figure 6.3: Upper Niger Basin domain superposed on correlation map (Figure 4.10c).

6.3. Trends in the Mean and Variability: While the abovementioned five model runs by no means constitute an exhaustive analysis of the latest round of global climate model analysis in concert with CMIP5, they do represent a range of outcomes and have each been cited in other recent literature regarding climate model analysis of Sahelian rainfall (Biasutti, 2013). In the (following) analysis shown here and in other literature (Biasutti, 2013), the GFDL CM3, NCAR CCSM4 and CNRM CM5 models produce a trend towards heavier precipitation in the 21st century (as compared to the late 20th century). Conversely, the GISS E2H and CSIRO MK 3.6 models show a drying trend in the 21st century (as compared to the late 20st century).

Furthermore, the GFDL, NCAR and CNRM models all project a trend towards increasing evaporation in the 21st century, while the GISS and CSIRO models produce a trend towards reduced evaporation in the 21st century. While a modeled result of a reduction in absolute evapotranspiration may seem inconsistent with the narrative of global and regional warming, prolonged desiccation/reduced rainfall in a region can compromise plant growth and biophysical feedbacks. While higher temperatures imply a greater potential evaporation, amount of water that is actually evaporated depends in part on the water available in surface water and plant resources. Consequently, it is not physically inconsistent for a model to produce warming and a decrease in absolute evapotranspiration if the water available for evaporation is reduced more dramatically.

Another parameter of interest is the Precipitation – Evaporation (P-E). Arguably, this kind of more refined index is a closer approximation to the "real" water stress experienced. At the all Sahel scale, for both RCPs of the GFDL and NCAR models, the increase in precipitation is enough larger than the increase in evaporation that the P-E trends positive in the 21st century. For the CSIRO model, where there is a trend of increasing evaporation and decreasing rainfall, there is a marked downward trend to the P-E. For the GISS model, the P-E trend is negative for RCP 8.5, but positive for RCP 4.5, whereas for the CNRM model, the P-E trend is positive for the RCP 8.5 and negative for the RCP 4.5.

One of the other important components of climate change is the projected change in variability. There is a good deal of literature discussing how changes in the standard deviation of a precipitation or temperature time series can have an impact on the frequency of extreme events, even without much in the way of a change in the mean (Meehl et al. 2000, Tebaldi et al. 2006). But clearly, when both the average and the standard deviation are changing over time, this can have significant implications for the frequency of extreme events and their potential human repercussions. Trends in variability tend to be of the same sign as trends in the mean of each index (i.e. a tendency towards reduced precipitation or evaporation tends to produce a reduction in the variance of this parameter in the late 21st century as compared to the 1980-2020 period, and conversely, an increase in precipitation or evaporation tends to produce a larger variance in the late 21st century as compared to the 1980-2020 period). There are some exceptions to this concept, but most of the late 21st century/1980-2020 variance ratios are around 1. The one very notable outlier is the GISS RCP 8.5 P-E index, which produces about two and a half times the standard deviation in the late 21st century as in the 1980-2020 period, but as this is only one of the 10 GCM/RCP combinations, it can be considered an outlier to the norm. With respect to extreme events, the decrease in variability in the GISS and CSIRO models at least partly compensates for the enhanced likelihood of drought conditions due to the drying trend.

As mentioned previously, the GFDL, NCAR and CNRM models had a wetting trend, whereas the GISS and CSIRO had a drying trend across the All Sahel domain. In a similar vein, there is a modeled increase in average variability for the CNRM and NCAR models and a decrease in average variability for the GISS and CSIRO models. For the All Sahel index of the GFDL model, the standard deviation increases for the RCP 8.5 scenario and decreases for the RCP 4.5 scenario.

The results of these ratios of the mean and variability are shown in Figures 6.4.

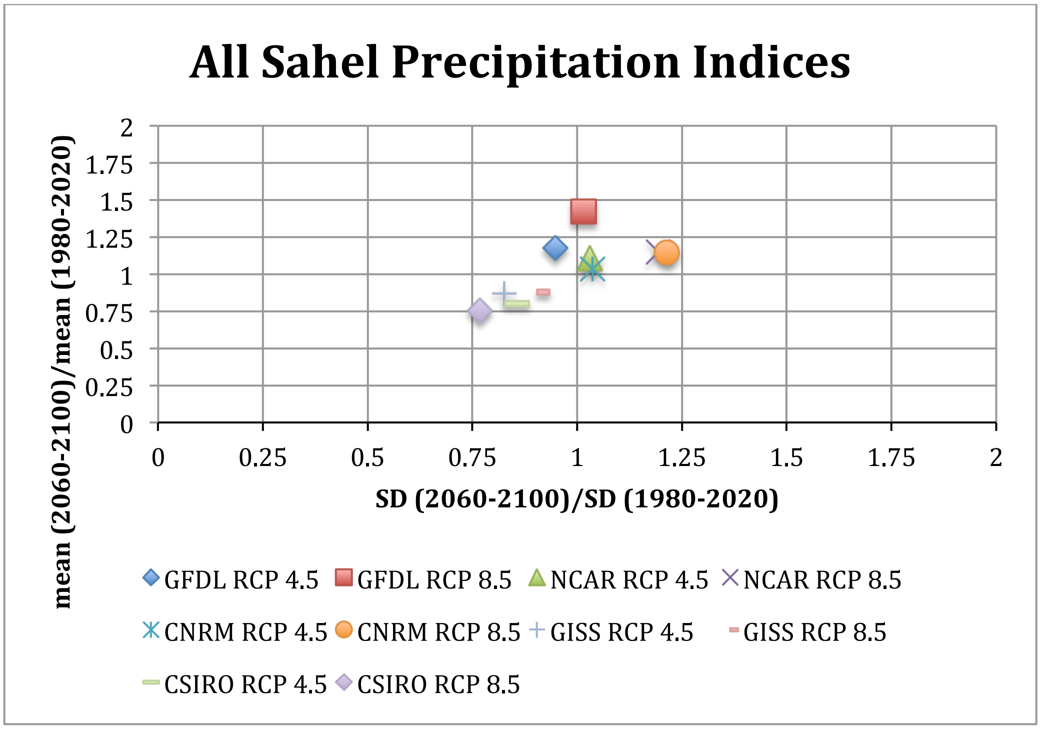


Figure 6.4a: Trends in All Sahel GCM precipitation mean and variability.

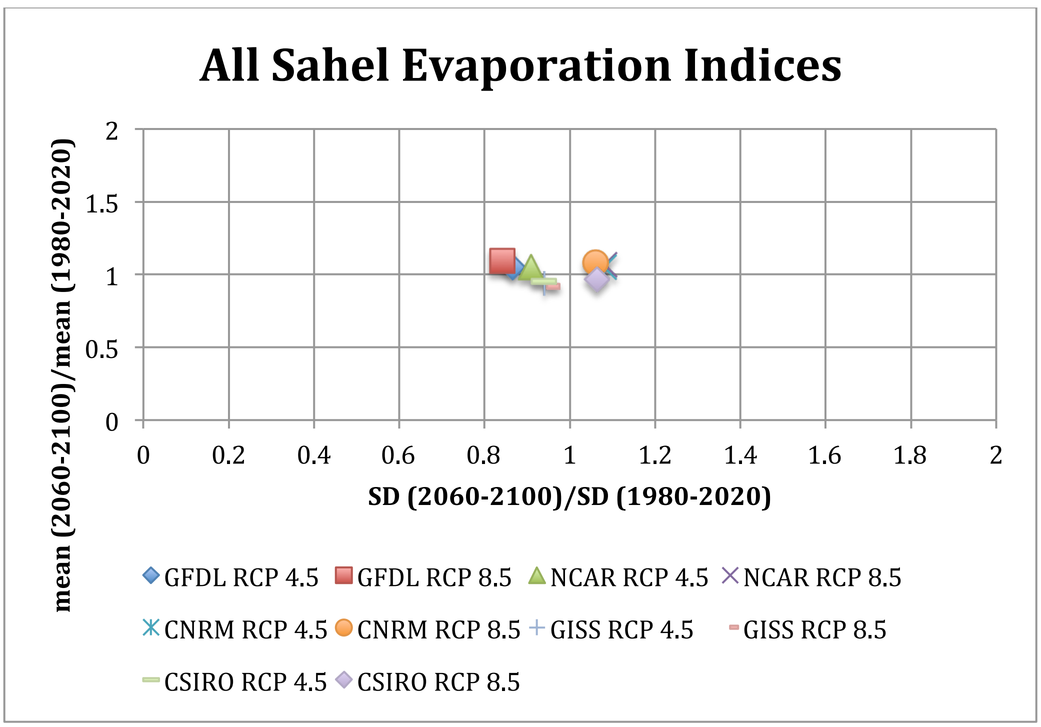
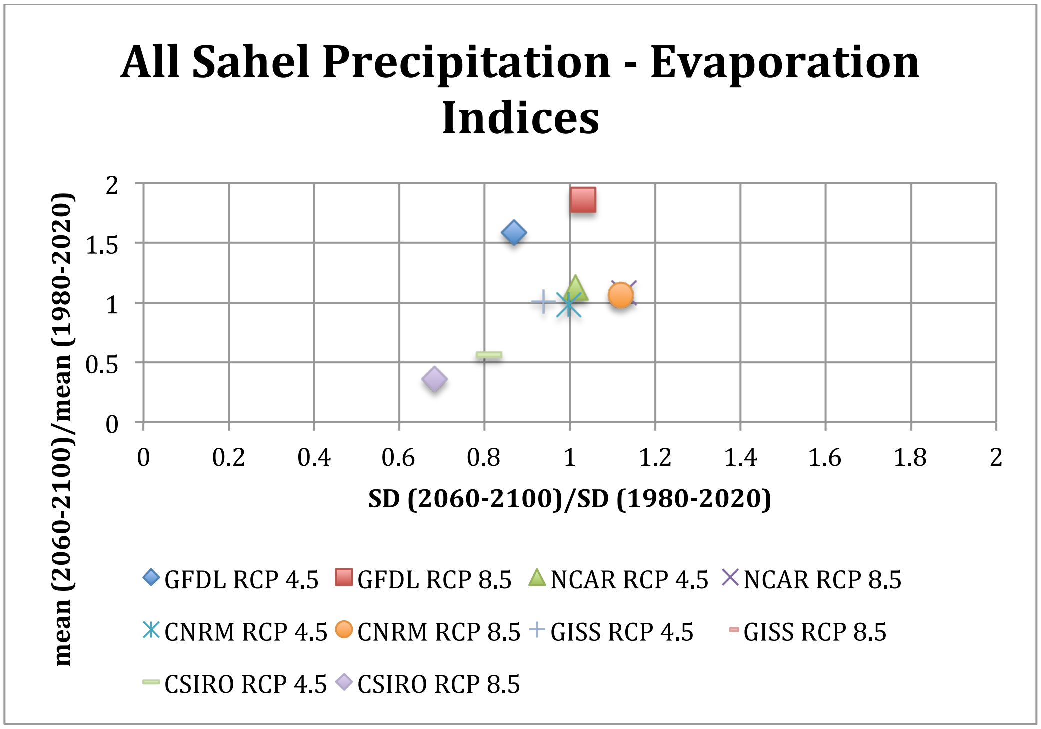


Figure 6.4b: Trends in All Sahel GCM evapotranspiration mean and variability.



Figures 6.4c: Trends in GCM precipitation-evapotranspiration mean and variability.

The values of the mean ratios in Figures 6.4 are shown Table 6-1, along with the +/- 1 standard deviation interval as calculated from the empirical data from all the Sahel gridboxes.

	Precipitation	Evaporation	Precipitation-Evaporation
GFDL 4.5	1.175 +/- 0.214	1.048 +/- 0.234	1.588 +/- 6.417
GFDL 8.5	1.423 +/- 0.572	1.095 +/- 0.696	1.86 +/- 9.6
NCAR 4.5	1.105 +/- 0.131	1.049 +/- 0.121	1.127 +/- 0.446
NCAR 8.5	1.149 +/- 0.319	1.069 +/- 0.264	1.084 +/- 1.329
CNRM 4.5	1.035 +/- 0.135	1.05 +/- 0.044	0.983 +/- 0.55
CNRM 8.5	1.146 +/- 0.165	1.082 +/- 0.08	1.061 +/- 0.994
GISS 4.5	0.868 +/- 0.251	0.941 +/- 0.093	1.011 +/- 0.865
GISS 8.5	0.879 +/- 0.139	0.917 +/- 0.124	0.82 +/- 7.845
CSIRO 4.5	0.8 +/- 0.109	0.952 +/- 0.141	0.565 +/- 1.644
CSIRO 8.5	0.754 +/- 0.192	0.967 +/- 0.201	0.361 +/- 12.427

Table 6-1: Average ratios of 2060-2100 mean/1980-2020 mean for All Sahel P, E and P-E indices for the various GCM/RCP combinations. Error values are for the +/- 1 standard deviation as sampled from the range of ratio values in the gridboxes within the Sahel.

While the spatial variability of the mean ratios of precipitation and evaporation are relatively small, there is significant spatial variability to the precipitation-evaporation index, indicating a possibility of a high level of spatial heterogeneity in the late 21st century water stress (with respect to the 1980-2020 period) across the Sahel. In almost every GCM/RCP combination, the +/- 1 standard deviation envelope includes a mean ratio of 1, indicating that even in many modeling scenarios where there is a pronounced regional trend in one direction or another, there is still enough spatial heterogeneity that a significant proportion of the Sahel grid-boxes respond in the opposite manner.

The same type of analysis as in Figures 6.4 is shown again for the country/region specific indices. Results are shown in Figures 6.5 and 6.6.

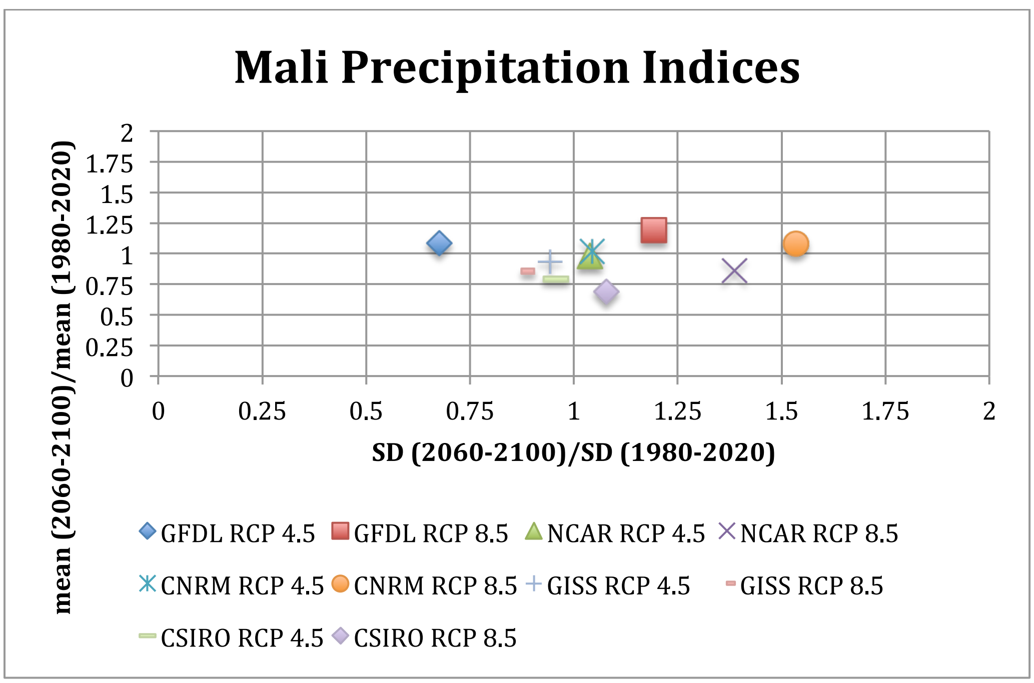


Figure 6.5a: Trends in GCM precipitation mean and variability for the Mali specific indices.

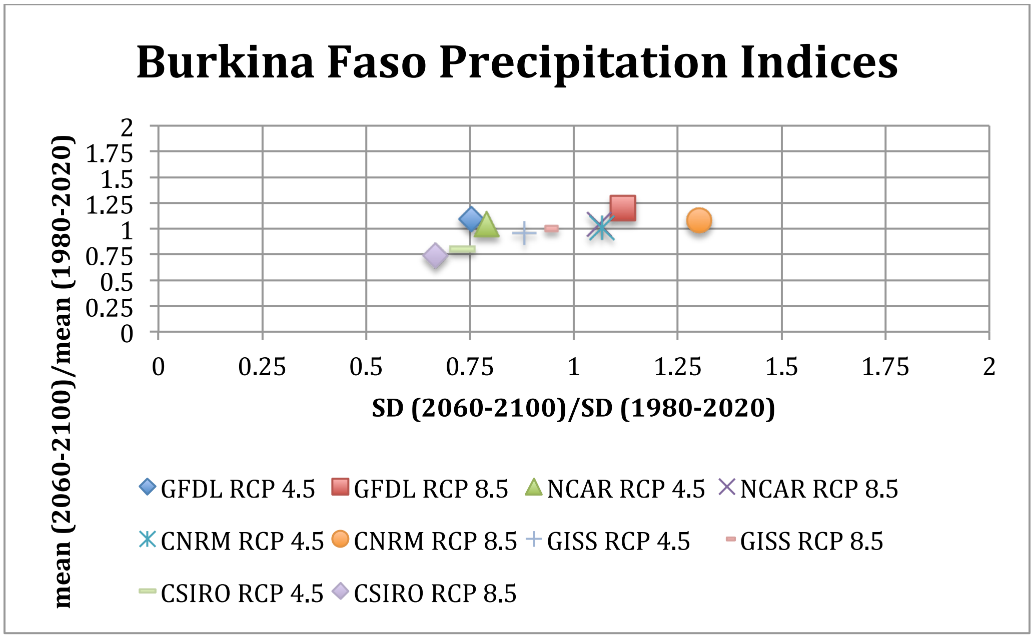


Figure 6.5b: Trends in GCM precipitation mean and variability for the Burkina Faso specific indices.

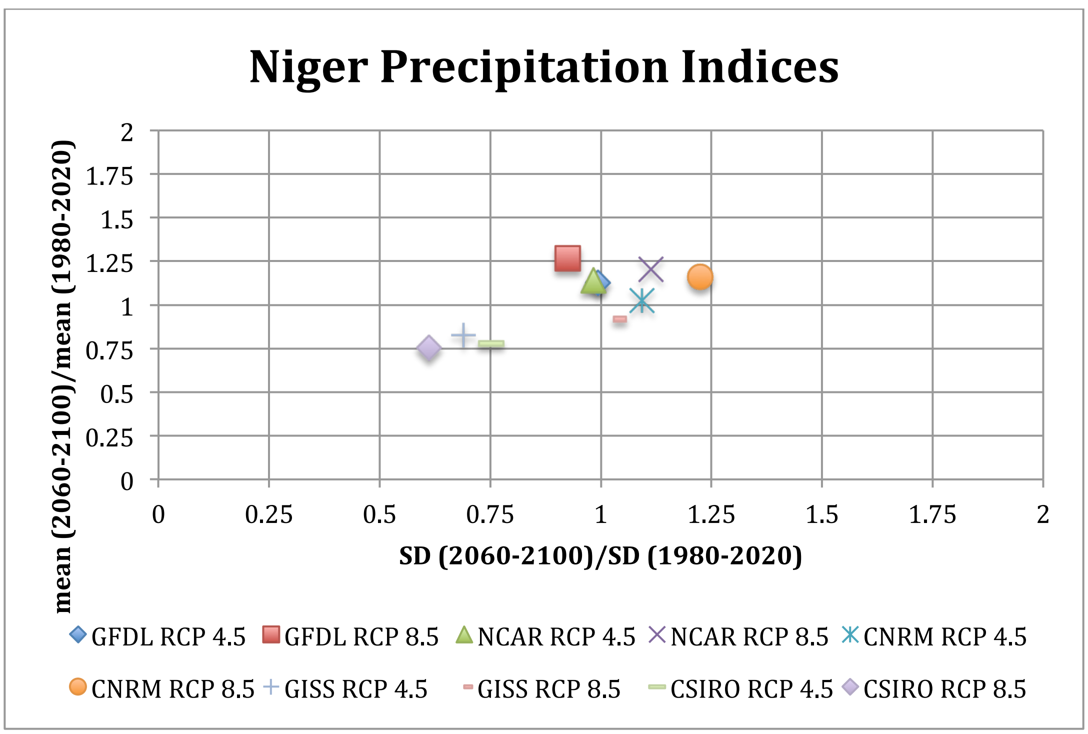


Figure 6.5c: Trends in GCM precipitation mean and variability for the Niger specific indices.

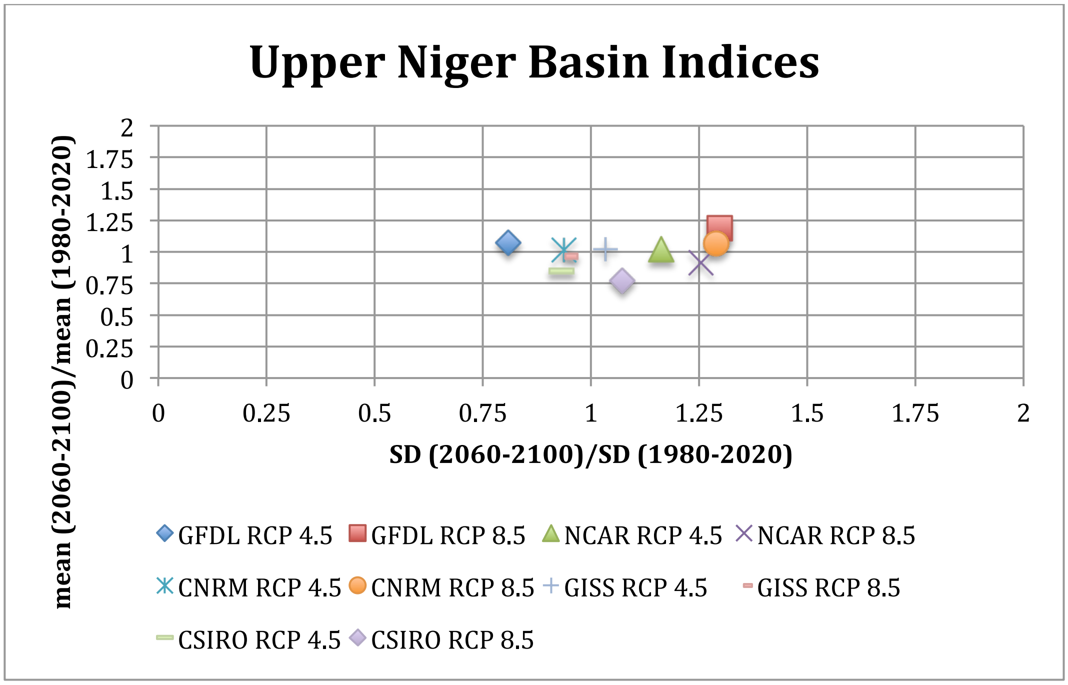


Figure 6.6: Trends in GCM precipitation mean and variability for the Upper Niger Basin specific indices.

6.4 Monte Carlo Simulation: Monte Carlo simulation methods used in this study borrow significantly from prior publications (Siebert and Ward 2011, Siebert and Ward 2013). Three different simulation experiments were run on the abovementioned country/region specific and All Sahel indices;

Experiment 1: a changing standard deviation (variability) only experiment

Experiment 2: a changing mean change only experiment and

Experiment 3: a combined experiment that has temporally evolving trend and standard deviation.

Trends in the mean and standard deviation were based on the mean and standard deviation ratios shown in Figures 6.4 through 6.6. Throughout this Monte Carlo simulation section, 1000 realizations were run for the period 2006-2100 for each experiment and inter-annual variability is sampled from the normal distribution. In addition to the three foundational experimental frameworks, each of these experiments, in turn was run using a range of temporal lag-1 autocorrelation values (0, 0.2, 0.4, 0.6 and 0.8) to simulate different scales of multi-decadal variability.

In addition to exploring the frequency of threshold crossing extreme events (TCEs) for the range of experiments discussed above, there will also be an exploration of the TCE frequency for two different potential threshold levels for the All Sahel indices.

Some literature from pilot projects in Africa suggests that in some field contexts, there may be a conceptual (and demonstrated) preference for higher payout frequency, higher premium contracts (Norton et al. 2014, Chantarat et al., 2013). Below, different possible thresholds are referred to by their frequency of payout during the base period (1980-2005). A contract with a "0.2" threshold pays out 20% of the time during the base period; a contract with a "0.1" threshold pays out 10% of the time.

6.5 Index Insurance Pricing in a non-Stationary Climate: If one were to assume that the climate system is statistically stationary (that the risk of extreme events is temporally invariant), and one were to design an index insurance contract as a simple step function with either zero payout or a full payout of 100% of insured liability for all events where the triggering threshold is crossed, then the raw climate-based actuarial premium for such an index insurance contract would be equal to the product of the payout frequency and the total insured liability (equation 2.3). For example, if a particular farmer had \$500 of insured liability and the contract was a simple step function based on a "0.2" threshold, the annual climate-risk component of the premium would be \$100.

The actual premium for such a contract would have to be higher for several reasons discussed in chapter 2. Clearly, there would also be a need from the client's perspective to keep these additional costs under control to ensure that the total premium was not usuriously expensive. This concern would be especially crucial in light of the poverty of much of the West African populace.

While the likelihood of a large number of payouts in a particular period also lends itself to statistical climate-related analysis, the regulation of salaries and profit margin is more of a legal matter and is somewhat beyond the scope of this study.

Expected Climate Risk: Clearly, however, the expected climate risk component of the premium price would not be constant in light of climate change and the experiments described above will help to quantify how the expected risk and "uncertainty risk" components of the premium may change over time.

Conceptually, in light of climate change, as the expected risk for a particular extreme event changes, there are three ways in which this changing expected risk can be expressed to the insured client. One way is through "price evolution" – where the threshold index value at which the insurance contract is triggered remains constant, but the index insurance price (premium) evolves as the climate system evolves to express the underlying changes to the TCE frequency. Another conceptual approach is through "threshold evolution", where the terms of the contract and the strike threshold level vary over time, but the actuarially fair price remains relatively constant. A third approach would be some sort of hybrid of the first two. Figures 6.7 illustrate these concepts with reference to a hypothetical drought index insurance contract that starts with a strike level of 70cm of rainfall and a $100 premium in the context of a drying trend.

In the context of the very limited economic means of many West African Sahelian farmers, there may be real income limitations to enabling the price to evolve (if the price is likely to rise significantly). At the same time, if there is really a need for protection against a certain measure of drought and a "threshold evolution" framework creates a situation where there is no payout during future crisis years because the threshold has changed, this scenario could potentially be quite ineffective.

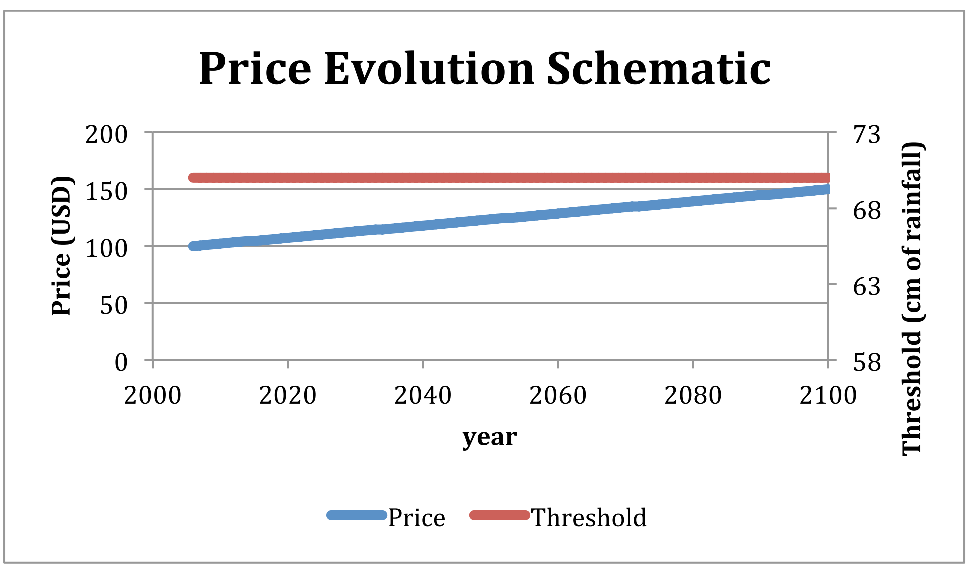


Figure 6.7a: Price Evolution Schematic – the threshold stays constant, but the price increases to express the trend towards increased drought risk.

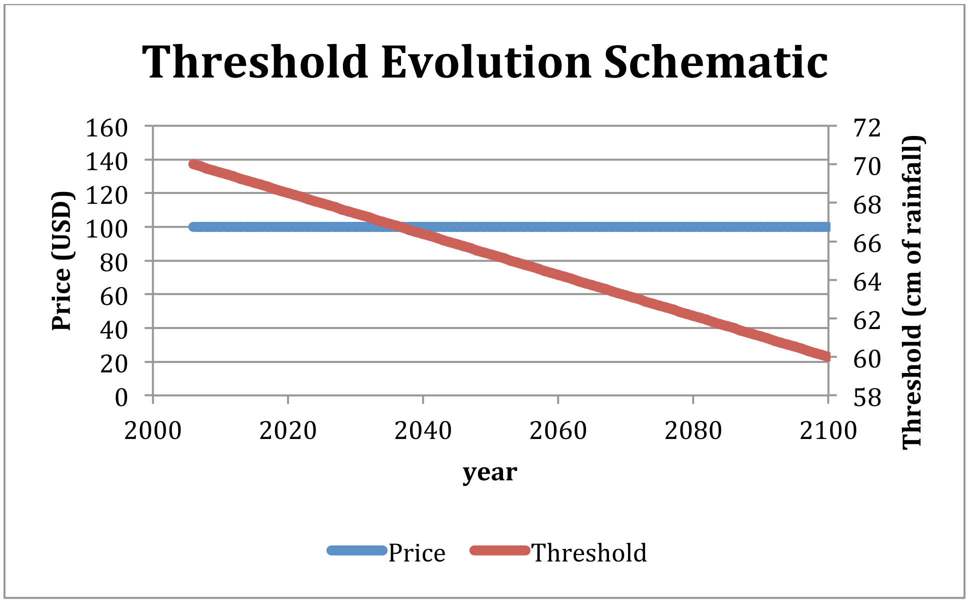


Figure 6.7b: Threshold Evolution Schematic – the price stays constant, but the threshold level of rainfall that triggers payout decreases to express the trend towards increased drought risk.

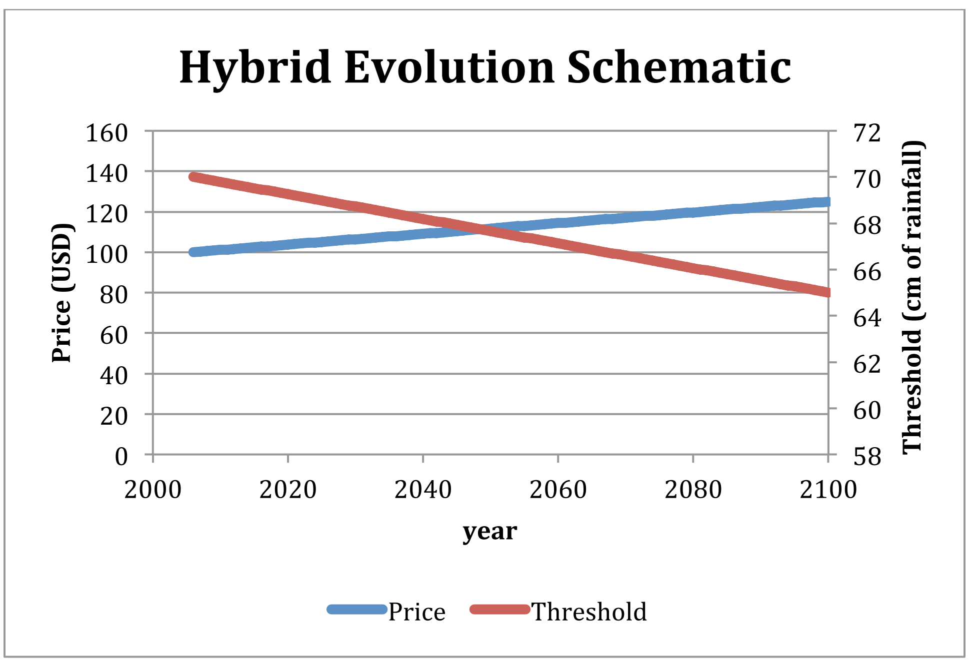


Figure 6.7c: Hybrid Evolution Schematic – the price rises to some degree and the threshold level of rainfall that triggers payout falls to some degree; both contributing to the expression of the drying trend in the region.

In terms of practical implementation, these details would have to be worked out on a continuous basis between the insurer and the client population and would have to take into account the changes to the climate risk and the needs and limitations of the agricultural community.

For the purpose of this theoretical study, there will be a focus on the “price evolution” scenario, where all of the change to TCE frequency is expressed in terms of an evolution of price. This is an acknowledged limitation/assumption to this study. Prior work (Siebert and Ward, 2011) has shown that by using temporally evolving threshold definitions, the actual premium/TCE probability can be held relatively constant, even in light of a significant trend in regional climate. Presumably, if the price of index insurance for a particular crop (millet) reaches too high a level, the client population may try to plant a different variety of the crop (if available), a different crop altogether, or buy an index insurance contract that is more limited in its coverage (and lower premium). Severe changes to regional climate may also lead to more dramatic adaptations, such as migration (Adger et al., 2003).

An additional subtlety of a changing climate is that the perception of the expected climate risk would not necessarily keep pace with the actual evolution of the climate risk. If there is a steady trend towards drier conditions, that would not be immediately apparent until the trend was somewhat developed. A similar concept to the one presented in (Siebert and Ward, 2011) could be explored – the premium itself could be based on the prior 20-30 years rather than the entire length of historical record. This way, if there is a persistent trend, the premium could respond in a relatively agile way to the evolving climate system. If the trend were truly linear, there would still be limitations even with this framework, and the temporal evolution of the premium (for drought insurance) would be too expensive in the case of a wetting trend and too inexpensive in the case of a drying trend. The degree of this underestimation or overestimation would be model and scenario specific, but could be interpolated by values between designated time horizons. For example, in the case of a constant linear drying trend, a premium based on the 2011-2040 period would most accurately represent the expected risks for 2026, rather than 2041. The true TCE frequency for 2041 would be more accurately represented by the 2026-2055 period, which in a case of linear trend would be the average of the 2011-2040 and 2041-2070 periods. Consequently, this underestimation/overestimation of premium could be calculated; by taking the difference of the 2026-2055 and the 2011-2040 periods. Practically, however, there would be no way to know in advance if a given trend would continue in a linear fashion, so over-reliance on this computation would be speculative.

But even with this limitation acknowledged, there is some value to using a “sliding window” approach to calculating the index insurance price. If the window is too short, the price will be too variable and will come closer to representing inter-annual variability. If the window is too long, the price will be too sluggish in response to significant decadal or centennial scale trends.

In the present study, the TCE frequency was computed for the 2011-2040, 2041-2070 and 2071-2100 time frames. If one were to use a 30 year sliding window (without explicitly accounting for the abovementioned subtleties), the price of the contract in 2041 would be based on the risk in 2011-2040, the price of the contract in 2071 would be based on the risk in 2041-2070 and the price of the contract is 2101 would be based on the risk in 2071-2100. In the formulation presented here, all changes to the mean and standard deviation are linear, so the three values calculated for the 2011-2040, 2041-2070 and 2071-2100 time horizons could be linearly interpolated to create a profile of the climate "expected risk" price evolution from 2006-2100.

Results of Experiments 1 and 2: Other literature (including Siebert and Ward, 2013) suggests that in the Sahel, a lag one-year autocorrelation in seasonal rainfall of approximately 0.6 is not an unreasonable assumption with respect to regional multi-decadal variability. Results from Experiments 1 (variability change only), based on a lag-1 autocorrelation of 0.6 are shown below in figures 6.8 below.

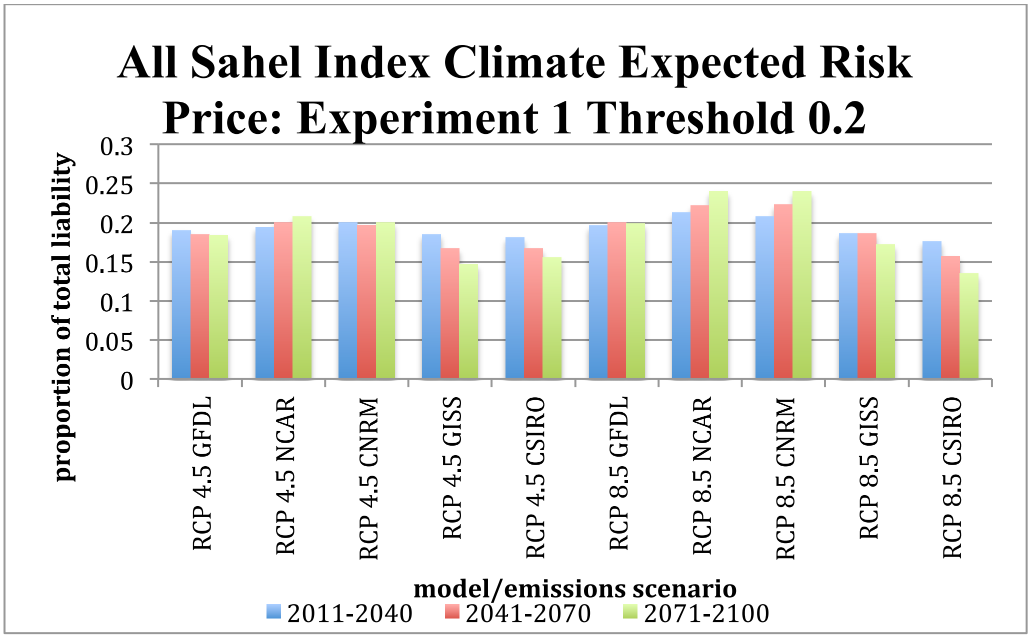


Figure 6.8 a: Modeled evolution of actuarial price (as a proportion of total insured liability) for All Sahel index drought risk, threshold 0.2, under Experiment 1 (variability change only).

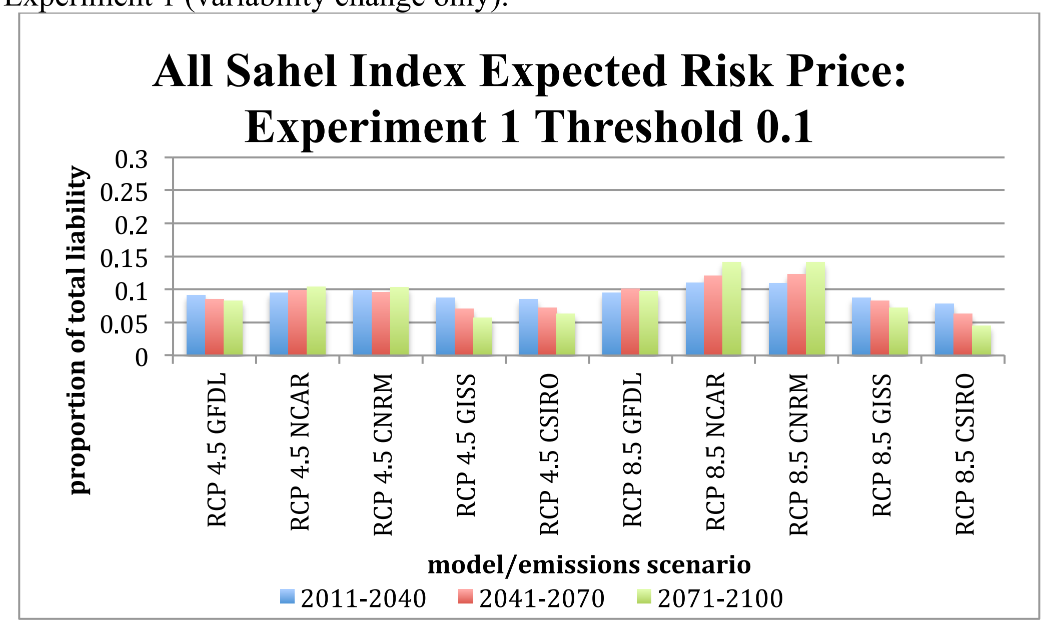


Figure 6.8b: Modeled evolution of actuarial price (as a proportion of total insured liability) for All Sahel index drought risk, threshold 0.1, under Experiment 1 (variability change only).

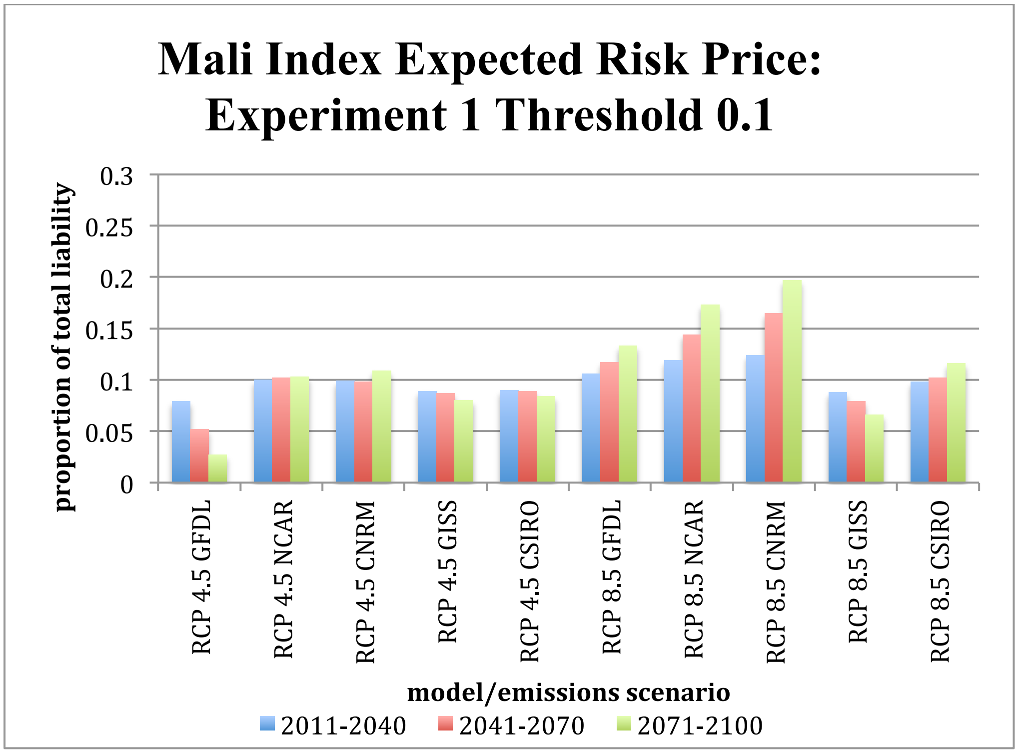


Figure 6.8c: Modeled evolution of actuarial price (as a proportion of total insured liability) for Mali index drought risk, threshold 0.1, under Experiment 1 (variability change only).

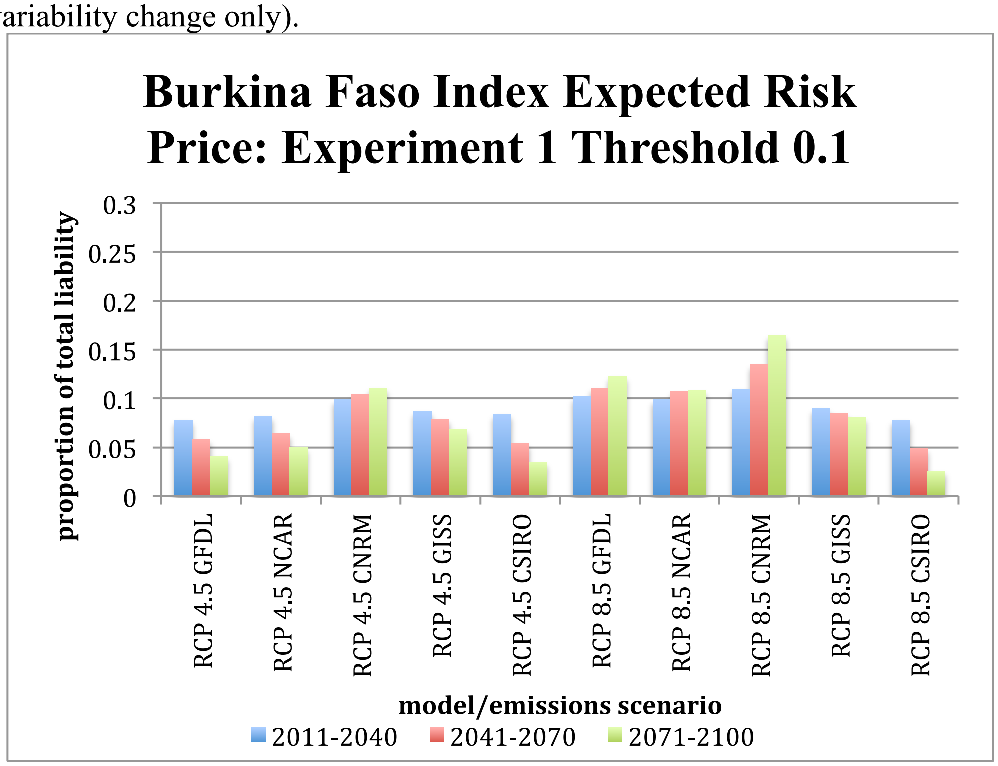


Figure 6.8d: Modeled evolution of actuarial price (as a proportion of total insured liability) for Burkina Faso index drought risk, threshold 0.1, under Experiment 1 (variability change only).

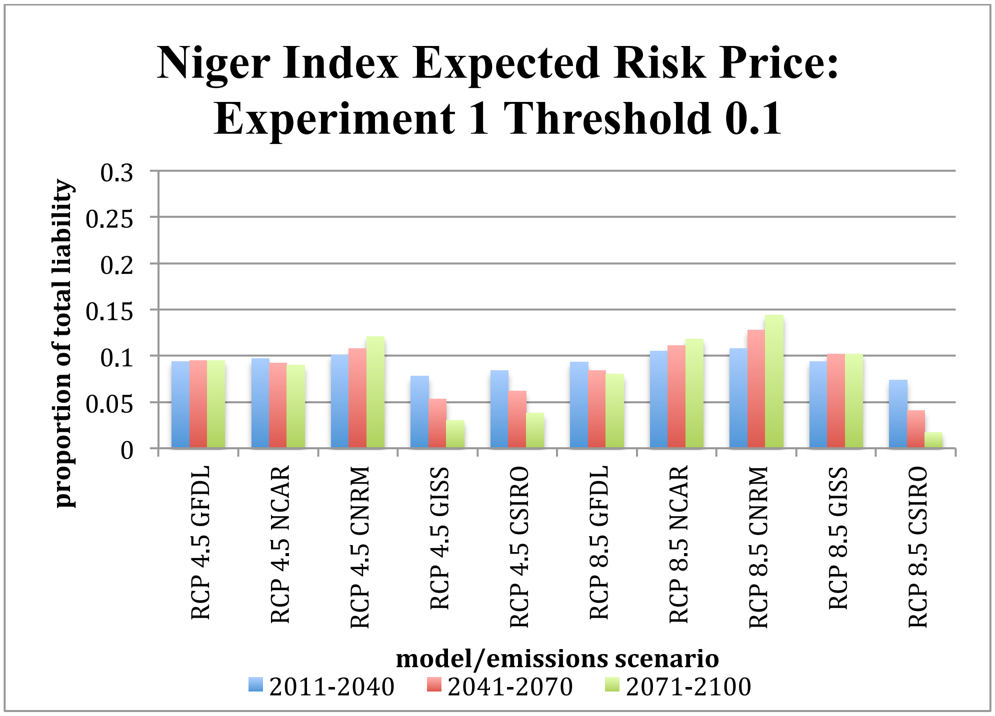


Figure 6.8e: Modeled evolution of actuarial price (as a proportion of total insured liability) for Niger index drought risk, threshold 0.1, under Experiment 1 (variability change only).

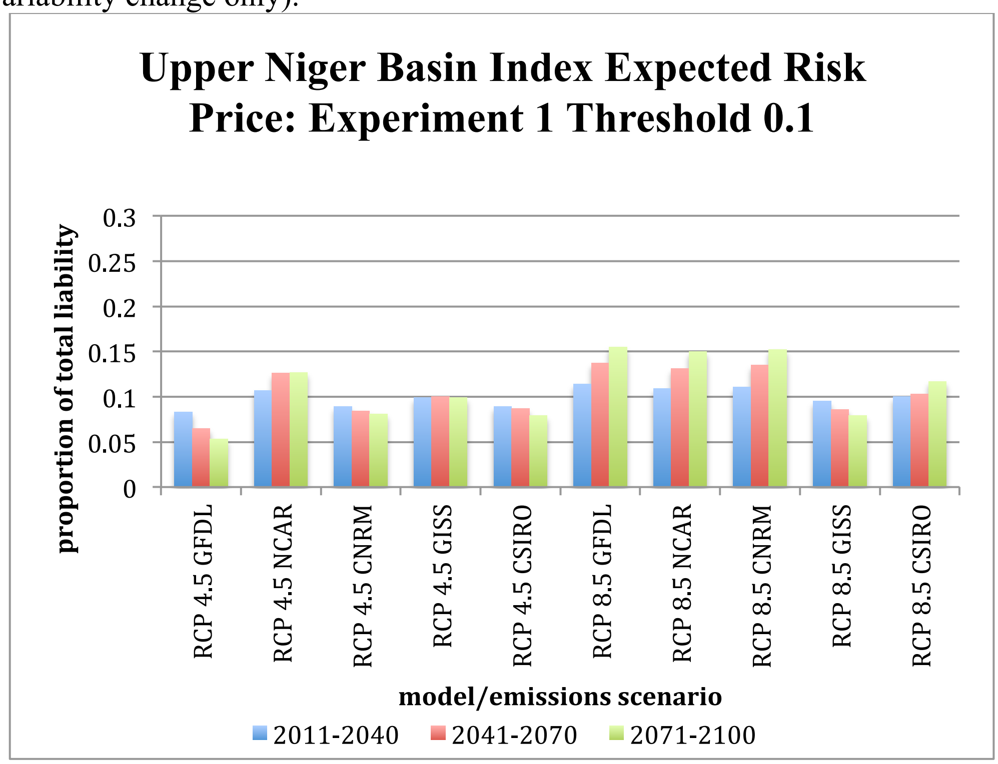


Figure 6.8f: Modeled evolution of actuarial price (as a proportion of total insured liability) for Upper Niger Basin index flood risk, threshold 0.1, under Experiment 1 (variability change only).

On balance, Figures 6.8 show that the changes to the expected risk price over time as a result of changes in the variance only are relatively modest. While there are individual model/RCP combinations that show a somewhat substantial reduction in expected risk price, and some which show a modest increase in expected risk price, there are no examples of a doubling of expected risk and only a few examples of a reduction of expected risk by more than half.

Results from Experiments 2 (mean change only), based on a lag-1 autocorrelation of 0.6 are shown below in figures 6.9 below.

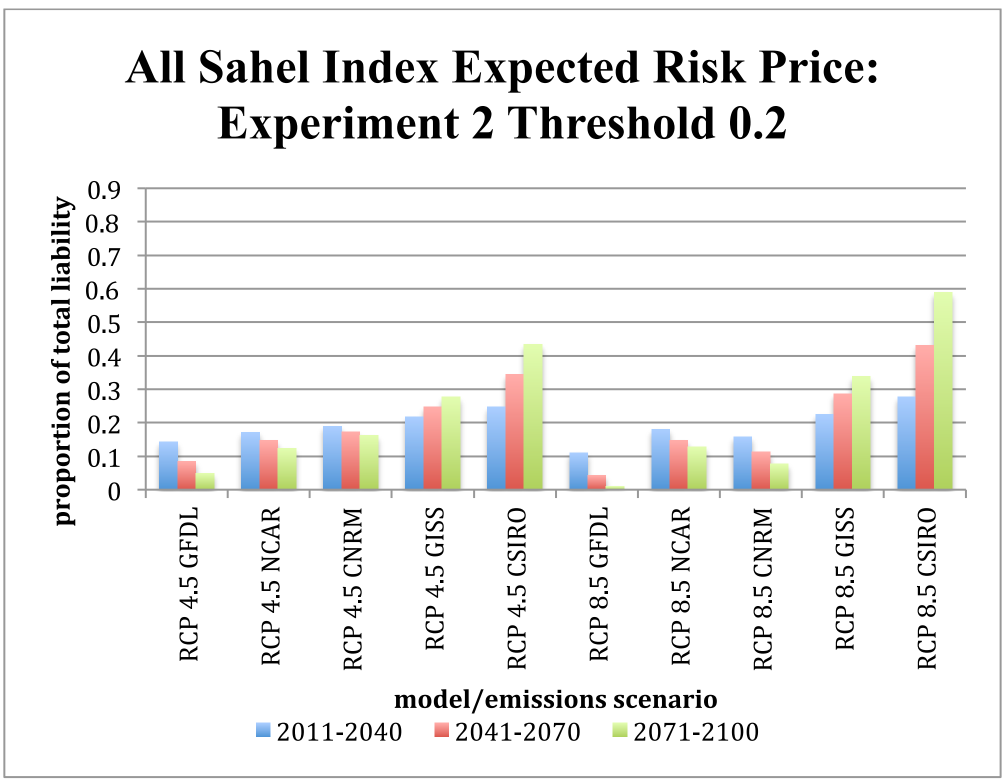


Figure 6.9a: Modeled evolution of actuarial price (as a proportion of total insured liability) for All Sahel index drought risk, threshold 0.2, under Experiment 2 (mean change only).

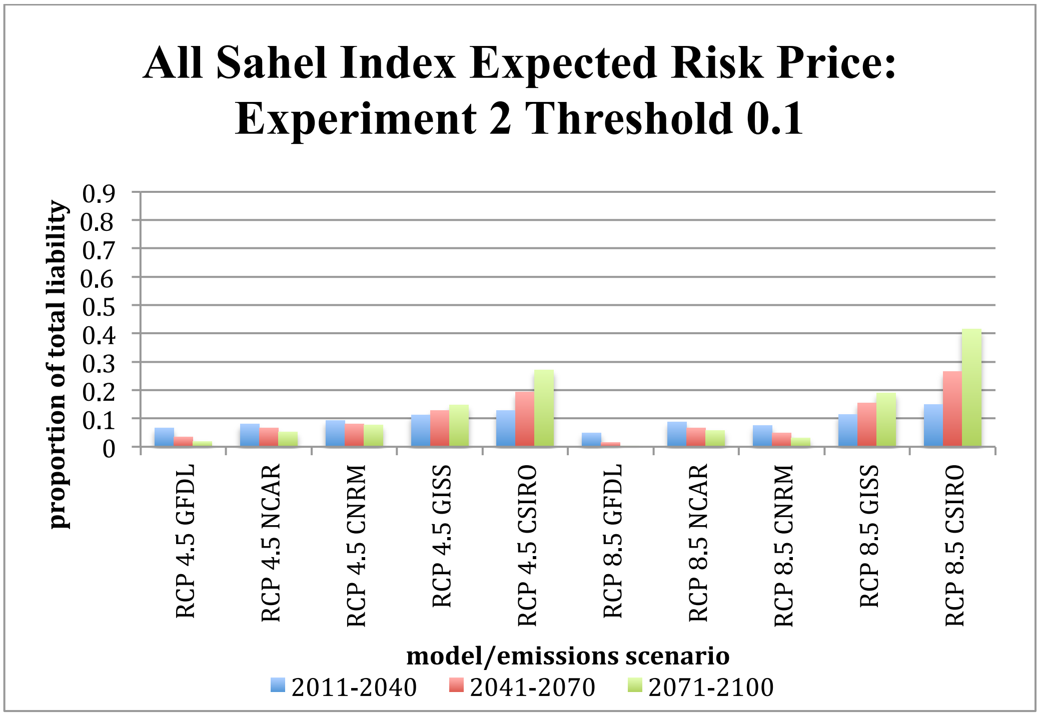


Figure 6.9b: Modeled evolution of actuarial price (as a proportion of total insured liability) for All Sahel index drought risk, threshold 0.1, under Experiment 2 (mean change only).

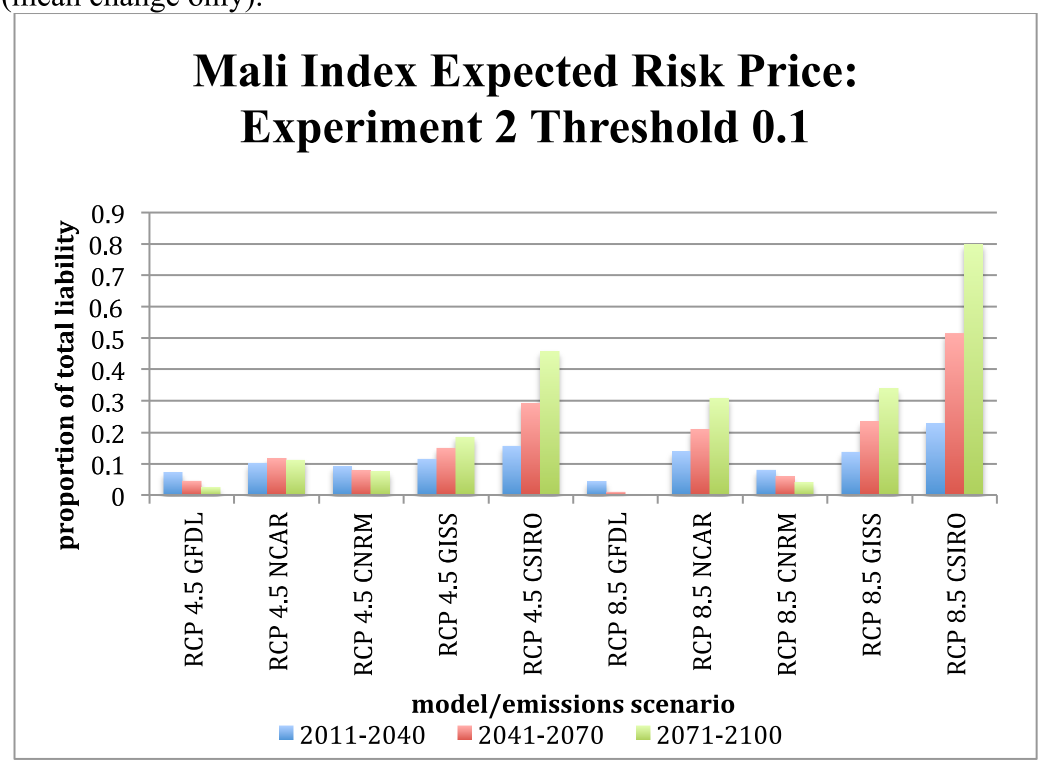


Figure 6.9c: Modeled evolution of actuarial price (as a proportion of total insured liability) for Mali index drought risk, threshold 0.1, under Experiment 2 (mean change only).

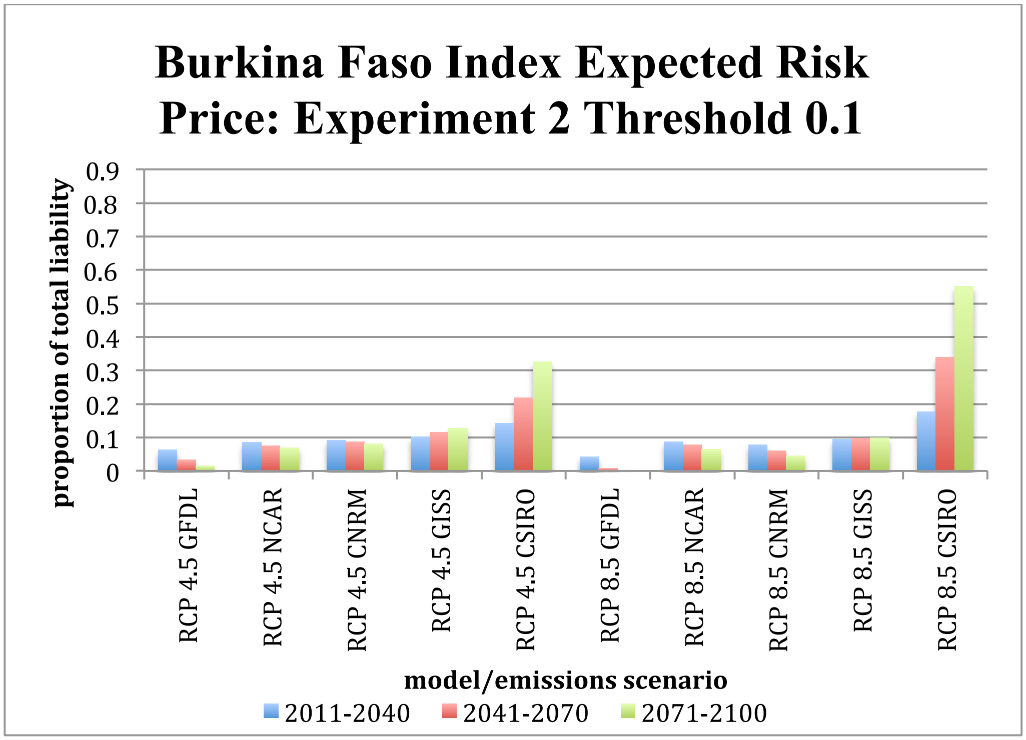


Figure 6.9d: Modeled evolution of actuarial price (as a proportion of total insured liability) for Burkina Faso index drought risk, threshold 0.1, under Experiment 2 (mean change only).

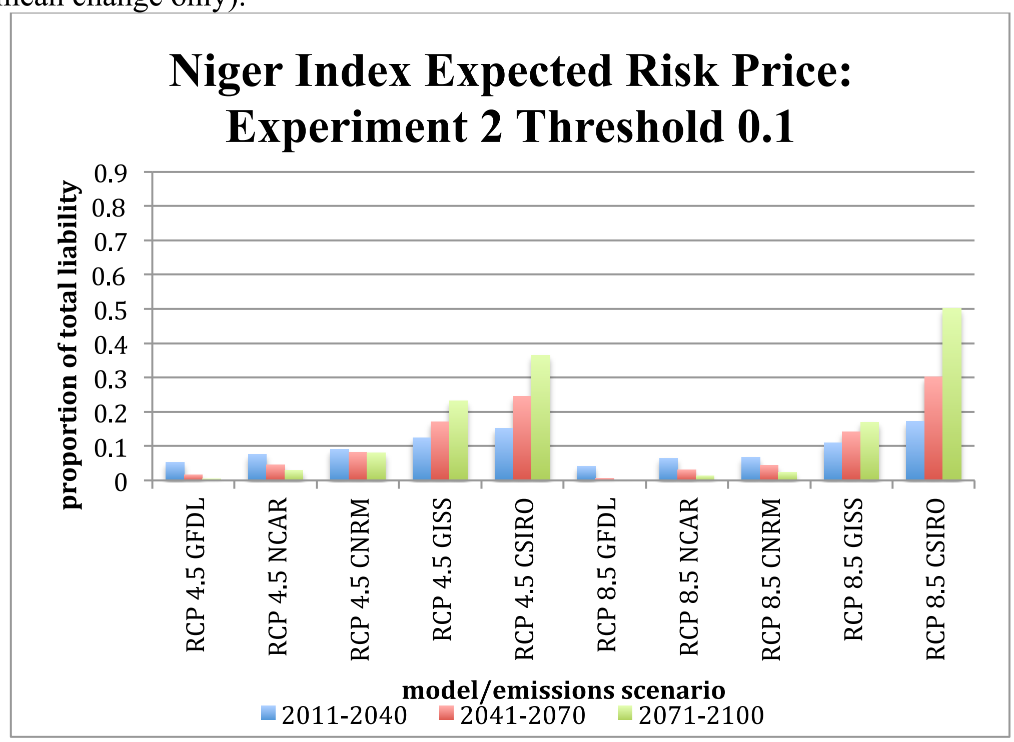


Figure 6.9e: Modeled evolution of actuarial price (as a proportion of total insured liability) for Niger index drought risk, threshold 0.1, under Experiment 2 (mean change only).

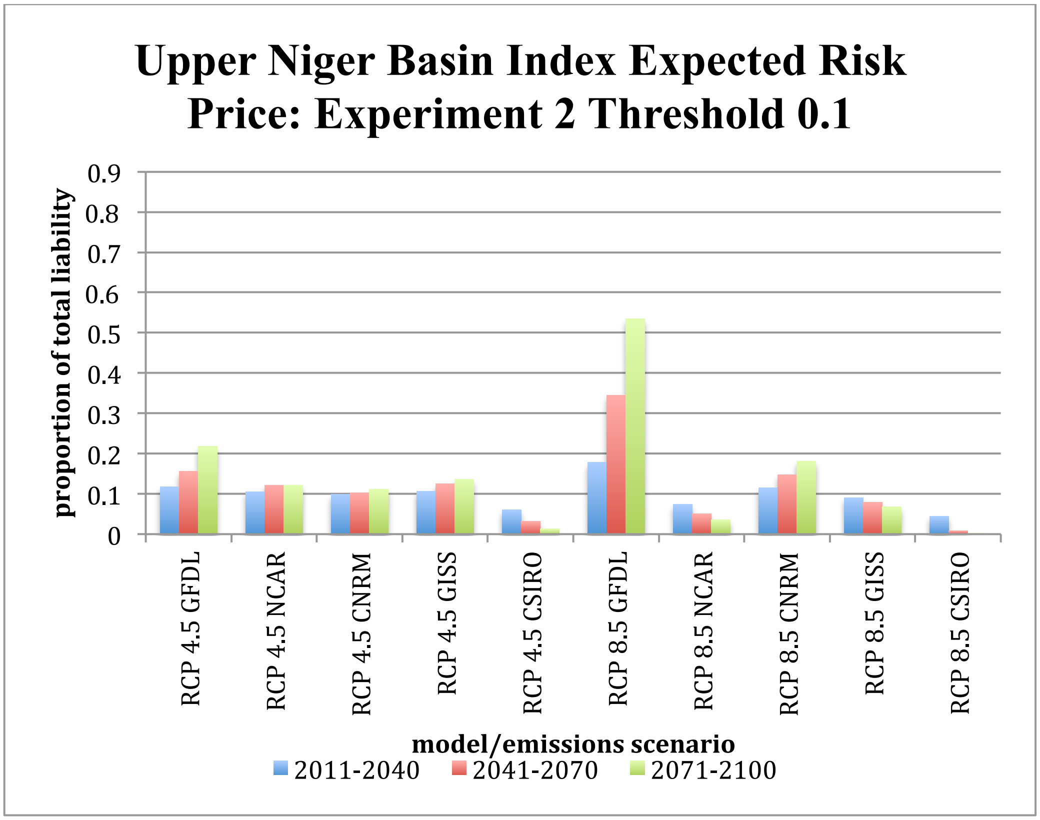


Figure 6.9f: Modeled evolution of actuarial price (as a proportion of total insured liability) for Upper Niger Basin index flood risk, threshold 0.1, under Experiment 2 (mean change only).

On balance, Figures 6.9 show that the changes to the expected risk price over time as a result of changes in the mean only are quite significant. The most extreme changes in expected risk price result from the model simulations with the strongest trends (CSIRO for drought and GFDL for flood risk). For these extreme cases, the frequency of threshold crossing increases dramatically to more than triple the baseline expected risk for the Sahel as a whole (in the RCP 8.5 scenario), and more than five times the baseline expected risk for the sub-regions. The GCMs that show the trend direction opposite the extreme (GFDL, NCAR and CNRM for drought, GISS and CSIRO for flood) tend to show substantial reductions in expected risk, making the late century expected risk price almost negligible in a number of cases.

Results of Experiment 3: Results from Experiment 3 (mean and variability change), based on a lag-1 autocorrelation of 0.6 are shown below in figures 6.10 below.

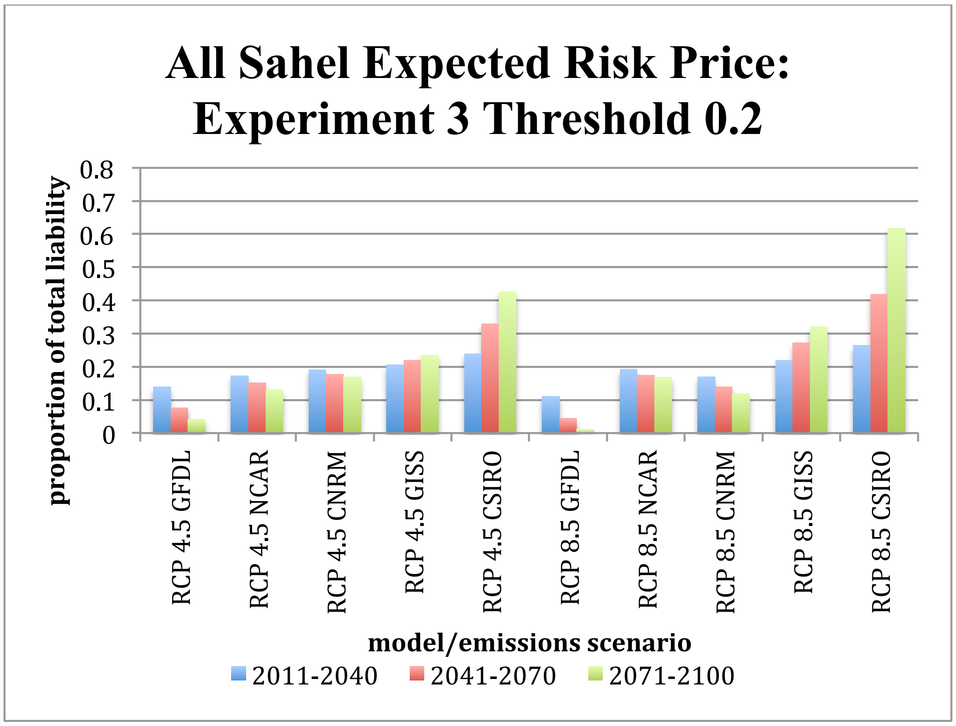


Figure 6.10a: Modeled evolution of actuarial price (as a proportion of total insured liability) for All Sahel index drought risk, threshold 0.2, under Experiment 3 (mean and variability change).

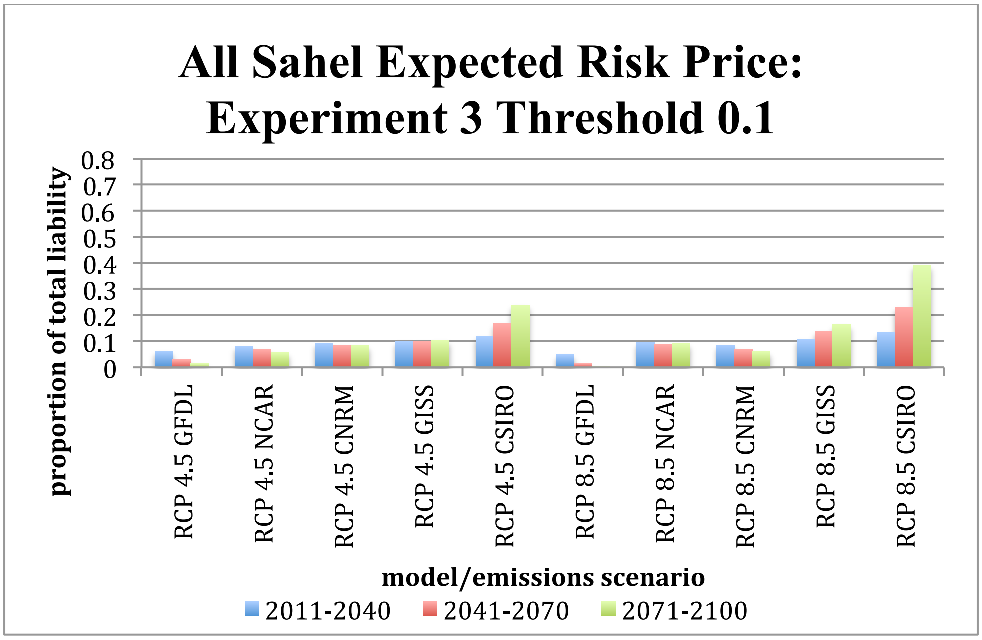


Figure 6.10b: Modeled evolution of actuarial price (as a proportion of total insured liability) for All Sahel index drought risk, threshold 0.1, under Experiment 3 (mean and variability change).

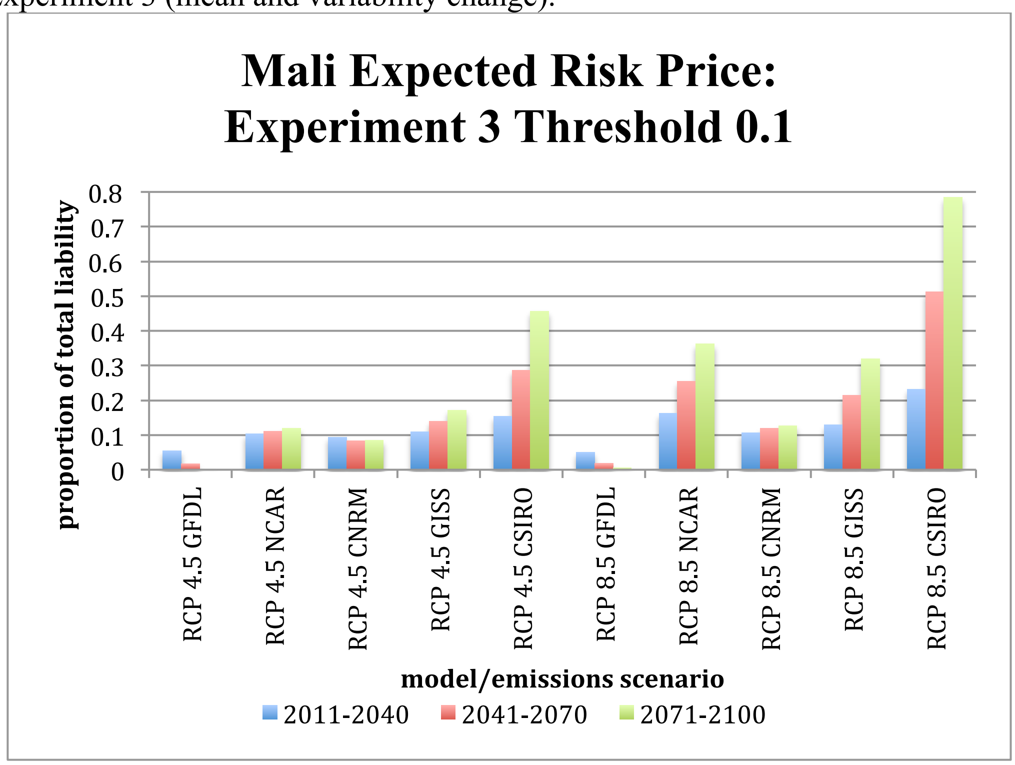


Figure 6.10c: Modeled evolution of actuarial price (as a proportion of total insured liability) for Mali index drought risk, threshold 0.1, under Experiment 3 (mean and variability change).

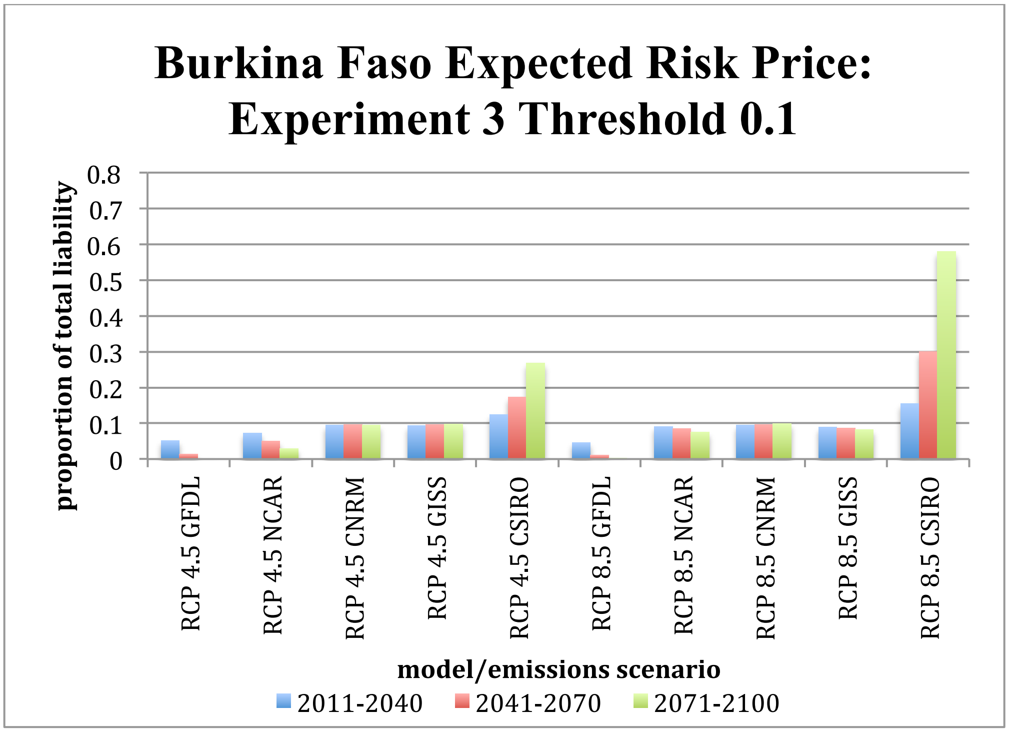


Figure 6.10d: Modeled evolution of actuarial price (as a proportion of total insured liability) for Burkina Faso index drought risk, threshold 0.1, under Experiment 3 (mean and variability change).

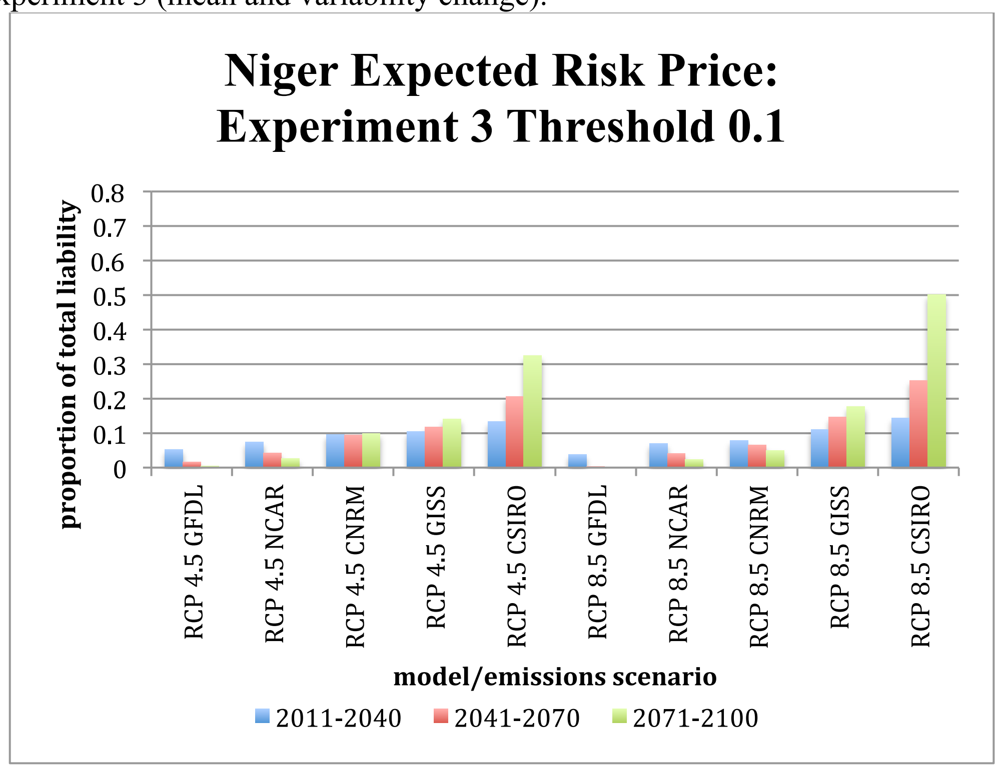
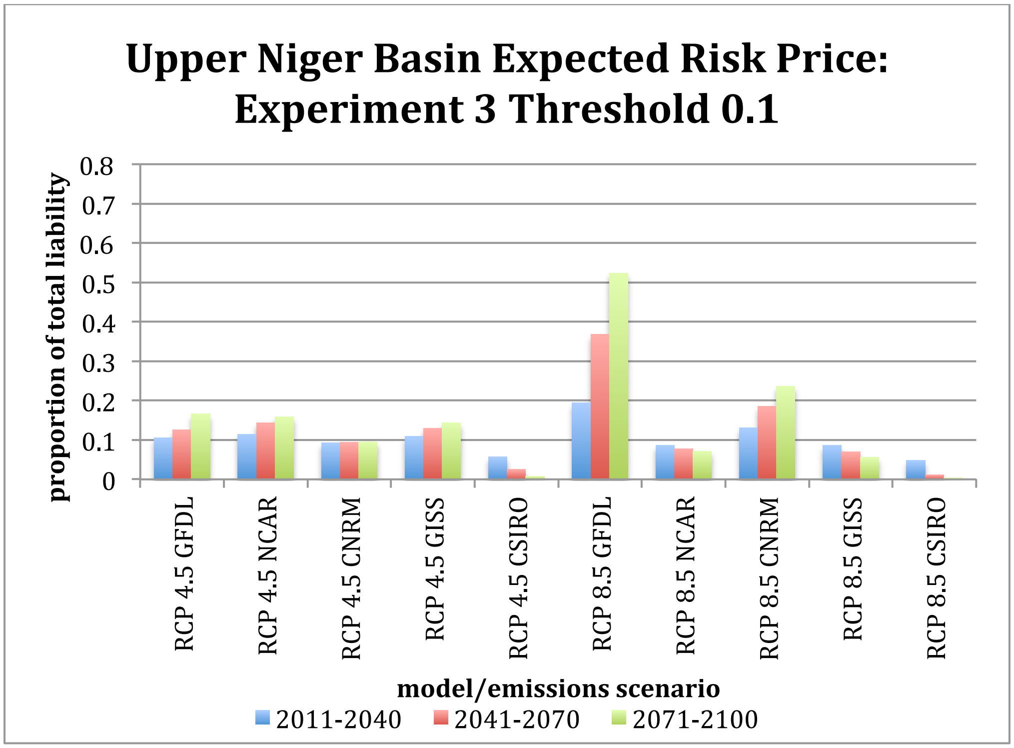


Figure 6.10e: Modeled evolution of actuarial price (as a proportion of total insured liability) for Niger index drought risk, threshold 0.1, under Experiment 3 (mean and variability change).



Figures 6.10f: Modeled evolution of actuarial price (as a proportion of total insured liability) for Upper Niger Basin index flood risk, threshold 0.1, under Experiment 3 (mean and variability change).

These results are largely in line with the results of Figures 6.9 from the mean change only experiment, indicating that when both mean and variance change are considered together, mean change is the dominant factor. This being said, when the trend in the variance is positive, the expected risk price change is even more dramatic than the mean change only scenario. Conversely, when the trend in the variance is negative, the expected risk price change is damped relative to the mean change only scenario.

Throughout this section, the change in the expected risk price tends to be greatest in the latest period (i.e. 2071-2100 represents the largest departure from the initial expected risk price). The three models that tend to show a wetting trend over the Sahel (GFDL, NCAR and CNRM), show a decline in expected risk price over time (for drought contracts). The two models that show a drying trend over the Sahel (GISS and CSIRO) show an increase in expected risk price over time (for drought contracts). The trends tend to be more pronounced for the RCP 8.5 scenario than the RCP 4.5 scenario.

For the Upper Niger Basin domain, flooding (high rainfall exceedance) risk was evaluated. Understandably, the models that simulated wetting tended to produce an increase in expected risk price over time, while the models that simulated a drying trend tended to produce a decline in expected risk price over time. The NCAR model in particular produced a wetting trend for the Sahel in general and for Burkina Faso and Niger in particular, but a drying trend for the Mali and the Upper Niger Basin domains. More generally, the models tend to produce more of a wetting trend in the eastern and central Sahel than the western Sahel. This is consistent with observational studies of recent trends in the Sahel and West Africa (Lebel and Ali, 2009) and some GCM related literature (Kamga et al., 2005). However, there is still uncertainty regarding the east/west distribution of precipitation changes in the near term to long-term future.

While the above discussion has focused on framing the GCM derived Monte Carlo simulations according to time horizon, subdomain, threshold, emissions scenario, and GCM, there is also be some need to understand a more comprehensive picture across the different models, in order to assess index insurance viability over time and for other climate risk management purposes. Discussions should not be overly focused on the most extreme changes to index insurance price or on the average expected changes to index insurance price, but should include some measure of the range of possible outcomes across different models in ensemble. To this end, Figures 6.11 show the inner quartile ranges of the expected risk (actuarial price) for the 2041-2070 and 2071-2100 time horizons.

As would be expected, the inner quartile range is somewhat larger for the 2071-2100 period than for the 2041-2070 period. Also as would be expected, the ranges for the 0.1 threshold indices are at a lower value than the ranges for the 0.2 threshold. There is some degree of spatial heterogeneity with the Mali subdomain having larger implicit actuarial costs than the other subdomains on both time horizons.

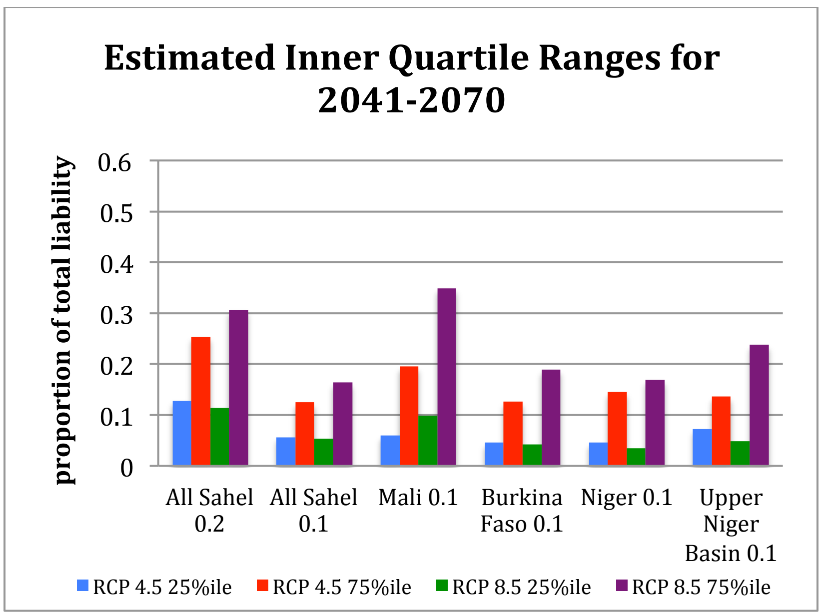


Figure 6.11a: Estimated inner quartile ranges for the 2041-2070 time frame for Experiment 3 (mean and variance change) expected risk (actuarial) price. The average and standard deviation used to calculate the inner quartile range were empirically derived from the model output of the five GCMS: GFDL, NCAR, CNRM, GISS and CSIRO. The assumption behind this estimation is that the range of GCM trends is normally distributed with the empirically derived mean and standard deviation.

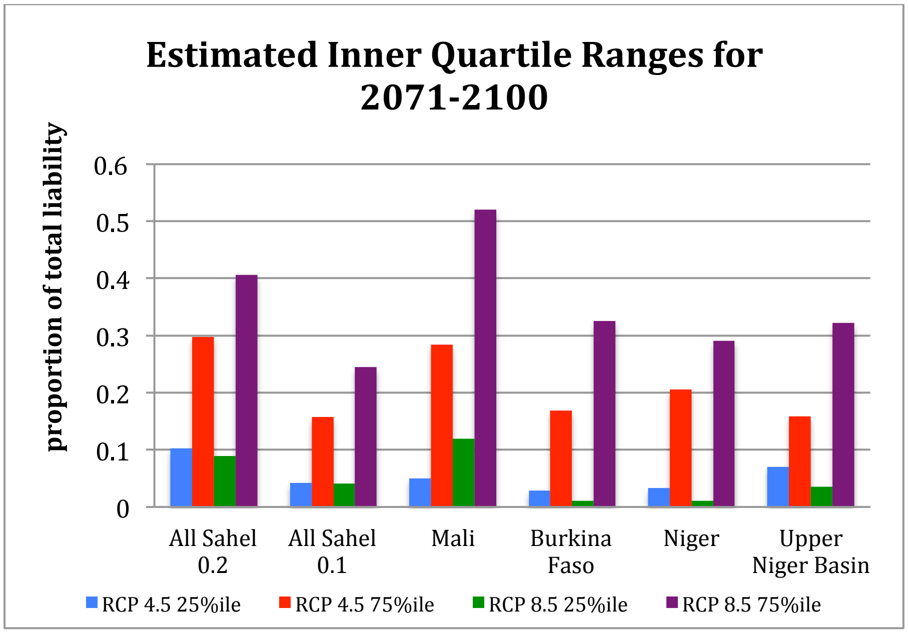


Figure 6.11b: Same estimation as for 6.11a, but for the 2071-2100 time frame.

A practical implication of this finding may be that as climate risks evolve, prices may increase to an unaffordable level in specific regions before others. This outlines the need to take account of both temporal and spatial variability of climate risks in assessing index insurance viability over time.

Climate Uncertainty Risk: In addition to the change in the price from the evolving climate "expected risk price" (which would most directly effect the actuarial price), there is also the evolving "uncertainty risk" associated with the probability of a large number of payouts in a short period (which would effect the "loading" costs). As was discussed in chapter 5, this additional uncertainty related "loading" cost could be expressed as a fraction of the total cost of 10 or more extreme events in 30 years, as in equation 5.2.

$P_d = L(p(r \leq r_{strike}) + fp(10\text{+TCEs in 30 years}))$

Two modeled scenarios could have the same climate “expected risk”, but the likelihood of a very large number of payouts in a defined period of time can be higher if there is persistence (strong decadal variability) in the regional climate system. As mentioned earlier, simulations were undertaken with a range of autocorrelation values from 0 to 0.8. A large autocorrelation value doesn’t tend to alter the expected TCE frequency, but does tend to alter (in most cases increase) the probability of a large number of TCEs in a short period. Monte Carlo simulation is especially helpful in ascertaining how wide the range of potential outcomes may be, even if the expected TCE frequency is comparable between two scenarios.

Figures 6.12 are contour plots showing the risk of 10 or more TCEs in a 30 year period at a range of autocorrelation values from 0 to 0.8 from 2025 to 2085. To be more explicit, the value shown at 2025 is the risk of 10 or more TCEs in the period from 2011-2040, the value shown at 2055 is the risk of 10 or more TCEs in the period from 2041-2070 and the value shown at 2085 is the risk of 10 or more TCEs in the period from 2071-2100.

As with Figures 6.10, the simulations shown here are for Experiment 3 (both mean and variance change). In each Figure, there are subplots of the RCP 4.5 and 8.5 for all five models. The GFDL and CSIRO represent the strongest wetting and drying trends and are shown first, followed by the NCAR, CNRM and GISS models.

Comparing figures 6.12a and 6.12b, the probability of 10 or more TCEs in a 30 year window in the case of the 0.2 threshold is generally higher than in the case of the 0.1 threshold for the All Sahel indices. This is an intuitively understandable result as a contract based on a higher threshold will have a higher number of expected payouts in a given time window (6 expected payouts in 30 years for a 0.2 threshold contract, versus 3 payouts in 30 years for a 0.1 threshold contract).

In figures 6.12a-b, the GFDL, NCAR and CNRM models show a peak probability of 10 or more TCEs in a 30 year window in the upper left corner of the figure; comparatively early in the 21st century and at high values of multi-decadal variability. This result is also intuitively understandable. At points later in the century, when the models' wetting trend has taken hold, the likelihood of a large number of drought years in a 30 year window is quite small. This same pattern is also visible in the CSIRO model results for flooding risk with respect to the Upper Niger Basin index in figure 6.12f. Conceptually, this is an illustration of the same kind of concept; when the strong drying trend of the CSIRO model has taken hold in the later part of the 21st century, the probability of a large number of extreme floods is suppressed.

The CSIRO results in figures 6.12a-e and the GFDL results in figure 6.12f show a somewhat more complex pattern. In each case, the absolute probability of 10 or more TCEs is far greater than for the complementary models (GFDL for figure 6.12a-e and CSIRO for figure 6.12f).

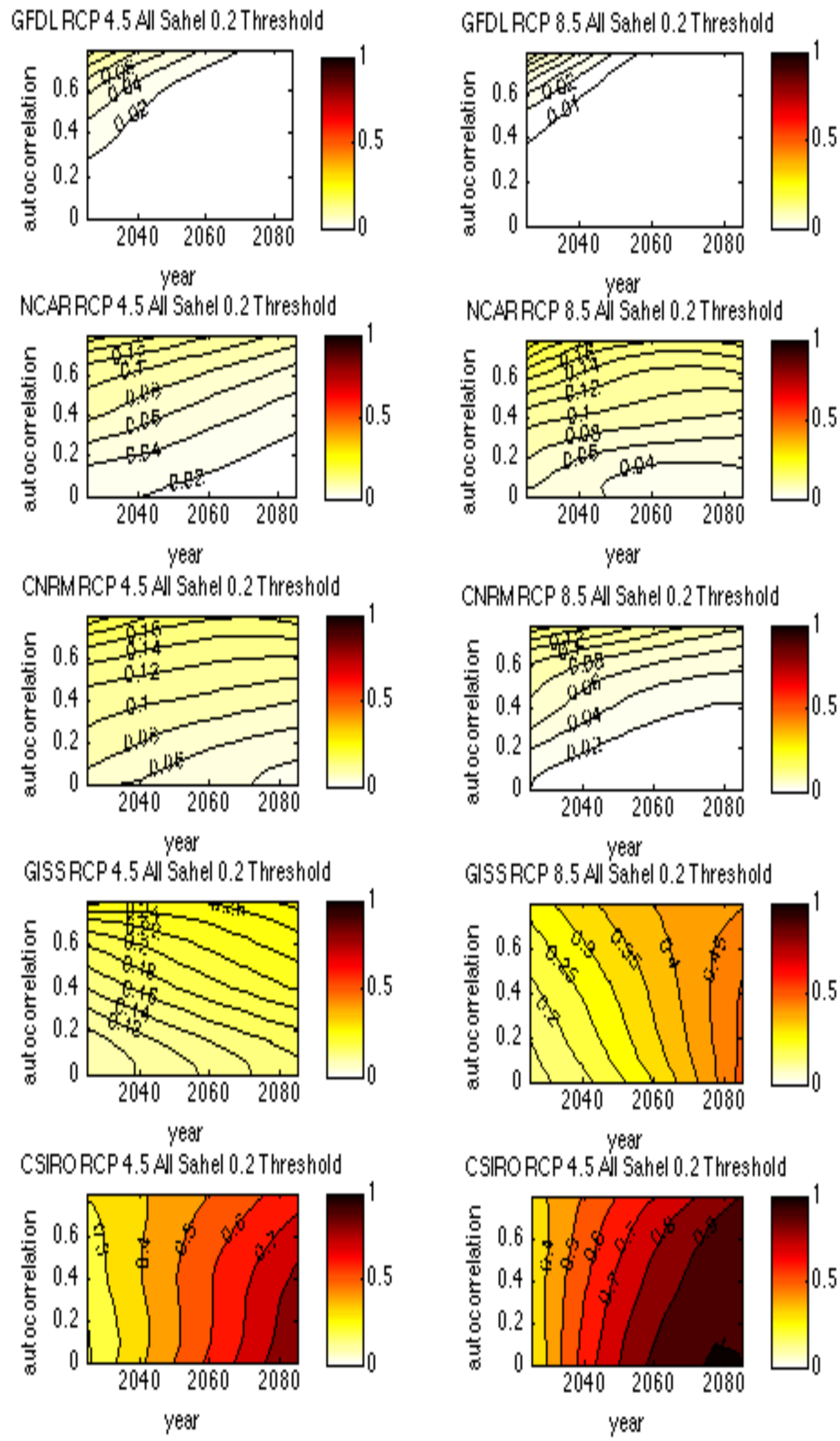


Figure 6.12a: All Sahel index 0.2 Threshold (probability of 10 or more droughts in 30 years).

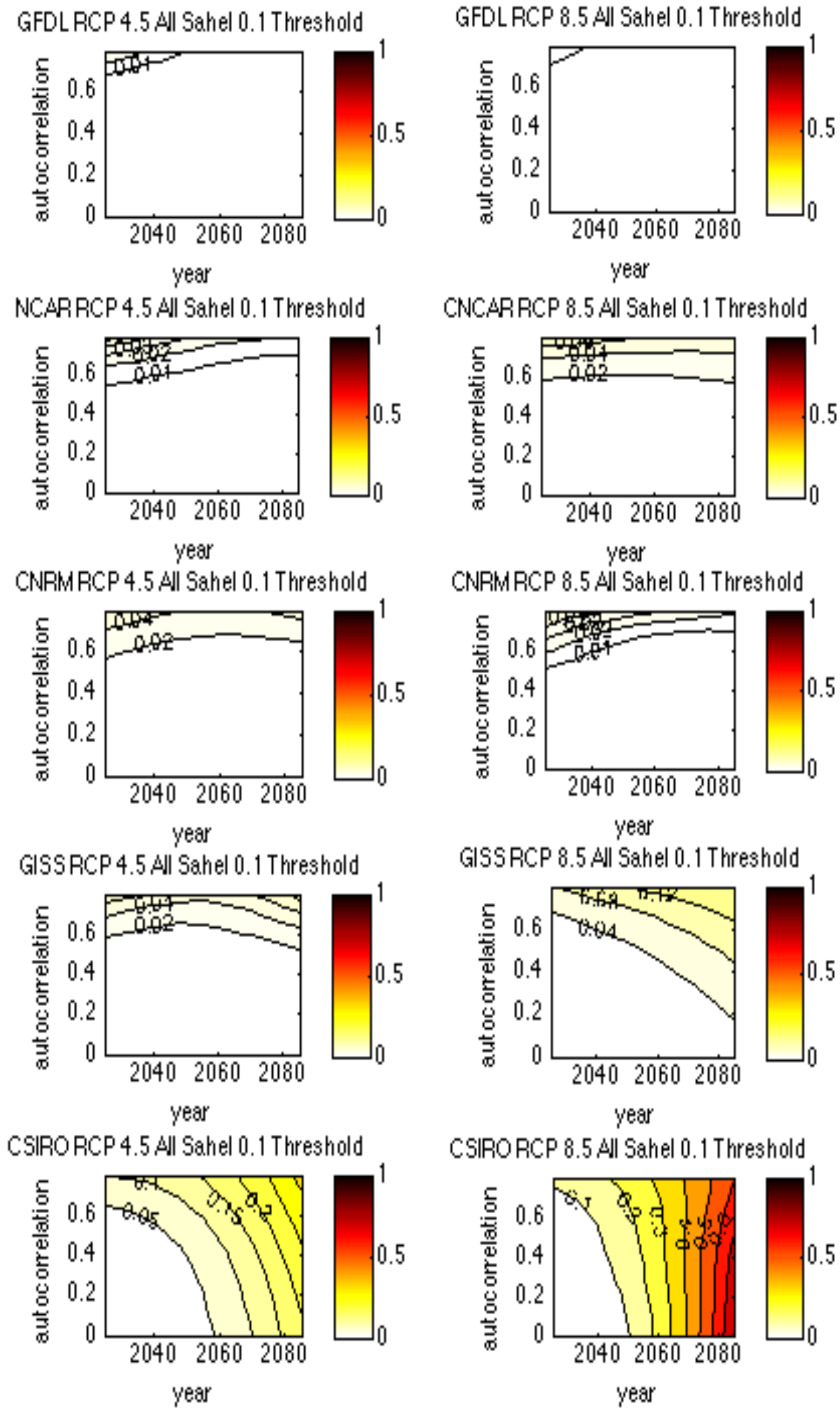


Figure 6.12b: All Sahel index 0.1 threshold (probability of 10 or more droughts in 30 years).

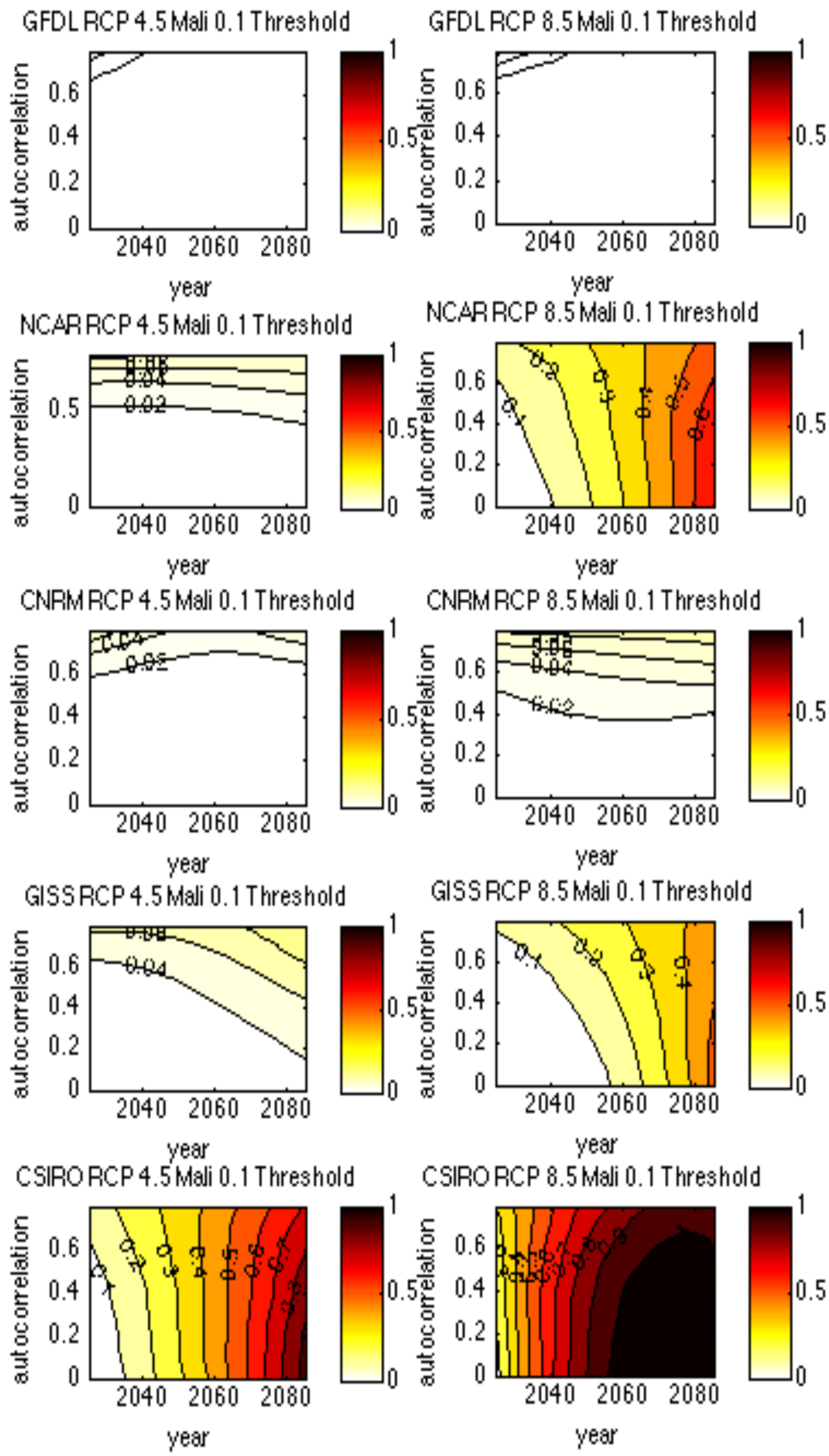


Figure 6.12c: Mali index 0.1 threshold (probability of 10 or more droughts in 30 years).

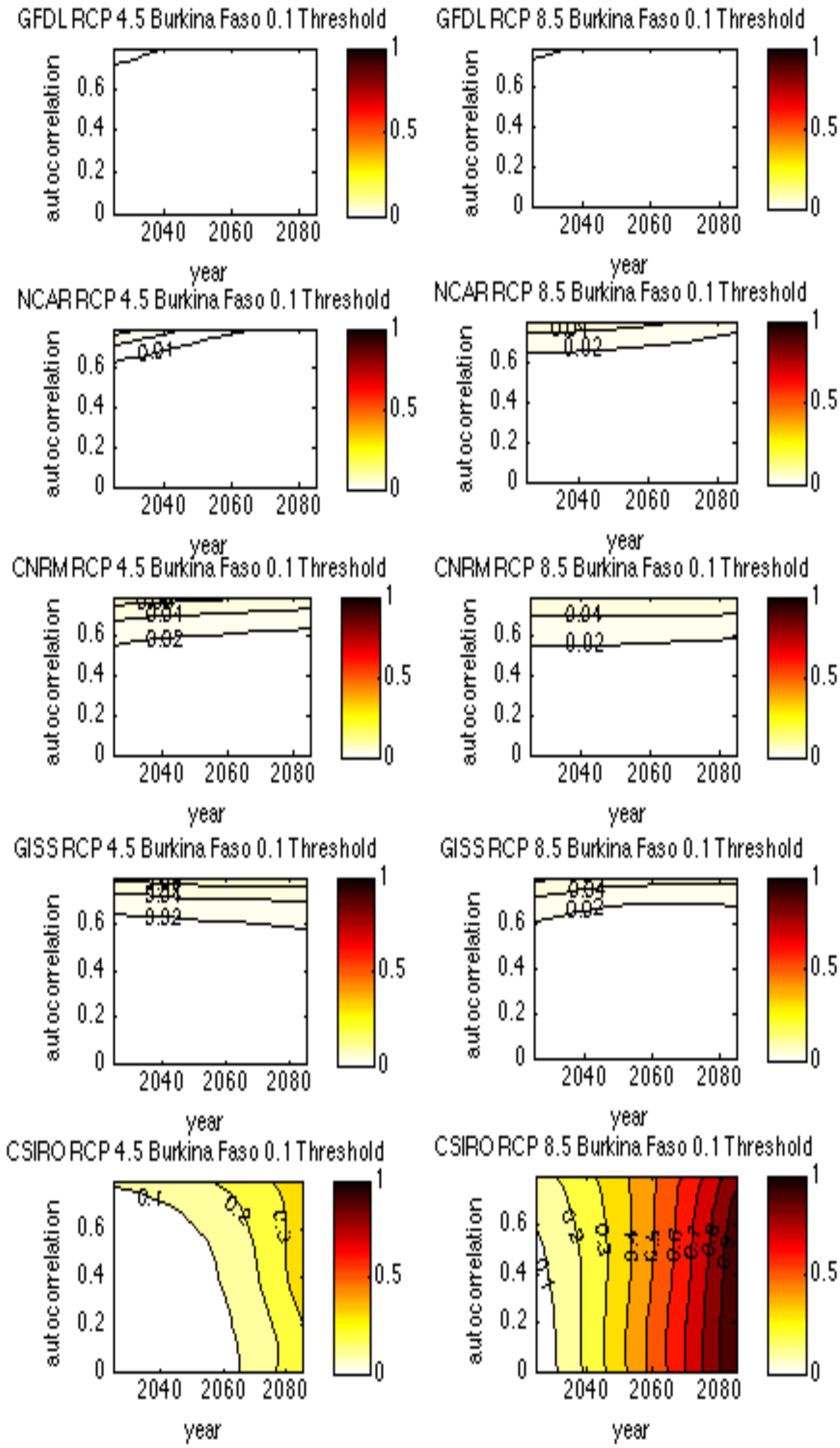


Figure 6.12d: Burkina Faso index 0.1 threshold (probability of 10 or more droughts in 30 years).

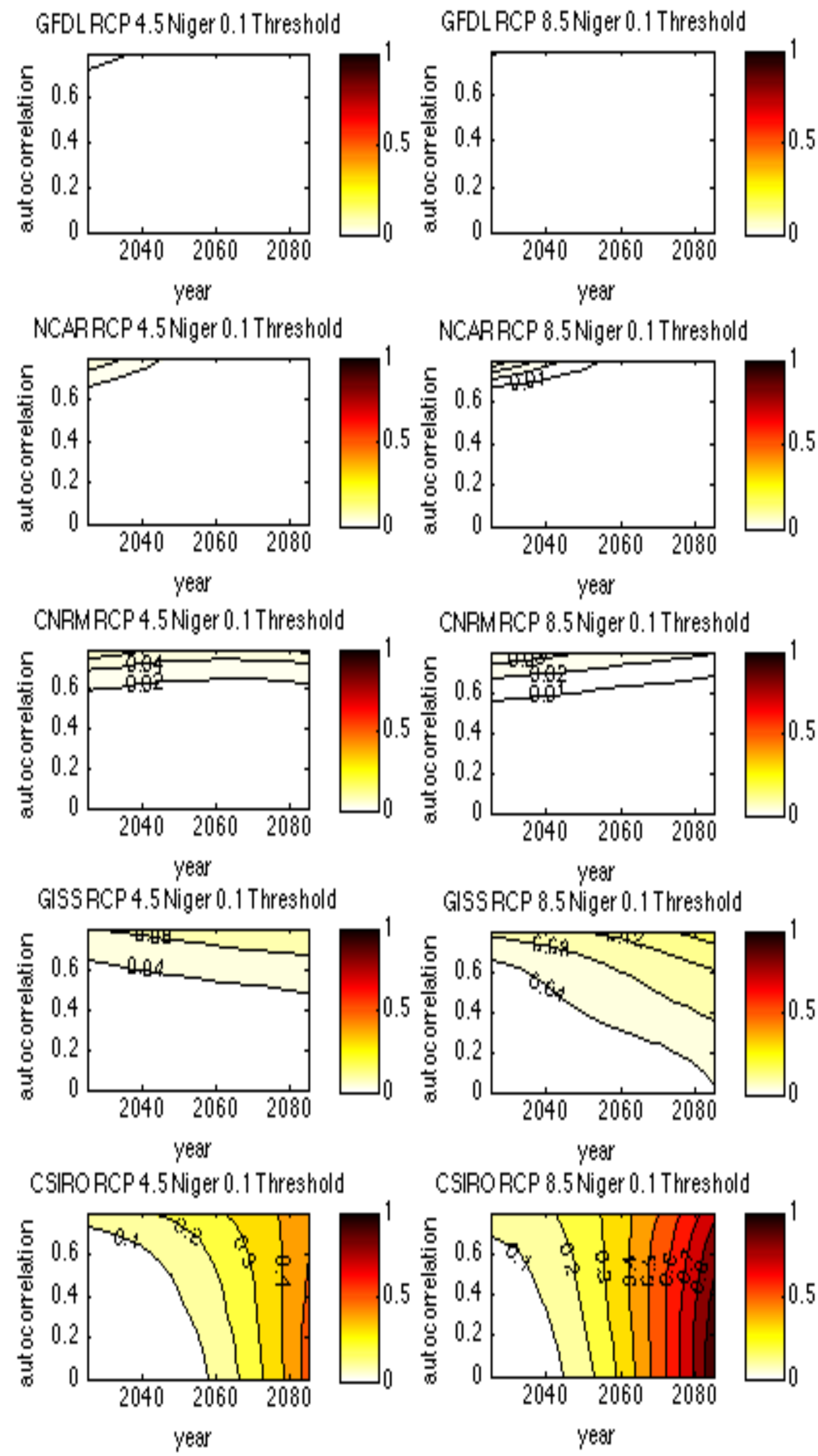


Figure 6.12e: Niger index 0.1 threshold (probability of 10 or more droughts in 30 years).

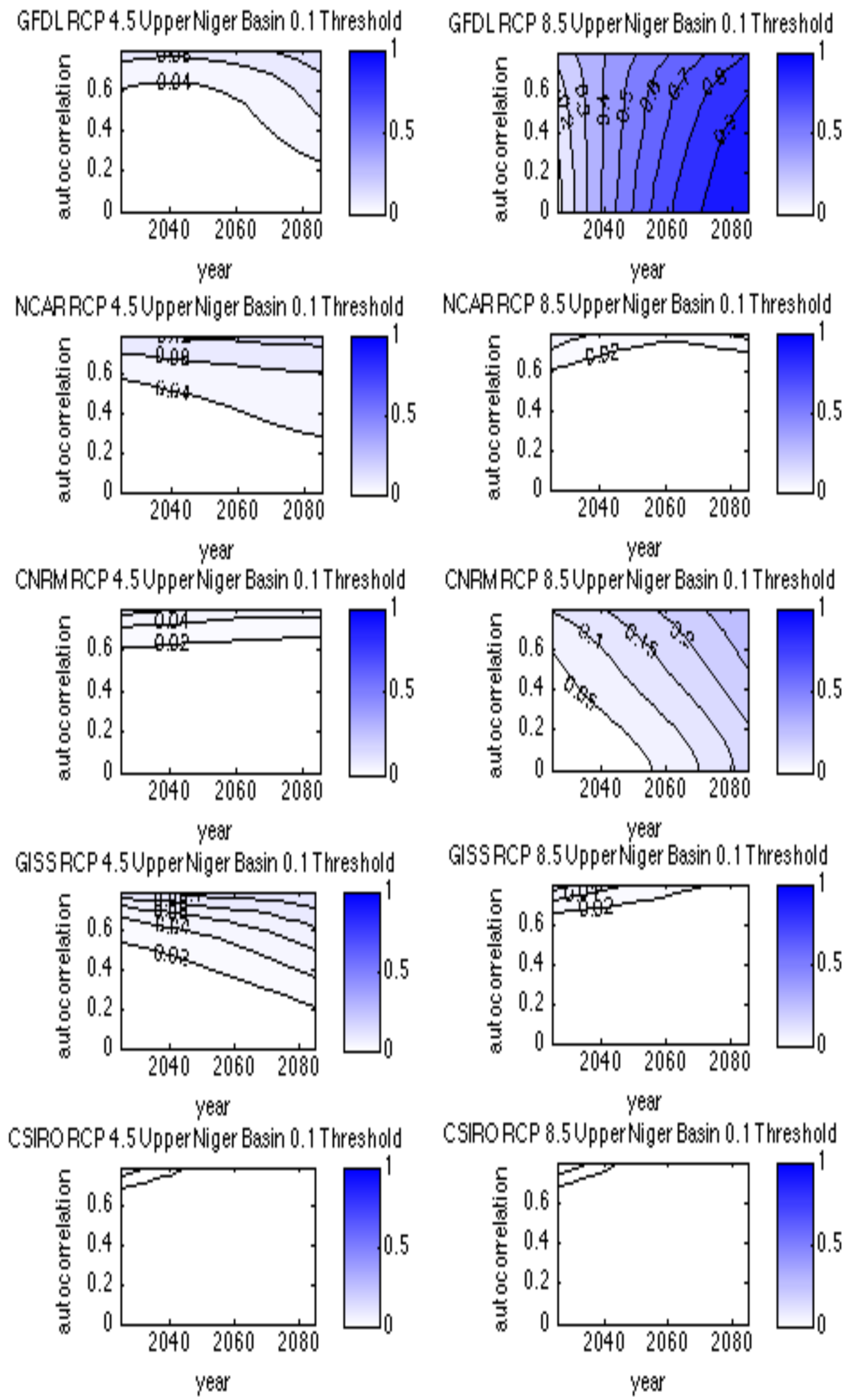


Figure 6.12f: Upper Niger Basin index 0.1 threshold (probability of 10 or more floods in 30 years).

In each case, the probability of 10 or more TCEs increases through the course of the century, as the trend of the model is towards more of the extreme being analyzed. For several of the RCP 4.5 subplots, the probability of 10 or more TCEs tends to increase with increasing autocorrelation. However, for a number of the figures, especially of the RCP 8.5 scenario, the isolines of probability are nearly vertical or the peak probability of 10 or more TCEs is at a relatively low autocorrelation late in the 21st century. In the most extreme cases, the new "climate normal" is actually over the threshold (drier than the drought threshold or wetter than the flood threshold – as defined by the historical period). In these extreme cases, the new "normal" state of affairs will be to exceed the threshold most of the time and a strong autocorrelation will only enhance the probability of an extreme of the other sign.

In less extreme cases where the trend is in the same direction as the extreme (drying trend, drought risk evaluation), but the new "normal" does not exceed the prior extreme event threshold, the peak probability of 10 or more TCEs is in the upper right corner (late century, relatively high autocorrelation). This is the case for many of the GISS simulations for figure 6.12a-e and for the CNRM RCP 8.5 and NCAR RCP 4.5 simulations for figure 6.12f.

The generally more complex pattern of the responses of the intermediate trend models (NCAR, CNRM and GISS) for the various sub-regions can be linked back to the more heterogeneous findings of Figure 6.9 and 6.10. The NCAR model projects a drying trend for Mali, wetting trends for Burkina Faso and Niger and RCP contingent responses for the Upper Niger Basin. The CNRM model projects a minimal trend for Burkina Faso, a wetting trend for Niger and RCP contingent responses for Mali and the Upper Niger Basin, with the RCP 4.5 simulating a drying trend and the RCP 8.5 simulating a wetting trend. The GISS model shows a drying trend for Niger and Mali and RCP contingent responses for Burkina Faso and the Upper Niger Basin.

The magnitude of the change in the probability of 10 or more extreme events in a 30-year window tends to be larger for the RCP 8.5 scenario than for the RCP 4.5 scenario. This would be expected; larger climate forcing leads to larger trends and those stronger trends lead to larger departures in the frequency of a large number of TCEs. These different models clearly will have very different implications for the risk of default of the different contracts and the additional uncertainty based "loading" cost that will need to be added to the actuarial premiums.

6.6: Conclusions Regarding the GCM Analysis: This chapter has explored the implications of five global climate models on the regional hydroclimatology of the West African Sahel and the potential impact of those modeled projections on index insurance pricing and viability as a financial adaptation for the region. Trends in precipitation, evaporation and precipitation-evaporation were analyzed for the All Sahel domain and country/region specific domains were established to serve as the basis for analysis for potential country specific hypothetical contracts.

As discussed in Chapter 4, the Niger, Burkina Faso and Mali millet production was positively correlated to rainfall, and as millet is the staple crop for much of the region's subsistence farmers, drought risk is a critical challenge for regional livelihoods. Also, as discussed in Chapter 4, the irrigated rice crop in Niger is negatively correlated to streamflow in the Middle Niger Basin (in December/January) and streamflow in the Middle Niger Basin (in December/January) is positively correlated with rainfall in the Upper Niger Basin/Guinea highlands area in the prior summer (July-September).

The five models analyzed in this chapter show a wide range of potential outcomes; the GFDL model generally being the model with the strongest regional wetting trend, CSIRO model generally being the model with the strongest regional drying trend, the NCAR and CNRM models generally being moderately wetting and the GISS model being moderately drying. The wetting trends models tended to project an increase in evapotranspiration, while the drying trend models tended to project a decrease in evapotranspiration. However, the precipitation-evaporation analysis tends to be dominated by the change in the precipitation more than the evaporation. There is still considerable uncertainty within the climate science and climate modeling community as to the sign of the regional moisture trend. Strong heating of the interior of northern Africa seems to be a robust conclusion from many modeling studies (Vizy et al., 2013; Liu et al., 2002). This projected strong heating in the Sahara and the Sahel may drive stronger zonal pressure gradients and onshore atmospheric flow during monsoon months. However, higher ambient air temperatures may also elevate the threshold for precipitation and cause less precipitation to fall. Additional heating in the Sahel may also drive stronger potential evapotranspiration, although the actual observed evapotranspiration will be dependent on both temperature changes and biophysical feedbacks. Furthermore, the critically important role of regional and global SSTs and biophysical feedbacks remain challenges to understanding the region's hydroclimatic future.

The models analyzed here tend to produce a drier trend for the western Sahel than for the central Sahel as is shown in the comparison between the different country specific boxes. In the Monte Carlo simulation section of this analysis, a thousand realizations were run for each model/RCP combination with changes in the mean and standard deviation projected linearly on the basis of the difference between the 2060-2100 and 1980-2020 periods. The expected frequency of the threshold crossing was explicitly calculated for the time periods 2011-2040, 2041-2070 and 2071-2100. The results of three experiments were presented: variance change only, mean change only and both mean and variance change. Additionally, the proportion of the thousand Monte Carlo simulations that produced 10 or more extreme events was quantified for the same time periods. This analysis was considered in the context of mean and variance change experiments for a range of autocorrelation values from 0 to 0.8 (to simulate different magnitudes of potential multi-decadal variability).

Changes in TCE frequency and "expected risk" price as a result of modeled variance change only were found to be relatively small with respect to similar changes induced by the mean change only or combined mean and variance change scenarios. The models with drying trends (GISS and CSIRO) tended to produce an increase in the frequency of TCE droughts. This would correspond to an increase in the frequency of drought index insurance payout and would consequently lead (in the price evolution framework) to an increase in the actuarially fair premium. Some of these modeled potential "expected risk" price increases are quite significant (with the CSIRO model/RCP 8.5 scenario, the 0.1 threshold contract price increases to almost 80% of liability for the case of Mali in the late 21st century). The models with trends towards wetter conditions (GFDL, NCAR and CNRM) tend to produce a decrease in the frequency of threshold crossing extreme events. This corresponds to a decrease in the frequency of drought index insurance payout and a reduction of price (under the price evolution framework). Some of these price reductions are also quite significant (with the GFDL model/RCP 8.5 scenario leading the 0.1 threshold contract to decrease in price to a fraction of a percent of total liability).

In addition to the change in the "expected risk" price which models the central tendency of the Monte Carlo simulation, there is also the "uncertainty risk" that accompanies an enhanced probability of a large number of threshold crossing extreme events (independent of the expected value). The figures illustrating this analysis show a similar pattern; the risk of a large number (10 or more) threshold crossing extreme events is generally quite low in absolute terms for drought risk for the GFDL model or for flooding risk for the CSIRO model. Conversely, the risk of a large number (10 or more) threshold crossing extreme events is generally quite high in absolute terms for drought risk for the CSIRO model and for flooding risk for the GFDL model. This risk tends to increase over the course of the 21st century for these model simulations. Models with intermediate trends show intermediate probabilities and more complex responses in the various sub-regions.

In a practical sense, if index insurance were to take hold in this region, an iterative approach (most likely using some sort of sliding window approach) to assessing price would be beneficial. One potential benefit of the design of this study is that the probability of a major regional drought and a major river flood in the same year are relatively low (although not without precedent). The scale of millet cultivation exceeds the scale of irrigated rice cultivation and the number of people vulnerable to drought risk most probably exceeds the number vulnerable to flooding risk. However, a diversified index insurance portfolio that targets both (negatively correlated) hydro-climatic risks simultaneously may create a modest degree of internal hedging that may help make such an index insurance portfolio more robust in the face of a changing climate.

In summary, these modeling results show a very wide range of potential outcomes and implications for index insurance viability, depending heavily on the sign of the modeled precipitation trend. In the most extreme cases, under a "price evolution" framework, the price will increase to clearly unsustainable levels and other adaptations will be necessary. In other scenarios, the increases in the price may be manageable and may enable index insurance to be a viable adaptation for some extended period of time into the 21st century. In still other scenarios, (such as a wetting trend for drought index insurance) the actuarial price may actual decrease over time. The role of multi-decadal variability is found to be a significant factor in assessing the likelihood of a run of extreme events, and implicitly in the risk of index insurance default. The fraction of these costs that are passed on to the client will play a significant role in index insurance affordability and default risk. As there are still considerable uncertainties in the climate science projections of regional precipitation and evapotranspiration in the West African Sahel and the dynamics of the region's multi-decadal variability, it would be inadvisable to take a particular GCM result in isolation as a cause for either optimism or pessimism. Rather, the foregoing analysis quantifies the implications of specific scenarios on different risks that would factor into index insurance pricing and illustrates that the viability of index insurance over time is highly dependent on how the regional climate system itself evolves.

References

-Adger, W. N., S. Huq, K. Brown, D. Conway, and M. Hulme, (2003). Adaptation to Climate Change in the Developing World. *Progress in Development Studies, 3*, 179-195.

-Biasutti, M., (2013). Forced Sahel rainfall trends in the CMIP5 archive. *Journal of Geophysical Research: Atmospheres, 118,* 1613-1623.

-Chantarat, S., A. Mude, C. B. Barrett and M. R. Carter, (2013). Designing Index-Based Livestock Insurance for Managing Asset Risk in Northern Kenya. *Journal of Risk and Insurance, 80,* 205-237.

-Cook, K., and E. Vizy, (2006). Coupled Model Simulations of the West African Monsoon System: Twentieth- and Twenty-First-Century Simulations. *Journal of Climate, 19,* 3681-3703.

-Donner, L., B. L. Wyman, R. S. Hemler, L. W. Horowitz, Y. Ming, M. Zhao, J.-C. Golaz, P. Ginoux, S.-J. Lin, M. D. Schwarzkopf, J. Austin, G. Alaka, W. F. Cooke, T. L. Delworth, S. M. Freidenreich, C. T. Gordon, S. M. Griffies, I. M. Held, W. J. Hurlin, S. A. Klein, T. R. Knutson, A. R. Langenhorst, H.-C. Lee, Y. Lin, B. I. Magi, S. L. Malyshev, P. C. D. Milly, V. Naik, M. J. Nath, R. Pincus, J. J. Ploshay, V. Ramaswamy, C. J. Seman, E. Shevliakova, J. J. Sirutis, W. F. Stern, R. J. Stouffer, R. J. Wilson, M. Winton, A. T. Wittenberg, and F. Zeng, (2011). The Dynamical Core, Physical Parameterizations, and Basic Simulation Characteristics of the Atmospheric Component AM3 of the GFDL Global Coupled Model CM3. *Journal of Climate*, *24,* 3484–3519.

-Gent, P. R., G. Danabasoglu, L. J. Donner, M. M. Holland, E. C. Hunke, S. R. Jayne, D. M. Lawrence, R. B. Neale, P. J. Rasch, M. Vertenstein, P. H. Worley, Z. -L. Yang, and M. Zhang, (2011). The Community Climate System Model version 4. *Journal of Climate*, *24,* 4973-4991

-Giannini, A., Saravanan, R. and Chang, P. (2003). Oceanic forcing of Sahel rainfall on interannual to interdecadal time scales. *Science, 302,* 1027–1030.

-Giannini, A., Salack, S., Lodoun, T., Ali, A., Gaye, A. and Ndiaye, O. (2013). A unifying view of climate change in the Sahel linking intra-seasonal, interannual and longer time scales. *Environmental Research Letters 8*, 024010.

-Hargreaves, G., and R. Allen, (2003). History and Evaluation of Hargreaves Evapotranspiration Equation. *Journal of Irrigation and Drainage Engineering, January/February*, 53-63.

-IPCC, (2013). Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. *Cambridge University Press,* Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

-Jeffrey, S. J., Rotstayn, L. D., Collier, M. A., Dravitzki, S. M., Hamalainen, C., Moeseneder, C., Wong, K. K., and J. I. Syktus (2013). Australia's CMIP5 submission using the CSIRO Mk3.6 model. *Australian Meteorological and Oceanographic Journal, 63,* 1–13

-Kamga, A., G. Jenkins, A. Gaye, A. Garba, A. Sarr and A. Adedoyin, (2005). Evaluating the National Center for Atmospheric Research climate system model over West Africa: Present-day and the 21st century A1 scenario. *Journal of Geophysical Research, 110*, D03106.

-Knight, J., Folland, C. and Scaife, A. (2006). Climate Impacts of the Atlantic Multidecadal Oscillation. *Geophysical Research Letters 33,* L17706.

-Lebel, T. and A. Ali, (2009). Recent trends in the Central and Western Sahel rainfall regime (1990–2007), Journal of Hydrology, 375, pp. 52-64.

-Liu, P., G. Meehl, and G. Wu, (2002). Multi-model trends in the Sahara induced by increasing CO_2. *Geophysical Research Letters, 29,* 28-1-28-4.
-Meehl, G. A., Karl, T., Easterling, D. R., Changnon, S., Pielke, R., Jr., Changnon, D., …, & Zwiers, F. (2000). An introduction to trends in weather and climate events; observations, socioeconomic impacts, terrestrial ecological impacts, and model projections. *Bulletin of the American Meteorological Society, 81,* 413–416.
-Monteith, J. L. (1965). "Evaporation and environment". *Symposia of the Society for Experimental Biology* **19**: 205–234.
-Norton, M., D. Osgood, M Madajewicz, E. Holthaus, N. Peterson, R. Diro, C. Mullally, T.L. Teh, and M. Gebremichael, (2014). Evidence of Demand for Index Insurance: Experimental Games and Commercial Transactions in Ethiopia. *Journal of Development Studies, 50,* 630-648.
-Penman, H.L. (1948). Natural evaporation from open water, bare soil and grass. *Proceedings of the Royal Society London A (194)*, 120-145.
-Schmidt, G.A., R. Ruedy, J.E. Hansen, I. Aleinov, N. Bell, M. Bauer, S. Bauer, B. Cairns, V. Canuto, Y. Cheng, A. Del Genio, G. Faluvegi, A.D. Friend, T.M. Hall, Y. Hu, M. Kelley, N.Y. Kiang, D. Koch, A.A. Lacis, J. Lerner, K.K. Lo, R.L. Miller, L. Nazarenko, V. Oinas, Ja. Perlwitz, Ju. Perlwitz, D. Rind, A. Romanou, G.L. Russell, Mki. Sato, D.T. Shindell, P.H. Stone, S. Sun, N. Tausnev, D. Thresher, and M.-S. Yao (2006). Present day atmospheric simulations using GISS ModelE: Comparison to in-situ, satellite and reanalysis data. *Journal of Climate 19,* 153-192.
-Siebert, A. and Ward, M. N. (2011). Future occurrence of threshold crossing seasonal rainfall totals: methodology and application to sites in Africa. *Journal of Applied Meteorology and Climatology 50,* 560–578.
-Siebert, A. and Ward, M. N. (2013). Exploring the frequency of hydroclimate extremes on the Niger River using historical data analysis and Monte Carlo methods. *African Geographical Review,* online publication.
-Tebaldi, C., K. Hayhoe, J. M. Arblaster, and G. A. Meehl, (2006). Going to the extremes: An intercomparison of model-simulated historical and future changes in extreme events. *Climatic Change, 79,* 185–211.
-Thornthwaite, C. W., (1948). An Approach Towards a Rational Classification of Climate. *Geographical Review, 38,* 55-94.
-Vizy, E., K. Cook, J. Crétat, and N. Neupane, (2013). Projections of a Wetter Sahel in the Twenty-First Century from Global and Regional Models. *Journal of Climate, 26,* 4664–4687.
-Voldoire, A., E. Sanchez-Gomez, D. Salas y Mélia, B. Decharme, C. Cassou, S.Sénési, S. Valcke, I. Beau, A. Alias, M. Chevallier, M. Déqué, J. Deshayes, H. Douville, E. Fernandez, G. Madec, E. Maisonnave , M.-P. Moine, S. Planton, D.Saint-Martin, S. Szopa, S. Tyteca, R. Alkama, S. Belamari, A. Braun, L. Coquart, F. Chauvin. (2011). The CNRM-CM5.1 global climate model: description and basic evaluation. *Climate Dynamics, 40*, 2091-2121.
-Wang, G. and Eltahir, E. (2000). Biosphere-atmosphere interactions over West Africa. 11: multiple climate equilibria. *Quarterly Journal of the Royal Meteorological Society 126,* 1261–1280.

Chapter 7: Conclusions and Future Work

7.1. General Conclusions: There are many conclusions to be drawn from the foregoing dissertation research. A critical analysis of the index insurance and financial adaptation literatures demonstrates a broad need for market-based, scalable approaches to climate risk management. More specifically, weather based index insurance, particularly when linked to credit can hold significant benefit as a climate risk management tool in the context of many developing economies (Hellmuth et al., 2009; Osgood et al. 2008). While subsidization is quite problematic for climate related risks in the developed world, some level of subsidization may be beneficial in the initiation and long-term viability of index insurance in the West African Sahel.

Regional livelihoods, economics and even politics in the West African Sahel nations of Niger, Burkina Faso and Mali are often highly contingent on how climate variability and climate extremes are addressed, particularly for the agricultural sector. Some 80% of the region's population is engaged in agriculture, livestock cultivation or some combination thereof and this population experiences considerable exposure to climate risks. Index insurance can help to address these vulnerabilities to some degree, but index insurance has important limitations, which must be communicated clearly in the practical implementation of any such project (Hellmuth et al., 2009; Skees, 2007).

The region's unimodal tropical monsoon climate system creates a relatively short window in which crops are grown and harvested before dry conditions and tropical heat deplete soil moisture. Regional climate history in both the observed and paleo-climatic periods has shown a pronounced tendency for multi-decadal variability (Shanahan et al. 2006; Nicholson, 2005; Mohino et al., 2011). There is also evidence from the paleo-climate literature for the potential of relatively abrupt large changes to regional hydro-climatology (deMenocal et al., 2000). This pronounced climate variability has been accompanied by large human migrations, and widespread food insecurity (Hiernaux, 1996; Barbier et al., 2009). The presence of multi-decadal variability in the climate record also makes the challenge of quantifying the frequency of extreme events more complex, posing challenges to the quantification of index insurance risks.

In conceptualizing this study, potential drought index insurance contracts were sought as the basis for hedging against limited millet yields for subsistence farmers in the region and potential flood index insurance contracts were sought as the basis for hedging against limited rice yield for irrigated farmers in the region. Engaging different farmer populations with negatively correlated risks may help to modestly reduce financial exposure to potential index insurance contracts. Throughout this study, potential index insurance contracts were conceptualized as simple step functions, primarily on the basis of a historical 10% exceedance threshold.

7.2. Technical Conclusions: Several different potential climate indices were analyzed in conjunction with de-trended national millet and rice data. Correlation analysis and Gerrity skill score analysis showed that two rainfall indices; NOAA Precipitation over Land and nationally-aggregated Global Historical Climate Network data show potential as bases for drought index insurance contracts for all three nations, with respect to de-trended national millet production. GPCP (satellite-based rainfall) and ENSO based indices proved less robust as potential bases for drought index insurance contract, while NDVI based indices showed some potential (although not as much as the abovementioned station based rainfall indices). Similar historical analysis of potential flood insurance contracts (based on Niger River streamflow values) showed that Niger River streamflow values in the middle part of the basin are significantly negatively correlated with de-trended Niger rice production.

One of the principle concerns of the potential farmer client population is the issue of basis risk (i.e. a very low yield season occurs, but no payout is made). This scenario can be likened to a "type 2" error. One of the principle concerns of any insurer is the probability of a "type 1" error (the index value triggers a payout, but yields are not particularly low). Methodologically, use of the Gerrity skill score or other comparable skill score metrics that explicitly explore the probability of type 1 and type 2 errors may be beneficial in other contexts where an emphasis may have been placed primarily on correlation analysis. Such skills score analysis may help to more clearly convey the "type 1" error rate and the basis risk to the parties involved in index insurance negotiation.

The Monte Carlo simulation methods developed in the later chapters of this dissertation are used to quantify potential future climate scenarios and assess how the expected and uncertainty related components of an index insurance pricing scheme might evolve as a function of time. More specifically, a 20% change in the mean streamflow of the Niger River is shown to simulate a change of at least a factor of between 2 and 4.5 depending on the underlying coefficient of variation. This is in concert with prior studies (Siebert and Ward 2011,2013; Ward et al., 2012) that showed that even a 10% change in mean could lead to change in the extreme event frequency by ~factor 2.

The role of the modeled multi-decadal variability on extreme event frequency is more complex. In the theoretical construction of Chapter 5, where both the trend in the mean stream-flow and the autocorrelation are imposed, the role of autocorrelation significantly enhances the risk of a large number of extreme events in a given period (relative to simulations with the same trend, but less autocorrelation). As Figure 5.13 illustrates, the probability of 10 or more floods in a 30-year period can roughly double with an increase in the temporal lag-1 autocorrelation from 0 to 0.6, even if when the mean trend is held constant. This is also conceptually true of the impact of the multi-decadal variability in situations of modest trends in the mean as illustrated by most of the GCMs used in Chapter 6 (GISS, CNRM and NCAR). However, in the case of the most extreme trend scenario (CSIRO and GFDL RCP 8.5), the late 21st century new “normal” may even cross the “extreme threshold” based on historical data. Consequently, in such scenarios, additional multi-decadal variability increases the probability of persistent anomalies opposite the extreme leading to a reduction in the expected likelihood of 10 or more extreme events in a 30-year window. It should be noted, however, that a practical approach to climate risk management, should focus on the most probable outcomes and not focus on the most extreme scenarios to the exclusion of the more likely, less extreme scenarios.

While GCM projected trends in variability are included in the analysis in Chapter 6 (along with GCM projected trends in mean), generally the magnitude of the impact of the trend in variability is less than the magnitude of the impact of either trends in mean or multi-decadal variability.

All in all, the viability and sustainability of future drought index insurance contracts for dryland farmers and flood insurance contracts for irrigated rice farmers are found to be highly contingent on modeled assumptions regarding changes to the regional climate system. A projection of drying will increase the cost of drought insurance contracts and reduce the cost of flood insurance contracts and the converse is also true. Projected changes in the variance tend to have less effect on price than changes in the mean and strong multi-decadal variability tends to increase the "loading costs" of index insurance in most cases. In a practical sense, a particular degree of change to the actuarial and/or loading costs may render an index insurance product unaffordable to populations who may have previously been able to afford such contracts. As with most commodities and financial instruments, there would generally be an expectation that the demand for index insurance would be vary inversely with the price, but the reduction in demand may prove discontinuous at certain critical price values. As is suggested by the findings of Chapter 6, different sub-domains may reach a critical price threshold at different times. Consequently, the long-term picture of index insurance viability in the region is likely to be both geographically and temporally heterogeneous and contingent on many subtleties of how the region's climate evolves.

There are competing mechanisms that influence the seasonal rainfall cycle in the region. The complexities of modeling the changes of the physics of these processes at the local scale and their integration into the more global climate system leads to considerable uncertainty regarding the expected sign of precipitation (and even absolute evaporation) change in the region in light of climate change (Biasutti, 2013; Nicholson, 1980; Sultan et al. 2003; Ndiaye et al., 2011). Consequently, explicit consideration of climate change (and its attendant uncertainties) in modeling the behavior of index insurance price will lead to additional uncertainty related costs and a potentially enhanced probability of large basis risk or default.

7.3. Future Technical Work: There are several possible avenues of future research; both technical and practical. One technical issue that has yet to be explicitly modeled is the possibility of temporally evolving skew. Some studies have shown a statistical relationship between climatological rainfall and the skew of the inter-annual distribution of rainfall values; generally drier climatologies tend to have more positive skew (Siebert and Ward, 2011; Batisani and Yarnal, 2010). Figure 7.1 shows an initial rainfall distribution and an altered (drier) rainfall distribution with more positive skew. In Figure 7.1, the depicted threshold is z=-1.3 (corresponding to a roughly 10% exceedance if the distribution were perfectly Gaussian).

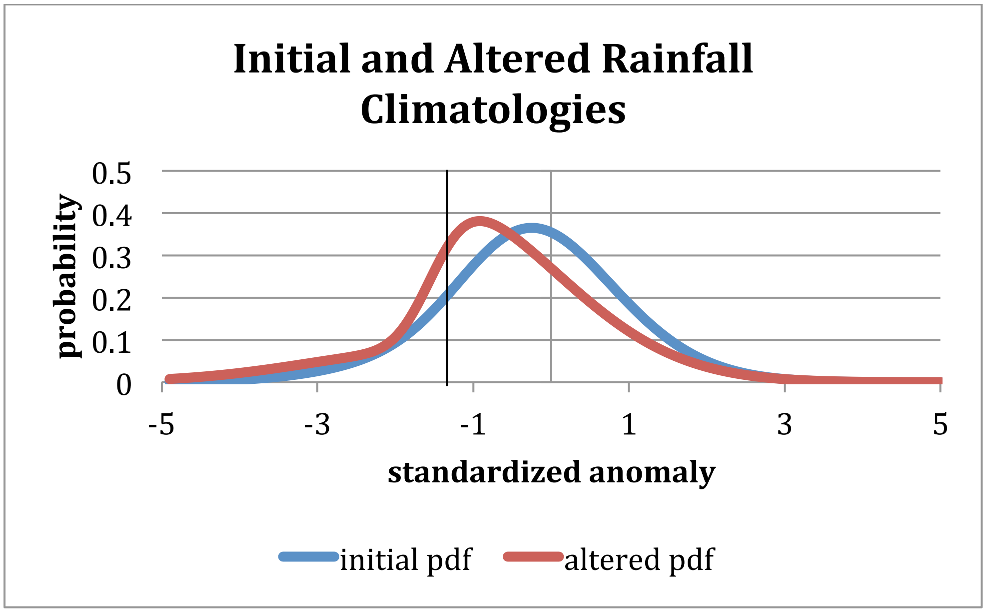


Figure 7.1: Schematic diagram of the probability density functions of an initial and altered climatic state with a threshold for drought index insurance payout at z = -1.3.

In the initial case, the mean is 0, the standard deviation is 1 and the skew is 0.3. In the "altered case", the mean is -0.3, the standard deviation is 1 and the skew is 0.8. The probability of the standardized anomaly being less than -1.3 in the initial case is about 17%, but in the altered case rises to about 26%.

In order to better characterize the rainfall distribution or the streamflow distribution over time, an exploration of the paleo-climate record may prove beneficial. Some aspects of paleo-climate study can also help to better elucidate how extreme event frequency may respond to a non-stationary climate (Bell et al., 2013). Other historical extension methods, such as use of Bayesian networks may also prove beneficial towards a similar end (Daron and Stainforth, 2014). These techniques could help refine the quantification of climate risks in a temporally evolving way with reference to different states of regional climate forcings (different phases of the AMO).

There is a clear a need from the analysis of regional streamflow variability and the recent extreme flooding events to explore the implications of land use change and evolving runoff coefficient on the relationship between rainfall and streamflow extremes (Amogu et al., 2010; Descroix et al. 2012). It seems evident that in recent years, river flooding is not responding in a linear fashion to seasonal rainfall. More detailed understanding of this surface hydrology would be critical to understanding livelihood risks and insurability with regard to flooding in the future.

Another technical area of further exploration is to explore more sophisticated methods of representing multi-decadal variability. This may include consideration of AR models at multiple lags or consideration of an ARMA or ARIMA model. More sophisticated time-series modeling that captures the slower decay of the observed rainfall and streamflow lag-correlation structure would be preferable.

In addition to the indices explored, the relationship between rainfall and evaporation could be explored in greater depth and a more sophisticated water balance model could be developed. Clearly, heat stress is a critical factor in crop survival (Tarhule and Akumaga, 2014).

If/when NDVI based contracts are pursued (either in the West African Sahel or in other contexts), it is important to understand, in a nuanced way, how NDVI responds to changes in the precipitation and evaporation. It is well established that NDVI is well correlated to rainfall in semi-arid environments (Li et al., 2004; Wang et al., 2003). It is further understood that there is a temporal lag associated with the relationship between rainfall and NDVI, but that the length of this optimal temporal lag period is context dependent (Ji and Peters, 2005; Wang et al., 2003). Understanding of this response function could help inform adaptive management to evolving trends in NDVI, and projections of NDVI based index insurance.

Surface water balance analysis could also be coupled with modeling of groundwater behavior. More explicit hydrological modeling could be engaged and integrated with GCM and RCM projections of precipitation and evaporation, (Oguntunde and Abiodun, 2013; Amadou et al., 2014). Modeled precipitation – evaporation could be engaged in more depth, especially if reliable historical evaporation data is available to inform the retrospective historical analysis of contract performance. Alternative metrics of water balance, such as the Water Requirement Satisfaction Index (WRSI) could be considered (Ward et al., 2008; Berg and Quirion, 2013).

In addition to agricultural applications, index insurance contracts could also be considered explicitly for regional water management applications (Brown and Carriquiry, 2007; Ward et al., 2012). As major environmental diseases such as malaria and meningitis tend to create considerable economic hardships in the West African Sahel (and elsewhere in the “developing” world) and may stress regional health facilities’ financial resources, it may be possible to develop a sort of parametric index insurance contract to be sold to regional health clinics based on projected malaria risks. This idea is yet unexplored and may not prove fruitful, but it may be worth consideration.

In theory, it may also be possible to create individual index insurance contracts (for either agricultural or water/reservoir management applications) that have strike values for both flooding and drought extremes, for crops that are sufficiently vulnerable to both extremes. While most of the index insurance literature relates to one extreme or the other, such a more complex contract is theoretically possible.

Another significant challenge to index insurance globally and to some degree regionally is the challenge of seasonal forecast skill. While the West African Sahel's pronounced multi-decadal variability is quite significant, there is some measure of seasonal predictability both from ENSO teleconnections (Janicot et al., 1996) and from local SST forcing (Giannini et al., 2003; 2013). As discussed in chapter 2, skillful seasonal forecasts in the hands of informed farmers can lead to adverse selection and skillful seasonal forecasts in the hands of insurance companies can lead to asymmetric access to information that can undermine the viability of index insurance and the trust of the potential clients. While issues of timing are critical, the challenges brought about by skillful seasonal forecasts need not be insurmountable (Osgood et al., 2008).

Another area of potential further development is the engagement of alternative contract designs. Throughout this analysis, simple step functions were the contract design of choice. However, gradient functions and multi-step functions should be analyzed with respect to the implications of climate change on their pricing. As discussed in chapter 2, even for a particular level of liability coverage and a particular premium price, potential client preferences regarding contract design type may be contingent on an understanding of regional climate. In modeling future climate impacts on index insurance, preferences may evolve as the climate risks evolve. The evolution of contract pricing will also depend on the format of the contract, in concert with the evolving climate risk.

Referring back to equation 2.1 reshown here as equation 7.1, we again consider four potential contract types discussed in chapter 2; simple step, two-step, gradient 1 and gradient 2.

$$P_d = \int_0^{rstrike} p(r)y(r)dr \tag{7.1}$$

Assume that in the initial, unperturbed climate state, as before, we have a climatological mean rainfall of 35" and that for the sake of argument, the standard deviation is 7" and the inter-annual distribution of rainfall totals is a normal distribution. In this situation, the probability that the rainfall will fall below the strike level of 30" is roughly 24%. If we then consider an altered climate situation, in which the mean rainfall is reduced to 32" and the standard deviation is increased to 10" and the rainfall is still normally distributed, the probability of drought insurance payout increases to 42% and the prices increase significantly. However, the consequent changes in the prices (calculated from equation 7.1) are not in equal proportion. Figure 7.2 shows the payout profiles and the left side of the respective rainfall probability distribution functions.

Table 7-1 shows the actuarially fair price as calculated by equation 7.1 for the two scenarios and the four contract designs. The premium for the simple step function doesn't quite double, the premium for the gradient 2 function slightly more than doubles and the premiums for the 2 step function and gradient 1 function roughly triple.

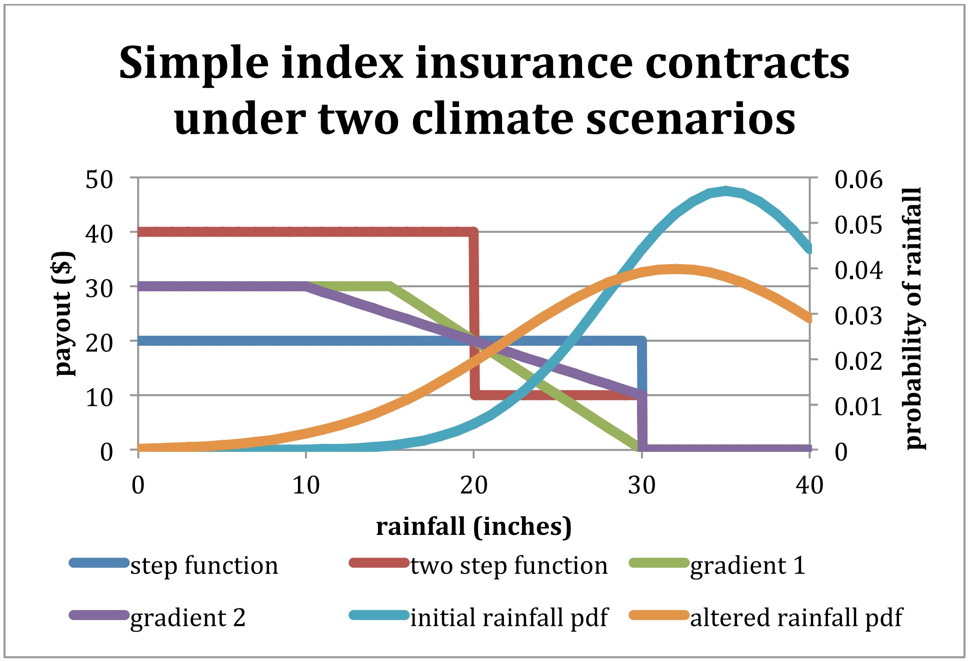


Figure 7.2: Schematic diagram of the payout functions of the same four hypothetical drought index insurance contracts presented in Figure 2.3, along with an initial and altered rainfall probability density function.

Price	Step function	2 step function	Gradient 1	Gradient 2
Initial (wetter) climate	$4.76	$2.86	$1.72	$3.24
altered (drier) climate	$8.41	$7.66	$5.40	$7.03

Table 7-1: Derived prices for the four payout functions under the two climate scenarios depicted in Figure 7.2, using equation 7.1.

It is also evident that with gradient or multi-step payout functions, changes in the variability and shape of the distribution become more important because nuances of the tail distribution have more significant implications for expected losses. Consequently, another avenue of future modeling research may be to more explicitly include how the severity of extreme events and the frequency of multiple levels of extremes change in a changing climate context. Such a study, while theoretically interesting, may be a bit premature in the absence of an experiential understanding of index insurance best practices. Furthermore, such a study, in exploring the more extreme tails of the distribution may need to make use of generalized extreme value theory.

7.4. Future Practical Work: In practical terms of index insurance implementation, future work should focus on multiple avenues of stakeholder engagement. In all likelihood, different farmers will have different needs and a range of potential index insurance products should potentially be offered to various client populations. Some may prefer higher premium cost, higher frequency of payout contracts as some experimental projects have found (Norton et al., 2014). Others may prefer lower cost, lower frequency of payout contracts, especially if there is a perception of a higher probability of basis risk. Clearly, there is also a potential need to explore insuring crops other than millet and irrigated rice. Clearly, one obvious response to these potentially differentiated preferences is to offer contracts based on a range of strike levels, so the insured population can choose their level of coverage. Furthermore, there may be differences in preference for different types of contract design; some may prefer simple step function, while others may prefer gradient or multi-step functions. If there is a range of contract options available, there may be more interest in index insurance, although the challenge of communicating and pricing the different options may also increase simultaneously.

Index insurance projects have been brought into existence at a wide range of scales from the village level to the national level and have been sold to individuals, groups and governments (Hellmuth et al., 2009; World Bank 2011). Stakeholder engagement at multiple levels will be critical to effectively implementing index insurance contracts that meet real needs in a changing climate context. Stakeholder and participatory methods will also be crucial to communicating the limitations of index insurance and eliminating cultural barriers and promoting trust.

While this dissertation research has focused on modeling the costs of drought index insurance for millet farmers and flood index insurance for irrigated rice farmers, future "bundled" contracts could also engage other populations, such as the pastoralist community who face significant drought exposure risk and/or the irrigated cotton farming populations of Mali and Burkina Faso. Engaging pastoralist communities (such as the Tuareg) may be politically and/or logistically challenging, but may also help to address that vulnerable population's needs. In a similar vein of intra-societal equity, arguably index insurance should be sensitive to existing gender divisions. If the vast majority of farmers who sign up for index insurance are male, this may become another avenue through which women are marginalized by well-intentioned adaptation projects. This being said, given the large cultural differences between the "West" and the West African Sahel, an overly autocratic (even if progressive) approach to gender issues (eg. if an index insurance provider were to insist that at least half of the policy holders in a particular town be female) could backfire and undermine the aggregate efficacy of such a project. One potential approach to helping women's climate risk is to create index insurance contracts for cowpeas which are traditionally cultivated and sold by women (Petra Tschakert, personal communication).

In the analysis in Chapter 6, price evolution has been the primary mechanism for communicating evolving climate risk over time. However, this presumption may or may not be in the interests of potential client population(s). While the typical African farmer is unlikely to be deeply knowledgeable about the climate science literature, there is arguably a need for some trusted entity acting on the farmers' behalf to play a role in critically determining whether evolving climate risks should be communicated primarily by evolving price, by evolving thresholds or by some combination of the two. If a European or international insurance company makes a unilateral decision that evolving climate risks should be managed in a particular way in index insurance contracts, without engaging the client population, advocates thereof, or the climate science community sufficiently, antagonism and misunderstanding may ensue and opportunities may be lost. It may be beneficial for this kind of multi-lateral discussion to take place between regional centers of climate research in Africa (like ACMAD, AGRHYMET and ICRISAT), in other regions (such as IRI), agricultural extension workers, local governments and the insurance industry (both large international insurers like Swiss Re and younger, regional insurers (eg. Sen Re, CNAAS, Aveni Re, etc.).

7.5. Final Remarks: This dissertation has discussed the potential of weather index insurance as a climate risk management tool in the West African Sahel in the broader context of global and regional climate adaptation literatures and the assessment of region-specific climate risks. Weather based index insurance holds the conceptual potential to be an adaptation tool for many subsistence farmers (and potentially pastoralists) in the region and some very limited index insurance projects in the region have already been explored within the last several years. Index insurance could be a complementary financial adaptation to pre-existing adaptive practices.

Drought index insurance contracts for subsistence millet farmers in Mali, Burkina Faso and Niger are conceptualized, as are flood insurance contracts for irrigated rice farmers in Niger. The potential of these contracts is evaluated by correlation and Gerrity skill score analysis. The region's climate history has shown significant potential for large changes in hydro-climatic state on multi-decadal time scales; both in the late 20th century and in the more distant past. These past changes to the region's hydroclimatology have been accompanied by significant hardships for the region's diverse populations, but also many forms of resilience and adaptive capacity.

The climate modeling literature remains unclear on how the region's hydro-climatology is likely to change and there are multiple meteorological mechanisms that effect regional hydro-climatology including SST variability in the Atlantic and other tropical basins, biophysical feedbacks on local rainfall and the competing hydrological effects of heat forcing in the interior of northwest

Africa. Monte Carlo simulations are used to simulate the implications of changes in the mean and variability on TCE frequency and the impact of multi-decadal variability on the uncertainty risks. Expected extreme event frequency is shown to be considerably sensitive to changes in the mean. This finding implies that the actuarial cost of index insurance is highly contingent on how the mean climate state changes over time. Multi-decadal variability is shown to be a significant factor in shaping uncertainty risk and consequently has significant implications for the loading costs of index insurance.

While there is no definitive answer to whether index insurance will be viable as an adaptation tool in the West African Sahel in the context of a changing climate, it is clear that the answer is highly contingent on how the region's climate changes and how such a venture is approached. There are many other theoretical and practical issues to be explored with regard to index insurance in this vulnerable region, which go beyond the scope of the present study. Future steps could include (but are not limited to) exploring indices like NDVI or water balance metrics, offering multiple contract design types and coverage levels to clients, linking index insurance to credit, promoting gender equity, and engagement of multiple potential client populations and stakeholders.

References

-Amadou, A., Djibo Abdouramane, G., Ousmane, S., Sanda Ibrah, S., & Sittichok, K. (2014). Changes to flow regime on the Niger River at Koulikoro under a changing climate. *Hydrological Sciences Journal*, (just-accepted).

-Amogu, O., L. Descroix, K. AS. Yero, E. LeBreton, I. Mamadou, A. Ali, T. Vischel, J.C. Bader, I. B. Moussa, E. Gautier, S. Boubkraoui and P. Belleudy, (2010). Increasing River Flows in the Sahel?, *Water, 2,* 170-199.

-Barbier, B. Yacouba, H., Karambiri, H., Zorome, M., Some, B. (2009). Human Vulnerability and Climate Vulnerability in the Sahel: Farmers' Adaptation Strategies in Northern Burkina Faso. *Environmental Management, 43,* 790-803.

-Batisani, N, Yarnal, B. (2010). Rainfall variability and trends in semi-arid Botswana: Implications for climate change adaptation policy. *Applied Geography, 30,* 483-489.

-Bell, A., D. Osgood, B. Cook, K. Anchukaitis, G. McCarney, A. Greene, B. Buckley, E. Cook, (2013). Paleoclimate histories improve access and sustainability in index insurance programs, *Global Environmental Change*, *23,* 774-781.

-Biasutti, M., (2013). Forced Sahel rainfall trends in the CMIP5 archive, *Journal of Geophysical Research: Atmospheres, 118,* 1613-1623.

-Brown, C., and Carriquiry, M. (2007). Managing hydroclimatological risk to water supply with option contracts and reservoir index insurance. *Water Resources Research 43,* W11423.

-Daron, J. and Stainforth, D. (2014). Assessing pricing assumptions for weather index insurance in a changing climate. *Climate Risk Management*, *1,* 76-91.

-Descroix, L., P. Genthon, O. Amogu, J. L Rajot, J. P. Vandervaere, D. Sighomnou, (2012). The Highest Red Flood of the Niger River Ever Recorded in Niamey: Climate Change or Land Use Change? Poster session 8A, Water Resources Quantification and Management and Floods and Extreme Events, *AMMA Conference,* Toulouse, France.

-deMenocal, P., J. Ortiz, T. Guilderson, J. Adkins, M. Sarnthein, L. Baker, and M. Yarusinsky, (2000). Abrupt onset and termination of the African Humid Period: rapid climate responses to gradual insolation forcing. *Quaternary Science Reviews, 19,* 347-361.

-Hellmuth M.E., Osgood D.E., Hess U., Moorhead A. and Bhojwani H. (eds) (2009). Index insurance and climate risk: Prospects for development and disaster management. Climate and Society No. 2. International Research Institute for Climate and Society (IRI), Columbia University, New York, USA.

-Hiernaux, P., (1996). The Crisis of Sahelian Pastoralism: Ecological or Economic? Network Paper 39a, *Overseas Development Institute*, Pastoral Development Network.

-Janicot, S., Moron, V., & Fontaine, B. (1996). Sahel droughts and ENSO dynamics. *Geophysical Research Letters*, *23*, 515-518.

-Ji, L., and Peters, A. (2005). Lag and Seasonality Considerations in Evaluating AVHRR NDVI Response to Precipitation. Photogrammetric Engineering & Remote Sensing, 71, 1053-1061.

-Li, J., Lewis, J., Rowland, J., Tappan, G., & Tieszen, L. L. (2004). Evaluation of land performance in Senegal using multi-temporal NDVI and rainfall series. *Journal of Arid Environments*, *59*, 463-480.

-Leblois, A., Quirion, P. (2013). Agricultural insurances based on meteorological indices: re- alizations, methods and research challenges. *Meteorological Applications, Royal Meteorological Society*, *20,* 1-9.

-Mohino E., S. Janicot and J. Bader, (2011). Sahel Rainfall and Decadal to Multi-Decadal Sea Surface Temperature Variability, *Climate Dynamics*, *37,* 419-440.

-Ndiaye, O., M. N. Ward and W. Thaw, (2011). Predictability of Seasonal Sahel Rainfall Using GCMs and Lead-Time Improvements Through the Use of a Coupled Model. *Journal of Climate*, *24,* 1931-1949.

-Nicholson, S. E., (1980). The Nature of Rainfall Fluctuations in Subtropical West Africa, *Monthly Weather Review*, *108,* 473-487.

-Nicholson, S., (2005). On the Question of the “Recovery” of the Rains in the West African Sahel. *Journal of Arid Environments, 63,* 615-641.

-Norton, M., Osgood, D., M Madajewicz, E. Holthaus, N. Peterson, R. Diro, C. Mullaly, T. L. Teh, and M. Gebremichael, (2014). Evidence of Demand for Index Insurance: Experimental Games and Commercial Transactions in Ethiopia. *The Journal of Development Studies, 50*, 630-648.

-Oguntunde, P. G., & Abiodun, B. J. (2013). The impact of climate change on the Niger River Basin hydroclimatology, West Africa. *Climate Dynamics*, *40*, 81-94.

-Osgood, D., P. Suarez, J. Hansen, M. Carriquiry, and A. Mishra, (2008). Integrating Seasonal Forecasts and Insurance for Adaptation among Subsistence Farmers: The Case of Malawi. *World Bank Policy Research Working Paper 4651.*

-Shanahan, T., Overpeck, J., Wheeler, C. W., Beck, J.W., Pigati, J., Talbot, M., Scholz, C., Peck, J. and King, J. (2006). Paleoclimatic variations in West Africa from a record of late Pleistocene and Holocene lake level stands of Lake Bosumtwi, Ghana. *Palaeogeography, Palaeoclimatology, Palaeoecology 242*, 287–302.

-Siebert, A. and Ward, M. N. (2011). Future occurrence of threshold crossing seasonal rainfall totals: methodology and application to sites in Africa. *Journal of Applied Meteorology and Climatology 50,* 560–578.

-Siebert, A. and Ward, M. N. (2013). Exploring the frequency of hydroclimate extremes on the Niger River using historical data analysis and Monte Carlo methods. *African Geographical Review,* online publication.

-Skees, J., (2007). Challenges for Use of Index-Based Weather Insurance in Lower Income Countries. *A GlobalAgRisk publication.*

-Sultan B., S. Janicot and A. Diedhiou (2003). “The West African Monsoon Dynamics. Part I: Documentation of Intraseasonal Variability”, *Journal of Climate, 16,* 3389-3406.

-Tarhule, A. and Akumaga, U., (2014). Climate Change Impacts on Rain-Fed Agriculture and Crop Yields in the Niger Basin. *Climate Risk Management Session, AAG annual meeting.*

-Wang, J., Rich, P., and Price, K. (2003). Temporal responses of NDVI to precipitation and temperature in the central Great Plains, USA. *International Journal of Remote Sensing, 24,* 2345-2364.

-Ward, M. N., E. M. Holthaus, A. Siebert, and D. Osgood (2008). Index Insurance for Drought in the Millennium Villages Project. *American Meteorological Society Conference*, 20th Conference of Climate Variability and Change, P1.9.

-Ward, M. N., Brown, C., Baroang, K., & Kaheil, Y. (2012). Reservoir performance and dynamic management under plausible assumptions of future climate over seasons to decades. *Climatic Change, 18,* 307–320.

-World Bank report, (2011). Weather Index Insurance For Agriculture: Guidance for Development Practitioners. Agriculture and Rural Development Discussion Paper 50.

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-Siebert, A., (2014). Hydroclimate Extremes in Africa: Variability, Observations and Modeled
Projections", *Geography Compass, 8,* 351-367.

-Siebert, A. and Ward, M. N. (2013). "Exploring the frequency of hydroclimate extremes on the Niger River using historical data analysis and Monte Carlo methods". *African Geographical Review*, online publication.

-Siebert, A. and Ward, M. N. (2011). Future occurrence of threshold crossing seasonal rainfall totals: methodology and application to sites in Africa. *Journal of Applied Meteorology and Climatology, 50,* 560–578.