CLIMATE CHANGE AND ITS ECOLOGICAL AND SOCIOECONOMIC IMPACT:

EVIDENCE FROM CHINA'S HISTORICAL DOCUMENT FOR QING DYNASTY

(1644-1911).

by

YUFEI WANG

A Dissertation submitted to the

Graduate School-New Brunswick

Rutgers, the State University of New Jersey

In partial fulfillment of the requirements

For the degree of

Doctor of Philosophy

Graduate Program in Ecology and Evolution

Written under the direction of

Ming Xu, Ph.D.

And approved by

____

____

____

____

New Brunswick, New Jersey

[May, 2010]

ABSTRACT OF THE DISSERTATION

CLIMATE CHANGE AND ITS ECOLOGICAL AND SOCIOECONOMIC IMPACT: EVIDENCE FROM CHINA'S HISTORICAL DOCUMENT FOR QING DYNASTY (1644-1911).

By YUFEI WANG

Dissertation Director:

Ming Xu, Ph.D.

Climate change is currently of great concern by scientist and public. However, the ecological and socio-economic effects of long-term climate change remains largely unknown. To study on the long-term climate change, and its impacts on the environmental conditions, ecological and socio-economic consequences, the long time series of climate related events from historical records are needed to fill the gap of the instrumental data. In this study, a unique data source -- "The compendium of Chinese Meteorological records of the Last 3,000 years (Zhang 2004) which contains invaluable information about climate related events recorded in the China's historical documents were digitized for the last Dynasty.

Pearson correlation test was conducted to test the relationship between crop harvest and climate events in case study one. The results revealed that climate conditions affected past agriculture harvest in China. Besides direct effect of cooling on the land carrying capacity, periodic ecological stresses such as drought events can significantly reduce the agricultural yield. The issue of stationarity of variables is the great concern in this study.

Local variations both in temporal and spatial scale analysis were considered in the following case studies. Second case study applied continuous wavelet analysis for analyzing the local variation in temporal scale. The result revealed that the periodicity of fluctuations of locusts, temperature and drought series are consistently at around 100 year's band. The consistent associations between locust and temperature, temperature and drought, locust and drought at same frequency and time space indicted the possible casual interlinks of temperature-drought-locust plague. The finding suggests that drought events driven by long term variation of temperature change explains locust dynamics better than floods.

The last case study used Geographically Weighted Regression methods for analyzing spatially varying relationships between determinate variable--famine and explanatory variables such as floods, droughts, poor harvest and locust outbreaks. The results implicated that all variables have significant effects on famine occurrence in last Dynasty of China. Among the explanatory variables, drought shows strongest effect on famine. The results also suggested that there are significant spatial variations across the study area. Therefore, it's important to consider the local regression methods for analyzing the relationships between famine and other climate conditions.

Dedication

This dissertation is dedicated to my parents, Zhongyi Wang and Yufang Han,

my brother, Yuchi Wang,

my wife, Pingli Jiang

and my daughter Jasmine Jiahui Wang.

Their love and support are behind every page.

Acknowledgement

First and foremost, I wish to thank my advisor, Dr. Ming Xu, for encouraging me to go abroad to continue my study, for his endless guidance and support. His guidance has played a critical role in the development of my research strategies. I am incredibly grateful for the time he has spent with me in the field and the laboratory. It is my sincere hope that we will continue our collaboration in the future.

I also thank the members of my dissertation committee, Dr. Peter Morin, Richard Lathrop, and John Kolassa for serving on my qualifying committee. Their expertise and advice have made a large contribution to this work.

I am deeply grateful to all members of the Ecology program who helped me through seven years of graduate student life. Sincere thanks also go to the staff of the Program, especially for Ms. Marsha Morin, who gave me solutions for every question I encountered. Without her help, everything would have been extremely difficult for an international student like me to survive here and finish the study.

Special thanks go to Dr. Shuo Li, a former visiting scholar from Nanjing Normal University, who helped me found most of the Chinese literature.

I also thank many individuals who helped in my study and research. Dr. Joan Ehrenfeld, David Robison for serving as committee member of qualifying exam and preliminary defense.

Dr. Lyna Wiggins kindly gave me guidance to start this research. Dr. Richard Lathrop and all the members of CRSSA lab, who provide the lab equipment and software, give me a great opportunity to learn and conduct the analysis. My sincere thanks also go to Dr. Peter Morin, who always answered my questions. I'm deeply grateful for his invaluable efforts for his comments on my draft and helping me correct grammar. My colleagues, Issani Sen, Kirsten Schwarz, Juan Wang, and Ai Wen, Han Han, Inga La Puma, Di Li, Kristen, Emily, Jeniffer et al. helped me for the courses. Ai Wen, Kenneth Elgersma, Dr. Wudeneh Letchamo and Mr. Laszlo Pokorny helped me to practice the dissertation defense.

I am also incredibly grateful to the graduate students in Ecology & Evolution. Thank you for helping me through these seven years for enjoying student life here. I will miss all of you for the time we spent together: graduate student seminar, Halloween party, agriculture field day, watching super bowl game, and intramural sports.

Again, I thank all people who stood behind this study and helped me make it through. Although it's only a small step for me, it would not be possible without all your help and support. It means a lot for me, I sincerely thank all of you.

Finally, I wish to thank my parents, my bother, and my friends for unending support and love. A very special thanks to my dear wife Pingli and my daughter Jasmine for the love they give to me.

TABLE OF CONTENTS

List of Tables

List of Figures

1 Genera Introduction

1.1 Background

1.1.1 The background of studies on climate change

Climate is changing throughout the planet's history, with events ranging from Ice Age to Medieval Warm Period (T. M. Cronina 2003). Historically, natural factors such as volcanic eruptions, changes in the Earth's orbit, and variation of the amount of energy released from the Sun affect the change of the Earth's climate (Lamb 1982; Thomas R. Karl 2003). Climate change has affected environment where the people live and further influenced human society through the history of civilization (P. M. Kelly 2000; Karen O'Brien 2004). Therefore it's not surprised that people started observing and recording the climate phenomenon since thousands of year ago (Chu 1926). Through those efforts and activities, scientists improved our understanding of the impact of climate events on the human society, predicting the future climate change and helping management and making policy decisions.

For the past 200 years, human activities associated with the Industrial Revolution were believed that has caused increasing of the concentration of "greenhouse gases" in the atmosphere (James E. Hansen 1990; J. F. B. Mitchell 1995; Bruce A. McCarl 2001; D. A. Stainforth 2005). According to NOAA and NASA data, the Earth's mean surface temperature has been increased by about 1.2 to 1.4ºF in the last 100 years (IPCC 2001). There is a high level of confidence that the global mean temperature during the last few decades is higher than any other period during the last 400 years (Gian-Reto Walther 2002). Eleven of the last twelve years rank among the 12 warmest years since 1850, with the warmest two years being 1998 and 2005 (Council 2006). Besides the warming temperature, other aspects of the climate are also changing, such as rainfall patterns, snow and ice cover, and sea level, etc (John J. Magnuson 2000; Lonnie G. Thompson 2002). Those events have evoked tremendous studies on the global climate change (Schneider 1989). Scientists now believe that human activities are one of the driven factors that change the composition of the atmosphere, which lead to increasing in the concentration of greenhouse gases and climate changing (Landsberg 1970). However, less confidence can be assigned to estimate hemisphere or global mean temperature prior to A.D. 900 due to limited data or challenges in analyzing historical data. Without information of long-term variations of climate, it's not confident to say that the magnitude and persistence of current climate has been systematically changed, or those dramatic changes could be a false impression generated by the improved observations and intensified studies. To extend our knowledge of the long term trend of climate change and its impacts on environment, ecosystem and human society, it's important to study the trends, patterns, variations and mechanisms of past climate. Nevertheless, the reliable instrumental measurements can only cover a minute fraction of history. To study past climate, especially the long term climate variation, it's necessary to use the variety of historical proxy data sources. Such proxy data sources can be environmental data--natural evidence or historical documents--human records. While the natural evidence can be interpreted by normal field and laboratory techniques and therefore provide the quantitative information; descriptions of climate related events in historical documents are another important potential data source to provide useful information about the past climate change.

1.1.2 The background of studies on past climate change and its impacts

The international conference on “Climate and history” in 1979 is the landmark of the first meeting that addressed the issues of past climate change and its impacts on human societies (T.M.L. Wigley 1981). In 1991, Past Global Changes (PAGES) was founded as a core project of the International Geosphere-Biosphere Programme (IGBP) to support the study which can improve our understanding of the Earth’s past environment. From then on, scientists from different perspectives started cooperation and conducted interdisciplinary studies (Schneider 1977; John Reilly 2001; Richard G. Pearson 2003; Stillman 2003). Instead of historians were not aware of the climate change and implication of impacts of climate change; or climatologists ignore the information of history, recent studies have used high-resolution proxy data to reconstruct past climate and developed the disciplines for palaeo-climatology (Mark Elvin 1998).

Flohn is one of the first scientists who used the historical records to reconstruct past climate data (M.J. Ingram 1981). He noticed that the ratio of days of snowfall to the days of rainfall in winter was well correlated with winter temperature. Based on the ratio of snow days to temperature from modern instrumental observation, he reconstructed the past winter temperature for Hven, Denmark, 1582-1597 and of Haller for Zurich 1546-1576. The limitation of such analysis is that it needs continuous series that recorded on a fixed observational time and are easily expressed in a numerical form.

There have been many studies focusing on reconstructing the past climate series, especially in terms of the temperature and precipitation. Those studies used either natural evidence or historical records to provide evidence of past climate change and reveal the temporal trends and spatial patterns of past climate, such as tree rings (Jan Esper 2002;

Keith R.Briffa 2002), corals (Michael N. Evans 2002; Kim M. Cobb 2003), ice cores (Yao Tandong 1996; Yao 1997), lake/ocean sediments (Oliver Heiri 2003), pollen (B. A. S. Davis 2003) and the historical records (P.D. Jones 1998; Thomas J. Crowley 2000; Bao Yang 2002; Bradley 2003). Most common methods for reconstructing the past climate are tried to find the correlation between proxy data and instrumental data and then applied this relationship to the past. Although some of reconstruction series have a high temporal resolution at annual scale, they can only represent a single point. Therefore we can not use it along to study the patterns of past climate at the large spatial scale (Mann 2002). To address this issue, multiple-proxy data network, such as Global Historical Climatology Network--GHCN (Thomas C. Peterson 1997), was founded to solve this problem and has significantly improved in high-resolution palaeo-climate reconstruction for the last 20 years by the multi-proxy data network. Besides focusing on the reconstruction of past climate data, there are also many studies that explored the information from historical documents to reveal the relationships and interactions between past climate change and environmental, ecological and socio-economic functions. Although such relationship have been studied by using the instrumental or survey data, people are seldom aware of history or have little knowledge about the past, especially for the pre-industry era when the impact of climate change on environment and ecology was more natural with mild human influence than current situation. Some of scientists tend to ignore the information from historical documents because they only believe the measurement, and then require data which are, in Le Roy adurie's words, "continuous, quantitative, and homogeneous." (Vries 1980). The question is if we are eager to learn the past, how can we interpret historical records?

1.1.3 The background of China's historical climate documents and related studies

1.1.3.1 General review of historical documents of China

Using climate records from historical documents to reconstruct past climate has been conducted in several areas around the world where the data are available, such as Europe and East Asia (Mikami 1996; Michael E.Mann 1998; Mark New 2000; Ju¨rg Luterbacher 2004; Rudolf BráZdil 2005; Mikami September 1999) and has been well acknowledged and cross-referenced by other methods and studies (Jiacheng Zhang 1989; Weihong Qian 2001; Quansheng Ge 2007).

Historical climate documents of China are by far the most extensive archives than any other historical dataset (Zhang 1991) and they represent one of the best historical records for the study of climate of the last 500 years (Jiacheng Zhang 1989). The reconstructed data extracted from the historical documents often has higher temporal and spatial resolution than those reconstructed from natural evidence. Such reconstructed past climate series have been used by many studies and show highly correlation with the data from other Northern Hemisphere land areas (Bradley 1993).

Although the historical records of climate events were believed that can cover three thousands year's history of China, those records were not extracted from the unique source. The source of these records can be Chinese classical documents, local gazettes and special archives. Therefore, the consistency and systematic methodology of records are not guaranteed through 3000 years. Only the period from 1400 to 1900 has the most comprehensive and consistent gazettes system within county-level. This period was also named as "Fang-Zhi (local gazettes) Epoch" by Chu CoChing, who was the leading geophysical scientist and establish the first geosciences' program and climate study in

China (Chu 1973). Local gazettes are comprehensive annual books in a given district (county, provinces, etc.), that consistently recorded all kinds of momentous climate related events, such as natural and social-economical events by officials and private scholars. Usually, the local gazettes have special volumes to collect description directly related with climatic phenomena, such as cloud, sunny/rain, frost/snow, wind, hail/thunder, sand/dust rain etc.; Local gazettes also contain other special volumes which record phenomena related to the extreme climate events, such as flood/drought, severe cold/warm and phenology events as well. Besides the volumes recording climate information, local gazettes also have special volumes to record disasters and other social-economical events such as agriculture harvest, crop failure, locust's outbreak, famines, plagues etc. Local gazettes established their systematic and sophisticate compiling manners in the Song Dynasty (from 960 A.D. – to 1279 A.D.) and got popular over the entire area where dominated by China's main nationalities in the Ming and Qing Dynasties (from 1368 A.D. – to 1911 A.D.). Therefore, Climatic information that recorded in the local gazettes during the "Fang-Zhi Epoch" period covers the widest area and has the most intensity and most systematic composing rules for the historical documents around the world. The limitation of most of other historical documents is that they were written by human being and has the bias of individual influence. For instance, that reliability of records depends on the spatial and temporal distance of location of recorder to climate phenomenon, which argued as "It's more accuracy if the recorders are closer to the events in terms of both time and space"(Quansheng Ge 1990).

1.1.3.2 Study of China past climate change using historical records

Chu published his eminent article “The preliminary study of climate change of China in 5000 years” in 1973 (Chu 1973). Since then, there has been many studies that explored the climate information from China historical documents (Wang 1979; Pao K. Wang 1988; GE Quansheng 1990) and evolved in the reconstruction of past climate change (Zhang 1979; Jiacheng Zhang 1989; Jianmin Jiang 1997; Kam-biu Liu 2001; Zhao Huixia ZJ 2004; GE Quansheng 2006; Quansheng Ge 2007).

Exploring the past climate information from tremendous historical documents directly can be an arduous task. Previous studies solve this problem by using some compendium which already published and collected the climate related documents (Chen 1939; Central Meteorological Institute 1981). Recent studies also explored useful information from some specialized archives based on the interested aspects. Those archives are either reconstructed series for special phenomena or established over 200 hundred years ago to systematically record special climate events. Such as, flood (Hu 1988), drought (Central Meteorological Institute 1981), “Yu-Xue-Fen-Cun” (Quansheng Ge 1990; Zheng Jingyun HZ 2004), war (Editorial Committee of China's Military History. (1985), locust (Ma 1958; Ma 1965). For instance, a co-operative team from the Research Institute of the National Meteorological Service, Nanjing University and Peking University studied on droughts and floods in the past 5000 years and published the reconstruction of a series of drought and flood charts from 1470 to 1977 (Central Meteorological Institute 1981). Based on these charts, empirical orthogonal analysis and power spectrum analysis were used to examine the spatial and temporal variations for drought and floods in China, 1470-1979 (Wang Shaowu 1981), as well as the drought

(Song 2000; W.-H. Qian 2003). The summary of sources of historical government documents and local gazette of China is in the appendix section.

Until recent years, most of previous studies using China's historical records to study past climate change focused on reconstructing past climate change, especially the reconstruction for temperature and precipitation series data. A general way to reconstruct the past climate data is to build the relationship between the historical records and instrumental data which are overlapped over same period and then apply this relationship back to the period which has the historical record to interpolate data. For instance, Zhou et. al. reconstructed the winter mean temperature in Hefei City in central China by constructing relationship between the mean temperature and snow-fall days using instrumental data from 1952 to 1970 and then supplemented the gap by regression based on this relationship (Qingbo Zhou PZ 1994). Zhang et al. used the cold winter, frost, flood, and drought as index to explore the relationship between the climate change and agriculture since 16th century (Zhang 1979). Ge et. al. reconstructed the winter half-year temperature for the middle and lower reaches of the Yellow River and Yangtze River based on the correlation between the individual sites and regional mean temperature from modern instrumental data (Ge Quansheng 2003).

Another way to reconstruct past temperature rising up recently used one special archive which contains more quantitative data, such as the "Yu-Xue-Fen-Cun" records (the infiltration of soil depth of rain and accumulate depth of snow) to provides quantitative information about past temperature and precipitation (GE Quansheng 2004; Zheng Jingyun HZ 2004; Zheng Jingyun HZ 2004; GE Quansheng 2005; Zheng Jingyun 2005). Hao et. al. (2003) reconstructed the annual winter mean temperature and seasonal precipitation series from l736 to 2000 based on snow, rainfall and harvest archives records in the Qing Dynasty and the modern meteorological observation data and the relationship between climate change and harvest was analyzed as well.

Besides using historical documents to reconstruct temperature or precipitation, recently some interdisciplinary studies explored the relationship between past climate change and ecological, social events by using historical documents. For an example, a case study on the impact of climate change on the environment by using multi-proxy reconstructed temperature, precipitation and drought index for the last 100 years which based on 35 stations of 10 regions (Weihong Qian 2001). David Zhang presented several studies to show relationship between frequency of war incidents and climate change (David D. Zhang 2006; David D. Zhang 2007; David D. Zhang 2007). Stige revealed the association between locust outbreak and temperature on a decadal scale (Leif Christian Stige 2007).

1.2 Objective and Project Significance

It is critical that fully understanding history will help us understand the current situation and better predict the future. After we learned from the past, we can study and understand the current situation to assess its future possibilities and probabilities. To achieve this goal, it is important to use surrogate data to examine long term variability and trends of climate change.

Historical documents of China have been well acknowledged in past climate change studies and have been extensively used to successfully reconstruct past climate (Chu 1973; Jiacheng Zhang 1989; QuangSheng Ge 2005; Quansheng Ge 2007). Most of those studies focused on reconstructing single type of past climate condition. Those reconstruction also relied on the records from single or a few locations (Quansheng Ge 2003; Zheng Jingyun HZ 2004). Therefore, the reconstructed series often lack of spatial representation. Few spatial analyses have been conducted due to lack of high spatial resolution data. Because the tremendous efforts needed to recover information from historical documents, previous studies mostly relied on a few compendiums. It's also hard to conduct interdisciplinary study to explore the association among climate phenomenon and other events because traditionally each compendium only collected information for one special type of events. Although studies on associations between the climate change and environment, ecosystem, and human society are expected since the end of the last century, few studies has addressed this issue due to data limitation on high resolution data about past climate events.

In this study I used a unique data source (Zhang 2004) to explore temporal-spatial trends and patterns of extreme climate events and their relationships with other environmental, ecological and social-economic events. The book provided invaluable information about climate conditions in the past and their effects on environment, ecosystem, and human society. It took over twenty years for Chinese scientist and historians to collect the information from the most extensive documentary archives in China. Because of it's potential value for past climate change in China, it has been mentioned and looking forward by other scientist (Cheke 2007). By using more integrative approaches, the compendium provides information on a large area, longer-term climate events to show promise in analyzing the impacts of past climate is general has become more variable or extreme.

However, the invaluable compendium is in Chinese, which is inaccessible to most scientists and historians outside China. The effort to translate them all into English and make them available electronically can not only make them more useful to the large research community, but also provide a foundation for future research on past climate change, with information about impacts on environment conditions, ecosystem, and human society.

The aim of the study is to conduct the case study based on the information provided by the compendium, by digitalizing the historical records, to improve our understanding of historical truth in climate change, and its impacts on environmental conditions, ecological process and socio-economic consequences. Thus, it is possible that long-term historical records in China could provide valuable indications on climatic variations over a large portion of the Northern Hemisphere. This study also examined possible climate events in terms of temporal and spatial variations of floods/droughts and its impact on ecological, environmental, and social-economic aspects. This will help us to understand the relationship between the climate change, environment and human society.

1.2.1 Ecological aspects (Agricultural harvest)

1.2.1.1 Introduction

Abnormal climate events have caused widespread concern among meteorologists and climatologist because it could cause severe disaster to natural environment and human society. Recently, besides analyzing the mean of global temperature change, scientists noticed the importance of the impacts of extreme events—in terms of variance of the climate change on the ecological service (Zhibin Zhang 1999). Giving the argument by some recent studies that climate change may cause decreasing in land carry capacity and therefore cause severe social-economic disaster, such as war, loss of human life, etc (David D. Zhang 2007), it's critical to examine the relationship between climate change and crop productivity in the history. Historical records not only extend our knowledge to the past, but also present us a 'new' world with less human disturbance. To understand how climate events and environmental conditions affect the agriculture harvest in the past is crucial for the study on the interaction between climate and ecology.

1.2.1.2 Hypotheses

The variation of agriculture harvest has been associated with climate change in the past.

Drought is the most significant variable which influences the agriculture harvest.

The relationship between climate change and crop harvest may vary in the different regions.

1.2.1.3 Methods

To test whether historical agricultural harvests, reconstructed climate data (in terms of temperature and precipitation), and past climate extreme events (drought and floods) are related with each other, the most common methods--Pearson's correlation test was used to measure the strength of an association between two variables.

To test the whether associations between variables have a time lag, the correlation test also conducted with the time lag.

To test whether variation of regional climate change affected the relationships between variables, the study area was divided into separate regions. Then Pearson's correlation test was conducted in each region to compare the difference of the associations among the regions.

Each variable was plotted on the map to examine the general spatial patterns of each variable, several spatial statistics were used to test the spatial clustering and spatial autocorrelation by using the spatial analysis tools in ArcGIS, and hot-spot analysis were employed to discover the hot-spots of interested events.

1.2.2 Ecological aspects (Locust outbreak)

1.2.2.1 Introduction

Locusts are regarded as one of most serious pests that impact the agricultural societies in terms of crop poor harvest, famine and economic loss (Seiji Tanaka 2005). In the ancient times, severe crop damage by locust plague may lead people starve to death and spread disease. Such locust plagues are often triggered by the climate factors, such as heavy rain, drought, or floods (Lima 2007). Therefore it's very important to explore the relationship between the climate change and the occurrence of locust plague. However, to distinguish the density-independent environmental factors and density-dependent population processes often require a longer series to reveal the properties of an underlying process (Gian-Reto Walther 2002; Tim G. Benton 2006). The 50 to 100 years instrumental observation is not sufficient for investigations of long- term variations of climate and its impact on the ecological aspects. Stige (2007) used the simple statistical model to analyze how a 1000-year time series of locust plague in China is related with the reconstructed climate. Although the locust dynamics are proved that positively correlated to temperature at the annual scale, in Stige's et al. study, there is a negative association between temperature and locust dynamics at the decadal and regional scales. This complex association reflects at the long-term change the driving factor for locust outbreak is the dynamics of suitable habitats rather than local fluctuations due to mortality and birth rates (Lima 2007). The process of population changes in long term underlying the low-frequency variability which related to habitat, vegetation and productivity patterns change in a large-scale are different with that in community scale This indicates that factors limiting natural populations will change and shift from time to time in terms of multi-decadal and century scale. Unfortunately, human societies are used to adapt the long and slow shift of climate change and failed to detect it. Moreover, human activities, such as pesticide and irrigation infrastructures, have changed both the endogenous and exogenous (climate) forces. Although the historical records of climate change and locust outbreak are criticized by some scientists that they are more descriptive and mostly depend on human interpretation, they can still provide direct evidences to examine the relationship between the naturally outbreak locust plagues and climate variation, such as temperature/precipitation, flooding/drought, etc. as well as the impact of locust plague on the harvest and famine. Historical records not only extend our knowledge to the past, but also present us a ‘new’ world with less human disturbance. To understand how heavy rainfall, droughts or flooding result in the locust plague is crucial for the study on the interaction between climate and ecology. The objective of this study is to explore the temporal trends and pattern of locust dynamics and other climate variables, such as temperature, precipitation, flood, and drought events.

1.2.2.2 Hypotheses

Low temperature and drought are two driving factors of locust outbreak in the natural ecosystem.

There is a possible link that climate change driven extreme events affect the outbreak of locust.

1.2.2.3 Methods

Wavelet transform methods and wavelet analysis was used in this study to reveal variation components in the historical series and reconstructed series, which has been widely applied in signal detection from climate variable series (K.-M. Lau 1995) and is most efficient and appropriate methods for studying non-stationary ecological time series. Wavelet analysis is becoming a common tool for analyzing localized variation of a time series (Christopher torrence, 1998). Wavelet analysis can determine the periodicity of variability and reveal how they vary in time, by decomposing a time series into a time-frequency space. A new wavelet analysis tool—SOWAS for continuous wavelet analysis (D. Maraun 2004; D. Maraun 2007), including statistical significance testing, was applied to the time series of locust plague, and other climate series, such as temperature, precipitation, floods, and droughts.

1.2.3 Social-economic aspects (Famine)

1.2.3.1 Introduction

Extreme climate events affect human society dramatically, in terms of crop damage, food deficiency, mortality and social unrest. In deed, a fundamental influence of climate change on human society is its effect on food production (Henry F. Diaz 2001). Sever famines have been a longstanding calamity for the natural agriculture societies everywhere. China experienced even more famine than any other country due to her large population and extensive cultivation history so that Walter H. Mallory named his book

“China: Land of Famine” (Mallory 1926). However, extreme event was often regarded as a random event rather than gradually climate change. Therefore, its impacts on social, economic aspects, such as famine, plague and war was rarely recognized by climate change studies. Recently scientists argued that sudden climate change does exist and has strong affect on human society. Such sudden events make human society unable to adjust to climate change which lead to severe immigration, starvation and social instability (Jonathan Adams 1999). For instance, strong and significant correlations were found between climate change, agriculture harvest and war occurrence in China over the last millennium by using the historical documents (David D. Zhang 2006).

Historically, Chinese agriculture has frequently suffered from climatic variations and changes such as floods, droughts, mud flows, landslides, typhoons, dust storms, and pests and diseases (Barry Smit 1996). Therefore, it’s not surprised that China has a long history of recording climate disaster events and harvest of crop. Ancient Chinese exploring the relationship between the climate variation and agriculture can be dating back to 4th century. In a famous ancient agronomy book “Qi-Min-Yao-Shu” (“Human’s skills for subsistence”) appeared in the northern Wei Dynasty (386-534AD), Jia Sixie pointed out that ‘Harvest can be achieved by less effort if the climatic rules are followed and the land suitability is taken into play’.

All of four components of food security---food availability, food accessibility, food utilization, and food production systems are affected by the changes in climate variability. Among those components, food availability is most intimately associated with climate and climate changes (FAO. 2008). Increased floods, droughts and locust outbreaks due to the climate change have an important implication for agriculture harvest. Increased frequency and intensity of drought and flood would be a great threat to stability of food availability.

Current studies on agriculture vulnerability focused on the physical and biological aspects of climate change by using simulation model to examine the effects of rapid climatic change on agriculture productivity (Gretchen C. Daily 1990; Fulu Tao 2003; M.L. Parry 2004), which focus on the effect of green house gas and simulated climate change, in terms of temperature, precipitation and CO_2. Only few studies addressed food supply under past climate change. For instance, Hao et al. explored the relationship between climate change and harvest, again using the "Yu-Xu-Fen-Cun" records (Hao Zhixin 2003).

In this study, I consider the effects of past climate change on food supply and famine through environmental conditions, and ecological consequences, expressed in terms of extreme drought/flood events and the agriculture poor harvest, locust plague. The goal of the study is to understand the nature of the complex interactions, and how they affect human society in terms of famine in the past three hundreds years.

1.2.3.2 Hypotheses

Proposed explanatory variables, such as flood, drought, agriculture poor harvest, and locust plague all affect the famine occurrence in the pre-industry society.

Water is the most critical factor for Chinese agricultural ecosystems.

Expected variation of climatic variables across the study area will indicate the spatial non-stationary of estimated parameters.

1.2.3.3 Methods

Geographically Weighted Regression Model (GWR) -- a non-parametric locally linear model was used in this study to analyze spatially varying relationships between determinate and explanatory variables.

Before conducted analysis by using GWR model, general global model-- Ordinary Least Squares (OLS) was used to test the spatial non-stationary of explanatory variables and select the candidacy model for fitting GWR.

1.3 Dada

1.3.1 GIS data

The study area was supposed to cover the entire area of China based on the original intention of the compendium. Since the county level was the finest level that the data is available in the compendium, the county-level administrative map of China was adopted in this study. Some modification was made either due to the counties and province which have little or no records or some historical administrative change. The details of reasons and modification methods were included in the appendix.

Because most of compilation works were conducted during the last two decades of the 20th century and compilers adopted the administrative division system in 1990 to relocate the location of each record to the contemporary county, the most suitable county level map is county boundary map for 1990. Therefore, the County Level of China Administrative GIS Data (1990) with 1:1M resolution was used in this study, downloaded from “China Dimensions Data Collection”, the Center for International Earth Science Information Network, Columbia University (http://sedac.ciesin.columbia.edu/China).

1.3.2 Historical climate and other environmental, ecological, social data

The historical data source of the study is from “The compendium of Chinese Meteorological records of the Last 3,000 years (Zhang 2004)”. The compendium is the result of the research projects “A study of the climatic change in China in the past 1000 years” (a key research project under the auspices of the National Meteorological Administration, 1985 -1998) and “Research and compilation of meteorological records in China in the last 3000 years” (under the auspices of Ministry of Personnel, China, 1991-1993). Four impressive volumes, 3666 pages book is the outcome 20 years of work by a team of Chinese scientist and historian led by Zhang De’er of China National Climate Center. The laboriously work started in 1985 and the first draft was completed in October 1994, followed by extensive revisions and finally finished in January 2002. The book includes fundamental data from multiple aspects of weather, climate, ecology, agriculture, meteorological disasters and impact of human activities. 8228 volume of historical documents and books were consulted and 7835 of them were adopted from 75 libraries and archives which located in 37 cities. Those documents include 7713 volumes of local gazette, 28 of chronicles and other governmental documents, memorial to the throne, personal notes and tablet inscriptions.

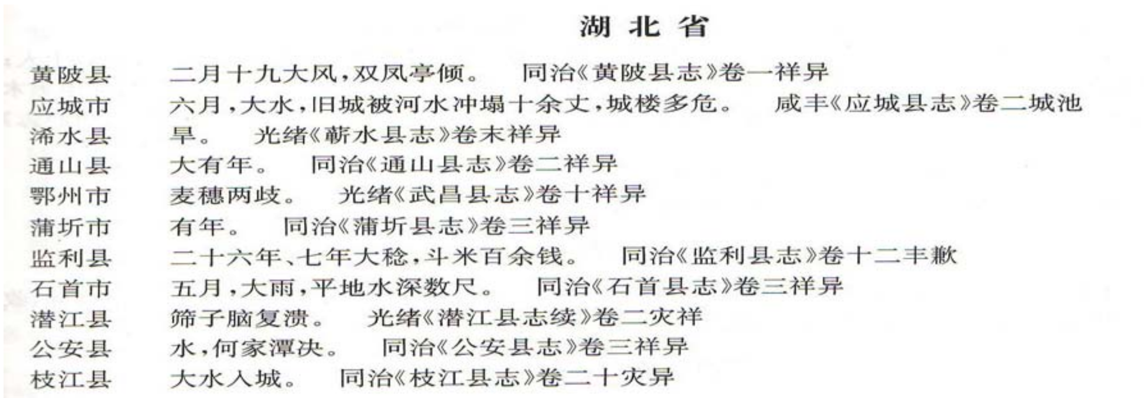
This book contains the mostly systematic and exhaustive collection of climate related information from the historical documents of China. It also represent utmost results of recently work of Chinese scientist who are interested in the past climate change. It is a unique data source with highest temporal-spatial resolution which compiled the various variables in the same dimensions at once. Many scientists are excited and expecting this invaluable information (Cheke 2007) .

The four volumes of compendium covered over three thousands years' history of China past climate change information. Historical records from last three volume were mainly collected from "Xianzhi" (county gazettes) which have been corrected to the current counties name and boundary based on the administrative district in 1990 by compilers. Due to time limitation, in this study only the last two volumes were digitized (Qing Dynasty 1644-1911 A.D.). The historical records of Volume II (Ming Dynasty 1368-1643 A.D.) are also belong to "Fang-Zhi Epoch" which have same recording methodology and description format as that of last two volume. In the future, there are easy to be interpreted and analyzed using the same methods in this study to extend the length of the series data.

In the compendium, not only the meteorological conditions, climate extreme events such as foods, droughts, rain/snow, temperature, frost, hail, wind, thunder, sand storm were collected from historical documents, but also the information about environmental, social phenomenon were also collected, such as agriculture harvest, insect pest, locust outbreak, famine, plague, and phenological records. For instance, a climatic record is like "there was a heavy snow" and an indirect record is "there was locust outbreak in a county in a particular year". To address the types of homogeneity and biasing problem, each record has been carefully checked for consistency with other documents. If discrepancies exist, the earliest source is adopted.

Remarkable compilation also organized the records by data and location, which provide clear reference for times and places—what happened, when, and where? Based on the information from each record and used the references of other study, the historical records were assigned a value depending on the severe level or duration days for each event. Details are in the appendix section. Below are the examples of some description records selected from P 3059, for 1846 of Hubei Province [1](Figure 1-1, **Table 1.1**).

Figure 1-1 Examples of historical records in China


湖 北 省

黄陂县	二月十九大风，双凤亭倾。	同治《黄陂县志》卷一祥异
应城市	六月，大水，旧城被河水冲塌十余丈，城楼多危。	咸丰《应城县志》卷二城池
浠水县	旱。	光绪《蕲水县志》卷末祥异
通山县	大有年。	同治《通山县志》卷二祥异
鄂州市	麦穗两歧。	光绪《武昌县志》卷十祥异
蒲圻市	有年。	同治《蒲圻县志》卷三祥异
监利县	二十六年、七年大稔，斗米百余钱。	同治《监利县志》卷十二丰歉
石首市	五月，大雨，平地水深数尺。	同治《石首县志》卷三祥异
潜江县	筛子脑复溃。	光绪《潜江县志续》卷二灾祥
公安县	水，何家潭决。	同治《公安县志》卷三祥异
枝江县	大水入城。	同治《枝江县志》卷二十灾异

Table 1.1 Translation of examples of historical records

County	Description	Sources[2]
Huangpi County	Feb. 19th, strong wind, the pavilion collapsed	Tongzhi Emperor <Huangpi Xianzhi> volume I (auspicious/strange)
Yingcheng City	June, big flooding, the rampart of old city was breached over 3.3 meters.	Xianfeng Emperor <Yingcheng Xianzhi> volume II (rampart)
Xishui County	Drought	Guangxu Emperor <Qishui Xianzhi> last volume (auspicious/strange)
Tongshan County	Very good harvest	Tongzhi Emperor <Tongshan Xianzhi> Volume II (auspicious/strange)
E'zhou city	Wheat has more than two fringes (usually indicate a good harvest)	Guangxu Emperor <Wuchang Xianzhi> Volume 10 (auspicious/strange)
Puqi City	Good harvest	Tongzhi Emperor <Puqi Xianzhi> Volume III (auspicious/strange)
Jianli County	Both this and the next year had a very good harvest, the price of rice is very low	Tongzhi Emperor <Jianli Xianzhi> Volume 12 (Good/poor harvest)
Shishou City	May, rainstorm, the rain accumulated on the ground about 10 cm.	Tongzhi Emperor <Shishou Xianzhi> Volume III (auspicious/strange)
Qianjiang County	Bank breached again	Guangxu Emperor <Qianqiang Xianzhi> Volume II (auspicious/disaster)
Gong'an County	Flooding, bank breached	Tongzhi Emperor <Gong'an Xianzhi> Volume III (auspicious/strange)
Zhijiang County	Big flooding breached rampart	Tongzhi Emperor <Zhijiang Xianzhi> Volume 20 (disaster/strange)

[1] (1846年，清宣宗道光二十六年 湖北省).

[2] Daoguang Emperor reined the country from 1821 to 1850 A.D. The sequence of Emperor of Qing Dynasty is Shun-zhi, Kang-xi, Yong-zheng, Qian-long, Jia-qing, Dao-guang, Xian-feng, Tong-zhi, Guang-xu, Xuan-tong.

1.3.3 Palaeo climate data

Recent studies have significantly improved high-resolution paleo-climate reconstructed data by using multi-proxy data networks. Those reconstructed temperature and precipitation data can be found in many open sources such as Global Historical Climatology Network (GHCN).

In this study, I used the reconstructed temperature series from Beijing (Ming Tan 2003) and compared it with the NH annual temperature anomaly (Mann 2003) which was adopted by Zhang's previous study. Precipitation data used in this study are reconstructed April-July (AJ) precipitation at Huashan Mountain in north-central China (Hughes 1996), based on Tree-Ring density and width from *Pinus armandii*.

References

Editorial Committee of China's Military History. (1985). Tabulation of Wars in Ancient China. Beijing, Editorial Committee of China's Military History. People's Libaration Army. **II**.

B. A. S. Davis, S. B., A. C. Stevensona, J. Guiot (2003). "The temperature of Europe during the Holocene reconstructed from pollen data." Quaternary Science Reviews **22**(15-17): 1701-1716.

Bao Yang, A. B., Kathleen R.Johnson, Shi Yifeng (2002). "General characteristics of temperature variation in China during the last two millennia." Geophysical Research Letters **29**(9): 381-384.

Barry Smit, C. Y. (1996). "Climate change and agriculture in China." Global Environmental Change **6**(3): 205-214.

Bradley, R. S., D. Shieu, W.-C. Wang (1993). "High resolution paleoclimate records from monsoon Asia." Eos Trans. Amer. Geophys. Union **74**(601): 603-604.

Bradley, R. S., K.R. Briffa, J. Cole, M.K. Hughes and T.J. Osborn (2003). The climate of the last millennium. Berlin, Springer Verlag.

Bruce A. McCarl, U. A. S. (2001). "Greenhouse Gas Mitigation in U.S. Agriculture and Forestry." Science **294**(5551): 2481 - 2482.

Central Meteorological Institute, P. U., Nanking University (1981). The drought and flood charts of China from 1470 to 1977. Beijing, Atlas Press.

Central Meterological Institute, P. U., Nanking University (1981). The drought and flood charts of China from 1470 to 1977. Beijing, Atlas Press.

Cheke, R. A. (2007). "Thinking long term." Science **318**: 577-578.

Chen, G. (1939). The Records of Disasters in Chinese History Jinan, China, Jinan Univ Book Series.

Chu, C. (1926). "Climatic Pulsations during Historic Time in China." Geographical Review **16**(2): 274-282.

Chu, C. (1973). "A preliminary study on the climatic fluctuations during the last 5000 years in China. ." Scientia Sinica (in Chinese) **16**: 226-256.

Council, N. R. (2006). Surface temperature reconstructions for the last 2,000 years. Washington, D.C. : , National Academies Press.

D. A. Stainforth, T. A., C. Christensen, M. Collins, N. Faull, D. J. Frame, J. A. Kettleborough, S. Knight, A. Martin, J. M. Murphy, C. Piani, D. Sexton, L. A. Smith, R. A. Spicer, A. J. Thorpe, M. R. Allen. (2005). "Uncertainty in predictions of the climate response to rising levels of greenhouse gases." Nature **433**: 403-406.

David D. Zhang, C. Y. J., George C-S Lin, Yuanqing He, James J. Wang, Harry F. Lee (2006). "CLIMATIC CHANGE, WARS AND DYNASTIC CYCLES IN CHINA OVER THE LAST MILLENNIUM." Climatic Change **76**: 459-477.

David D. Zhang, J. Z., Harry F. Lee, Yuan-qing He (2007). "Climate Change and War Frequency in Eastern China over the Last Millennium." Human Ecology **35**: 403-414.

David D. Zhang, P. B., Harry F. Lee, Yuan-Qing He, Jane Zhang (2007). "Global climate change, war, and population decline in recent human history." PNAS **104**(49): 19214-19219.

FAO. (2008). Climate change and food security: a framework document. Rome, Food and Agriculture Organization of the United Nations.

Fulu Tao, M. Y., Yousay Hayashi, Erda Lin (2003). "Future climate change, the agricultural water cycle, and agricultural production in China." Agriculture, Ecosystems and Environment **95**: 203-215.

GE Quansheng , W. S., ZHENG Jingyun (2006). "Reconstruction of temperature series in China for the last 5000 years." PROGRESS IN NATURAL SCIENCE **16**(8): 838-845.

GE Quansheng , Z. J., MAN Zhimin , FANG Xiuqi, ZHANG Piyuan (2004). "Key points on temperature change of the past 2000 years in China." PROGRESS IN NATURAL SCIENCE **14**(8): 730-737.

GE Quansheng , Z. P. (1990). "The evaluation on climatic information in the historical literatures." ACTA GEOGRAPHICA SINICA (in Chienese) **45**(1): 22-30.

Gian-Reto Walther, E. P., Peter Convey, Annette Menzel, Camille Parmesan, Trevor J. C. Beebee, Jean-Marc Fromentin, Ove Hoegh-Guldberg, Franz Bairlein (2002). "Ecological responses to recent climate change." Nature **416**: 389-395.

Gretchen C. Daily, P. R. E. (1990). "An exploratory model of the impact of rapid climate change on the world food situation." Proceedings: Biological Sciences **241**(1302): 232-244.

Hao Zhixin, Z. J., Ge Quansheng (2003). "Climate change and Harvest in Xi'an since 1736: the high-resolution data derived from the archives in the Qing Dynasty." ACTA GEOGRAPHICA SINICA (in Chienese) **58**(5): 735-742.

Henry F. Diaz, R. S. K., Anthony, J. McMichael, Neville Nicholls (2001). Climate and Human Health Linkages on Multiple timescales. . History and Climate: Memories of the Future? A. E. J. O. P. D. Jones, T. D. Davies, K. R. Briffa, Kluwer Academic/Plenum Publishers.

Hu, M., Luo, CZ (1988). Chinese historical great flooding events. Beijing, Book Store Press.

Hughes, M. K., X. D. Wu, X. M. Shao, G. M. Garfin (1996). Precipitation Reconstruction for Huashan, China., International Tree-Ring Data Bank. IGBP PAGES/World Data Center for Paleoclimatology Data Contribution Series # 96-020. NOAA/NGDC Paleoclimatology Program, Boulder CO, USA.

IPCC (2001). Climate Change 2001: Working Group I: The Scientific Basis. . Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Y. D. J.T. Houghton, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, C.A. Johnson (eds.) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

J. F. B. Mitchell, T. C. J., J. M. Gregory, S. F. B. Tett (1995). "Climate response to increasing levels of greenhouse gases and sulphate aerosols." Nature **376**: 501-504.

James E. Hansen, A. A. L. (1990). "Sun and dust versus greenhouse gases: an assessment of their relative roles in global climate change. ." Nature **346**: 713-719.

Jan Esper, E. R. C., Fritz H. Schweingruber (2002). "Low-Frequency Signals in Long Tree-Ring Chronologies for Reconstructing Past Temperature Variability." Science **295**: 2250.

Jiacheng Zhang, T. J. C. (1989). "Historical Climate Records in China and Reconstruction of Past Climate." **2**(8): 833-849.

Jiacheng Zhang, T. J. C. (1989). "Historical climate records in China and reconstruction of past climates." American Meterological Society **2**: 833-849.

Jianmin Jiang, D. E. Z., Klaus Fraedrich (1997). "Historic Climate Variability of Wetness in East China (960-1992): A Wavelet Analysis." International Journal of Climatology **17**: 969-981.

John J. Magnuson, D. M. R., Barbara J. Benson, Randolph H. Wynne, David M. Livingstone, Tadashi Arai, Raymond A. Assel, Roger G. Barry, Virginia Card, Esko Kuusisto, Nick G. Granin, Terry D. Prowse, Kenton M. Stewart, Valery S.

Vuglinski (2000). "Historical Trends in Lake and River Ice Cover in the Northern Hemisphere." Science **289**(5485): 1743.

John Reilly, P. H. S., Chris E. Forest, Mort D. Webster, Henry D. Jacoby, Ronald G. Prinn (2001). "Uncertainty and climate change assessments." Proceedings of Science **293**(5529): 430-433.

Jonathan Adams, R. F. (1999). "Sudden climate transitions during the Quaternary " Progress in Physical Geography **23**(1): 1-36.

Ju¨rg Luterbacher, D. D., Elena Xoplaki, Martin Grosjean, HeinzWanner (2004). "European Seasonal and Annual Temperature Variability, Trends, and Extremes Since 1500." Science **303**: 1499-1503.

K.-M. Lau, H. W. (1995). "Climate Signal Detection Using Wavelet Transform: How to Make a Time Series Sing." Bulletin of the American Meteorological Society **76**(12): 2391-2402.

Kam-biu Liu, C. S., Kin-sheun Louie (2001). "A 1,000-Year History of Typhoon Landfalls in Guangdong, Southern China, Reconstructed from Chinese Historical Documentary Records." Annals of the Association of American Geographers **91**(3): 453-464.

Karen O’Brien, R. L., Ulka Kelkar, Henry Venema, Guro Aandahl, Heather Tompkins, Akram Javed, Suruchi Bhadwal, Stephan Barg, Lynn Nygaard, Jennifer West (2004). "Mapping vulnerability to multiple stressors: climate change and globalization in India." Global Environmental Change Part A **14**(4): 303-313.

Keith R.Briffa, T. J. O. (2002). "Blowing Hot and Cold." Science **295**: 2227-2228.

Kim M. Cobb, C. D. C., Hai Cheng, R. Lawrence Edwards (2003). "El Niño/Southern Oscillation and tropical Pacific climate during the last millennium." Nature **424**: 271-276.

Lamb, H. H. (1982). Climate, History and the Modern World. London, Methuen.

Landsberg, H. E. (1970). "Man's activities have altered the climate of urbanized areas and may affect global climate in the future " Science **170**(3964): 1265-1274.

Leif Christian Stige, K.-S. C., Zhibin Zhang, David Frank, and Nils C. Stenseth (2007). "Thousand-year-long Chinese time series reveals climatic forcing of decadal locust dynamics." PNAS **104**: 16188-16193.

Lima, M. (2007). "Locust plagues, climate variation, and the rhythms of nature." PNAS **104**: 15972-15973

Lonnie G. Thompson, E. M.-T., Mary E. Davis, Keith A. Henderson, Henry H. Brecher, Victor S. Zagorodnov, Tracy A. Mashiotta, Ping-Nan Lin, Vladimir N. Mikhalenko, Douglas R. Hardy, Jürg Beer (2002). "Kilimanjaro Ice Core Records: Evidence of Holocene Climate Change in Tropical Africa." Science **298**(5593): 589.

M.J. Ingram, D. J. U., G.Farmer (1981). The use of documentary sources for the study of past climates. Climate and History: Studies in past climates and their impact on Man. M. J. I. T. M. L. Wigley, G. Farmer. London, Cambridge University Press.

M.L. Parry, C. R., A. Iglesias, M. Livermore, G. Fischer (2004). "Effects of climate change on global food production under SRES emissions and socio-economic scenarios." Global Environmental Change. **14**: 53-67.

Ma, S. (1958). "The population dynamics of the Oriental migratory locust Locusta migratoria manilensis (Meyen) in China." Acta Entomologica Sinica **8**(1): 1-40 (In Chinese with English summary).

Ma, S., Ting Y. C.. Li D. M. (1965). "Study on long-term prediction of locust population fluctuations." Acta Entomologica Sinica **14**: 319-338 (in Chinese).

Mallory, W. H. (1926). China: Land of Famine. Freeport, New York, Books for Libraries Press.

Mann, M. E. (2002). "The Value of Multiple Proxies." Sience **297**: 1481.

Mann, M. E., P.D. Jones (2003). "Global Surface Temperatures over the Past Two Millennia." Geophysical Research Letters **30**: 1820.

Mark Elvin, L. T. u.-j., Ed. (1998). Sediment of Time: Environment and Society in Chinese History, Cambridge Univeristy Press.

Mark New, M. H., Phil Jones (2000). "Representing twentieth-century space-time climate variability. Pari II: Development of a 1901-96 monthly grids of terrestrial surface climate." American Meteorological Society **13**: 2217-2238.

Michael E.Mann, R. S. B., Malcolm K.Hughes (1998). "Global-scale temperature patterns and climate foring over the past six centuries." Nature **392**(779-787).

Michael N. Evans, A. K., Mark A. Cane (2002). "Pacific sea surface temperature field reconstruction from coral Δ^{18}O data using reduced space objective analysis." PALEOCEANOGRAPHY **17**(1): (7)1-13.

Mikami, T. (1996). "Long term variations of summer temperatures in Tokyo since 1721. ." Geographical Reports of Tokyo MetropolitanUniversity **31**: 157-165.

Mikami, T., M. Zaiki, G.P. Können, P.D. Jones, Ed. (September 1999). Proceedings of the international conference on climate change and variability Winter temperature reconstruction at Dejima, Nagasaki based on historical meteorological documents during the last 300 years. Tokio, Japan.

Ming Tan, T. L., Juzhi Hou, Xiaoguang Qin, Hucai Zhang, Tieying Li (2003). "Cyclic rapid warming on centennial-scale revealed by a 2650-year stalagmite record of warm season temperature." GEOPHYSICAL RESEARCH LETTERS **30**(12): 1617.

Oliver Heiri, A. F. L., Sonja Hausmann, Felix Kienast (2003). "A chironomid-based Holocene summer air temperature reconstruction from the Swiss Alps." The Holocene **13**(4): 477-484.

P. M. Kelly, W. N. A. (2000). "Theory and Practice in Assessing Vulnerability to Climate Change and Facilitating adaptation." Climatic Change **47**(4): 325-352.

P.D. Jones, K. R. B., T.P. Barnett, S.F.B. Tett (1998). "High-resolution palaeoclimatic records for the last millennium: interpretation, integration and comparison with General Circulation Model control-run temperatures." The Holocene **8**(4): 455-471.

Pao K. Wang, D. e. Z. (1988). "An introduction to some historical govermental weather records of China." Bulletin American Meteorological Society **69**(7): 753-758.

Q.-S. GE J-YZ, Z.-X. H., P.-Y. ZHANG, W.-C. WANG (2005). "RECONSTRUCTION OF HISTORICAL CLIMATE IN CHINA--High-Resolution Precipitation Data from Qing Dynasty Archives." American Meteorological Society: 671--679.

Qingbo Zhou PZ, Z. W. (1994). "Reconstruction of Annual Winter Mean Temperature Series in Hefei Area During 1736--1991 A.D. ." ACTA GEOGRAPHICA SINICA (in Chienese) **49**: 332--337.

QuangSheng Ge, J. Z., Zhixin Hao, Peiyuan Zhang, W.-C. WANG (2005). "Reconstruction of historical climate in China: High-resolution precipitation data from Qing Dynasty archives." American Meteorological Society: 671--679.

Quansheng Ge, J. Z., Yanyu Tian, Wenxiang Wu, Xiuqi Fanga, and Wei-Chyung Wang (2007). "Coherence of climatic reconstruction from historical documents in China by different studies." INTERNATIONAL JOURNAL OF CLIMATOLOGY.

Quansheng Ge, P. Z. (1990). "The evaluation on climatic information in the historical literatures. ." ACTA GEOGRAPHICA SINICA (in Chienese) **45**: 22--30.

Quansheng Ge, X. F., Zhimin Man, Xueqin Zhang, Piyuan Zhang, Wei-Chyung Wang (2003). "Winter half-year temperature reconstruction for the middle and lower reaches of the Yellow River and Yangtze River, China, during the past 2000 years. ." The Holocene **13**: 933--940.

Richard G. Pearson, T. P. D. (2003). "Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful?" Global Ecology & Biogeography **12**: 361-371.

Rudolf BráZdil, C. P., Heinz Wanner, Hans Von Storch, JüRg Luterbacher (2005). "Historical Climatology In Europe – The State Of The Art." Climatic Change **70**: 363-430.

Schneider, S. H. (1977). "Climate change and the world predicament: A case study for interdisciplinary research. ." Climatic Change **1**(1): 21-43.

Schneider, S. H. (1989). "The Greenhouse Effect: Science and Policy " Science **243**(4892): 771-781.

Seiji Tanaka, D. Z. (2005). "Outbreakd of the migratory locust Locusta migratoria (Orthoptera: Acrididae) and control in China." Appl. Entomol. Zool. **40**(2): 257-263.

Song, J. (2000). "CHANGES IN DRYNESS:WETNESS IN CHINA DURING THE LAST 529 YEAR." INTERNATIONAL JOURNAL OF CLIMATOLOGY **20**: 1003-1015.

Stillman, J. H. (2003). "Acclimation capacity underlies susceptibility to climate change." Science **301**: 65.

T. M. Cronina, G. S. D., T. Kamiya, S. Schwede, D. A. Willard (2003). "Medieval Warm Period, Little Ice Age and 20th century temperature variability from Chesapeake Bay." Global and Planetary Change **36**(1-2): 17-29.

T.M.L. Wigley, M. J. I., and G. Farmer. (1981). Climate and history : studies in past climates and their impact on man, Cambridge University Press.

Thomas C. Peterson, R. S. V. (1997). "An Overview of the Global Historical Climatology Network Temperature Database." Bulletin of the American Meteorological Society **78**(12): 2837-2849.

Thomas J. Crowley, T. S. L. (2000). "How Warm Was the Medieval Warm Period?" Ambio **29**(1): 51-54.

Thomas R. Karl, K. E. T. (2003). "Modern Global Climate Change." Science **302**(5651): 1719-1723.

Tim G. Benton, S. J. P., Tim N. Coulson (2006). "Complex population dynamics and complex causation: devils, details and demography." Proceedings of Royal Society: Bioligical Science. **273**(1173-1181).

Vries, J. d. (1980). "Measuring the Impact of Climate on History: The Search for Appropriate Methodologies." Journal of Interdisciplinary History **10**(4): 599-630.

W.-H. Qian, D. C., Y. Zhu, H.-Y. Shen (2003). "Temporal and spatial variability of dryness/wetness in China during the last 530 years." Theor. Appl. Climatol. **76**: 13-29.

Wang, P.-K. (1979). "Meteorological Records from Ancient Chronicles of China." Bulletin of the American Meteorological Society **60**(4): 313-318.

Wang Shaowu, Z. Z. (1981). Drooughts and Floods in China, 1470-1979. Climate and history : studies in past climates and their impact on man. . a. G. F. T.M.L. Wigley MJI, Cambridge University Press.

Weihong Qian, Y. Z. (2001). "Climate change in China from 1880 to 1998 and its impact on the envrionmental condition." Climatic Change **50**: 419-444.

Yao, T. (1997). "Climatic and Environmental record in the past about 2000 years from Guliya ice core." Quanternary Sciences **1**: 52-61.

Yao Tandong, L. G. T., Qin Dahe, Tian Lide, Jiao Keqin, Yang Zhihong, Xie Chao (1996). "Variations in temperature and precipitation in the past 2000a on the Xizang(Tibet) Plateau--Guliya ice core record." Science in China Ser. D Earth Sciences **39**(4): 425-433.

Zhang, D. e. (2004). The compendium of Chinese Meteorological records of the Last 3,000 years.

Zhang, J., Ed. (1991). Climate of China. A series of Climate for China. Beijing, Meteological Press. (in Chinese).

Zhang, P. (1979). "Some characteristics of climatic fluctuations in China since 16th century." ACTA GEOGRAPHICA SINICA (in Chinese) **34**: 238-247.

Zhao Huixia ZJ, G. Q. (2004). "THE RECONSTRUCTION OF 1755 AND 1849 SEVERE FLOOD EVENTS IN JIANGSU AND ANHUI PROVINCES. ." Scientia Meteorologica Sinica (in Chinese) **24**: 460--467.

Zheng Jingyun, H., GQ (2005). "Variation of precipitation for the last 300 years over the middle and lower reaches of the Yellow River." Science in China Ser. D Earth Sciences **48**: 2182-2193.

Zheng Jingyun HZ, G. Q. (2004). "Method for seasonal precipitation reconstruction derived from snow and rainfall archives in Qing Dynasty: A case study in Shijiazhuang. ." Progress in natural science **14**.

Zheng Jingyun HZ, G. Q. (2004). "Seasonal precipitation reconstruction and analysis in Shandong Province derived from the archives in the Qing Dynasty since 1736." Climatic and Environmental Research (in Chinese) **9**(4): 551-566.

Zhibin Zhang, D. L. (1999). "A possible relationship between outbreaks of the oriental migratory locsut (*Locusta migratoria manilensis Meyen*) in China and the El Nino episodes." Ecological Research **14**: 267-270.

Zhixin Hao, J. Z., Quansheng Ge (2003). "Climate change and Harvest in Xi'an since 1736: the high-resolution data derived from the archives in the Qing Dynasty." ACTA GEOGRAPHICA SINICA (in Chienese) **58**(5): 735-742.

2 Chapter One
Climate Change, Harvest and Drought/flooding in Qing Dynasty (1644-1911)

2.1 Introduction

The mean temperature of Earth has increased approximately 0.6°C over the last 100 years (IPCC 2001). Global warming is currently of great concern in many scientific fields. There is abundant evidence now that recent climate changes have affected the environment and ecological systems (Vitousek 1994; McCarty. 2001; Nils Chr. Stenseth 2002). However, the ecological and sociological responses to past climate changes remain largely uncertainty. Previous studies on global climate change show that there is a correlation between changes in mean temperature and natural extreme events (Richard W. Katz 1992; Gao Xuejie 2002; T. N. Palmer 2002; Noah S. Diffenbaugh 2005). Furthermore, the changes of frequency and magnitude of such extreme events could have great impacts on socioeconomic activities (David R. Easterling 2000). Recently, David Zhang presented several studies to show relationship between frequency of war incidents and climate change (David D. Zhang 2006; David D. Zhang 2007; David D. Zhang 2007). The hypothesis that Zhang et al. proposed is that long-term climate change would have significant direct effects on land-carrying capacity. Therefore, the shortage of food supply caused by decreasing land-carrying capacity will increase the possibility of occurrence of war, famine, and epidemic disease. By using the Chinese war data complied by Nanjing Academy of Military Sciences and reconstructed temperature time series for Northern Hemisphere (Mann 2003), Zhang et al. found that oscillations of war frequency and population changes followed with temperature change, which implied that climate change may have a more important role for the occurrence of war than that of social mechanism.

However, to demonstrate that such historical cultural breaks are mainly caused by limited resources under ecological adaptation, it's important to get direct evidence of impacts of past climate change on agricultural production from historical data and scientific methods. Nevertheless, the ecological response, especially the agricultural yield in response to the past climate change, has not been addressed in the literature.

Temperature and moisture are two key factors affecting natural agricultural yields (Barry Smit 1996; Fulu Tao 2003). For instance, a case study at Xi'an city in central China revealed that most of years during which agricultural harvests failed have a significant decrease in precipitation (Hao Zhixin 2003). Historical written records of climate conditions such as flooding, drought incidents in China, as well as harvest records can serve as a proxy data for instrumental observations. Analysis of long ecological and climate proxy time series allows us to discover the dynamics that could not be revealed by short term instrument records.

The objective of this study was to answer the following questions: "Was change of mean temperature related with agricultural failure in the past of China? Besides the direct effect of temperature, did temperature-driven extreme precipitation disasters, in terms of drought/flood events, also affect the agricultural harvest in the past history in China? In other words, the hypothesis here is: climate change will lead to an increase of extreme events. Increased frequency of such extreme events (droughts/floods) has negative effects on agricultural harvests. This question has never been addressed before due to the lack of data and the interdisciplinary nature of these studies. The purpose of study is to investigate the statistical relationship between historical dry/wet records, agricultural harvests in China by using the proxy data for Qing Dynasty (the last dynasty of China) and other reconstructed climate series. As expected, if climate change would affect agricultural yields during the past, it would increase our understanding of the dynamic nature of natural ecosystems and support studies of social and economic systems that incorporate ecological evidence.

2.2 Data and Methods

2.2.1 Data

Historical climate data and agricultural harvest data

The data of historical climate events were interpreted and extracted from a multi-volume compendium that contains exhaustive information on various historical documents for past climate events in China such as rain/snow/wind storms, drought, flooding and ecological and socioeconomic events, such as agriculture harvest, famine, locust outbreaks, plague, phenology, etc. (Zhang 2004) (the details of information contained in the compendium are in introduction section of this dissertation). In this study, the records of good agricultural harvests, agricultural poor harvests, and drought/flood events were used. Based on the temporal and spatial location of historical records, the incidence of each event was digitalized as 1, otherwise is 0 (the scale of events were also considered during the data compilation, however, was not addressed in the present study). The frequency of studied variables was then counted based on the spatial or temporal information provided. The records of past climate events compiled in the compendium can be traced back to 3000 years before the present, however, due to the special characteristics of historical documents of China, the most comprehensive and systematic historical climate data only covered the period from Ming to Qing Dynasty, known as “Fang-Zhi (local gazettes) Epoch (1368-1911)”. In this study, only data for Qing Dynasty (1644-1911) was used because of timing constraints for data collection. The frequency of each analyzed variable for each year was calculated for use in correlation analysis.

Paleo-climate data

Recent studies have significantly improved high-resolution paleo-climate reconstruction data by using multi-proxy data networks. Briffa et al. (2002) reviewed five of the most representative and latest reconstructed temperature anomalies series of the last millennium in the Northern Hemisphere, including the data from China (Keith R.Briffa 2002). Although those data showed high accuracy of reconstructions and were used to present the past temperature in China in many studies, I used the reconstructed temperature series from Beijing (Ming Tan 2003) and compared it with the NH annual temperature anomaly (Mann 2003) which was adopted by Zhang’s in the previous study, to check and ensure the assumptions of adopted analysis methods in this study were met,.

Temperature data:

Tan’s reconstructed temperature data is a 2650-year (BC665-AD1985) warm season (MJJA: May, June, July, August) temperature series, which is derived from a correlation between thickness variations in annual layers of a stalagmite from Shihua Cave, Beijing, China and instrumental meteorological records. The Northern Hemisphere mean surface temperature over the past two Millennia which was adopted in the previous study (David D. Zhang 2007) were reconstructed by using high-resolution Multi-proxy Temperature data, such as tree-rings, historical records, lake sediments, ice cores, fossil shells, and boreholes (Mann 2003). This reconstructed proxy data can be downloaded from http://www.ncdc.noaa.gov/paleo/metadata/noaa-recon-6306.html.

The reconstructed Tan's temperature, precipitation data and the frequency of historical records for harvest data over Qing Dynasty are shown in Figure 2-1.

Precipitation data

Precipitation data adopted in this study are May-June (MJ) and April-July (AJ) precipitation at Huashan Mountain in north-central China which were reconstructed by Hughes et al. (Hughes 1996), based on tree-ring density and width from *Pinus armandii*. The reconstructed precipitation proxy data can be downloaded from ftp://ftp.ncdc.noaa.gov/pub/data/paleo/treering/reconstructions/china/huashan.recons . The reconstructed precipitation data has been calibrated and cross-validated against local instrumental data. For instance, a major drought was reconstructed for the mid- and late 1920s, which was confirmed by local documentary sources for the drought was the most severe of the 389-yr period for MJ and second most severe for AJ, after an event ending in 1683. Also, there are significant correlations between the two reconstructions and a regional dryness/wetness index (DW) based on document sources. For this study, AJ was adopted for correlation analysis.

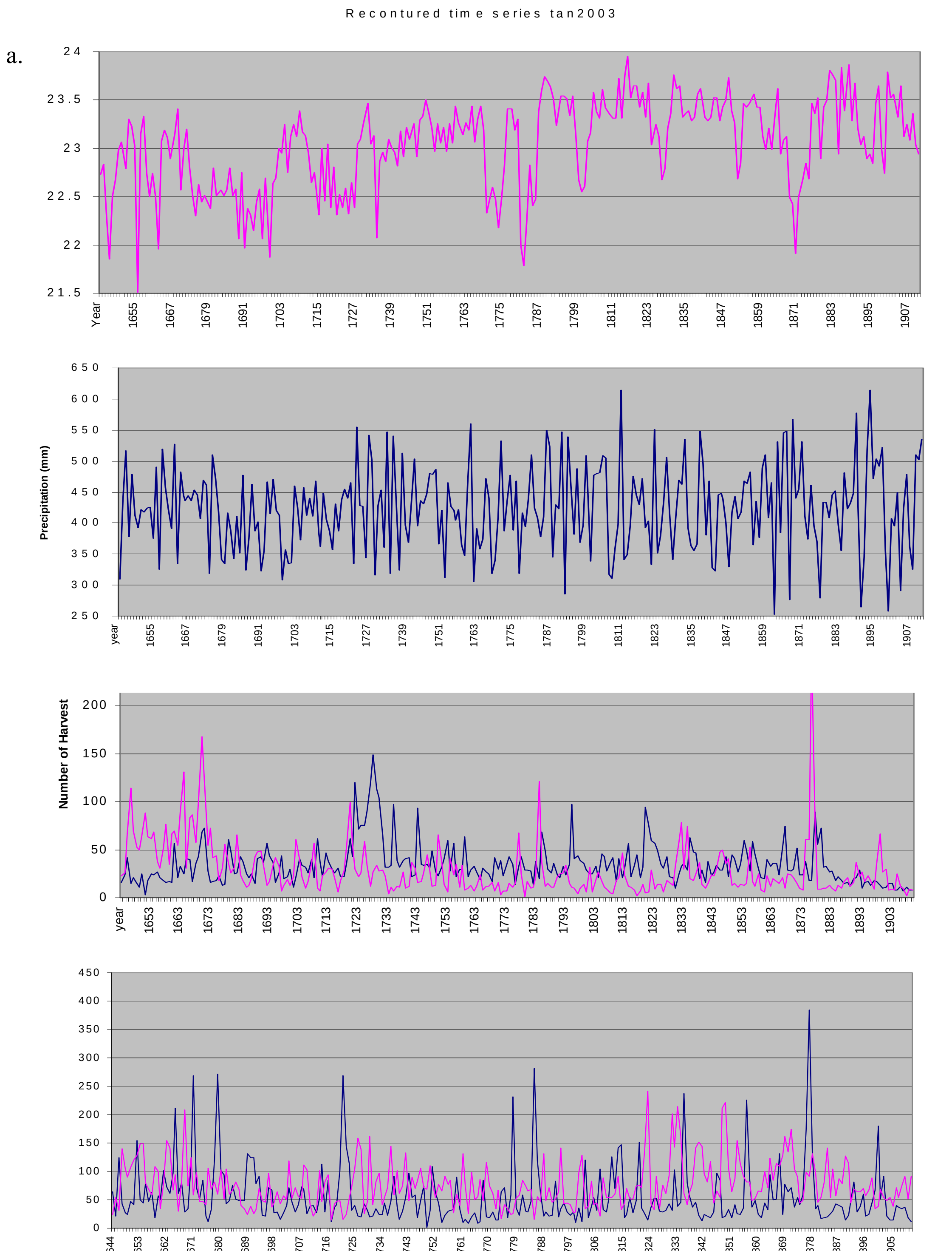


Figure 2-1 Climate series for Qing Dynasty. a) Reconstructed temperature anomaly in Beijing (Tan 2003); b) Precipitation; c) Frequency of Good and Poor harvest. Pink is poor harvest, blue is good harvest. d) Blue is drought, pink is flood.

GIS data

Because most of the compilations were conducted during the last two decades of the 20th century and compilers used the administrative division system in 1990, the most suitable county level map is county boundary map for 1990. In this study, the County Level of China Administrative Regions GIS Data in 1990 with 1:1M resolution was adopted. The data can be downloaded from "China Dimensions Data Collection" on the website of

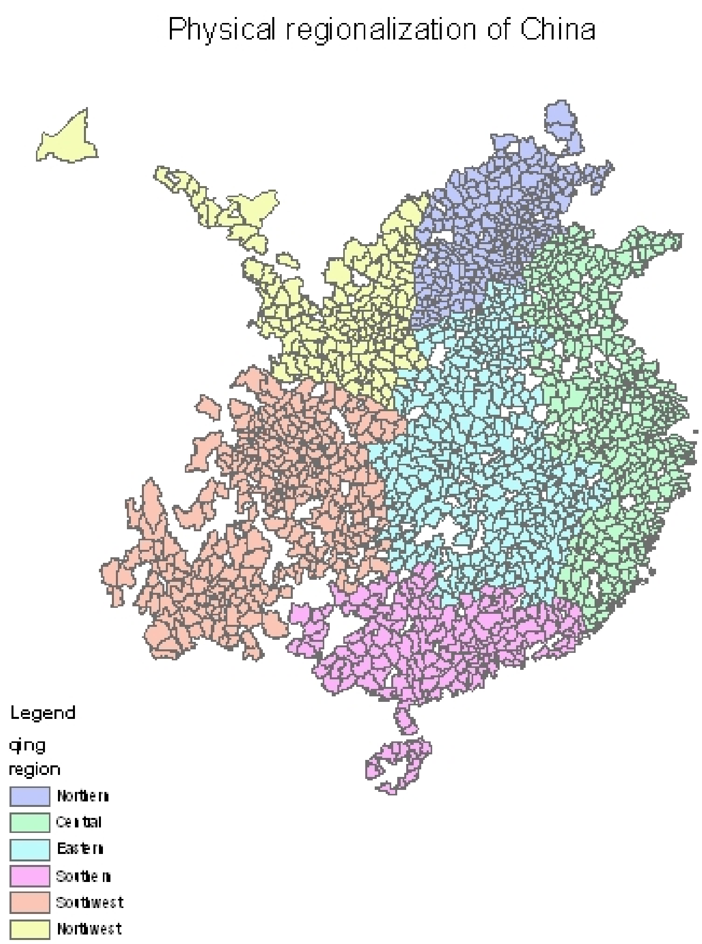


Figure 2-2 Regionalization map of the study area.

“Center for International Earth Science Information Network”, Columbia University (http://sedac.ciesin.columbia.edu/china/).

The historical records in the compendium were relocated to each current corresponding county as the basic statistical unit by compilers because the county is the most stable administrative unit of China through history. Due to historical reasons, such as “Shi-Qu” and “Shi-Xian” issues which were discussed in the appendix, boundaries of “Shi-Qu” or “Shi-Xian” which share the same name were merged as a single county level division.

In this study, the counties which have no records during the entire Dynasty, which were mostly due to the historical administrative reason, were also removed from the map. There are 1501 counties that have historical records of past climate conditions within the study area. Based on the regionalization of administrative management, the study area was divided into six regions as shown in Figure 2-2.

2.2.2 Methods

Correlation analysis

Frequencies of historical records of climate events, such as poor/good harvest and flooding/drought records were counted for each year in the study area to get the time series. To test whether historical agricultural harvests, reconstructed climate data (in terms of temperature and precipitation), and past climate extreme events (drought and floods) are related with each other, the most common methods is the Pearson correlation test, which measures the strength of an association between two variables. The Pearson correlation test was conducted at annual scale within the entire study area and different regions. The correlation coefficients with different lengths of time lag were also computed. one-year lag was computed from year 1 to year 5, and five-year lag was computed from year 5 to 30. Pearson correlation analysis between reconstructed climate and historical records was conducted by using Proc Corr in SAS (SAS Institute Inc. 2000-2004). Pearson's correlation coefficients between flooding, drought, poor harvest, and temperature, precipitation revealed associations between climatic change and past events. This degree of association is reported as a number (the correlation coefficient) that ranges from –1 to +1.

Spatial statistical analysis

The object of further analysis was to look for the spatial pattern of interesting variables, to examine their extent of spatial clustering or autocorrelation. The general pattern of spatial distribution of each variable can be displayed by using graduated symbol map in ArcGIS (Hillier 2007).

To test spatial autocorrelation and spatial patterns, several spatial statistical tools in ArcGIS were used, such as "High/Low Clustering (Getis-Ord General G)", "Spatial Autocorrelation (Moran's I)", and "Multi-Distance Spatial Cluster Analysis (Ripley's k-function)".

The General G tool calculates the value of the General G statistic for a given set of features and an associated Z score value which is a measure of statistical significance. The higher the Z score, the stronger intense of the clustering. Global Moran's I basically operates same way as Getis-Ord statistics, to evaluate whether the pattern of given features is clustered, dispersed, or randomly distributed. Ripley's K-Function is another way to analyze the spatial pattern of point features. The advantage of Ripley's K-Function is that it illustrates whether the spatial clustering or dispersion occurs over a range of distances.

If the interesting features are clustered, generally the next interesting question will be where they are clustered. Hotspot analysis can help us visually assess patterns of features where such clusters occur. Basically, a hot spot is a feature with a high statistical value, which means it is surrounded by other features with high values, and vice versa for cold spots.

Hot spot analysis for analyzed variables can be conducted by using “Hot Spot Analysis with Rendering (Spatial Statistics)” to calculate the Getis-Ord Gi* statistic for each feature in a weighted set of features by comparing it to its neighbors and then applying a cold-to-hot type of rendering of the output Z scores.. Given a set of weighted features, Gi* statistics can identify clusters of features with high values and clusters of features with low values, to show where are the events concentrated.

For statistically significant positive Z Scores, the larger the Z score, the more intense the clustering of high values—hot spots(>1.96); For statistically significant negative Z scores, the smaller the Z Score , the more intense the clustering of low values—cold spots(<-1.96).

2.3 Results and Analysis

2.3.1 Descriptive analysis

The time series of historical records of climate extreme events as well as agricultural harvest and reconstructed climate data (temperature and precipitation) are displayed in Figure 2-1. The reconstructed temperature series show that there is a cold period for the Qing Dynasty before the 19th century, and the climate started warming at the beginning of the 19th century, except a short period during 1860-1880, which corresponds to the "Taiping rebellion". This may support the findings of a previous study (David D. Zhang 2007), that peak of war frequency occurred in cooling phases. Precipitation shows less variation during the cold period and tends to have a larger variance during the warm period. The incidence of poor and good harvests shows a cyclic pattern with a turbulent period during cold period followed by relative tranquil period during warmer period except that there is a extreme value in 1876 which corresponded to the abrupt decrease of precipitation in that year. The frequency of floods shows similar trends as that of reconstructed precipitation, whose variance in the warm period is larger than that in the cold period. The frequency of drought shows there is a significant drought year in 1877 which can be explained as the effect of decreasing precipitation in the previous year. The extreme drought event in 1877 which caused widespread famine and the death of 9 to 13 million people in northern China are well known in other studies (Dorte Eide Paulsen 2003; Caiming Shen 2007). The same relationship between precipitation and drought can be also found in another example when precipitation decreased in 1899 and a severe drought event occurred in the next year. Those two severe drought years, 1877 and 1900, were also confirmed with the findings in case study at Xi'an (Hao Zhixin 2003). The interesting thing for those time series is that there is an abrupt change during the 1870's. Temperature, precipitation, poor harvest and drought all showed a highest/lowest peak over the whole Qing Dynasty in this decade.

To explore whether temperature change has an effect on other variables, the mean value for each variable for cold (temperature lower than median) or warm years (temperature higher than median) is shown in Table 2.1. From the results, we can see that the ratio of good vs. poor harvests in warm years (ratio=1.326) is significantly larger than that in the cold years (ratio=1.086), which suggests that cold temperature may have a positive association with agricultural failures. The results also show that although cold years tend to be wetter than warm years, the ratio of drought vs. flood is 0.836 for cold years and 0.631 for warm years, respectively, which is a significant difference. This may suggest that cold years have an effect on the incidence of drought and flood events.

Table 2.1. Mean value of frequency of incidents within cold/warm year.

	Good harvest	Poor harvest	drought	flood	temperature[3]	precipitation	Ratio of good vs. poor harvests	Ratio of Drought vs. flood
Cold	34	32	60	72	22.674	425	1.086	0.836
Warm	35	26	52	83	23.415	421	1.326	0.631

2.3.2 Temporal analysis

Before conducting Pearson correlation tests, it's important to test the normality of each variable and linearity of relationships between the analyzed variables, two basic assumptions of the Pearson correlation test (Larry L Havlicek 1977). Figure 2-3 a. shows the histogram of four original recently reconstructed temperature time series which were used by most of studies, for instance, the mann2003d which was used in David Zhang's study. Mann2003d showed extremely skew at two sides and further analysis didn't show linear relationships between temperature and other variables, even post-transformation. That is the reason this dataset was not chosen for this study. Instead, Tan 2003 which is reconstructed at Beijing, is more appropriate for our study area, compared with mann2003, which represents the whole northern hemisphere. Also it shows good normality after

[3] Tan 2003.

transformation in Figure 2-3.a. Reconstructed temperature by tan 2003 was transformed to the eighth power or original values. Flood, drought, precipitation and poor harvest were log transformed. The histograms of variables after transformation, such as temperature (Tan2003), drought, floods, poor harvest are shown in Figure 2-3 b.

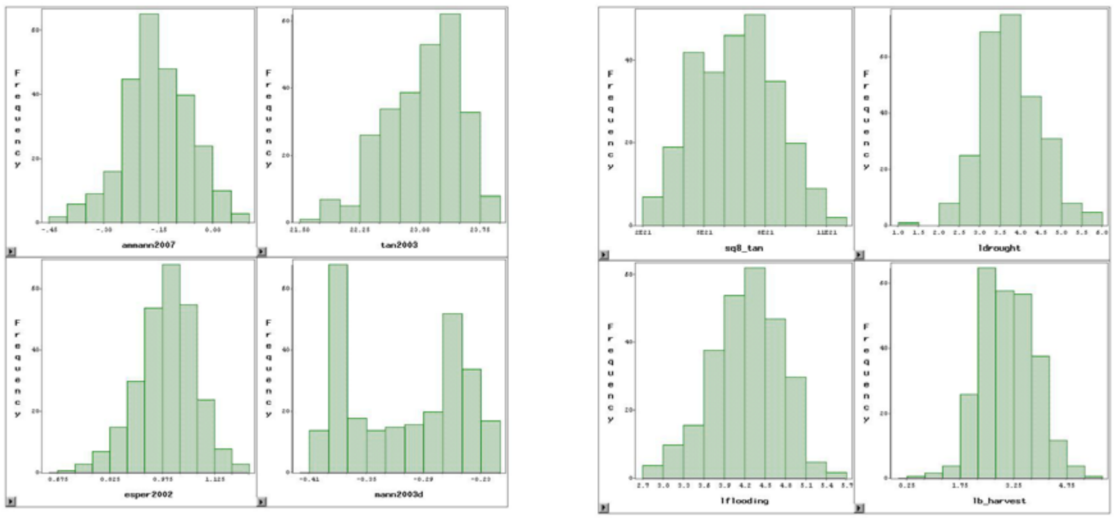


Figure 2-3 a. Histogram of reconstructed temperature series, reconstructed temperature anomaly by amman2007, tan2003, esper2002 and mann2003d; b) transformed variables, from upper left to lower right are: tan2003, drought, flood and poor harvest.

All of the transformed data were tested by Proc Univariate procedure in SAS, and the results of normality tests (Shapiro-Wilk, Kolmogorov-Smirnov, Cramer-von Mises, and Anderson-Darling) are all non-significant, which suggests that the hypothesis of an underlying is not rejected.

Figure 2-4 shows the scatter plots for the studied variables to check another assumption of the Pearson correlation test, the linear relationship between variables. We can see drought has strong positive linear relationship with poor harvest, flood show some kind of linear relationship with poor harvest, and temperature shows a roughly positive linear relationship with flood and weak negative relationship with drought and poor harvest.

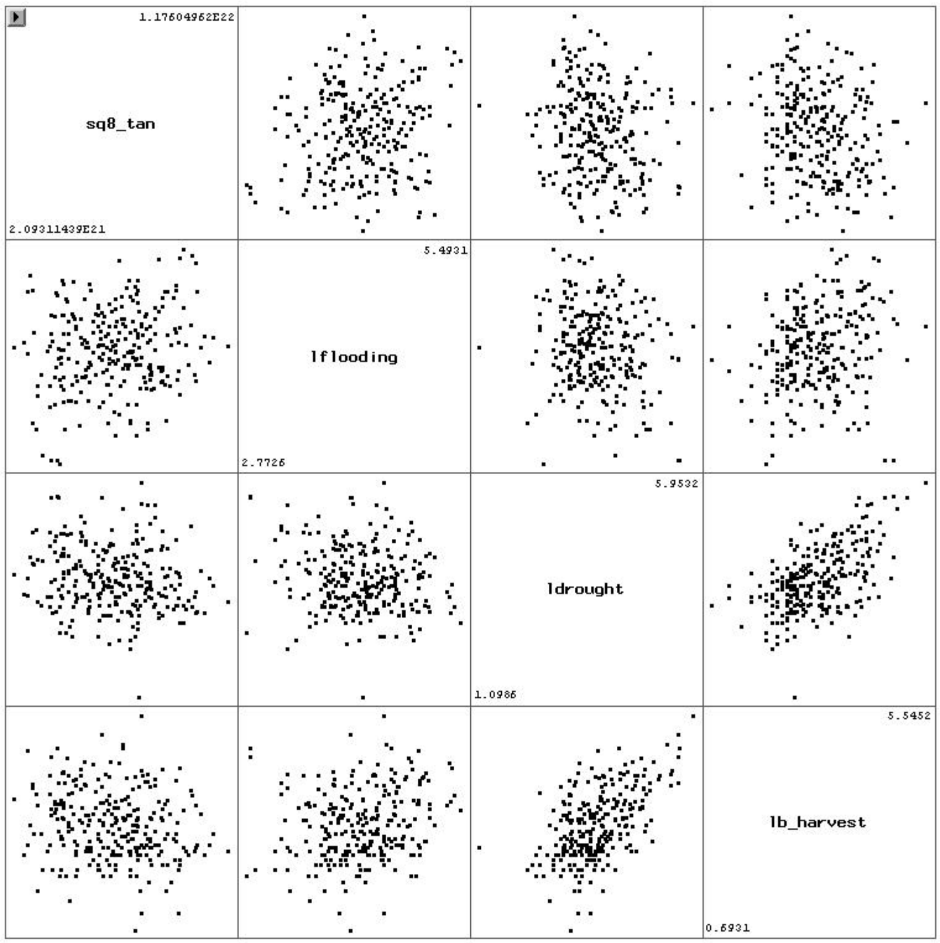


Figure 2-4 Scatter plot of transformed variables

Figure 2-5 shows a clear linear relationship between agriculture poor harvest and temperature. The fitted line suggests that it is reasonable to consider the relationship between temperature and poor harvest to be linear.

The results of Pearson correlation tests are shown in

Table 2.2. For correlation analysis at an annual scale, drought is significantly negative related with temperature and precipitation at p = 0.001 levels while flood is positively correlated with temperature at p = 0.05 levels. Agricultural poor harvest is significantly negatively related with temperature and positively related with floods and drought at p = 0.001 levels. Precipitation is negatively related with drought at p = 0.001 levels. Floods and drought are negatively related.

Because the effects of temperature change on environmental conditions and ecological responses to such changes may exhibit time lags, the correlation tests between reconstructed temperature and floods, drought, poor harvest with time lags were calculated. The results are shown in

Table 2.3. The first part of table shows the correlation analysis with a range of lags incremented by 5 years. We can see with first 5 year lag, the absolute value of correlation coefficients for drought and temperature is the highest within 5 years lag. The correlation coefficient for flood with temperature shows 25 years and 30 years lag are more significant and stronger. While correlation coefficient for agriculture poor harvest and temperature within 5 years lag shows the same pattern of that between drought and temperature, the first five years lag shows the strongest and most significant correlation, the relationship between temperature and poor harvest is negative.

The second part of the table is correlation analysis with one year time lag, the results shows that for relationship between flood and temperature, 4 years time lag is most correlated in 0.001 levels; for the relationship between drought and temperature, poor harvest and temperature, the 4 years lag shows strongest and significant negative relationship. Combined those two parts, we can conclude there is time lag issue with the correlation between temperature and floods, droughts, agriculture poor harvest. The coefficient value increase with time lag until 4 years lag and then decrease, except flood and poor harvest shows other significant relations after 25 to 30 years delay.

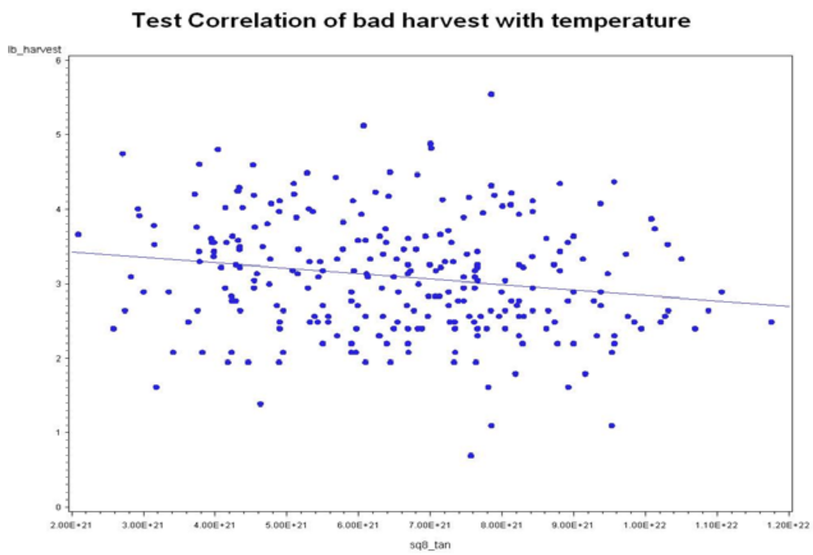


Figure 2-5 Scatter plot of poor harvest against reconstructed temperature.

Table 2.2. Pearson's correlation between studied variables:
Flood, drought, agriculture failure, temperature, and precipitation.
(* indicate 0.05 significance level and ** indicate 0.001 significance level)

Entire period (N=268)		Flooding	Drought	Poor harvest
	MEAN	4.233	3.769	3.092
	STD	0.511	0.723	0.778
Temperature	Corr	0.156*	-0.162**	-0.185**
Precipitation	Corr	0.111	-0.166**	-0.048
lflooding	Corr	1	-0.148*	0.199**
ldrought	Corr	-0.148*	1	0.555**
By temperature		Flooding	Drought	Poor harvest
Cold (N=137)	MEAN	4.173	3.866	3.201
	STD	0.506	0.691	0.766
Temperature	Corr	0.091	-0.129	-0.130
Precipitation	Corr	0.115	-0.147	-0.075
lflooding	Corr	1	-0.162	0.073
ldrought	Corr	-0.162	1	0.611
Warm (N=131)	MEAN	4.296	3.668	2.978
	STD	0.510	0.744	0.778
Temperature	Corr	0.115	-0.049	-0.111
Precipitation	Corr	0.116	-0.194*	-0.031
lflooding	Corr	1	-0.108	0.370**
ldrought	Corr	-0.108	1	0.483**

Table 2.3. Pearson's correlation between flood, dought, poor harvest, and temperature with various time lags.
(* indicate 0.05 significance level and ** indicate 0.001 significance level)

Temperature	Flooding	Drought	Poor harvest
Lag0	0.156*	-0.162**	-0.185**
Lag5	0.094	-0.202**	-0.309**
Lag10	0.105	-0.091	-0.149
Lag15	0.123	0.002	-0.069
Lag20	0.077	0.052	-0.148*
Lag25	0.221**	-0.070	-0.145*
Lag30	0.151*	-0.061	-0.215**
Lag1	0.125*	-0.140*	-0.194**
Lag2	0.082	-0.135*	-0.248**
Lag3	0.110	-0.216**	-0.313**
Lag4	0.150*	-0.227**	-0.325**
Lag5	0.094	-0.202**	-0.309**

2.3.3 Spatial statistical analysis

Regional analysis

The incidence of harvest, drought, and flood events for cold or warm years in each region and the ratios of good to poor harvests and drought to floods is show in the **Table 2.4**. The results show that temperature has strong impact on harvest ratio in region 2 and 3 (Eastern and Center), where cold years have lower good vs. poor harvest ratios than that of the warm years. This result suggests that temperature has significant impacts on harvests in region 2 and 3. During the cold years, there were more poor harvests than in warm years. For the ratio of drought to flood, cold years have effect on regions 4, 5 and 6, where cold years tend to be drier than warm year. **Table 2.5** shows the results of correlation test between flood, drought, poor harvest, temperature and precipitation by each region. Reconstructed temperatures are significantly correlated with floods, droughts, and harvests at the $p = 0.001$ level in region 2, and are correlated with at least two of those variables in regions 3, 5, and 6. Temperature only has a significant correlation with harvest in region 1 and shows no significant correlation with any of the three variables in region 4.

Droughts are positively correlated with harvests for all of 6 regions at $p = 0.001$ levels. Floods show correlation with harvest for 5 regions except region 4. Precipitation only shows significant correlation with drought variables and only significantly in region 6.

The correlations between drought, flood, and poor harvest in the entire study area were also tested. The frequency of incidence for each variable was counted for each county. The results were shown in **Table 2.6** below:

For entire study area, poor harvest is highly related with droughts and floods, the correlation coefficients are 0.683 and 0.516, respectively. Harvests are highly correlated with drought in each region and the correlation coefficients fall between 0.503 and 0.683. Harvests are also highly correlated with floods in each region; however, the range of the coefficient is between 0.287 and 0.575, which shows a great range of variation. (All correlation coefficients are significant at 0.001 levels.)

Table 2.4. Number of records of variables and ratio of good vs. bad, drought vs. flood in cold and warm years in different regions

region	1(Northern)		2(Eastern)		3(center)		4(Southern)		5(Southwest)		6(Northwest)	
var	Cold	Warm	Cold	Warm	Cold	Warm	Cold	Warm	Cold	Warm	Cold	Warm
g_harvest	979	938	1059	1023	1343	1459	553	407	501	514	283	228
b_harvest	811	782	1647	1200	1121	764	258	187	181	220	328	294
drought	1253	1191	3083	2266	2375	1672	653	648	408	558	485	491
flooding	1441	1488	3618	3927	2773	3200	995	1019	712	873	332	305
ratio_harvest	1.21	1.20	0.64	0.85	1.20	1.91	2.14	2.18	2.77	2.34	0.86	0.78
ratio_drought/flood	0.65	0.66	0.53	0.53	0.47	0.46	0.40	0.29	0.44	0.39	0.68	0.60

Table 2.5. Pearson correlation coefficients between variables in different regions

Region	1			2			3			4			5			6		
	flood	drought	harvest	flood	drought	harvest	flood	drought	harvest	flood	drought	harvest	flood	drought	harvest	flood	drought	harvest
MEAN	2.04	1.73	1.47	3.19	2.66	2.08	2.88	2.26	1.60	1.85	1.42	0.71	1.67	1.15	0.66	0.94	1.03	0.80
STD	0.94	1.06	0.95	0.64	0.87	0.87	0.76	1.01	1.00	0.78	0.83	0.70	0.78	0.86	0.68	0.73	0.90	0.80
tan	0.07	-0.06	-0.15*	0.13*	-0.20**	-0.16**	0.09	-0.24**	-0.22**	0.02	0.09	-0.04	0.26**	0.17**	0.11	0.16**	-0.02	-0.13*
precip	0.04	-0.20**	-0.09	0.09	-0.10	0.05	0.10	-0.11	-0.11	-0.01	0.02	0.04	0.02	0.03	0.04	0.08	-0.31**	-0.12
flood	1	-0.09	0.14*	1	-0.18**	0.29**	1	-0.09	0.17**	1	-0.21**	0.11	1	0.24**	0.24**	1	-0.06	-0.08
drought	-0.09	1	0.60**	-0.18**	1	0.45**	-0.09	1	0.56**	-0.21**	1	0.43**	0.24**	1	0.54**	-0.06	1	0.40**

Table 2.6. Pearson's correlation coefficients between variables for entire studied area

Total	b_harvest	Drought	Flooding
b_harvest	1	0.683	0.516
Drought	0.683	1	0.653
Flooding	0.516	0.653	1
Region			
1 (N=236)	1	0.628	0.287
	0.628	1	0.416
	0.287	0.416	1
2 (N=356)	1	0.683	0.575
	0.683	1	0.693
	0.575	0.693	1
3 (N=335)	1	0.600	0.451
	0.600	1	0.656
	0.451	0.656	1
4 (N=165)	1	0.553	0.480
	0.553	1	0.733
	0.480	0.733	1
5 (N=264)	1	0.503	0.423
	0.503	1	0.499
	0.423	0.499	1
6 (N=148)	1	0.662	0.478
	0.662	1	0.442
	0.478	0.442	1

Graduated symbol map for each variables:

The frequency of each variable was counted by county over the last Dynasty and county polygons were used to transformed point data by assigning values to polygon centroids. The number of recorded years for each county was used to normalize and give the weight for the recorded incidences due to the potential influence caused by the recorder and complier's bias. The maps in Figure 2-6 show some interesting patterns. Good harvests are clustered at Sichuan, Hubei, Hunan, and Shanxi provinces. All are famous for agriculture yields in China's history except Shanxi province.

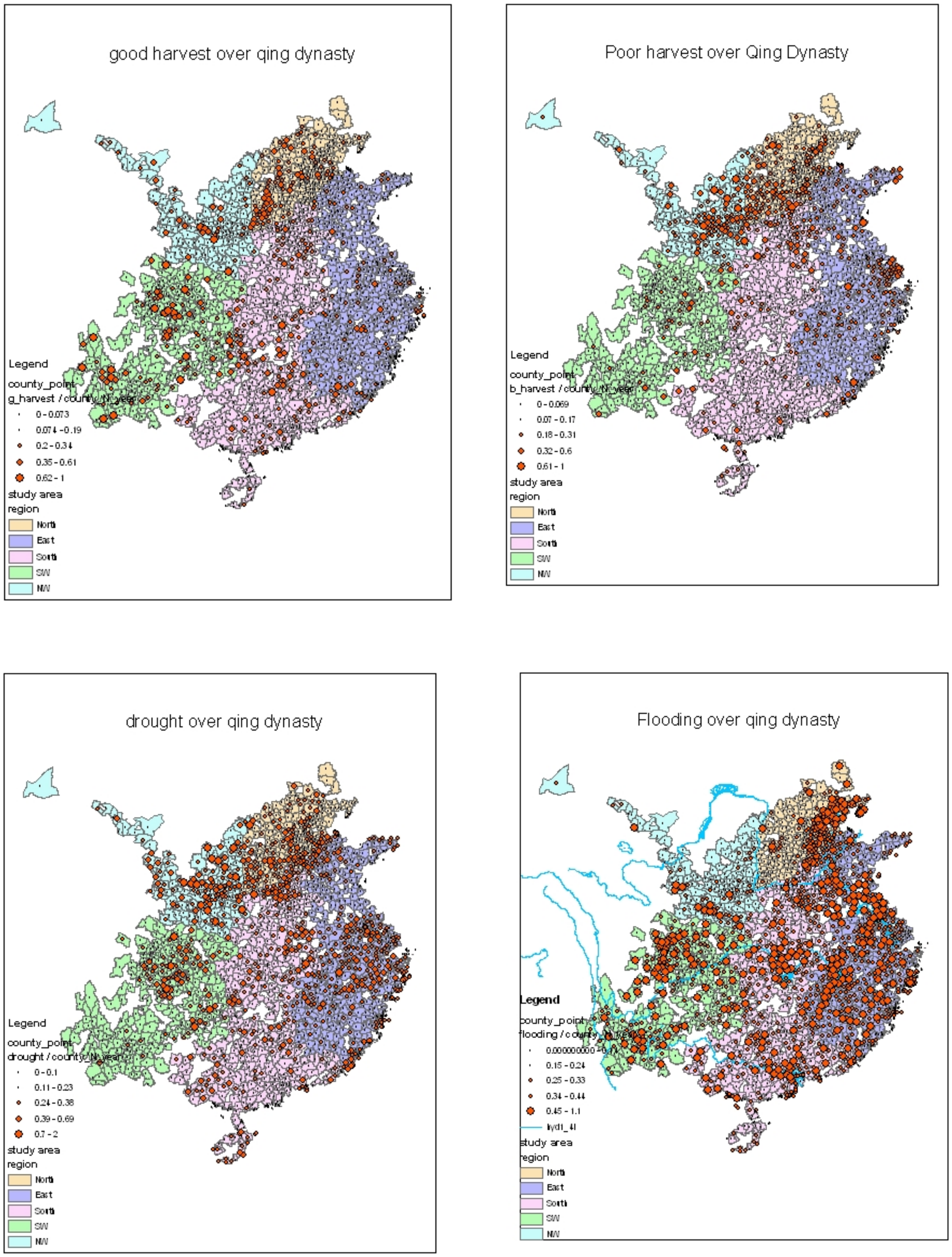


Figure 2-6 Graduated symbol map for each variable: a) Agriculture harvest; b) poor harvest; c) drought; d) flood.

For poor harvests, Shaanxi, Shanxi, Hebei, Henan, and part of Gansu provinces which are located at Northern or Northern west semi-arid region show strong clustering. The Yangtze Delta and some coast areas also show some clustering pattern of poor harvest which could be explained as the effect of flood events. The map of flood events shows a strong linear trend, which follow the several major river paths, such as Yellow River, Yangtze River and Pearl River. Drought shows a spatial clustering pattern in Northern and Northwest part of China, which are both semi-arid regions, and some clustering at the low Yangtze River as well.

Spatial patterns (clustering) and spatial Autocorrelation

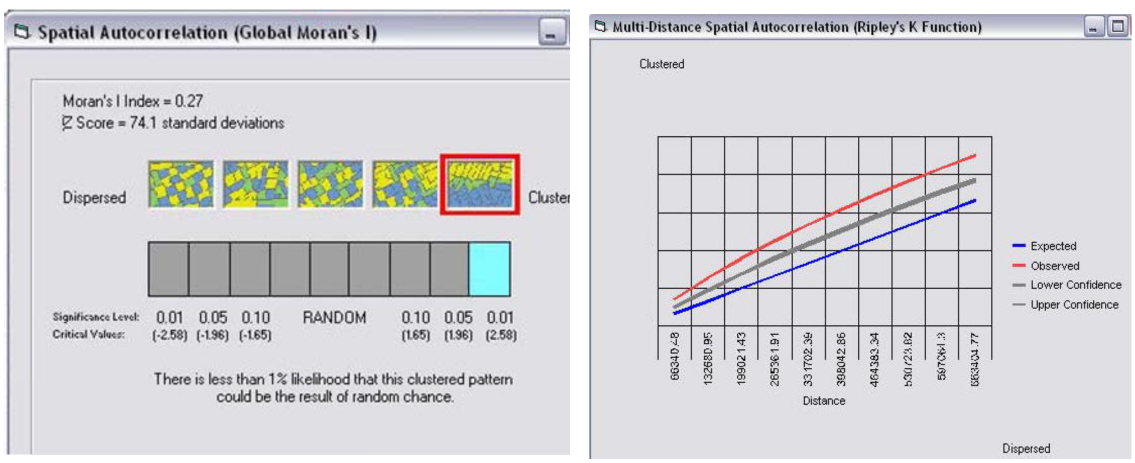


Figure 2-7 Moran's I index and Ripley's K Function for poor harvest.

By using spatial statistics tools in ArcGIS, the spatial analysis of agriculture harvest and poor harvest as well as extreme flood and drought events was conducted and results for all variables show high spatial clustering and spatial autocorrelation. For instance, Local Moran's I value and associated Z scores for agriculture harvest and poor harvest, floods, and droughts are 0.28(69.13), 0.08(20.85), 0.24(61.29) and 0.24(60.11), respectively. Figure 2-7 shows one visual example of spatial autocorrelation from ArcGIS tools by using

Global Moran's I methods. Moran's I Index is 0.27, meaning that agriculture poor harvest is highly clustered in the sample features. The Z score represents the statistical significance of the index value. Here the Z-score for poor harvest is 74.1 (standard deviations), meaning that there is less than 1% chance that the highly clustered Moran's I value is a result of random chance (high statistical significance). Ripley's K Function statistics of poor harvest shows that deviation of the observed line above the expected line indicates that the dataset is exhibiting clustering at that distance. The results of high/low clustering (Getis-Ord General G) also illustrate that poor harvest has clustered in the high ranges of its values. The Z-score is 29.13 (standard deviations), indicating the statistical significance of the cluster.

Mapping patterns--hot spot analysis

The result of Hot-Spot Analysis Tools for maps of poor harvest, drought, and flood are shown in the Figure 2-8. The result of hotspot analysis for poor harvest revealed that most parts of Shanxi, Shaanxi, Henan provinces are hot spots for agriculture failure over the Qing Dynasty. Although hot spot analysis of drought shows a slightly smaller hot spot than that of poor harvest, the spatial pattern and location of hot spots for drought are very similar as that of poor harvest, which may explain why the Pearson correlation coefficient between drought and poor harvest are consistently significant. The hot spot analysis of floods shows that the middle of Yangtze River is the hot spot of floods over the Qing Dynasty. In contrast, the Shanxi, Shaanxi provinces are the cold spots which are also consistent with the results of hot spots analysis for drought events.

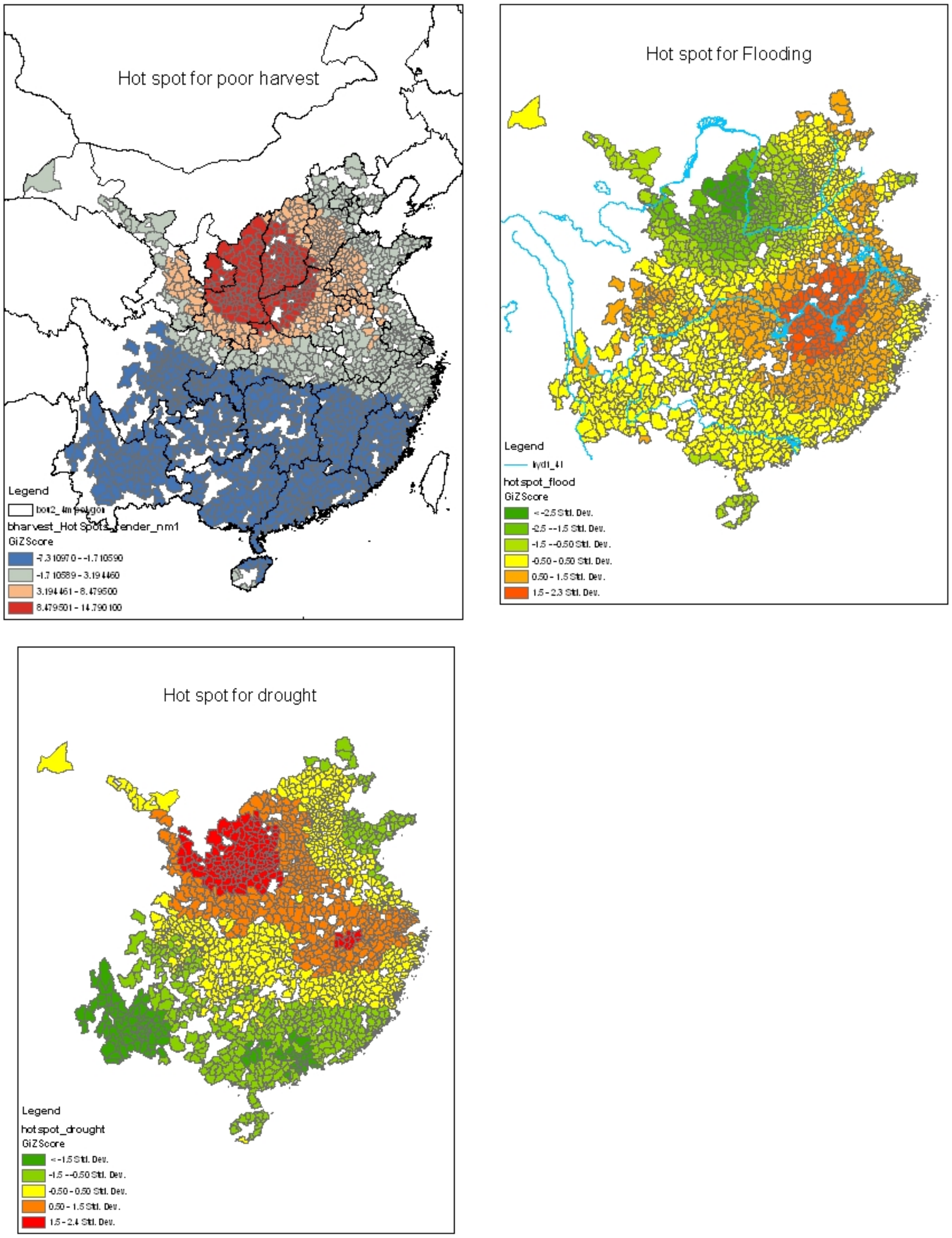


Figure 2-8 Hotspot analysis for: a) poor harvest; b) flood; c) drought.

2.4 Discussion

Harvest and temperature changes

The evidence for relationships between climate change and land carrying capacity has been explored by numerous scientists (McMICHAEL 1993; D. J. Rapport 1998; IPCC 2007). Although many studies have forecasted the impacts of potential global warming on the future food supply (C. Rosenzweig 1994; Roy Darwin 2000; M.L. Parry 2004), there are few scientific studies that have quantitatively analyzed the association between historical agricultural poor harvest and past climate change using historical records and reconstructed proxy data. The correlation coefficients allow us to determine if there is a possible linear relationship between natural agricultural poor harvest and climate conditions in the human history. In this study, Pearson's correlations revealed there is a linear relationship between agricultural poor harvest and climate variables, in terms of temperature and drought. The same method was also adopted by previous study (David D. Zhang 2007) which revealed the relationship between historical cycles of war and past climate change. The results of our finding support the hypothesis proposed by Zhang that the past climate change had effects on the natural agricultural ecosystem, and eventually affect the incidences of war in the history. Before using the Pearson correlation coefficient as a measure of association, I tested its normality assumptions to select the appropriate reconstructed temperature series. I found that the reconstructed temperature series (Mann 2003d) in Zhang's study doesn't meet the normality assumption. The most likely reason is that the series has been smoothed by moving averaging. Meanwhile, other Northern hemisphere reconstructed temperature series didn't show linear relationships between temperature and other variables. The main reason could be that such series covers much larger areas than our study area, obscuring correlations between variables. In contrast, the selected temperature time series which was reconstructed based on the proxy data at Beijing, shows good relationships between other variables, especially for some regions, such as the East and Center part of China, shows significant relationships between temperature and poor harvest. It demonstrated that it's important to use the appropriate reconstructed climate proxy data which is suitable for the study area and meet the assumption of selected statistic methods. In this case, normality and linear relationship required by the Pearson correlation test are met.

A previous study shows there is a significant correlation between temperature anomalies and autumn harvest at Yangtze River region with coefficient is 0.854 during 1730-1850 (David D. Zhang 2007). Nevertheless, within the same figure presented they showed that there is a significant opposite trend after 1850. This reveals the importance of studying the long time trend of climate change, and carefully explaining the relationship between climate change and social-economic phenomena. In this case study, Pearson correlation coefficients showed that temperature has a significant negative relationship with poor harvest over the entire studied period at annual scale. Besides Pearson correlations, chi-square test were also conducted between poor harvest , temperature, in terms of cold or warm year, flooding, drought, and the results suggest the relationship between variables are all significant (P<0.001).

A logistic regression model was also fitted for poor harvest with reconstructed temperature, precipitation, historical records of flood and drought as explanatory variables. All of variables are significant and the results are shown in the equation:

Logit(P[poor harvest])= $\log\frac{\theta(x)}{1-\theta(x)} =$

1.85-0.26*temperature+1.54*flood+2.57*drought-0.001*precipitation

The equation shows clear positive relationship between flood, drought events and poor harvest, and negative relationship between temperature and harvest.

Temperature--Flooding/drought and harvest

From the Table 1.1, the ratio of drought to flood within colder years is higher than that of warmer years, and colder years tend to have lower ratio of good harvest vs. poor harvest. This result not only supports that China experienced more droughts and floods in the colder periods than in the warmer periods (Zhibin Zhang 2009), but also indicted that there is a possible link of effects of climate change on agricultural harvest—colder weather triggers the more extreme drought events, and both temperature and water factors have significant effect on the ecological capacity of agricultural crops. The results in **Table 2.5** also suggested that the association between temperature, drought, and harvest may vary regionally. Specifically, I found positive associations between flood frequency and temperature and negative relationships between temperature, drought, and poor harvest in the East part of China.

Although the results show temperature has a negative effect on poor harvest, the analysis also showed that temperature is not the strongest factor affecting agricultural harvests. For instance, the slope of drought events is 2.57 in the logistic model, indicating that drought has the strongest influence on poor harvest among climate variables. This result is also consistent with the Pearson’s correlation test which showed that drought had largest absolute value of correlation coefficients. This may suggest that instead of direct effect of cooling on the land carrying capacity, periodic ecological stresses such as drought events can significantly reduce the agricultural yield.

Spatial patterns of change

The results of spatial analysis revealed that all studied variables showed spatial clustering and strong spatial autocorrelation. The hotspot analysis further revealed the existence of hot spots of drought, flood, and poor harvest incidence over the Qing Dynasty. The magnitude of the effects on the poor harvest may vary due to the variation of crop response to climate driven factors. For instance, the poor harvests are strongly clustered at Northern and North West part of China, which is a semi-arid area; hence water deficiency could be the most important factor limiting the agricultural yield. In contrast, the Yangtze River Delta and some coast areas also show some clustering pattern of poor harvest, which could be the effect of the other extreme climate events, such as floods, snow storms, or typhoons. Therefore, spatial modeling should be considered when analyzing the relationship between agriculture harvest and climate conditions or improve the analysis through the regionalization. Spatial modeling will be discussed further in chapter three.

Other factors

Beside the climate driven factors or environment conditions which affect natural ecological subsystems, there are some social-economic factors that may also affect agricultural systems. The irrigation system, agricultural technology and planting system may all affect agricultural yield. That is especially true for China, a country that has a long and intensive agricultural history. For 3000 years China has constructed impressive irrigation projects. For an example, the “Dujiang Yan” irrigation system in the Minjiang River basin was built around 250 BC to control sedimentation and floods, and facilitate irrigation and it remains in good condition today. Another example is the Grand Canal, which is the longest artificial waterway in the world and was begun in BC 486 and finished in the Sui Dynasty (AD581–618) to divert water from the Yangtze river to Northern part of China to support irrigation system in the semi-arid area. Such irrigation systems can be of great help to mitigate drought during less severe drought years.

Some social factors can interact with climate factors. For instance, the double cropping system for rice crop which was adopted by Chinese farmer in Yangtze River region can be tracked back to Tang Dynasty (AD 618-909). This method significantly improved the agriculture yield; however, the double cropping system can also be affected by the climate change. If temperature decreased, the double cropping system could fail due to lack of a long enough growing season during the cold period. Therefore, besides the direct impact on the agriculture yield, the climate change may also have indirect effect on it through the social-economic links.

Conclusion

Using the historical data, the relationship between past climate change and agriculture harvest was analyzed. For the old and more natural agricultural ecosystem, the climate shows strong influence on the agriculture harvest through direct and indirect links. The hypothesis in the previous studies that cold temperature may lower the land carrying capacity was supported by my findings. The results also show that besides the direct effect of cold temperature on crop growth, water deficiency is the most important factor limiting crop yields in China for the last Dynasty. The extreme drought events that increased during the cold period, which could be driven by the decreased temperature, have the strongest correlation with poor harvest among the variables explored here. Meanwhile, the regional analysis and spatial analysis revealed the spatial variation and clustering for each variable. The effect of climate change on crops is also depends on location. For instance, the

Northern crop species are more resistant to the cold than the species at South part of China, while Northern China experienced more severe winter storm than the Southern part. Therefore, a severe winter storm may cause substantial poor harvest in the next year, while a less sever storm which has less effect or even some benefit for the Northern species may cause a severe consequence at humid tropical and subtropical south China.

Climate change is the one of most important factors affected agriculture harvest in china history. This study using scientific approach and historical data fill the gap of our knowledge between agriculture failure and past climate conditions, such as warming/cooling, drought/wetness over Qing Dynasty (1644-1911). The historical records were cross checked with other references, and show a good match. For instance, both of the severe drought events in 1877 and the severe floods in 1739, and 1757 were recognized in previous studies Figure 1-1. The results revealed the possible effect of past climate change on the agricultural harvest in China by using the historical records of ecological, environmental phenomenon and recent reconstructed paleo-climate data. The results support that the cold weather affects agricultural capacity and eventually influence of human society (perhaps through war). The results also indicated the possible links of mechanism how the climate change affect agricultural harvests. Future studies will need improve several aspects: including some social-economic factors, such as population and agricultural techniques; extend the series of historical records to explore the longer trend of climate change effects, in this case study, the same systematic data source can be at least extend to include the Ming Dynasty.

References

Barry Smit, C. Y. (1996). "Climate change and agriculture in China." Global Environmental Change **6**(3): 205-214.

C. Rosenzweig, M. L. P. (1994). "Potential impact of climate change on world food supply." Nature. **367**: 133-138.

Caiming Shen, W.-C. W., Zhixin Hao, Wei Gong (2007). "Exceptional drought events over eastern China during the last five centuries. ." Climatic Change **85**(3-4): 453-471.

D. J. Rapport, R. C., A. J. McMichael. (1998). "Assessing ecosystem health." Trends in Ecology & Evolution **13**(10): 397-402.

David D. Zhang, C. Y. J., George C-S Lin, Yuanqing He, James J. Wang, Harry F. Lee (2006). "CLIMATIC CHANGE, WARS AND DYNASTIC CYCLES IN CHINA OVER THE LAST MILLENNIUM." Climatic Change **76**: 459-477.

David D. Zhang, J. Z., Harry F. Lee, Yuan-qing He (2007). "Climate Change and War Frequency in Eastern China over the Last Millennium." Human Ecology **35**: 403-414.

David D. Zhang, P. B., Harry F. Lee, Yuan-Qing He, Jane Zhang (2007). "Global climate change, war, and population decline in recent human history." PNAS **104**(49): 19214-19219.

Dorte Eide Paulsen, H.-C. L., Teh-Lung Ku (2003). "Climate variability in central China over the last 1270 years revealed by high-resolution stalagmite records " Quaternary Science Reviews. **22**(5-7): 619-701.

Easterling, D. R., G.A. Meehl, C. Parmesan, S.A. Changnon, T.R. Karl, L.O. Mearns (2000). "Climate extremes: Observations, modeling, and impacts. ." Science **289**: 2068-2074.

Fulu Tao, M. Y., Yousay Hayashi, Erda Lin (2003). "Future climate change, the agricultural water cycle, and agricultural production in China." Agriculture, Ecosystems and Environment **95**: 203-215.

Gao Xuejie, Z. Z., Filippo Giorgi (2002). "Changes of extreme events in regional climate simulations over East Asia. ." Advances in Atmospheric Sciences. **19**(5): 927-942.

Hao Zhixin, Z. J., Ge Quansheng (2003). "Climate change and Harvest in Xi'an since 1736: the high-resolution data derived from the archives in the Qing Dynasty." ACTA GEOGRAPHICA SINICA (in Chienese) **58**(5): 735-742.

Hillier, A. (2007). "ArcGIS 9.3 manual".

Hughes, M. K., X. D. Wu, X. M. Shao, G. M. Garfin (1996). Precipitation Reconstruction for Huashan, China., International Tree-Ring Data Bank. IGBP PAGES/World Data Center for Paleoclimatology Data Contribution Series # 96-020. NOAA/NGDC Paleoclimatology Program, Boulder CO, USA.

IPCC (2001). Climate Change 2001: Working Group I: The Scientific Basis. . Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Y. D. J.T. Houghton, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, C.A. Johnson (eds.) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2007). Summary for policymakers, in Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, . O. F. C. M.L. Parry, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson. Cambridge University Press, Cambridge, UK.**:** 7-22.

Keith R.Briffa, T. J. O. (2002). "Blowing Hot and Cold." Science **295**: 2227-2228.

Larry L Havlicek, N. L. P. (1977). "Effect of the violation of assumptions upon significance levels of the Pearson r." Psychological Bulletin. **84**(2): 373-377.

M.L. Parry, C. R., A. Iglesias, M. Livermore, G. Fischer (2004). "Effects of climate change on global food production under SRES emissions and socio-economic scenarios." Global Environmental Change. **14**: 53-67.

Mann, M. E., P.D. Jones (2003). "Global Surface Temperatures over the Past Two Millennia." Geophysical Research Letters **30**: 1820.

McCarty., J. P. (2001). "Ecological Consequences of Recent Climate Change." Conservation Biology **15**(2): 320-331.

McMICHAEL, A. J. (1993). "Global Environmental Change and Human Population Health: A Conceptual and Scientific Challenge for Epidemiology. ." International Journal of Epidemiology. **22**(1): 1-8.

Ming Tan, T. L., Juzhi Hou, Xiaoguang Qin, Hucai Zhang, Tieying Li (2003). "Cyclic rapid warming on centennial-scale revealed by a 2650-year stalagmite record of warm season temperature." GEOPHYSICAL RESEARCH LETTERS **30**(12): 1617.

Nils Chr. Stenseth, A. M., Geir Ottersen, James W. Hurrell, Kung-Sik Chan, Mauricio Lima (2002). "Ecological Effects of Climate Fluctuations. ." Science **297**(5585): 1292 - 1296.

Noah S. Diffenbaugh, J. S. P., Robert J. Trapp, Filippo Giorgi (2005). "Fine-scale processes regulate the response of extreme events to global climate change. ." PNAS **102**(44): 15774-15778.

Richard W. Katz, B. G. B. (1992). "Extreme events in a changing climate: Variability is more important than averages." Climatic Change. **21**(3): 289-302.

Roy Darwin, D. K. (2000). "Economic effects of CO2 fertilization of crops: transforming changes in yield into changes in supply." Environmental Modeling and Assessment **5**(3): 157-168.

SAS Institute Inc. (2000-2004). "SAS 9.1.3 Help and Documentation."

T. N. Palmer, J. R. (2002). "Quantifying the risk of extreme seasonal precipitation events in a changing climate. ." Nature **415**: 512-514.

Vitousek, P. M. (1994). "Beyond Global Warming: Ecology and Global Change." Ecology **75**(7): 1862-1876.

Zhang, D. E., Ed. (2004). The compendium of Chinese Meteorological records of the Last 3,000 years. (in Chinese). Nanjing, China, Jiangsu Education Publishing House.

Zhibin Zhang, B. C., Huidong Tian, Leif Christian Stige, Achim Bräuning, Nils Chr Stenseth (2009). "Periodic temperature-associated drought/flood drives locust plagues in China." Proceedings of Royal Society: Bioligical Science. **276**: 823-831.

3 Chapter Two
Climate change driven locust plague dynamics in Qing Dynasty

3.1 Introduction

The world is undergoing potential global warming driven by greenhouse gas emissions, which results in increasing mean temperature and changes in the variance in climate conditions. Given the changing world, how may ecological communities respond to the global warming? Generally, there are two fundamental questions. First, how can we use time series of climate change and ecological events to explore the trends and patterns of such change? Second, how can we explain the characteristics of ecological time series and further estimate the relationships between those environmental series and ecological series? The second question is important to understand the interaction between ecological and environmental processes in ecological modeling. Therefore, there is an important challenge to explain the coherence between ecological time series and environment time series. There has been many studies emphasizing the ecological patterns and processes affected by climate changes (Bjørnstad 2001; Nils Chr. Stenseth 2002), especially those studies on ecosystems and populations driven by large scale climatic variations (Cazelles 2004; Mads C. Forchhammer 2004; Me´nard F 2007).

Locusts are regarded as one of most serious pests that impact agricultural societies in terms of crop poor harvest, famine and economics loss (Ge Yu 2009). Locust plagues were also the severe natural disasters in human history in China (Yonglin Chen 1999). Therefore, it is important to study the periodicity of locust plague incidence and the environmental factors that may force natural population dynamics. However, to distinguish the density-independent environmental factors and density-dependent population processes often require a longer series to reveal the properties of an underlying process. China has the longest and the most comprehensive time series of historical documents that record the various natural environmental disaster events and corresponding human activities. There are also a number of historical documents containing tremendous records about locust plagues which occurred in the China's history. The earliest Chinese character for locusts and locust nymphs was found on the Oracle inscription from the Shang Dynasty (11^{th} century B.C). An Emperor had prompted collecting and recording Chinese migratory locust events as early as 707 B.C. The records of locust disasters in Chinese historical documents can be found in 'Shijing' (the Book of Songs), 'Chunqiu' (the Spring and Autumn Annals), 'Wuxingzhi' (Five Elements) and many other books, literature and local gazettes. For an example, there is a locust plague which spread over the entire country from spring to fall, with 296 counties reported this severe outbreak in the compendium (Zhang 2004). The example reported "the swarm of migrating locust shadow the sunlight in Juan, 1857 and made severely damaged crops at Zhengding County, Hebei Province; The swam of locust ate all of the crop before the harvest in the fall, 1857 at Huolu County, Hebei Province. There were no harvests at all at that year. The residents had to feed on the grass (Zhang 2004)."

By using these kinds of historical locust records in China, a number of studies explored the interactions between past climate change and historical locust plague, however, most of them (Tsao 1950; Ma 1958; Ma 1965) focused on inter-annual timescale rather than the longer-term variation. For instance, Li et al demonstrated that locust plague records had a negative correlation with summer half-year precipitation and a positive correlation with winter half-year temperature in a case study at Shaanxi province in central

China (Gang Li 2007); Chen et al revealed that locust (*L. m. tibetensis)* plagues occurred successively in 12 years from 1846 to 1867 in Xizang (Tibet) by using historic literature of locust disasters. They also found that another locust outbreak occurred at same time period in Yellow river basin and Huaihe River Basin in East China which caused by another migratory locust subspecies—*L. m. manilensis* (Yonglin Chen 1999). Their study on those two contemporary locust outbreaks suggested that there is the possible relationship between the outbreak of the migratory locust and coincident drought events.

One of earliest studies to explore long term locust dynamics found that the variability of locust plagues increased at longer time-scales in a 1000 year Chinese locust record time series (Sugihara 1995). A recent study using the same series revealed that locust abundance has a negative correlation with temperature on a decadal scale (Leif Christian Stige 2007). Their results showed how temperature and precipitation influenced migratory locust abundance at time scales between 50 and 200 years, the results also challenged the traditional point of view that locusts are positively correlated with temperature on an annual scale. By using signal analysis on a multi-decadal scale, they found both floods and drought are more common in cold, wet climate periods, which both have a multiplicative effect on locust plague incidence. Hence, there are more locust plagues triggered by environmental conditions at cold and wet periods rather than warm and dry periods.

Spectral analysis is one of time series analysis methods that has been extensively used in ecology and population dynamics (Trevor Platt 1975; Ripley 1978). However, one of important assumptions of spectral analysis is that it requires the analyzed time series to be stationary, an assumption that often not justified for ecological series. The traditional

Fourier transform approach can only provide information on a single frequency, which does not vary with time. In contrast, wavelet analysis is a method for time-scale resolved analysis to detect and analyze exceptional co-oscillations. “The wavelet transform in the wavelet analysis is the method can provide localized time and frequency information without requiring stationary assumption of time series. It transforms a one-dimensional function of time into a two-dimensional function of time and frequency or, equivalent scale (Liu 1994).”

Usually, an ecological event might be triggered by unexpected co-variation of relevant environmental process at various temporal scales, for instance, precipitation, temperature and soil moisture. Therefore, another advantage of wavelet analysis is that it can help to understand the interaction between climatic and ecological processes. It investigates when and at which temporal scales these processes are co-oscillating by using cross wavelet analysis, which is also very important for ecological modeling. Moreover, combined with a robust significance test, wavelet analysis opens a new perspective on time series analysis in ecological processes.

Wavelet analysis was first introduced by Grossmann and Morlet (Grossmann A 1984) and has been applied in a wide range of methods and fields since then, such as in geosciences (Andreas Prokophi 1996; Kumar P 1997; A. Grinsted 2004). Early applications of wavelet analysis to ecology described the synchrony of measles outbreaks in the UK (B. T. Grenfell 2001). The method became increasingly popular after continuous wavelet analysis demonstrated the relationship between the El Nino Southern Oscillation Index (SOI) and sea surface temperature (SST) (Christopher Torrence 1998). Recently, case studies of applied wavelet analysis on ecological process were reviewed by Bernard

Cazelles (Bernard Cazelles 2008). Meanwhile, there are also some studies on historical climate series that have adopted this method, for instance, by using a wetness index derived from historic chronicles and documents Jiang et al. identified variation of different frequencies and abrupt climate changes in East China from 960 to 1992 (Jianmin Jiang 1997).

In the present study, I'm interested in the co-oscillating properties of ecological processes and climate events. To understand the interaction between climate change and ecological processes, I investigated possible mechanisms of climate triggering of locust events and applied wavelet analysis to detect potential environmental conditions (flood/drought) triggering locust plagues in Qing Dynasty (1644-1911) of China. Particularly, I focused on the application of continuous wavelet analysis (CWT) of reconstructed temperature, precipitation series and historical drought/flood records, which offers a powerful tool to detect potentially climate driven effects on locust plagues, by investigating when and at which temporal scales these events are co-oscillating.

3.2 Data and Methods

3.2.1 Data

The instrument-based climate records in China are of short duration, spanning less than 100 years; however, the historical documents in China span more than 3,000 years and have been widely used in recent studies (Chu 1973; Quansheng Ge 2003).

Six data sets were used in this paper to analyze climate variability and possible links between climate variables, environmental conditions and locust plagues (Figure 3-1). Poor harvest data were used to explore possible effect of locust plagues. Environmental condition variables included floods and drought, locust plague incidence frequency, and poor harvests. These events were extracted from historical documents and digitized at four different time scales (year, season, month, and day) depending on the temporal information recorded.

(a) Locust, flood, drought, poor harvest frequency data

The historical climate disaster (droughts/floods), agricultural harvest, and locust events data were interpreted and extracted from a multi-volume compendium that records relevant climatic information, such as flooding/drought events and socioeconomic records, such as agricultural harvest, which can be traced back to 3000 years ago (Zhang 2004) (Details can be seen in introduction section). In this study, the time series of locusts, floods, droughts and poor agricultural harvests are proxies based on the number of records reported by each administrative unit for the entire Qing Dynasty.

(b) Reconstructed Temperature, precipitation data

The historical climate change data are the results of recent reconstructed Paleo-climate data. Recent research has significantly improved high-resolution paleo-climate reconstructed data. For instance, see the data reconstructions of Northern Hemisphere mean surface temperature by using multi-proxy data networks (Keith R.Briffa 2002; Mann 2003). In this study, to better represent the past temperature of the study area and to meet the annual scale of the historical records, the reconstructed temperature series at Beijing on in China was used (Ming Tan 2003).

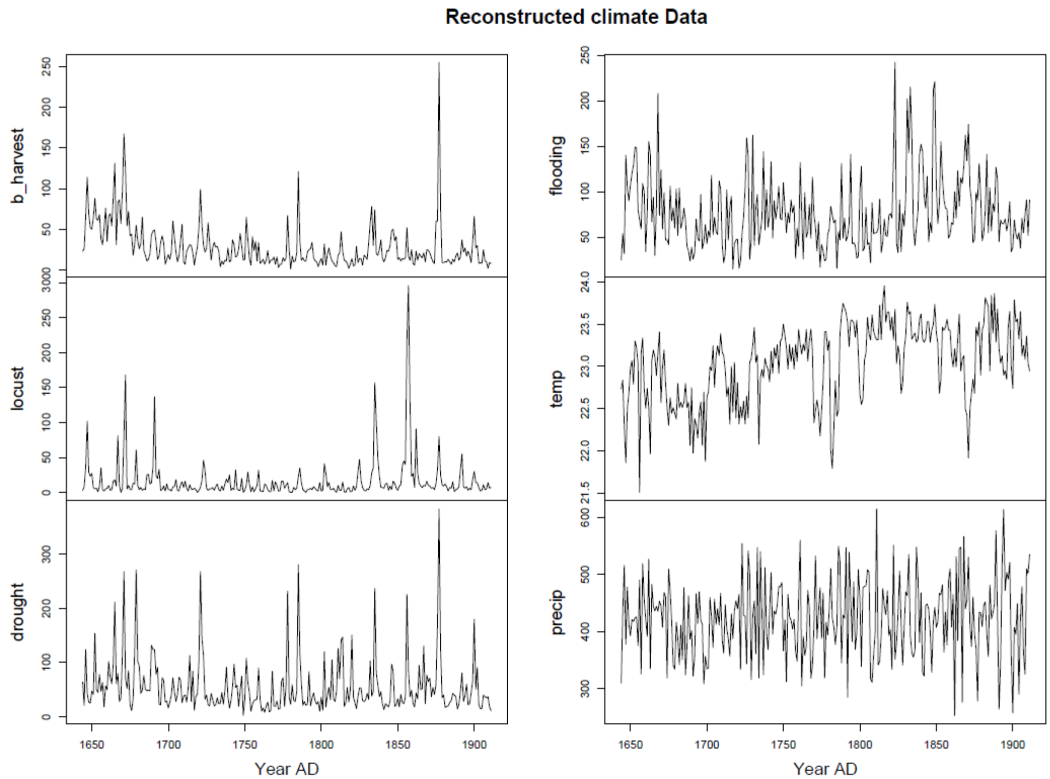


Figure 3-1. The reconstructed climate and historical locust time series

Paleo-climate precipitation series adopted in this study are reconstructed April-July (AJ) precipitation at Huashan in north-central China (Hughes 1994; Hughes 1996) based on tree ring density and width from *Pinus armandii*. The reconstructed precipitation data has been calibrated and cross-validated against local instrumental data (Hughes 1996).

3.2.2 Methods

(a) Intra/Inter-annual analysis:

Based on the information of records, the relationship between each variable within each year was analyzed by counting the frequency of events at each scale (month, season) and compared the patterns between each variable. A Pearson correlation analysis was conducted between locust and other variables in an annual scale (SAS Institute Inc. 2000-2004).

(b) Wavelet analysis

Wavelet transform methods and wavelet analysis was used in this study to reveal variation components in the historical series and reconstructed series, which has been widely applied in signal detection from climate variable series (K.-M. Lau 1995) and is one of the most efficient and appropriate methods for studying non-stationary ecological time series.

Before conducting the wavelet analysis, the original time series of locust abundances, temperature, precipitation, and floods/droughts were de-trended by removing linear trend and removing high frequency noise by the classical 'low-pass filter' (Robert H. Shumway 2006). By rescaling the variance, the smoothing highlighted the periodic components masked by the trend. The detrended time series are displayed in Figure 3-2, which have been standardized to zero mean and unit s.d.

After the detrending the time series, the SOWAS Package in R was used to conduct cross wavelet analysis for the estimation of wavelet spectra, cross spectra and coherence (D. Maraun 2004; D. Maraun 2007). First, the 'Morlet Wavelet' was used for wavelet decomposition to localize wavelets in frequencies and to give more quantitative information for interactions between two time series. The continuous wavelet transform (CWT) decomposed the time series into both a time domain and a frequency space which gives the possibility of estimating the distribution of variance between periodic or frequency bands and different time locations. CWT was also used to generate the wavelet power spectrum.

Cross-wavelet analysis was constructed to identify wavelet coherencies in both time and frequency space to quantify the relationships between two non-stationary signals. The coherence function is an equivalent measure of the linear correlation between the spectra of two time series (Chatfield 1989; Bernard Cazelles 2008), which shows the significant relations at different periods or frequency bands. A value of one implies a perfect linear relation, while a value less than one indicates that a perfect linear relation is created by noise, by external influences on at least one of the series, or when the relation is not linear.

The significance levels were set at $p<0.05$ and computed based on 1000 'Beta-Surrogate' series by using Bootstrap methods to quantify the statistical significance of the computed patterns (Tristan Rouyer 2008). The wavelet phase spectrum was constructed by using phase analysis to estimates the phase difference of two time series, which can reveal the phase associations and the time lag between two time series with respect to time and scale.

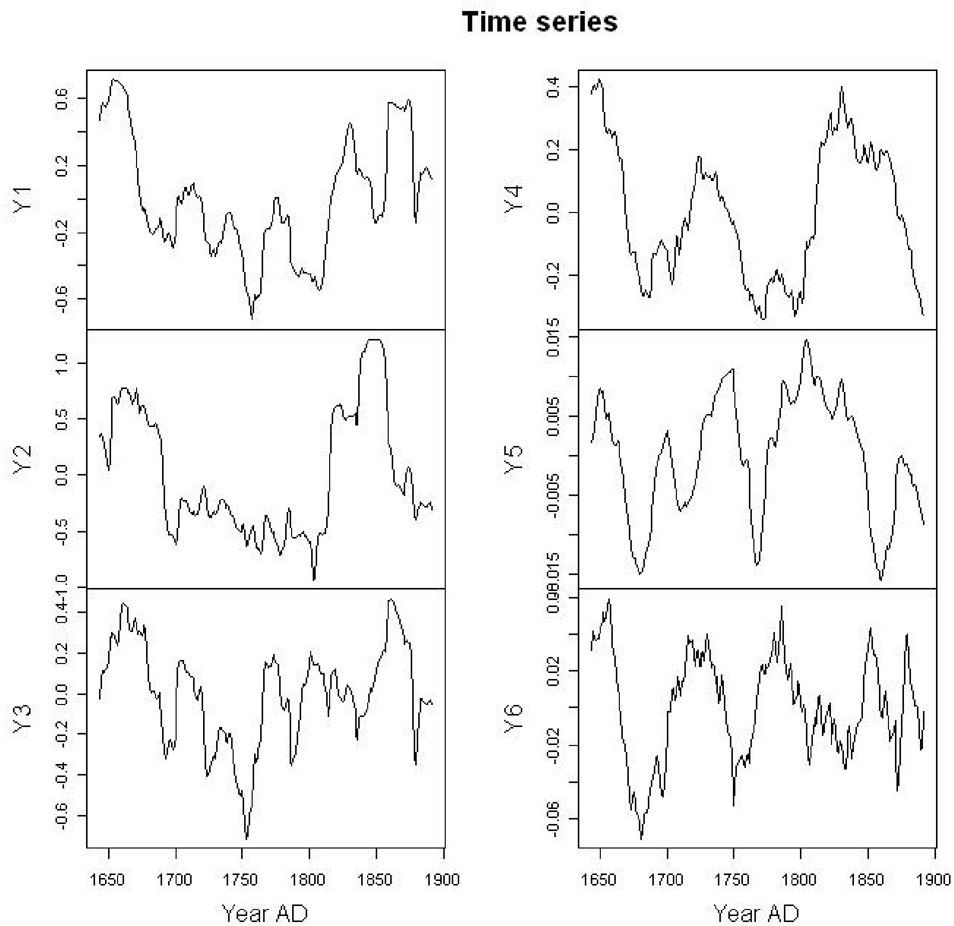


Figure 3-2. De-trended time series for each variable: Variables Y1 to Y6 are poor harvest, locust, drought, flooding, temperature, and precipitation, respectively.

3.3 Results

3.3.1 Temporal analysis:

Intra annual analysis

The monthly frequency of historical records of locust plagues, floods, droughts, famines, poor harvest, and plague is shown in the Figure 3-3. Peaks of locust plagues are highly concentrated in June and July, with substantial numbers of drought in March and

August. Drought events show similar distributions as locust plagues, except locusts tend to lag one month lag after the droughts. Floods show peaks between June and August, while some events in May and September. . Poor harvests are evenly distributed in the growing season. Famines are significantly concentrated in the spring before the harvest season. Plagues lag two months behind famines.

Examining the distribution of frequency of events by month shows some interesting patterns, nevertheless, it's also illuminating to examine the distribution of events by season. It may be particularly useful as it may increase statistical power by increasing the sample size of records. The seasonal results are shown in Figure 3-4. Locusts and floods occurred mainly in the summer. Drought peaks in the summer, however, the spring and autumn also show substantial occurrence of drought. Poor harvest has very similar pattern as locust plagues. Famine shows an increasing trend before spring most likely due to lack of food supply and a decreasing trend after spring. Plagues peak in summer perhaps due to floods and with some high frequency in spring might due to famine or suitable environment condition for disease dispersal.

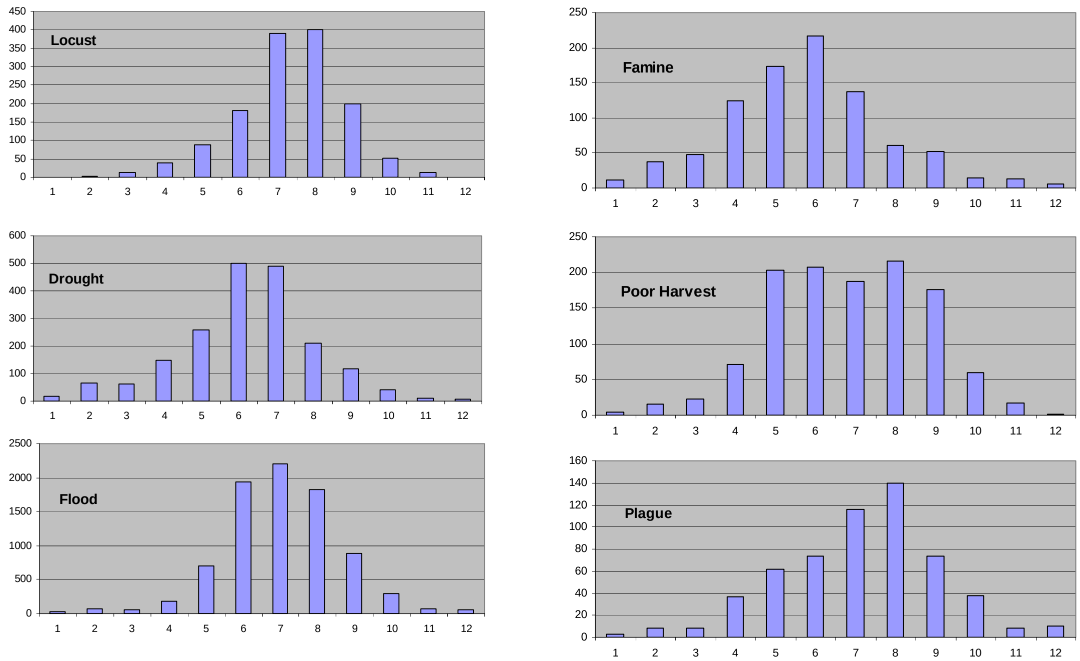


Figure 3-3. The frequency of historical events counted by month.

Inter-annual analysis

The correlation analysis between locusts and reconstructed past climate variables (temperature/precipitation) as well as other historical climate records (drought/flood) revealed associations between climatic change and past events. Pearson's correlation coefficients between locust and flooding, drought,

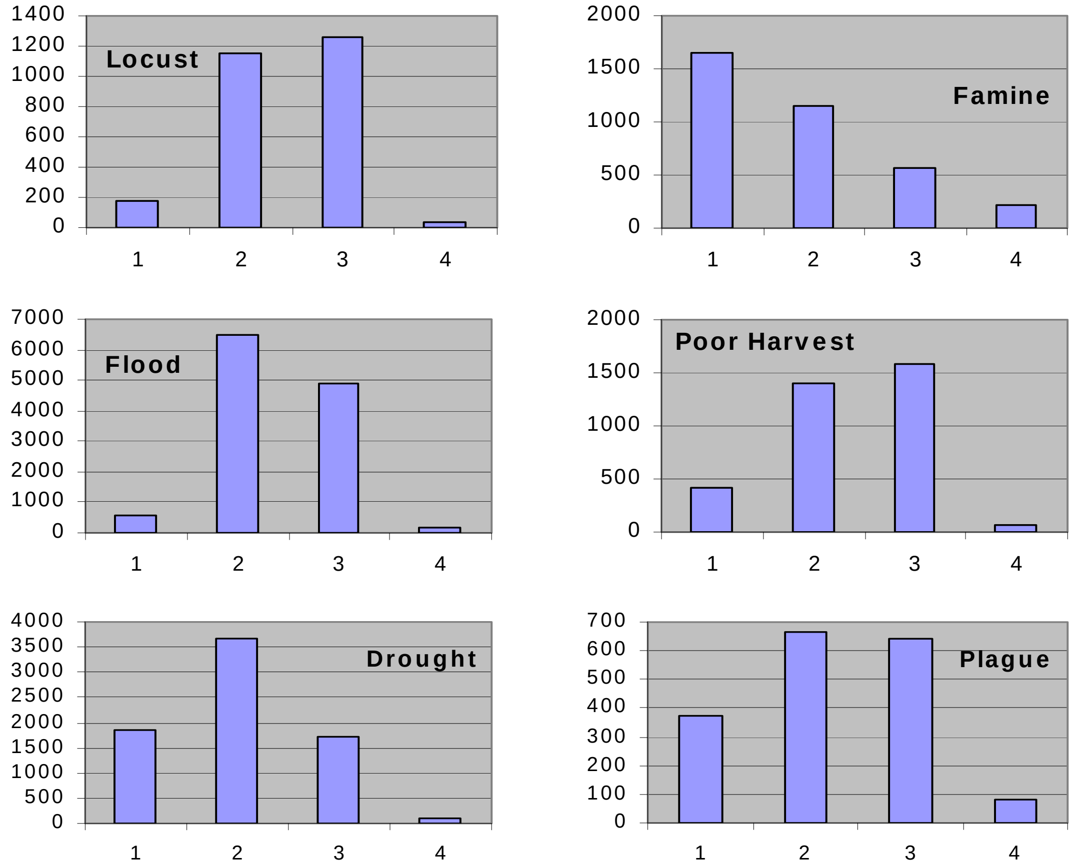


Figure 3-4. The frequency of historical events counted by season

For Table 3.1, temperature is significantly negatively correlated with locust plagues at $p = 0.05$ levels; drought has a significantly positive relationship with locust plagues. Precipitation and flooding shows a weak non-significant negative relationship with locusts.

Table 3.1.Pearson's correlation between locusts and other variables

	Temperature	Precipitation	Drought	Flood
Coefficient	-0.12	-0.08	0.43	-0.06
P value	0.05	0.20	<0.0001	0.34

3.3.2 SOWAS--WAVELET analysis:

Continuous Wavelet Power Spectrum

After detrending the time series to reduce non-stationarity, the first observed peak for locust plague occurrence around AD1670 and a second broader peak between AD1830 and 1850 (Figure 3-2). Nevertheless, this classic approach may lead to a misleading interpretation of the dominant oscillating components and their time localization. Wavelet analysis allowed us to decompose the locust plague variability as a function of period and time. Figure 3-5 shows the continuous wavelet power spectrum of the analyzed climate, environmental conditions and ecological time series in the study. It demonstrated that the oscillating components of locusts and droughts consistently and significantly occurred at periods of 120-140 years. Temperature also consistently and significantly oscillated at periods of 80-120 years. Floods varied mainly at 80-120 years bands between 1700 and 1850. This gives us further confidence that we can detect some coherence between locusts, droughts and temperatures in the cross wavelet analysis.

The oscillating components of precipitation and poor harvest are only present for some restricted time for the 80 year periodicity. However, part of the peaks for precipitation and poor harvest are out of region delineated by "the cone of influence"[4], the indication of results should be interpreted carefully. These results emphasize remaining non-stationary behavior and the absence of a single persistent mode of variability for the analyzed time series.

---

[4] The zone where edge effects are present, is called the ''cone of influence'' (see Torrence and Campo 1998) and the information above the cone is lacking in accuracy and should be interpreted with caution. Zero padding caused edge effects, while it is introduced to artificially increase the time series to avoid false periodic events. However, the disadvantage of Zero padding is when

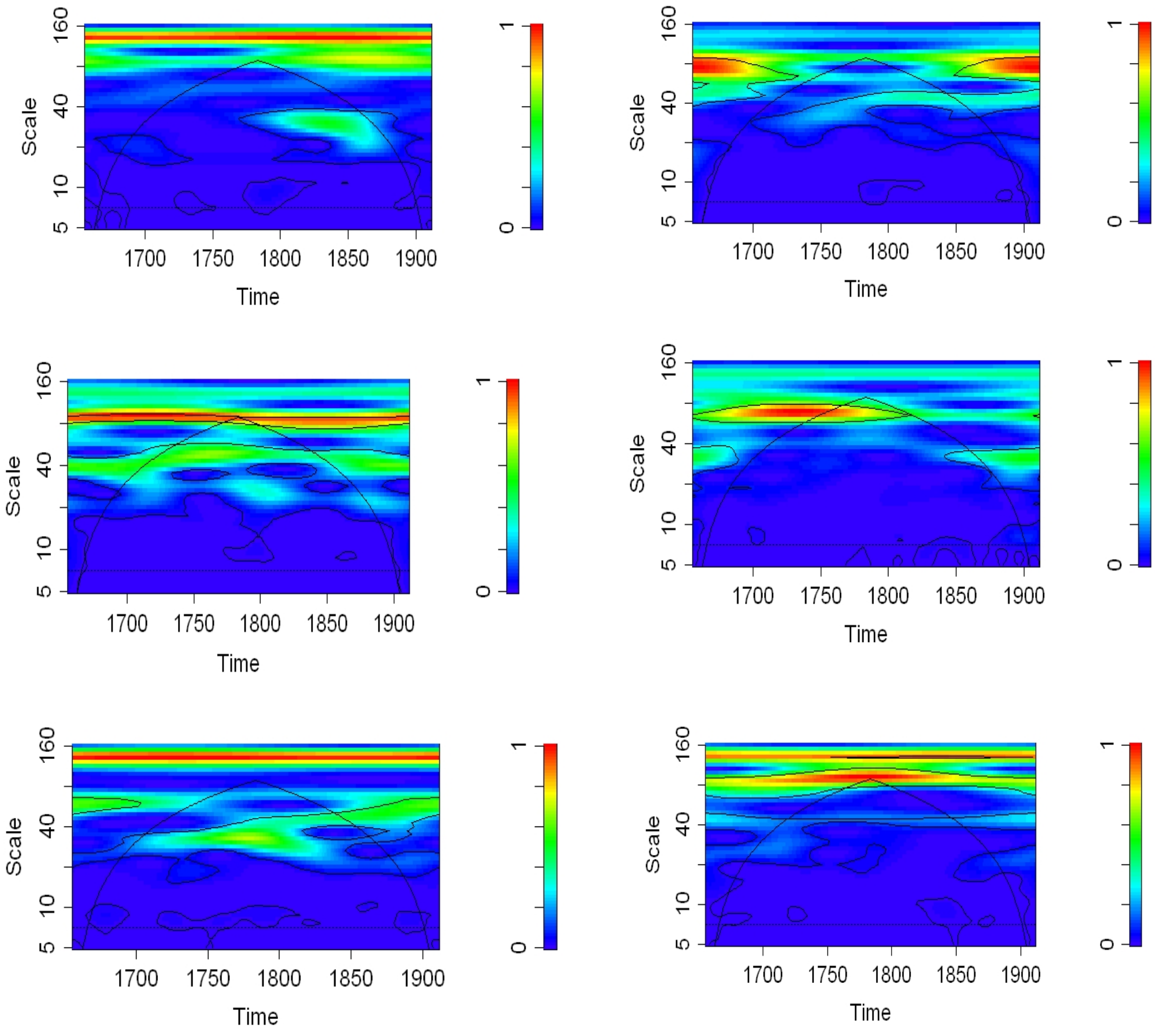


Figure 3-5. The continuous wavelet power spectrum of the signals for: locust plague, poor harvest, temperature, precipitation, drought and flood. The colors code for power values from dark blue represent low values to dark red represent high values. P-values associated with the values within the area delineated by the thin black lines are less than 5% based on 1000 Markov bootstrapped series and the thick black line indicates the cone of influence that delimits the region not influenced by edge effects.

Continuous wavelet coherency spectrum

An analysis of the coherence between the historical locust and reconstructed temperature and precipitation series, detected the following typical situations.

---

wavelet gets closer to the boundary of the time series, the values of the wavelet transform are

1. The results of continuous wavelet power spectra of locusts and temperature were shown in Figure 3-6(a), peaks in the spectrum (periodogram) indicated which frequencies are contributing the most to the variance of the series. The association between locust plagues and temperature appear significant in the 8–16 years periodic bands for the time periods 1675–1700, 1770–1810, and gradually changed during 1830-1880.

2. Patches of high coherence between locust and precipitation can be seen at scales between 10 and 20 years for the time periods at 1670-1730 and 1780-1840 (Figure 3-6.b).

3. It is noteworthy that there is a significant coherence between drought and locusts in the 4–10 periodic bands during two major periods: 1710-1810 and 1870 to 1910 (Figure 3-7. a.); while the association between locusts and floods is only significant in 4-10 year bands during periods: 1720-1740 and 1850-1880 (Figure 3-7 b).

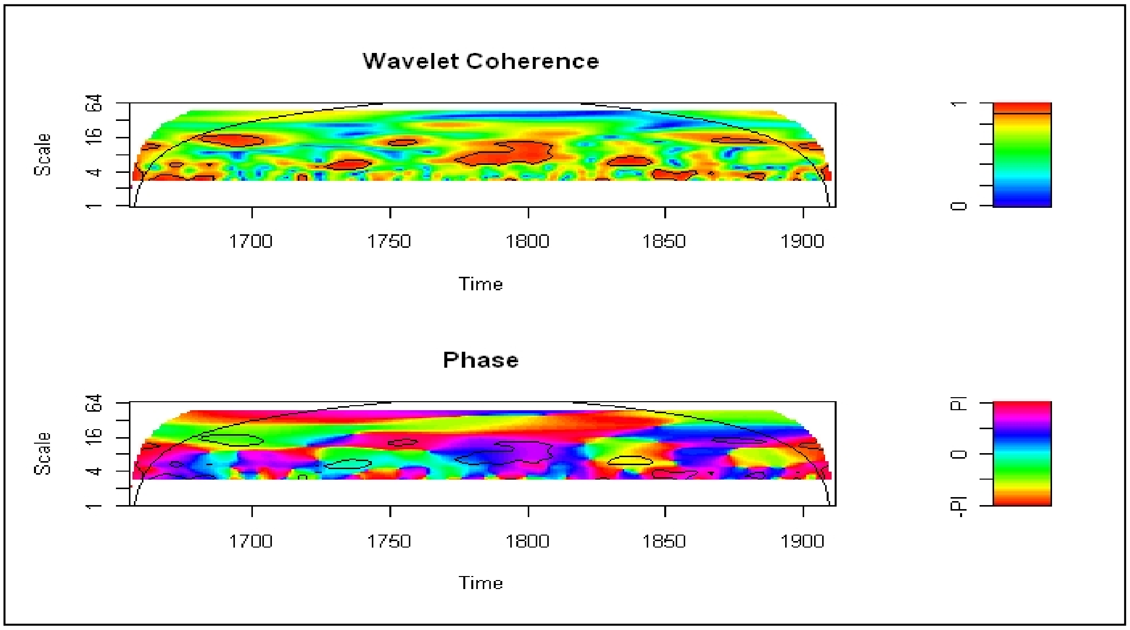
4. The association between temperature and drought shows significant coherence in the 10–20 year periodic bands for the time periods 1740–1770 and gradually changed to 8-10 year bands for the time periods 1800 and then back to 10-20 year bands from 1820 to 1840 and from 1860 to 1910 (Figure 3-8 a); significant coherence between temperature and floods can be seen at scales between 15 and 20 years for the time periods at 1700-1750 and gradually variation between 1840 and 1910 (Figure 3-8.b). Precipitation doesn't show significant coherence with drought and flood except some small patches (Figure 3-9.)

The wavelet phase spectrum estimates the phase difference of two processes with respect to time and scale. A positive value indicates a lead of the first series significantly against the second series, and a negative value indicates a lag. For instance, a negative value within contour line indicates there is significantly short lag of locust record with respect to the reconstructed temperature data, among those significant patches, most of

---

reduced by the zeros.

them indicate the locust plague are lag of temperature (Figure 3-6 a). The phase difference between locusts and precipitation (Figure 3-6 b.) also showed that locusts lag precipitation in the two significant patches at 1670-1730 and 1780-1840. The phase analysis between locusts and droughts showed a 4-10 year lag of locust with respect to the drought; while the phase association between locusts and floods didn't show any consistent trends (Figure 3-7). The phase analysis of temperature and drought shows opposite trend as that of temperature and flood 1800. Before 1800, which is a cold period, temperature leads drought and lags floods.



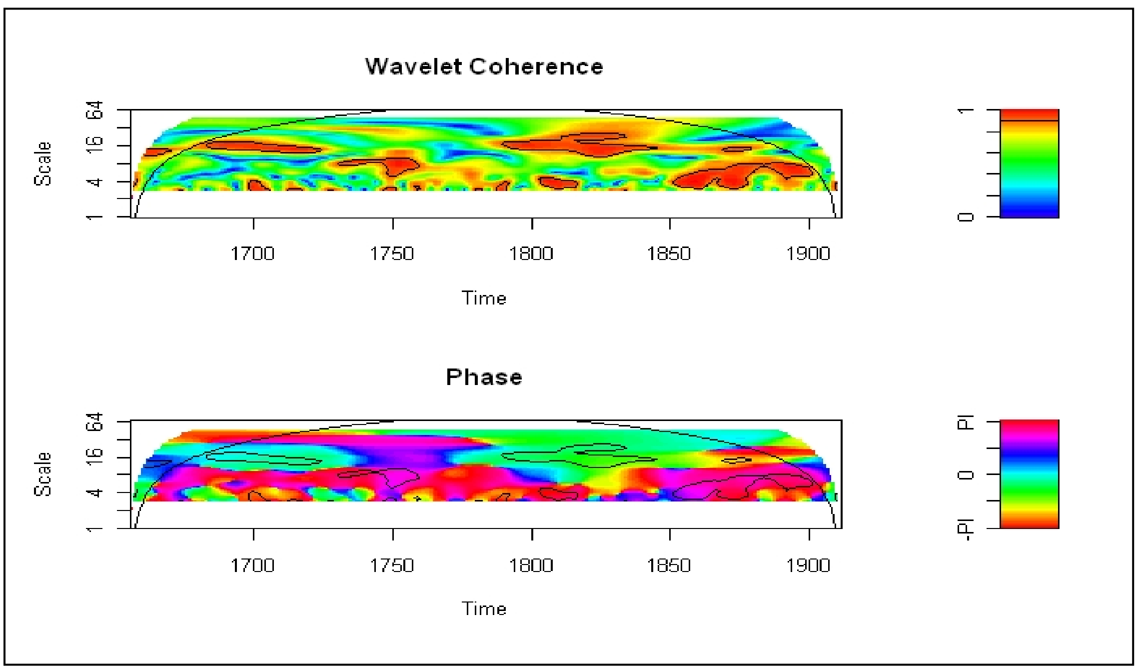


Figure 3-6. A. Wavelet coherence and wavelet phase spectrum between locust and temperature. B. locust and precipitation. The color codes for coherence values from dark blue (low values) to dark red (high values). The 5% significance levels computed based on 1000 Markov bootstrapped series and the thick black line indicates the cone of influence that delimits the region not influenced by edge effects. The wavelet phase spectrum estimates the phase difference of two processes with respect to time and scale. A positive value indicates a lead of the first process against the second one, a negative value indicates a lag.

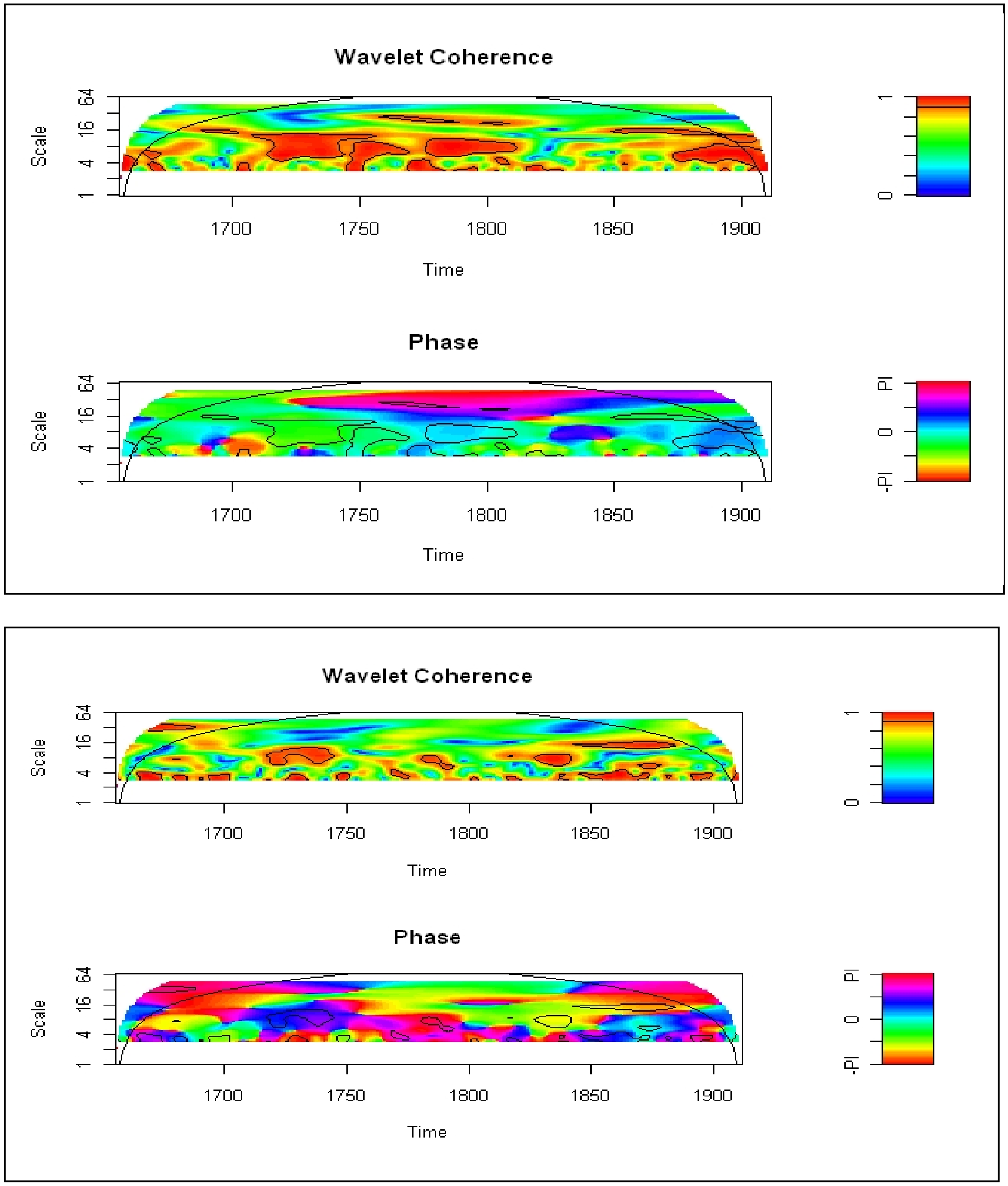


Figure 3-7. a. Wavelet coherence and wavelet phase spectrum between locust and drought. B. locust and flood. The color codes for coherence values from dark blue (low values) to dark red (high values). The 5% significance levels computed based on 1000 Markov bootstrapped series and the thick black line indicates the cone of influence that delimits the region not influenced by edge effects. The wavelet phase spectrum estimates the phase difference of two processes with respect to time and scale. A positive value indicates a lead of the first process against the second one, a negative value indicates a lag.

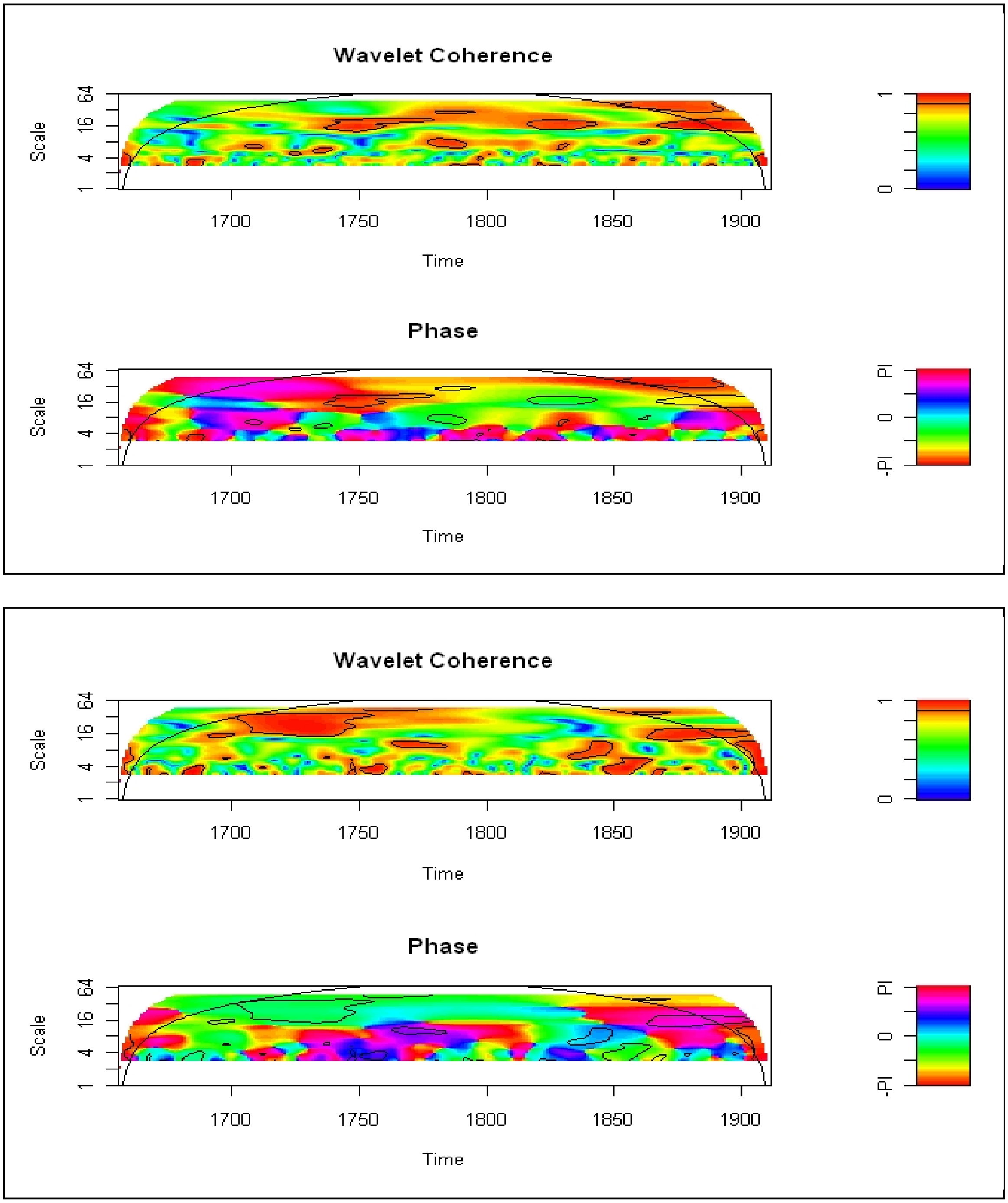
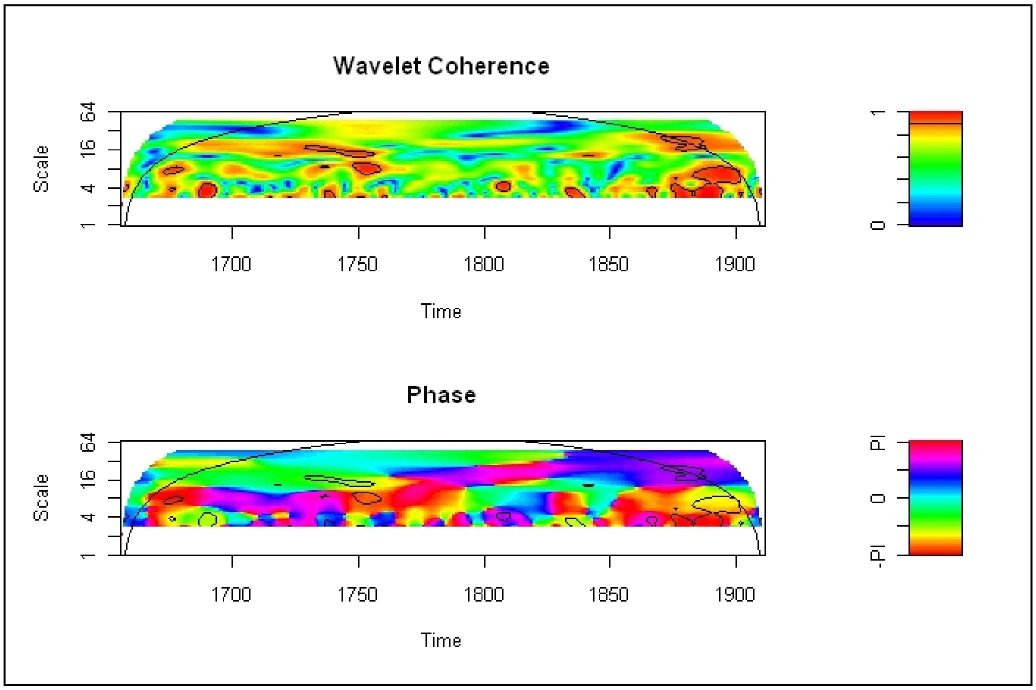


Figure 3-8. a. Wavelet coherence and wavelet phase spectrum between temperature and drought. B. temperature and flood. The color codes for coherence values from dark blue (low values) to dark red (high values). The 5% significance levels computed based on 1000 Markov bootstrapped series and the thick black line indicates the cone of influence that delimits the region not influenced by edge effects. The wavelet phase spectrum estimates the phase difference of two processes with respect to time and scale. A positive value indicates a lead of the first process against the second; a negative value indicates a lag.



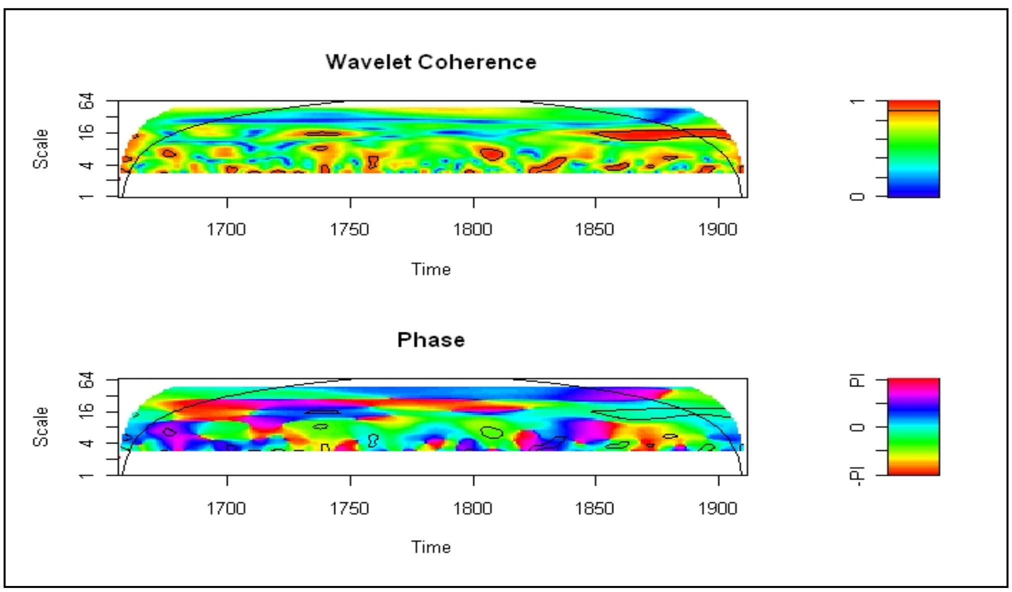


Figure 3-9 a. Wavelet coherence and wavelet phase spectrum between precipitation and drought. B. precipitation and flood. The color codes for coherence values from dark blue (low values) to dark red (high values). The 5% significance levels computed based on 1000 Markov bootstrapped series and the thick black line indicates the cone of influence that delimits the region not influenced by edge effects. The wavelet phase spectrum estimates the phase difference of two processes with respect to time and scale. A positive value indicates a lead of the first process against the second; a negative value indicates a lag.

3.4 Discussion

Significance

The present study addressed evidences from historical records of locust plague time series, as well as environmental conditions variables--drought, flood events and reconstructed climate time series. The results supported the hypothesis that periodic climate change forced locust plagues, by analyzing unique historical from the last dynasty (1644-1911) of China, combined with. This case study especially emphasized the importance of low-frequency phenomena, which involve oscillations of locust plagues detected at time scales longer than a year. The aim of the study was to reveal the periodicity of locust plagues and other factors in the long term change and possible relationship between them, which is important to understand the possible causes of climate driven locust outbreaks.

The outbreak of locusts can be triggered by many different climatic factors, such as rains, drought, and floods. Therefore, it's crucial to understand the interactions between climate and ecological systems, especially over long but slow changes in climatic conditions and their ecological consequence that humans tend to ignore.

In spite of efforts by many scientists and managers, locust plagues still occur often in various areas in China, and the locusts are still regarded as serious pests. In the present study, wavelet analysis of coherence between locust plagues and agricultural poor harvests revealed the relationship between two series in a natural ecosystem. The results show that there are several significant coherences between two series in 4-8 year periodic bands for the time periods 1700-1740, 1770–1810, and 1870-1910 (Figure 3-10). The results of phase analysis of those two series suggest that all locust plagues precede the agriculture poor harvests in those periods. Combined with results of coherence between drought and locust, these analyses show that droughts, locusts, and poor harvests are strongly associated in a clear sequence. The consistency of associations among them at the same frequency-time space from 1770 to 1810 indicated the possible link of drought→locust→harvest.

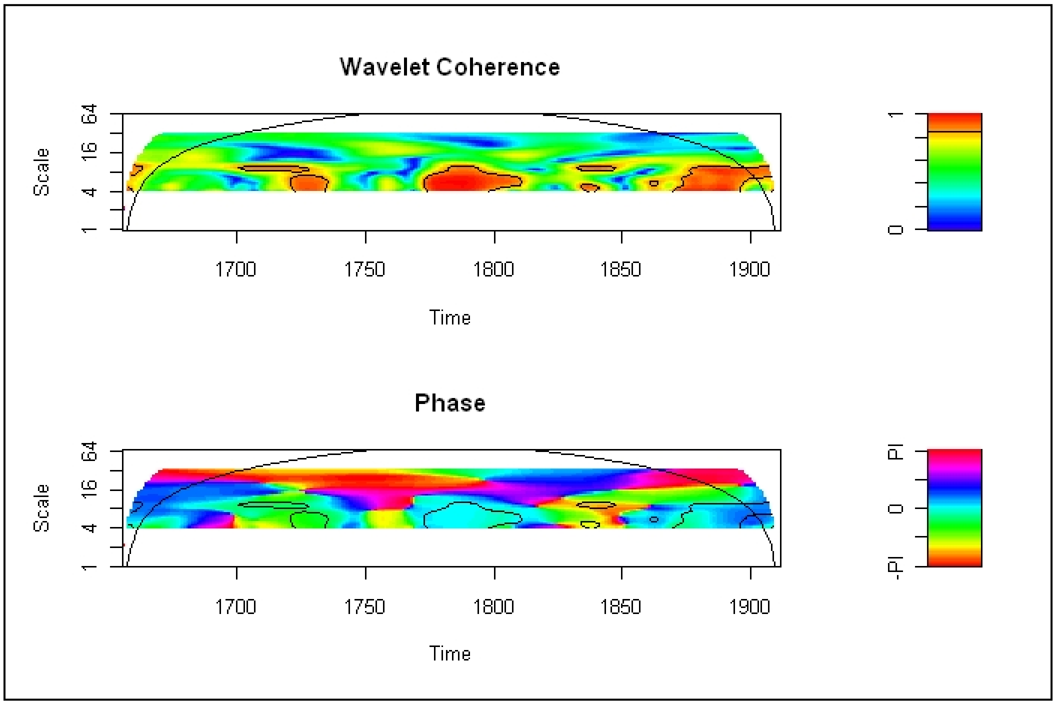


Figure 3-10. Wavelet coherence and wavelet phase spectrum between locust and poor harvest. The color codes for coherence values from dark blue (low values) to dark red (high values). The 5% significance levels computed based on 1000 Markov bootstrapped series and the thick black line indicates the cone of influence that delimits the region not influenced by edge effects. The wavelet phase spectrum estimates the phase difference of two processes with respect to time and scale. A positive value indicates a lead of the first process against the second; a negative value indicates a lag.

Potential mechanisms of locust outbreak

Locusts at low densities exhibit what is called the “solitary phase”, which causes little damage to agricultural crops. Nevertheless, when the population density increases, locust morphology, physiology and behavior change substantially. Locusts exhibit a “gregarious phase” after several generations under high-density.

In the gregarious phase, adults swarm and migrate over long distances and even nymphs show an aggregating behavior has significant potential damage to crops.

Long-term changes in climate have large effects on the dynamics of locust plague which has been revealed by studies using long-term historical records and other reconstructed climate series. For instance, previous studies showed that temperature and soil moisture are the most important factors affecting reproduction and survival of the locust (Ma 1958; Ma 1965).

Drought could accelerate the outbreaks of migratory locusts and aggravate the seriousness of locust plagues by providing extremely suitable environment conditions for the reproduction and migration (Zhibin Zhang 1999). Droughts allow locusts to lay eggs in favorable habitats while retreating floods will provide ideal breeding conditions for locust. Effects of rainstorms on locusts survival may vary according to species and depending on spatial-temporal characteristics of the storm (Robert A. Cheke 2007). Chen found the most probable relationship between locusts and the drought in China is that both events occur at the same time, and the second most probable phenomenon is that locust outbreaks follow in years after a drought event. There is also some regional variation in the relationship. For instance, in Huaihe Basin, the most likely timing of locust outbreaks is the year after flooding (Ma 1958; Yongling 1979). The positive correlations between temperature and locusts are mostly due to direct effects on locust development, reproduction, and survival.

Recent studies have shown that factors affecting population dynamics can change and switch at multi-decadal scales. Moreover, either low or high moisture can facilitate locust outbreaks, operating through different processes. At the annual time scale, the basic ecological process that predict population dynamics are mortality, birthrate and fitness of individuals under changes of ecological factors, such as density, food, enemies and climate (Lima 2007). However, the factors driving the long-term dynamics of locust population can differ from those operating on an annual timescale. At the larger temporal (decadal) or spatial (regional) scale, the existence of suitable breeding habitats rather than the local fluctuations driven by birth and mortality rate have dominant effects on the long-term dynamics of natural populations. Such low-frequency climate driven effects are typically not recognized due to the relatively short life time span of human observers and the available duration of instrument-based data. Therefore, using historical series to study the fluctuations of ecological process associated with climate change and environment conditions are important for us to understand the mechanism under the long term change and help us to predict the locust plagues.

In present study, the periodicity of fluctuations of locusts, temperature and drought series are consistently at around 100 year's band, which is consistent with previous studies (Weihong Qian 2007; Zhibin Zhang 2009). Further analysis of coherence revealed there are consistent associations at 1777-1810 around 10 year's periodic bands between locust and temperature, temperature and drought, locust and drought. Such consistency at same frequency and time space indicted the possible casual interlinks of temperature-drought-locust plague, while the causal chain of temperature→flood→locust didn't show such consistent and significant association in the same frequency-time space. The finding suggests that drought events driven by long term variation of temperature change explains locust dynamics better than floods.

Variation of past climate change

Climatic extreme events on the decadal timescale are important in determining the composition of natural ecosystems. Since the last decade of 20th century, there have been a number of studies on decadal-scale climate variability. These studies evaluated the unique characteristics of past climate changes and assess whether the changes result from natural variation or anthropogenic factors (Masahiro Watanabe 1999; IPCC 2001). Among those studies, studies on inter-decadal climate variations of precipitation and temperature in East Asia, especially in China have been increasing in number and have significantly improved our understanding of long-term climate variability (Graham 1994; Congbin Fu 1999; L. Wang 1999; Crowley 2000; Yongsheng Zhang 2004).

Recent studies using historical documents and instrumental records from China applied signal analysis from wavelet transforms and revealed that temperature series have two multi-decadal oscillations at quasi-20-year and quasi-70-year timescales since the 1750s (Weihong Qian 2007). Climatic regime shifts in North China in the last 200 years transitioned from dry to wet periods around 1800, 1875, and 1940 while the transitions from wet to dry periods appeared around 1840, 1910, and the late 1970s.

Recently, Gao and Zhang (2005) also reported multi-timescale oscillations of 60–70 years using various climate series such as the Northern Hemispheric tree-ring index, and dry–wet indices in North China and the lower Yangtze River Valley.

The quasi-70-year oscillation observed in North China is consistent with 60–70-year oscillation in the lower Yangtze River and Seoul, however, has an opposite trend.

As the results of CWT show in the case study, droughts and locusts peaked in the 1880's with 120 to 140 years bands periodicity. From this pattern, I might predict that droughts and locusts will peak again between 2000 and 2020, which is consistent with studies by Gao and Zhang (2005), who suggest that the coming dry–wet transition will be near the early 2010s.

Uncertainties associated with this study

One possible of uncertainty of this study is that the different species of locusts may respond differently in their behavior and relationship with climate and environmental factors. Based on the previous study (De-Xing Zhang 2003), there are about ten species of migratory locusts in the world, however only three of them have been recognized in China: *L. m. manilensis* (the oriental migratory locust), *L .m .migratorya* (the Asiatic migratory locust) and the *L. m. tibetensis Chen* (the Tibetan migratory locust), respectively. More important, those three species are distributed in the three natural regions of China: the eastern monsoon region, the northwestern arid region and the Qinghai-Tibet Plateau, therefore, in this case study, study area are mostly covered the eastern monsoon region, corresponding to the area of where species *L .m. manilensis* present, and only covered a very small part of northwestern arid region, which corresponding to the area of where species *L. m. migratorya* live. Therefore, effects of species variation are not likely to compromise this study.

Density-dependent responses of different subspecies to climate change should be considered to correctly interpret the relationship between ecological systems and environmental conditions. In the future, this uncertainty should be addressed by using the different climate series according to the subspecies ranges to examine their association at finer scales rather than the whole of China.

Another uncertainty of the present study is the length of available time series. The periodicity of time series may have some internal relations through the time and can be applied to project future climatic change. The periodicity inferred from the wavelet analysis needs a longer series, in case shorter series are not sufficient to capture some long term periods. The previous study (Zhibin Zhang 2009) demonstrates a more consistent periodic components and coherence among the climate and locust series at 160-170 years bands. The results of this case study supported their findings that periodical bands around 40-60 years and 60-80 years were detected only for limited time periods. To investigate the effects of long term climate change on the historical locust plagues, the longer series are needed.

Both reconstructed temperature and precipitation series span over 1000 years, however, because of time constraints of the present study, the digitalized historic series can only cover the last dynasty of China. Increasing the length of historical record for drought, flood events and locust plague, as well as other interested phenomenon series will allow us to conduct further statistical determinations for longer periods.

Further improvement for the case study are likely to extract the information from the records from the same compilation (Zhang 2004) and extend length of past climate, environmental and ecological data length to at least 600 years length, which will not only give a chance to explore the relationship at the longer-term trend but also in the multi-decadal scale to compared with other studies which have been done.

In the present study, the reconstructed temperature series from Beijing and precipitation series from Xi'an were used to represent the entire study area, showing a good match with the historical data and other studies. However, for future studies using a finer geophysical scale to carefully investigate the subspecies response of climate change, the appropriate regional reconstructed temperature and precipitation series should be chose according to the subspecies spread area.

Also, there are some others factors may affect the locust plagues in the long term climate change. For instance, previous studies have demonstrated that the oscillations of solar cycle could have a strong association with local climate fluctuations and then have an indirectly impact on fluctuations of animal populations (Elton 1924; A. R. E. Sinclair 1997).

It also should be noted that the historical records depended on some individual recorders with different biases in recording the climate phenomena. There could be some temporal and spatial gaps and blind points in the historical records series. When the series was used in the final scale study, the results should be explained carefully and more work on the data validation may be needed.

Advantage of CWT methods

The main advantage of wavelet approaches for ecological systems is the method does not require the assumption of stationary and can detect transient associations between time series that vary in time by decomposing the time series to a local time-scale. Ecological systems are typically nonstationary systems with short-lived transient components (Liu 1994; Bernard Cazelles 2008). For instance, 16- and 17-year cycles of locust plagues were detected in desert ecosystems (Robert A. Cheke 1993; Martin C. Todd

2002). This case study revealed that locust plagues in the last dynasty of China consistently and significantly occur in periods of 120-140 years. Also wavelet analysis can analysis the relationships between two time series, especially appropriate for gradual change forced by exogenous variables. Most importantly, wavelet analysis can provide quantitative information about where the two non-stationary time series are linearly correlated at a particular frequency (or frequency band) and revealed its temporal location both in the time–frequency dimensions. This linear relationship between two time series, also called wavelet coherence, can be interpreted as the fractional portion of power of a linear relationship with that of at a particular time and frequency band. When the coherence is equal to 1, there is a perfect linear relation at specific time location and frequency between the two time series.

This case study shows how wavelet analysis can help us to understand association between complex ecological systems and climate change through time, by extracting the periodic components and associations among those variables. Wavelet analysis can help us to interpret multi-scale, non-stationary time-series data and visualize the long term change we couldn’t observe in instrument data using traditional methods. Wavelet analysis is thus becoming an important method used to analyze low frequency time series, and thus has important practical applications in ecology. The future improvement of the methods is that extend it to the multi-variate analysis to beyond the limitation of current methods which can be only applied for bi-variate analysis.

References

A. Grinsted, J. C. M., S. Jevrejeva (2004). "Application of the cross wavelet transform and wavelet coherence to geophysical time series." Nonlinear Processes in Geophysics **11**: 561-566.

A. R. E. Sinclair, J. M. G. (1997). "Solar Activity and Mammal Cycles in the Northern Hemisphere." The American Naturalist **149**(4): 776-784.

Andreas Prokophi, F. B. (1996). "Detection of Nonstationarities in Gegolocial Time Series: Wavelet Transform of Chaotic and Cyclic sequences." Computers & Geosciences **22**(10): 1097-1108.

B. T. Grenfell, O. N. B., J. Kappey (2001). "Travelling waves and spatial hierarchies in measles epidemics. ." Nature **414**: 716-723.

Bernard Cazelles, M. C., Dominique Berteaux . Fre´de´ric Me´nard, Jon Olav Vik, Ste´phanie Jenouvrier, Nils C. Stenseth. (2008). "Wavelet analysis of ecological time series. ." Oecologia **156**: 287-304.

Bjørnstad, O. N., Grenfell, B.T. (2001). "Noisy clockwork: time series analysis of population fluctuations in animals. ." Science **293**: 638-643.

Cazelles, B. (2004). "Symbolic dynamics for identifying similarity between rhythms of ecological time series." Ecology letters **7**(9): 755-763.

Chatfield, C. (1989). The Analysis of Time Series: An Introduction, Chapman and Hall.

Christopher Torrence, G. P. C. (1998). "A practical guide to wavelet analysis." Bulletin of the American Meteorological Society **79**(1): 61-78.

Chu, C. (1973). "A preliminary study on the climatic fluctuations during the last 5000 years in China. ." Scientia Sinica (in Chinese) **16**: 226-256.

Congbin Fu, G. W. (1999). "Variation of Ecosystems over East Asia in Association with Seasonal, Interannual and Decadal Monsoon Climate Variability " Climatic Change **43**(2): 477-494.

Crowley, T. J. (2000). "Causes of Climate Change Over the Past 1000 Years " Science **289**(5477): 270-277.

D. Maraun, J. K. (2004). "Cross wavelet analysis: significance testing and pitfalls." Nonlinear Processes in Geophysics **11**: 505-514.

D. Maraun, J. K. a. M. H. E., 016707, 2007 (2007). "Nonstationary Gaussian Processes in Wavelet Domain: Synthesis, Estimation and Significance Testing." Phys. Rev.E **75**(1): 016707.

De-Xing Zhang, L.-N. Y., Le Kang, Ya-Jie Ji (2003). "Some unorthodox views on the classification and evolution of the migratory locusts in China prompted by molecular population genetic study." Current Zoology (formerly Acta Zoologica Sinica) **49**(5): 675-681.

Elton, C. S. (1924). "Periodic Fluctuations in the Numbers of Animals: Their Causes and Effects." Journal of Experimental Biology **2**: 119-163.

Gang Li, N. a. W., Chunhui Zhang, Wenyong Feng, Cuiyun Wang (2007). Climate change and disaster response -Case study of historical locust plagues of Shaanxi in Central China. Geoscience and Remote Sensing Symposium, IGARSS 2007. IEEE International.

Ge Yu, H. S., Jian Liu (2009). "Impacts of climate change on historical locust outbreaks in China." Journal of Geophysical Research **114**.

Graham, N. E. (1994). "Decadal-scale climate variability in the tropical and North Pacific during the 1970s and 1980s: observations and model results." Climate Dynamics **10**(3): 135-162.

Grossmann A, M. J. (1984). "Decomposition of Hardy functions into square integrable wavelets of constant shape." SIAM journal on mathematical analysis **15**: 723-736.

Hughes, M. K., X. D. Wu, X. M. Shao, G. M. Garfin (1994). "A preliminary reconstruction of rainfall in north-central China since A.D. 1600 from tree-ring density and width. ." Quaternary Research **42**: 88-99.

Hughes, M. K., X. D. Wu, X. M. Shao, G. M. Garfin (1996). Precipitation Reconstruction for Huashan, China., International Tree-Ring Data Bank. IGBP PAGES/World Data Center for Paleoclimatology Data Contribution Series # 96-020. NOAA/NGDC Paleoclimatology Program, Boulder CO, USA.

IPCC (2001). Climate Change 2001: Working Group I: The Scientific Basis. . Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Y. D. J.T. Houghton, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, C.A. Johnson (eds.) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jianmin Jiang, D. E. Z., Klaus Fraedrich (1997). "Historic Climate Variability of Wetness in East China (960-1992): A Wavelet Analysis." International Journal of Climatology **17**: 969-981.

K.-M. Lau, H. W. (1995). "Climate Signal Detection Using Wavelet Transform: How to Make a Time Series Sing." Bulletin of the American Meteorological Society **76**(12): 2391-2402.

Keith R.Briffa, T. J. O. (2002). "Blowing Hot and Cold." Science **295**: 2227-2228.

Kumar P, F.-G. E. (1997). "Wavelet analysis for geophysical applications. ." Rev Geophys **35**(4): 385-412.

L. Wang, M. S., H. Erlenkeuser, J. Grimalt, P. Grootes, S. Heilig, E. Ivanova, M. Kienast, C. Pelejero, U. Pflaumann (1999). "East Asian monsoon climate during the Late Pleistocene: high-resolution sediment records from the South China Sea." Marine Geology **156**: 245-284.

Leif Christian Stige, K.-S. C., Zhibin Zhang, David Frank, and Nils C. Stenseth (2007). "Thousand-year-long Chinese time series reveals climatic forcing of decadal locust dynamics." PNAS **104**: 16188-16193.

Lima, M. (2007). "Locust plagues, climate variation, and the rhythms of nature." PNAS **104**: 15972-15973

Liu, P. C. (1994). Wavelet spectrum analysis and ocean windwaves. Wavelets in geophysics. P. K. Efi Foufoula-Georgiou. New York, Academic Press. **4:** 151-166.

Ma, S. (1958). "The population dynamics of the Oriental migratory locust Locusta migratoria manilensis (Meyen) in China." Acta Entomologica Sinica **8**(1): 1-40 (In Chinese with English summary).

Ma, S., Ting Y. C.. Li D. M. (1965). "Study on long-term prediction of locust population fluctuations." Acta Entomologica Sinica **14**: 319-338 (in Chinese).

Mads C. Forchhammer, E. P. (2004). "Using large-scale climate indices in climate change ecology studies." Population Ecology **46**(1): 1-12.

Mann, M. E., P.D. Jones (2003). "Global Surface Temperatures over the Past Two Millennia." Geophysical Research Letters **30**: 1820.

Martin C. Todd, R. W., Robert A. Cheke, Dominic Kniveton (2002). "Brown Locust Outbreaks and Climate Variability in Southern Africa " Journal of Applied Ecology **39**(1): 31-42.

Masahiro Watanabe, T. N. (1999). "Decadal Changes in the Atmospheric Circulation and Associated Surface Climate Variations in the Northern Hemisphere Winter." Journal of Climate **12**(2): 494-510.

Me´nard F, M. F., Bellier B, Cazelles B (2007). "Climatic oscillations and tuna catch rates in the Indian Ocean: a wavelet approach to time series analysis." Fish Oceanography **16**: 95-104.

Ming Tan, T. L., Juzhi Hou, Xiaoguang Qin, Hucai Zhang, Tieying Li (2003). "Cyclic rapid warming on centennial-scale revealed by a 2650-year stalagmite record of warm season temperature." GEOPHYSICAL RESEARCH LETTERS **30**(12): 1617.

Nils Chr. Stenseth, A. M., Geir Ottersen, James W. Hurrell, Kung-Sik Chan, Mauricio Lima (2002). "Ecological Effects of Climate Fluctuations." Science **297**(585): 1292 - 1296.

Quansheng Ge, X. F., Zhimin Man, Xueqin Zhang, Piyuan Zhang, Wei-Chyung Wang (2003). "Winter half-year temperature reconstruction for the middle and lower reaches of the Yellow River and Yangtze River, China, during the past 2000 years. ." The Holocene **13**: 933--940.

Ripley, B. D. (1978). "Spectral analysis and the analysis of pattern in plant communities." Journal of Ecology **66**: 965-981.

Robert A. Cheke, J. A. T. (2007). "**Migration, Patchiness, and Population Processes Illustrated by Two Migrant Pests**." Bioscience **57**(2): 145-154.

Robert A. Cheke, J. H. (1993). "Complex dynamics of desert locust plagues." Ecological Entomology **18**(2): 109-115.

Robert H. Shumway, D. S. S. (2006). Time Series Analysis and Its Applications With R Examples, Springer Berlin.

SAS Institute Inc. (2000-2004). "SAS 9.1.3 Help and Documentation."

Sugihara, G. (1995). "From out of the blue." Nature **378**: 559-560.

Trevor Platt, K. L. D. (1975). "Spectral Analysis in Ecology." Annual Review of Ecology and Systematics **6**: 189-210.

Tristan Rouyer, J.-M. F., Nils Chr. Stenseth, Bernard Cazelles (2008). "Analysing multiple time series and extending significance testing in wavelet analysis." MARINE ECOLOGY PROGRESS SERIES **359**: 11-23.

Tsao, C. (1950). "Historical distributions of locust plagues in China. (in Chinese)." Chin. J. Agric. Res. **1**: 57-66.

Weihong Qian, X. L., Yafen Zhu, Yuan Xu, Jiaolan Fu (2007). "Climatic regime shift and decadal anomalous events in China." Climatic Change **84**(2): 167-189.

Yonglin Chen, D. e. Z. (1999). "Historical Evidence for Population Dynamics of Tibetan Migratory Locust and the Forecast of its Outbreak." Entomologia Sinica **6**(2): 135-145.

Yongling, C. (1979). Elimination of Oriental migratory locust Locusta migratoria manilensis (Meyen) infestations by combined measures of reconstruction and chemical control. . Integrated Control of Major Insect Pests in China. A. S. Institute of Zoology, Science Press**:** 252-280

Yongsheng Zhang, T. L., Bin Wang (2004). "Decadal Change of the Spring Snow Depth over the Tibetan Plateau: The Associated Circulation and Influence on the East Asian Summer Monsoon." Journal of Climate **17**(14): 2780-2793.

Zhang, D. E., Ed. (2004). The compendium of Chinese Meteorological records of the Last 3,000 years. (in Chinese). Nanjing, China, Jiangsu Education Publishing House.

Zhibin Zhang, B. C., Huidong Tian, Leif Christian Stige, Achim Bräuning, Nils Chr Stenseth (2009). "Periodic temperature-associated drought/flood drives locust plagues in China." Proceedings of Royal Society: Bioligical Science. **276**: 823-831.

Zhibin Zhang, D. L. (1999). "A possible relationship between outbreaks of the oriental migratory locsut (*Locusta migratoria manilensis Meyen*) in China and the El Nino episodes." Ecological Research **14**: 267-270.

4 Chapter three
Modeling spatial variation of famine patterns in China over the Qing Dynasty

4.1 Introduction

Global climate change and its potential impacts on human society have been of great concern to scientists and the general public (Alistair Woodward 1998; Stern 2008). Although the nature of climatic change is not yet clearly understood, the unprecedented magnitude and pace of such climate change could have profound effects on many aspects of human society (Linda O. Mearns 1984; Oreskes 2004). Among the consequences of climate change on human society, effects of climate change on agriculture and food security are concerns world-wide (Martin Parry 1999; Josef Schmidhuber 2007).

The general conclusions of the first modeling effects of climate change on global food supply are still valid: “Climate change is likely to reduce global food supply and the risk of hunger will increase in the most marginalized societies.” (C. Rosenzweig 1994). Food security is extremely important for China, which has a population of 1.4 billion , of whom approximately 721,350,000 are farmers who rely on agriculture for their livelihood (P.R.C 2008). China has experienced periods of famine through its history, although the food security problem has been improved in past 60 years due to government efforts to develop improved agricultural techniques and policies. Nevertheless, the agricultural ecosystem of China has already been exploited intensively for thousands of years by a large population. Such agricultural ecosystems and their dependent societies are highly vulnerable to climate change and extreme climate events. While unprecedented climate change could have significant effects on vulnerable agricultural systems, it’s important to understand how the deterministic factors affected the pattern and variation of famine in

Chinese history. Although studies on food supply and security under climate change have been increasingly frequent, with a focus on ecological responses (Fulu Tao 2003; M.L. Parry 2004) and effects on human society (Alistair Woodward 1998; Anthony J McMichael 2006), those pioneer studies mainly focused on the prediction of possible consequences of future climate change scenarios. A few exceptions include studies of famine through history (Lee 1982; Li 1982; Wong 1982), however, those studies have a historical and social perspective, and lack a rigorous analysis based on long term data and statistical methods. The challenge for studies linking climate change and its consequences for past natural ecological systems and human society is to choose the appropriate statistical methods and to find the historical data of sufficient duration to perform the statistical analysis and reveal the relationship between the climate change, ecological systems, and human society. One of the biggest obstacles is the lack of the high-resolution data both on temporal and spatial scales.

Variation and trends in extreme climate events have received much attention since the last decade of 20th century (David R. Easterling 2000). In terms of climate change, extreme climate events have much more direct and severe impacts on mean temperature change. Human society and ecological systems have become more vulnerable to extreme weather, in terms of loss of human life and food supply shortages (D.R. Easterling 2000). Previous study revealed that climatic disasters, such as when flood and drought occurred within a warm-dry or cold-wet climate period, could cause severe negative impacts on natural agricultural ecosystems as well as human society in northern China China (Weihong Qian 2007). For instance, a severe drought in 1927–1929 in northern China within a warm and dry decade caused large-scale famine in nine provinces. Evidence of climate change comes from the observation that the frequency and severity of suddenly extreme climate disasters has increased (D.R. Easterling 2000). China has witnessed consecutive droughts over recent years, which have posed a serious threat to water security. For instance, in 2007 a drought disaster affected many provinces, which quickly spread across the county from the northwest and the northern China to the areas south to the Yangtze River, which historically had abundant precipitation, but now records dry weather more frequently. Although China is no stranger to drought, the severity of drought in 2007 was unprecedented and caused a serious shortage of water. Hainan, a rainy island province in southernmost China, saw around 100 reservoirs and ponds dry up, with about half million of people experiencing a shortage of drinking water. Because of the drought, the water level of the Yangtze River and the Pearl River decreased rapidly in 2007. Since entering low water season, the precipitation within the drainage area of the Pearl River has reduced severely. Lately the river exhibits the lowest water level since 1956. Previous studies also revealed that there is a long term decrease in precipitation that has caused an increase in the area of drought and decrease in the area with excessive precipitation over China (Ye 1996).

The main factors of climate change which affect agriculture are biophysical and socio-economic (M.L. Parry 2004). Currently, studies on agriculture vulnerability to climate change focus on the physical and biological aspects of climate change by using simulation models to examine the effects of rapid climatic change on productivity (Gretchen C. Daily 1990; M.L. Parry 2004). These studies focus on the effect of green house gases and simulated climate change, in terms of temperature, precipitation, and CO_2. However, these methods do not consider past climate change and extreme climate events.

Therefore, it's important to have a historical perspective on the past climate change and extreme climate events on human society. Although many Chinese scientists have explored the relationships between climate change and agriculture for many years (W.-H. Qian 2003; Song Yanling 2005; Eryuan Liang 2006; Gang Li 2007; Daniel R. Chavas 2009), the studies addressing effects of climate disasters on human society are less common. Historical written records of climate conditions such as flooding, drought incidents in China, as well as harvests, locust plagues, and famine records can serve as proxy data for studies explore the relationship between extreme climate disasters and their implications for agriculture and human society.

To examine the historical effects of climate change on agricultural societies, it is difficult to create process-based models at large scales, especially due to lack of the large amount of input information required and difficulties in parameterization. Therefore, empirical approaches are still good methods to derive important relationships in large-scale famine simulations. Ordinary Least Squares (OLS) is one of most common empirical approaches that have been applied in simulations. The parameters of regression models are assumed to apply globally over the entire region, based on the assumption of spatial stationarity in the relationship between the variables under study (Foody 2004). However, the influence of environment variables is often not necessarily uniform across the study area, given that different climate type of region and agricultural system. In other words, such relationship varies over space (Foody 2003; Getis 2003; LI and Yeh 2004; Zhang, Bi et al. 2004). In a multivariate framework, this is called spatial non-stationary which means the measurement of a relationship depends on where the measurement is taken. Therefore, the parameters of the model vary from place to place (Fotheringham, Brunsdon et al.

2002). If the assumption of spatial stationarity doesn't hold, the global models would conceal spatial variations in the relationships and interpret the local information improperly when trying to represent the study area with one single "accurate" value. This failure to account for spatial autocorrelation prevents a thorough interpretation of most of geographical analyses in ecology (W. Jetz 2005).

Compared with the OLS method, spatial autoregressive models typically have an additional parameter which can be treated as the localized version of traditional global multivariate techniques. Most recently-developed spatial autoregressive models include: the spatial expansion method; spatially adaptive filtering; multilevel modeling; random coefficient models and spatial regression models. Each has limitations when applied to analysis of spatially non-stationary multivariate relationships. More recently, a Geographically Weighted Regression model (GWR), has been developed to provide a more appropriate and accurate method for descriptive and predictive analysis with the spatial non-stationarity of empirical relationships, by allowing parameters to vary locally within the study area (Foody 2003; Jonathan Corcoran 2007) . Initially, GWR was applied to social science study (Fotheringham, Charlton et al. 1998;John J. Magnuson 2000; Farrow, Larrea et al. 2005; Wheeler, Rigby et al. 2006), because physical processes were believed to be spatially stationary while social scientists account for more spatial non-stationarity in their research. Recently, the numbers of studies applying GWR to natural science have been increasing and have revealed that natural systems are not spatially stationary, such as soil erosion (Atkinson, German et al. 2003), fragmentation of urban development (Trevor Platt 1975; Luo and Wei 2005), NPP estimation (Wang, Ni et al. 2005) and spatial heterogeneity of tick-borne pathogens (Michael C. Wimberly 2008).

A detailed description of GWR is given by Fotheringham, Brunsdon et al. (2002). The software has been adopted in many popular statistical software packages, such as: R, Matlab, and ArcGIS version.

The objective of this study is to derive a regression model to highlight the effectiveness of factors which can explain the pattern and variations of famine in China, including climatic disasters, such as drought and flood, and ecological variables, such as locusts and agriculture poor harvests. Given the considerable variation of climatic variables across China, the model is focusing on the spatial non-stationarity of estimated parameters as based on the GWR method. The dependent variable is famine, derived from the frequency of famine incidence for each county in the study area over the Qing Dynasty. To assess climate change impacts on famine, the independent variables, such as poor harvest, locust plagues, drought and flood data were derived by the same methodology and from the same data source. It is worthwhile to examine further the relationship between famine and each variable in the case of whole country level, where a large number of county data have been compiled.

The goal is to try to understand patterns and mechanisms of famines and effects of climate variables on agricultural ecosystems and human society which haven't been addressed by previous studies due to the lack of long term data on climate change and environmental factors. With advances in recently published compilation and improvement of spatial modeling methods application in ArcGIS tools, it is now possible to understand this complex issue.

4.2 Data and Methods

4.2.1 Data

There are many historical documents containing information about past climate change. Previous studies on past climate change in China have used various data, such as harvests, locusts, droughts, and floods (Ma 1965; Central Meteorological Institute 1981).

Independent explanatory variables were interpreted and extracted from a multi-volume compendium that contains exhaustive records from various historical documents for past climate events in China, such as rain/snow/wind storm, drought, flooding and ecological and socioeconomic events, such as harvests, famine, locust, plague, phenology, etc. (Zhang 2004). In this study, the records of agricultural poor harvest, locust plague, drought and floods events at 1570 counties were digitized. Based on the location of historical records, the frequency of incidence of each variable was then counted. The advantage of this data source is not only provide a long term data at high temporal and spatial resolution, but also the internal consistency of data for all information recorded, which was compiled by same methodology and extracted from the same source.

4.2.2 Methods

In this study, Ordinary Least Squares (OLS) and GWR models were used to model spatial relationships between dependent and explanatory variables. Both of them are available in spatial statistics tools in ArcGIS 9.3 (Hillier 2007).

Global statistical Analysis--OLS

Ordinary Least Squares (OLS) is one of best known regression techniques. It creates a global model—using single regression equation to represent the predicted variables or process for the whole study area.

OLS is a proper starting point for all spatial regression analyses. To prevent the multi-collinearity problem, the different combinations of explanatory variables were fitted in the model by using OLS. For instance, environment variables, such as drought and flood, as well as ecological response variables—locust and agricultural poor harvest were included as potential explanatory variables in the global models for predicting famine. Therefore, there are 15 different combinations of explanatory variables (**Table 4.3**). For each set of these combinations, I fitted a global model by using OLS to examine whether adding any or all of the variables contributed to the fit of the model. The Akaike information criterion (AIC) statistic was computed for each model to assess the goodness-of-fit for the number of parameters for various combinations. The final model with the lowest AIC value, which indicates the best fit, was then selected and used for the further exploratory analysis in the GWR analysis.

Another reason for using the OLS method is to assess the spatial stationarity of each explanatory variable. If the explanatory variables show spatial nonstationarity, then a global regression method is not appropriate for spatial analysis. By diagnosing the results of OLS, such as The P-Value of Koenker (BP) Statistic, and examining the map of output feature class residuals, the stationarity of variables can be determined. Also, by fitting the same model under GWR, comparing the results of OLS with GWR can also assess whether a GWR model is necessary.

Local statistical analysis--GWR

Geographically Weighted Regression (GWR) is one of several spatial regression techniques that has been increasingly used in geography and other disciplines (Fotheringham, Brunsdon et al. 2002; Lebreton 2005). Geographically Weighted Regression (GWR) is a non-parametric locally linear model. GWR analyze spatially varying relationships by using distance weighted sub-samples of the data and assigns greatest weights to nearest geographical and then builds a local regression equation for each feature in the dataset.

Theoretical background

The basic linear regression model may be expressed in the form:

$$y = \alpha + \beta x + \varepsilon$$

The independent variable x are related to dependent variable y. α is the intercept and β expresses the slope of the relationship between the two variables, and ε is the error term.

When there is more than one independent variable, typically global multiple linear regressions, e.g., ordinary least-squares regression (OLS) is used and can be expressed as,

$$y_i = \beta_0 + \sum_k \beta_k x_{ik} + \varepsilon_i$$

K independent variables x_i are related to the dependent variable y at spatial location *i*, β_0 is an intercept coefficient, β_k is a vector of regression coefficients for location *i*, and ε_i is independent normally distributed error terms with zero means, N(0, σ^2I). Estimates of the parameters β_k can be obtained by the least-squares method as:

$$\hat{\beta} = (x^T x)^{-1} x^T y$$

Where $\hat{\beta}$ is a single column vector of coefficients, the independent variables are the columns of x, the dependent variable is the single column of y, and superscript T indicates the transpose of a matrix.

However, for a point in the space which has a set of coordinates (u_i, v_i), the coefficient is not random but rather a deterministic function of location. The model for GWR is

$$y_i = \beta_0(u_i, v_i) + \sum_k \beta_k(u_i, v_i) x_{ik} + \varepsilon_i$$

Where (u_i, v_i) is the coordinates of the i^{th} point in space and $\beta_k(u_i, v_i)$ is the matrix, the k^{th} parameter at location *i*. The aim of GWR is to obtain non-parametric estimates for each independent variable X_k and each geographic location *i*. The simple yet powerful idea is by using sub-samples of data around the specific point *i*, the closer the point is the larger the weight. That is why this local spatial analysis method is named as Geographically Weighted Regression (GWR). Then the GWR method can use weighted least-squares regression to estimate the model coefficients,

$$\hat{\beta}_{(u_i, v_i)} = (X^T W_{(u_i, v_i)} X)^{-1} X^T W_{(u_i, v_i)} y$$

The weight matrix W_i is an n by n matrix,

$$W_i = \begin{pmatrix} w_{i1} & 0 & \ldots & 0 \\ 0 & w_{i2} & \ldots & 0 \\ \ldots & \ldots & \ldots & \ldots \\ 0 & 0 & \ldots & w_{ik} \end{pmatrix}$$

If W_i=I (identity matrix), the GWR model is equivalent to the OLS model.

Several methods have been proposed to determine the weighting matrix (Fotheringham and Brunsdon 1999). For fixed kernel size with a Gaussian function, the weight matrix (W_{ik}) is computed according the distance(d_{ik}), which is the distance for each neighboring point k to the center point *I*,

$$W_{ik} = \exp[-\frac{(d_{ik}/b)^2}{2}]$$

where b is referred to as the bandwidth.

As the bandwidth increases, the parameter estimates will tend to be same as the estimate from a global model. Therefore, parameter estimation in GWR is highly dependent on the weighting function of the bandwidth of the kernel used. The selection of the weighting function and bandwidth can be determined using a cross validation (CV) approach or AIC (Fotheringham, Brunsdon et al. 2002).

4.3 Results and Analysis

4.3.1 Checking for linear relationship by scatter plot

Before fitting OLS and GWR, it's important to check the assumption of whether there is a linear relationship between the dependent variable and explanatory variables. From the scatter plot in Figure 4-1, we can see that famine does have roughly linear relationship with each explanatory variable. Therefore, it's reasonable to fit a linear regression model for the case study.

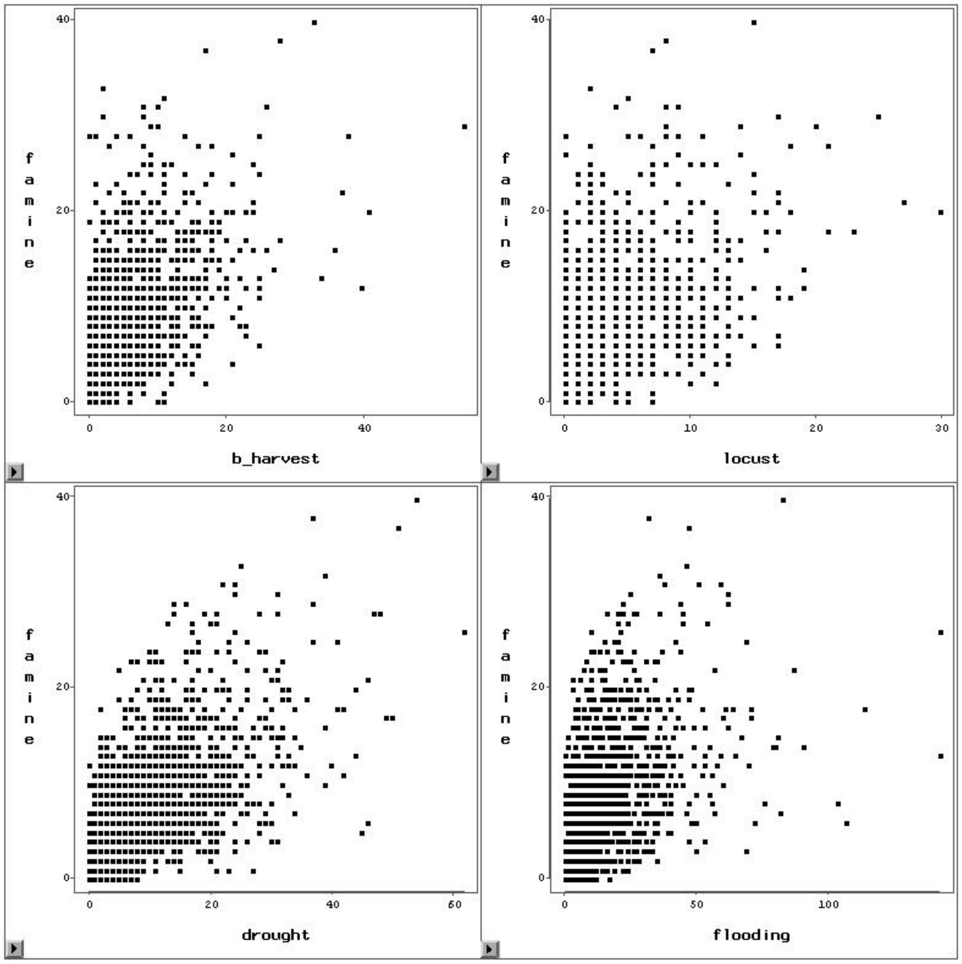


Figure 4-1. The scatter plot of famine against the explanatory variables: (a) poor harvest, (b) locust, (c) drought, (d) flood.

4.3.2 Ordinary Least Squares (OLS)

The first step of the regression analysis is to fit a global regression model by using the full model, in which famine is the dependent variable, and all other variables were treated as explanatory variables. The objective is to examine the spatial stationarity of the variables and goodness of fit of the model. The statistical results of the OLS model is shown in Tables 1 and 2. The results of model fitting were examined by the following steps:

Table 4.1. Summary of OLS results

Variable	Coef	StdError	t_Stat	Prob	Robust_SE	Robust_t	Robust_Pr	VIF
Intercept	2.900	0.185	15.652	0.000	0.171	16.9597	0.000	
B_HARVEST	0.240	0.027	8.833	0.000	0.034	7.0591	0.000	1.725
LOCUST	0.127	0.039	3.289	0.001	0.051	2.4982	0.013	1.619
DROUGHT	0.247	0.020	12.565	0.000	0.026	9.5981	0.000	2.297
FLOODING	0.064	0.010	6.443	0.000	0.014	4.7770	0.000	1.586

Table 4.2. OLS Diagnostics

Sigma2	21.9803	AIC	8819.9598
R2	0.4646	AdjR2	0.4632
F-Stat	321.5051	F-Prob	0.0000
Wald	751.1568	Wald-Prob	0.0000
K(BP)	186.7593	K(BP)-Prob	0.0000
JB	372.2068	JB-Prob	0.0000

Assess model performance: The R-Squared value is 0.4646, indicating that OLS model explains approximately 46.5% of the variation in the dependent variable.

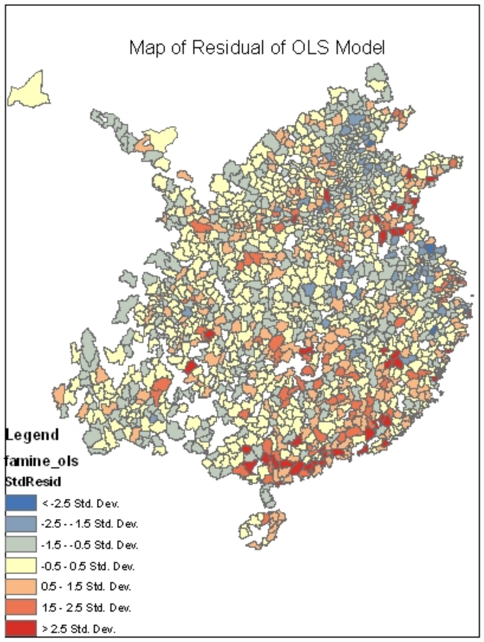
Assess explanatory variables: The coefficients for explanatory variables reflect both the strength and type of relationship between explanatory variable and the dependent variable. All of explanatory variable in OLS model have a positive effect on the dependent variable – famine. The strength (absolute value of coefficient) ranged from highest to lowest for drought, poor harvest, locust plague, and floods, which are 0.2471, 0.2397, 0.1271 and 0.0643 respectively. Since the Koenker (BP) test is statistically significant, robust probabilities were used to assess statistical significance of explanatory variables, rather than using t-test statistics. Robust probabilities show that all of the explanatory variables in the model are statistically significant. The variance inflation factor (VIF) was used to measure redundancy among explanatory variables. Generally, if VIF of an explanatory variable is larger than 7.5, then the variable should be removed from the regression model. In this case, no explanatory variables has a VIF larger than 7.5.

Assess model significance: Since the Koenker (BP) statistic is significant, the Joint Wald Statistic was used to determine overall model significance instead of the Joint F-Statistic. Joint Wald Statistic tests indicate that the full model is significant; therefore, all of the explanatory variables in the model are effective.

Assess stationarity: The P-Value of Koenker (BP) Statistic (Koenker's studentized Bruesch-Pagan statistic) is less than 0.0001, indicating that there is statistically significant spatial heteroscedasticity. In other words, the explanatory variables are spatially non-stationary. Consequently, the OLS model, which shows statistically significant non-stationarity, is good candidate for GWR analysis.

Assess model bias: The significant Jarque-Bera statistic indicates that the residuals are not normally distributed, which suggests that there is a model misspecification (a key variable is missing from the model). Results from a misspecified OLS model are not trustworthy.

Assess residual spatial autocorrelation: A spatial autocorrelation (Moran's I) tool was used to check the spatial randomness of the regression residuals. Statistically significant clustering of high and/or low residuals (model under and over predictions) indicates a key variable is missing from the model. In this case, the key variable is spatial autocorrelation. From the results, we can infer that the residuals are highly clustered; therefore, OLS results cannot be trusted when the model is misspecified. The results are shown in **Figure 4-2**. a:



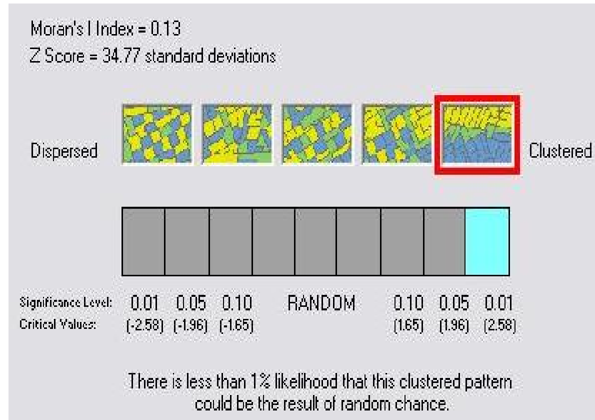


Figure 4-2. the results of OLS model: a) the residual map of OLS model. B) the Moran's I index of OLS residual.

Another way to assess the spatial stationarity of the variables is to examine output feature class residuals. Over or under predictions for a properly specified regression model should be randomly distributed. Clustering of over and/or under predictions indicates that at least one key explanatory variable is missing (**Figure 4-2**. b).

Model selection: The last step of global analysis is to compare different sets of variables in various combinations for model selection. The fitted model with smallest Akaike Information Criterion (AIC) value will provide a better fit to the observed data. 15 candidate models using combinations of the explanatory variables were fitted by both OLS and GWR (**Table 4.1**). The results show that the full model has lowest AIC among candidate's models. Also the R^2 of model using GWR methods is better than each of the models using OLS methods. Therefore, the next step of analysis is fitting a full model by using GWR.

Table 4.3. Ranked candidates OLS regression models based on AIC Statistics.

		OLS		GWR	
Rank	Independent variables	AIC	R2	AIC	R2
1	Poor harvest, locust, drought, flood	8819.96	0.46	8338.76	0.69
2	Poor harvest, drought, flood	8828.77	0.46	8366.59	0.69
3	Poor harvest, locust, drought	8859.04	0.45	8414.95	0.66
4	Poor harvest, drought	8876.27	0.44	8462.70	0.66
5	Locust, drought, flood	8894.26	0.44	8392.91	0.68
6	drought, flood	8919.18	0.43	8414.03	0.68
7	locust, drought	8932.80	0.42	8458.08	0.66
8	Poor harvest, locust, flood	8968.49	0.41	8502.56	0.64
9	drought	8970.81	0.41	8502.02	0.65
10	Poor harvest, flood	9011.67	0.39	8604.26	0.63
11	Poor harvest, locust	9102.38	0.35	8698.33	0.57
12	locust, flood	9175.99	0.32	8668.78	0.61
13	Poor harvest	9210.94	0.30	8947.92	0.49
14	flood	9329.06	0.24	8803.39	0.57
15	locust	9373.97	0.22	8950.12	0.49

4.3.3 Geographically Weighted Regression (GWR)

Model comparison

Based on the previous analysis, the full model was fitted by GWR, which has the smallest AIC value and highest R^2 compared with other candidate OLS models.

Comparing the statistics output from both models (**Table 4.2**, **Table 4.3**), the GWR has a lower AIC, but higher R^2 and R^2 adjusted value than that in OLS model.

Table 4.4. Statistical report from GWR model

Neighbours	113
ResidualSquares	18790.5074
EffectiveNumber	205.4656
Sigma	3.8292
AICc	8338.7635
R^2	0.6912
R^2 Adjusted	0.6419

AIC is a measure of model performance. It is not an absolute measure of goodness of fit, but is helpful for comparing models with different explanatory variables, taking into account model complexity. The general criterion is that if the AIC values for two models differ by more than 3, the model with the lower AIC value provides a better fit to the observed data. Although a local regression model (GWR) is more complex than global model (OLS), adding one more variable, spatial autocorrelation, gives us a significant improvement in model performance, in terms of lower AIC, compared with OLS model. R-Squared is a measure of goodness of fit. From the results in **Table 4.4**, the GWR significantly improve the fit of the model compared with OLS model.

Therefore, it is reasonable to use the GWR rather than OLS model for prediction of famine variation with the same set of explanatory variables.

Table 4.5. Summary statistics for GWR parameter estimates

LABEL	MIN	MAX	MEAN	%positive	%negative
Intercept	-0.38861	6.245383	2.144452	98.18	0.02
C1_b_harve	-0.26445	0.983311	0.262409	91.26	0.09
C2_locust	-1.47495	1.551653	0.354955	87.96	0.12
C3_drought	-0.17258	0.675797	0.231037	94.75	0.05
C4_floodin	-0.125	0.361545	0.116509	87.09	0.13

All the variables have both positive and negative parameter values, with differences in the proportions of both values (**Table 4.5**). This suggests that even from the aspatial perspective, the assumption of stationarity for parameter estimates in the global regression model might be questionable.

Output feature class residuals

Figure 4-3 presents the spatial distribution of local R^2 and residuals in the GWR model. Compared with the map for OLS model, the positive and negative residuals were randomly distributed, which suggests that there is no obvious spatial pattern that can be determined. Also the Spatial Autocorrelation (Moran's I) analysis on the regression residuals shows that they are spatially random.

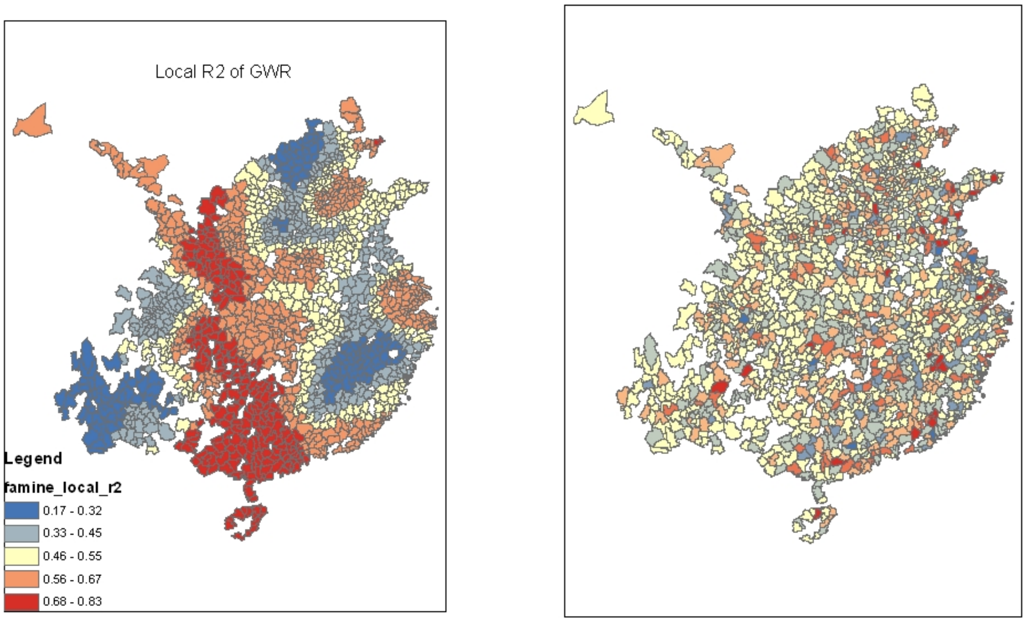


Figure 4-3. a) the local r2 map of GWR; b) the residual map of GWR model

In addition to checking model regression residuals, local R^2 values in the output feature class of GWR model can be also the evidence of model performance. Basically, the map of local R^2 shows where GWR predicts well and where it predicts poorly (**Figure 4-3**).

Condition numbers were also checked as a diagnostic to evaluate local collinearity. Presence of strong local collinearity (condition numbers larger than 30) indicates results may be unstable. The highest condition number in GWR model is 9.5, therefore, the results are stable.

Spatial variations of patterns for coefficients

I'm not only interested the predicted values for dependent variable, but also interested in the factors that contribute to the variation of the dependent variable.

Examining the maps of coefficient values for each variable can help us better understand regional variation in the explanatory variables.

The spatial distribution of parameters for explanatory variables is shown in the panels of **Figure 4-4**. Panel a shows spatial variation in the intercept, which had a range of -0.4 to 6. Most of east part of China has a higher positive value except the Jiangsu Province. In contrast, most of west part of China has a lower value, especially for Guangxi Province, which has a negative value.

The coefficient for poor harvest (panel b) had a range of -0.3 to 1.1. Highest positive values occurred at some part of Southern and West Southern China. Some part of Northern, eastern China showed negative values.

Panel C shows the spatial variation of the fitted coefficient for drought. The coefficient had a range from -0.21 to 0.69. Most of Northern, Eastern China has a lower value. Some parts of West Southern China also showed lower value. In contrast, other areas show a higher positive relationship.

Panel D indicates the spatial distribution of the fitted coefficient for flood. The coefficient had a range from -0.13 to 0.37. Lower values are mainly in northern, central, and eastern China, which is the middle and lower reach of Yellow River and Yangtze River.

Panel E (**Figure 4-5** a) indicates the spatial distribution of the fitted coefficient for locusts. The coefficient had a range from -1.7 to 2.2, which shows most variation among four variables. Most of the area has positive values.

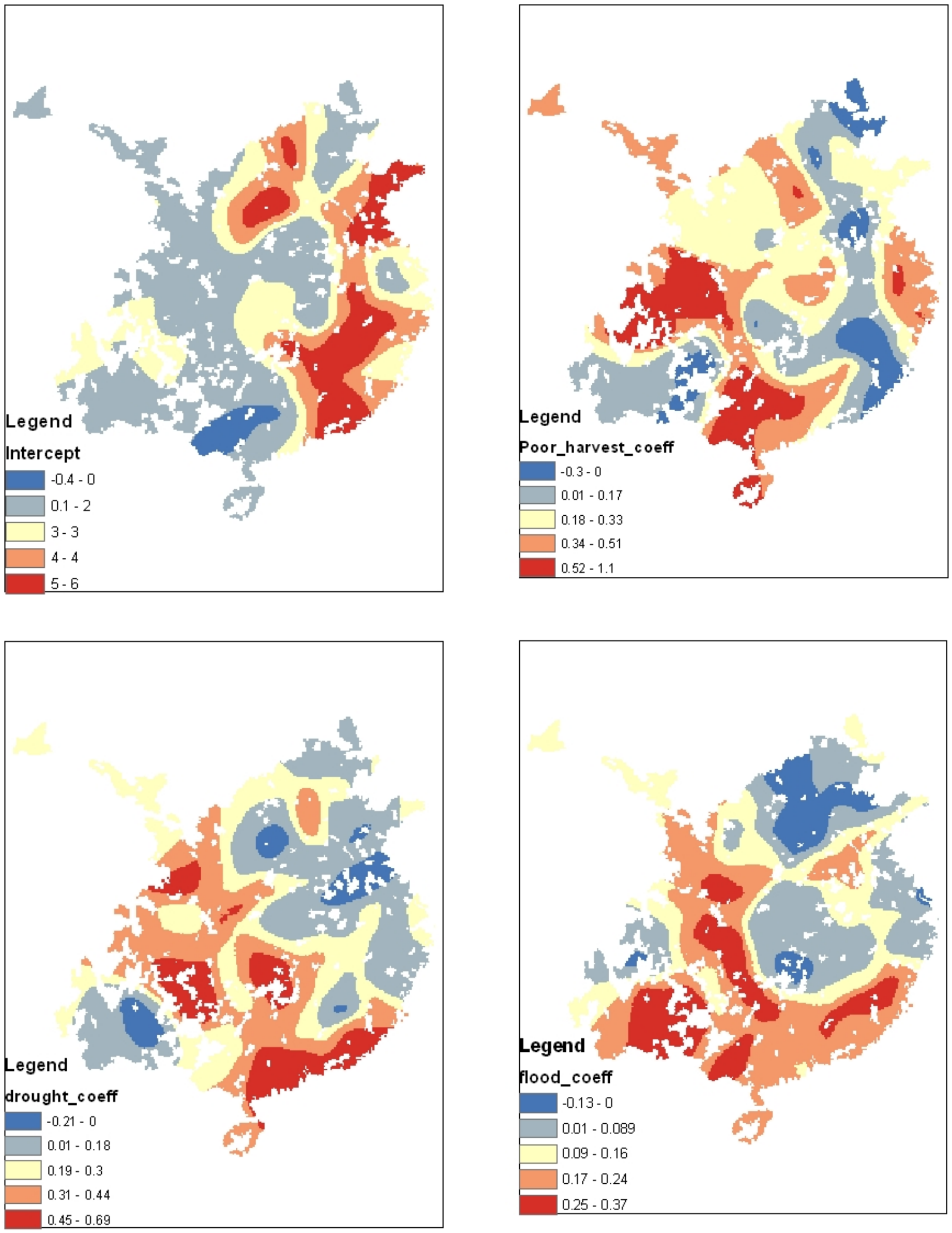


Figure 4-4. GWR parameter features: intercept (a); poor harvest (b); Drought (c); flood (d).

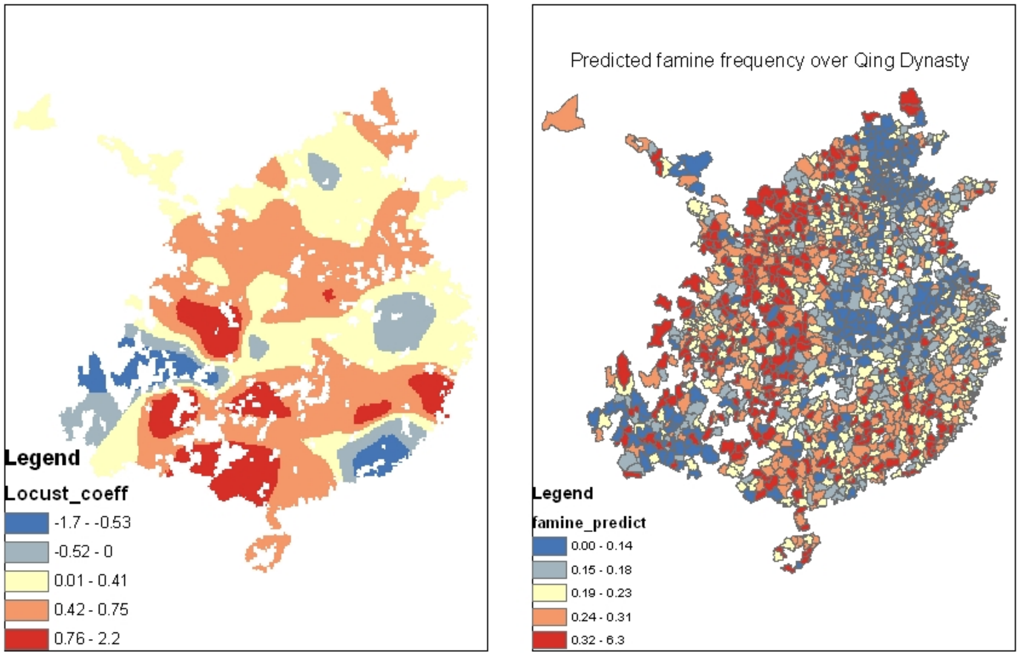


Figure 4-5.GWR parameter features: locust (a); prediction of famine (b).

Mapping GWR Predictions

The spatial distribution of estimated (or fitted) famine by GWR was shown in figure above **Figure 4-5** b). Because the estimated value is the predicted frequency for famine incidence, the value shown in the map was normalized by frequency of reported years for each county. Western and Southern China has a higher frequency of famine compared with Northern and Eastern China. The middle and low reach of Yellow River and Yangtze River has the least occurrence of famine.

Ecological interpretation of GWR estimates

The results shown above clearly indicate spatially non-stationary relationships between famine and explanatory variables (poor harvest, locust, drought and flood). To better understand these relationships, it’s important to interpret them using ecological principles.

Famine shows an increasing trend toward inner land along longitudinal gradients due to the decrease of precipitation or water supply and the change in other environmental factors.

However, water supply is not the only limiting factor for famine, and the magnitude of effect of each variable changes over space. For instance, the low reach of Yangtze River or Yellow River may relive precipitation insufficiency by irrigation. Some parts of West Southern China also show less occurrence of famine, which could be influenced in the same way by some other larger rivers, such as NuJiang River, etc. However, it could be also due to the difference in climatic regions. The southwest area is closer to tropical areas and is dominated by the Indian Ocean monsoon, which has higher temperatures and precipitation. Therefore, cold and drought are not likely to appear as the dominant factors affecting the agriculture and human society. The map of the coefficient values for floods shows higher values along the southern part of China, and is extremely high at in the Southwest. This pattern may suggest how different explanatory variables influence the incidence of famine. In this case, the comparison of coefficients for drought and flood clearly shows that drought is most important factor for famine in the semi-arid region, however, in tropical area, flooding is the most important factor affecting agricultural productivity.

4.4 Discussion

As a local regression technique for investigating spatial non-stationarity, GWR has been increasingly applied in recent biogeographical research (Foody 2004; Bickford 2006; Gavin 2006; Shi, Laurent et al. 2006). However, due to the limitation, spatial models for past climate and/or historical ecologic and social-economic phenomena are seldom used.

Therefore, one great strength of the present case study is to reveal spatially varying relationships between famine patterns and underlying historical determinants, which are important for a better understanding the factors affected famine and to help us to predict the future. Based on recent developments in GIS and spatial modeling methods, I employed both global and local regression models to reveal the relationship between famine and a set of spatial variables through a case study in China.

The OLS model was used to test the spatial stationarity and to select the model that has best combination of explanatory variables. By using selected variables and fitting them in the Geographically Weighted Regression (GWR) model for prediction of famine, the results of the GWR model significantly improved the OLS model in terms of goodness-of-fit and lower level of spatial autocorrelation of residuals. More importantly, the local estimates of parameters of spatial variables enable us to investigate spatial variation of the influences of spatial variables on famine incidence. I found distinctive local patterns and effects of famine in the study area, shaped by local spatial structures. A predicted probability map of famine, which is generated from an ArcGIS tool by calculating among the parameter and variable features, provides a clear scenario of famines incident patterns and can be useful for prediction.

I found that in the GWR model, all of the explanatory variables are statistically significant and based on the model selection by using global model (OLS), the full model has the best explanation for predicting famine. This study made efforts to improve the understanding of famine patterns and identifying correlated factors in China over the last Dynasty. This study also shows the importance of future study in the interpretation of results generated from statistical and GIS modeling.

Implication of spatial autocorrelation

The main strength of GWR is its ability to detect spatial variability in relationships between environments—ecological/social system that is not revealed from traditional global regression models. Spatial autocorrelation is not only common in social data but also in ecological and environmental data. The importance of considering the spatial autocorrelation in famine analysis is to avoid underestimation of famine incidence if a positive autocorrelation is present when using OLS regression. This case study investigated the relationship between famine and environmental as well as ecological factors in China over the Qing Dynasty, and included effects of drought, flood, locust plagues and agriculture poor harvest. Both OLS and GWR methods were tested and compared.

I found that the GWR model performed better than the OLS model. GWR model has a much better fit to the data than the global regression model, and perform better in exploring the relationships between famine occurrences and explanatory variables than the global regression model. Furthermore, the residuals of the global regression model exhibit significant spatial dependence, which violates the assumption of uncorrelated errors, while the residuals in GWR model are no longer spatially dependent.

The powerful analysis tools in ArcGIS provide several ways to examine the autocorrelation of famine and other variables. For instance, the BP test is highly significant. Both mapping of residual and application of spatial analysis (hot analysis, Moran's I index) on the residuals supported this conclusion. The map of OLS model residuals show a strong cluster pattern and Moran's Index also indicates that residuals of the OLS model are significantly spatially clustered. In contrast, no spatial autocorrelation was found for the

GWR Model residuals indicate that the GWR model is the better model than OLS, especially dealing with spatially non-stationary problems.

More importantly, the GWR model allows the model parameters to vary across space, which provides deep insights into the spatial variation of the famine occurrence pattern. It has been demonstrated that the spatial variability of each factor influencing famine is significant and presents different patterns. The predicted feature surface of famine occurrences, which is based on the parameter surfaces from GWR estimates, provide us with an accurate visualization for famine occurrences. In general, GWR analysis reveals different effects of determinants in different parts of the study area.

Key factors affecting famine

Although the local regression approach has also been criticized as being overly flexible, potentially increasing the complexity of model and creating nonsensical parameter estimates (Jetz W 2005), this case study did not only focus on the improvements in model fit. Moreover, the analysis emphasizes making ecological interpretations of spatial variability in the parameter estimates. The spatial non-stationarity of famine and environmental/ecological relationships suggests that the global OLS models are not suitable for modeling the responses of famine to climate change. In particular, maps of GWR coefficients can provide a more intuitive framework for visualizing and interpreting the ecological implications of spatial non-stationarity than complex equations with multiple interaction terms.

Moisture availability and climatic extremes are among the key factors affecting agricultural ecosystems (Barry Smit 1996). Climate change, extreme climate disasters and their impacts on human society have received increasing attention in China during recent years, particularly with respect to agricultural, economic losses from extreme flood and drought events (IPCC 2001). Therefore, understanding the mechanism of effect of climate change on famine occurrence is theoretically and practically meaningful for management and the reduction of food shortages. A first step towards an understanding of the underlying processes is the analysis of famine and climate change in the past.

I found that among the explanatory variables, drought has the strongest effect on famine, followed by poor harvest, which indicates the possible pathway of how climate change affects human society, in terms of famine occurrence.

By using the OLS model, I showed how drought is the variable that explains most of variance of famine. The model with single variable, drought, can explain 41% of the variance in famine. Adding other variables can improve the model fit, and some other potential social factors which were not included in the case study due to the lack of data, (such as war incidence, agriculture technology, administrative disaster relief) could also have effects on agriculture.

The relationships between famines and humidity/dryness reflect the influences of climate on water supply. The results are consistent with previous studies that have found strong influences of temperature and moisture on the geographical distributions of agricultural poor harvest (Linda O. Mearns 1997). The GWR analysis demonstrates that these relationships are spatially variable. In particular, the influences of drought are strongest in vulnerable regions, such as in the arid and semi-arid regions of northern China, whereas part of Northern, Eastern China and Southwest China showed less influence of drought on famine.

Extreme drought disasters could cause potentially severe negative impacts on natural ecosystem in the vulnerable region over China. For an example, in the 1920s nine provinces in northern China suffered the severe precipitation deficiency beginning 1922 and the resulting sustained drought coincided with an anomalous warm period. The severe climate catastrophes eventually lead to a famine disaster from 1927 to 1929, where 34 million people suffered from the severe drought and famine, and at least 10 million died during the period (Eryuan Liang 2006).

In the semi-arid region of northern China, agriculture and society are highly vulnerable to limited precipitation. Therefore, it is not surprising that drought has strongest effect on famine in this area. The possible connection of the drought coincided with high temperature in 1920s over northern China can be linked with the severe drought in the Untied States during 1930s (Siegfried D. Schubert 2004). The severe dry climate and high temperature also caused swarms of locusts and widespread crop failure.

Due to the lack of high resolution climate data for temperature and precipitation for each county, those variables are not included in the case study. However, in the future, the spatial variability corresponding to climate type should be tested in the different regions, such as arid region, or monsoon affected areas.

Potential factors/mechanisms (socio-economic scenarios)

Although the present study includes the climate, ecological and social variables, and the local model already accounts for 69.1% of variance, there are still other factors that can affect the incidence of famine. Human population pressure and immigration as well as agricultural irrigation systems and cropping systems all have potential effects on the occurrence of famines. Beside the natural shortages of rainfall, water shortages caused by increased population and rapidly developing socio-economic phenomena will also increase the pressure on vulnerable agricultural ecosystems. Marginal agricultural communities with high exposure to natural hazards and high dependence on climate sensitive source, such as land, plant, animals, water, have a limited capacity to adapt to the climate change.

This case study revealed that the water supply is the single most important factor affecting vulnerable agricultural systems. The prospect of global climate change causing more serious water shortages makes the issue particularly urgent. The observed runoff from the 6 largest rivers in China showed a decrease trend over the past 40 years. The estimated decrease range can reach 20%～40% for the Yellow River catchment. Therefore reducing population growth rates and increase water use efficiency should be the key strategy for minimizing the impact of global climate change and maintaining food supplies for human society.

Although GWR can more efficiently reveal the spatial variation of the influence of spatial variables on famine occurrences, interpretation of such variation requires care and should related to the contextual information of the study area. Comparison with other pioneering studies will help us in interpreting the results and understanding the varied effects of determinant variables. Future studies should incorporate more socio-economic variables, which are potentially recorded in the other historical documents for the study area, into the Global GWR model for investigating the interactions between climate change, environmental conditions, ecological response and socio-economic conditions.

References

Alistair Woodward, S. H., Philip Weinstein. (1998). "Climate change and human health in the Asia Pacific region: who will be most vulnerable?" Climate Research **11**(31-38).

Anthony J McMichael, R. E. W., Simon Hales (2006). "Climate change and human health: present and future risks." Lancet **367**: 859-869.

Atkinson, P. M., S. E. German, et al. (2003). "Exploring the relations between riverbank erosion and geomorphological controls using geographically weighted logistic regression." Geographical Analysis **35**(1): 58-82.

Barry Smit, C. Y. (1996). "Climate change and agriculture in China." Global Environmental Change **6**(3): 205-214.

Bickford, S. A., Laffan, S.W. (2006). "Multi-extent analysis of the relationship between pteridophyte species richness and climate." Global Ecological Biogeography **15**: 588-601.

C. Rosenzweig, M. L. P. (1994). "Potential impact of climate change on world food supply." Nature. **367**: 133-138.

Central Meteorological Institute, P. U., Nanking University (1981). The drought and flood charts of China from 1470 to 1977. Beijing, Atlas Press.

D.R. Easterling, J. L. E., P.Ya. Groisman, T.T. Karl, K.E. Kunkel, P.Ambenje (2000). "Observed Variability and Trends in Extreme Climate Events: A Brief Review." Bulletin of the American Meteorological Society **81**(3): 417-425.

Daniel R. Chavas, R. C. s. I., Allison M. Thomson, Xuejie Gao (2009). "Long-term climate change impacts on agricultural productivity in eastern China." Agricultural and Forest Meteorology **149**: 1118-1128.

David R. Easterling, G. A. M., Camille Parmesan, Stanley A. Changnon, Thomas R. Karl, Linda O. Mearns. (2000). "Climate extremes: Observations, modeling, and impacts. ." Science **289**: 2068-2074.

Eryuan Liang, X. L., Yujiang Yuan, Ningsheng Qin, Xiuqi Fang, Lei Huang, Haifeng Zhu, Lily Wang, Xuemei Shao (2006). "The 1920S Drought Recorded by Tree Rings and Historical Documents in the Semi-Arid and Arid Areas of Northern China." Climatic Change **79**(3-4): 403-432.

Farrow, A., C. Larrea, et al. (2005). "Exploring the spatial variation of food poverty in Ecuador." Food Policy **30**(5-6): 510-531.

Foody, G. M. (2003). "Geographical weighting as a further refinement to regression modelling: An example focused on the NDVI-rainfall relationship." Remote Sensing of Environment **88**(3): 283-293.

Foody, G. M. (2004). "Spatial nonstationarity and scale-dependency in the relationship between species richness and environmental determinants for the sub-Saharan endemic avifauna." Global Ecology and Biogeography **13**(4): 315-320.

Fotheringham, A. S. and C. Brunsdon (1999). "Local forms of spatial analysis." Geographical Analysis **31**(4): 340-358.

Fotheringham, A. S., C. Brunsdon, et al. (2002). Geographically weighted regression : the analysis of spatially varying relationships. Chichester ; Hoboken, N.J., Wiley.

Fotheringham, A. S., M. E. Charlton, et al. (1998). "Geographically weighted regression: a natural evolution of the expansion method for spatial data analysis." Environment and Planning A **30**(11): 1905-1927.

Fulu Tao, M. Y., Yousay Hayashi, Erda Lin (2003). "Future climate change, the agricultural water cycle, and agricultural production in China." Agriculture, Ecosystems and Environment **95**: 203-215.

Gang Li, N. a. W., Chunhui Zhang, Wenyong Feng, Cuiyun Wang (2007). Climate change and disaster response -Case study of historical locust plagues of Shaanxi in Central China. Geoscience and Remote Sensing Symposium, IGARSS 2007. IEEE International.

Gavin, D. G., Feng, S.H. (2006). "Spatial variation of climatic and non-climatic controls on species distribution: the range limit of Tsuga heterophylla." Journal of Biogeography **33**: 1384-1396.

Getis, A. (2003). "Geographically weighted regression: The analysis of spatially varying relationships." Journal of Regional Science **43**(4): 794-796.

Gretchen C. Daily, P. R. E. (1990). "An exploratory model of the impact of rapid climate change on the world food situation." Proceedings: Biological Sciences **241**(1302): 232-244.

Hillier, A. (2007). "ArcGIS 9.3 manual".

Hu, M., Luo, CZ (1988). Chinese historical great flooding events. Beijing, Book Store Press.

IPCC (2001). Climate Change 2001: Working Group I: The Scientific Basis. . Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Y. D. J.T. Houghton, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, C.A. Johnson (eds.) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jetz W, R. C., Lichstein JW (2005). "Local and global approaches to spatial data analysis in ecology. ." Global Ecological Biogeography **14**: 97-98.

John J. Magnuson, D. M. R., Barbara J. Benson, Randolph H. Wynne, David M. Livingstone, Tadashi Arai, Raymond A. Assel, Roger G. Barry, Virginia Card, Esko Kuusisto, Nick G. Granin, Terry D. Prowse, Kenton M. Stewart, Valery S. Vuglinski (2000). "Historical Trends in Lake and River Ice Cover in the Northern Hemisphere." Science **289**(5485): 1743-1746.

Jonathan Corcoran, G. H., Chris Brunsdon, Andrew Ware, Paul Norman (2007). "The use of spatial analytical techniques to explore patterns of fire incidence: A South Wales case study." Computers, Environment and Urban Systems **31**: 623-647.

Josef Schmidhuber, F. N. T. (2007). "Global food security under climate change." PNAS **104**(50): 19703-19708.

Lebreton, M. (2005). "The NCSTAR model as an alternative to the GWR model." Physica a-Statistical Mechanics and Its Applications **355**(1): 77-84.

Lee, J. (1982). "Food Supply and Population Growth in Southwest China, 1250-1850." The Journal of Asian Studies **41**(4): 711-746.

Li, L. M. (1982). "Food, Famine, and the Chinese State." The Journal of Asian Studies **41**(4): 687-707.

LI, X. and A. G. Yeh (2004). "Analyzing spatial restructuring of land use patterns in a fast growing region using remote sensing and GIS." Landscape and Urban Planning **69**: 335-354.

Linda O. Mearns, C. R., Richard Goldberg (1997). "Mean and variance change in climate scenarios: Methods, agricultural applications, and measures of uncertainty." Climatic Change **35**: 367-396.

Linda O. Mearns, R. W. K., Stephen H. Schneider (1984). "Extreme high temperature events: changes in their probabilities with changes in mean temperature." Journal of Climate and Applied Meteorology **23**: 1601-1613.

M.L. Parry, C. R., A. Iglesias, M. Livermore, G. Fischer (2004). "Effects of climate change on global food production under SRES emissions and socio-economic scenarios." Global Environmental Change. **14**: 53-67.

Ma, S., Ting Y. C.. Li D. M. (1965). "Study on long-term prediction of locust population fluctuations." Acta Entomologica Sinica **14**: 319-338 (in Chinese).

Martin Parry, C. R., Ana Iglesias, GuK nther Fischer, Matthew Livermore (1999). "Climate change and world food security: a new assessment." Global Environmental Change **9**: S51-S67.

Michael C. Wimberly, M. J. Y., Adam D. Baer, Vivien G. Dugan, William R. Davidson. (2008). "Spatial heterogeneity of climate and land-cover constraints on distributions of tick-borne pathogens. ." Global Ecology and Biogeography **17**: 189-202.

Oreskes, N. (2004). "BEYOND THE IVORY TOWER: The Scientific Consensus on Climate Change." Science **306**(5702): 1686.

P.R.C (2008). China Statistical Yearbook. National Bureau of Statistics of China. Beijing:, China Statistics Press.

Shi, H., E. J. Laurent, et al. (2006). "Local spatial modeling of white-tailed deer distribution." Ecological Modelling **190**(1-2): 171-189.

Siegfried D. Schubert, M. J. S., Philip J. Pegion, Randal D. Koster, Julio T. Bacmeister (2004). "Causes of Long-Term Drought in the U.S. Great Plains." Journal of Climate **17**(3): 485-503.

Song Yanling, E. S., Chen Deliang, Dong Wenjie (2005). "Infuence of Climate Change on Winter Wheat Growth in North China During 1950-2000." ACTA METEOROLOGICA SINICA **19**: 501-510.

Stern, N. (2008). "The Economics of Climate Change. ." American Economic Review: Papers & Proceedings **98**(2): 1-37.

Trevor Platt, K. L. D. (1975). "Spectral Analysis in Ecology." Annual Review of Ecology and Systematics **6**: 189-210.

W.-H. Qian, D. C., Y. Zhu, H.-Y. Shen (2003). "Temporal and spatial variability of dryness/wetness in China during the last 530 years." Theor. Appl. Climatol. **76**: 13-29.

W. Jetz, C. R., J.W. Lichstein (2005). "Local and global approaches to spatial data analysis in ecology." Global Ecology and Biogeography **14**: 97-98.

Wang, Q., J. Ni, et al. (2005). "Application of a geographically-weighted regression analysis to estimate net primary production of Chinese forest ecosystems." Global Ecology and Biogeography **14**(4): 379-393.

Weihong Qian, X. L., Yafen Zhu, Yuan Xu, Jiaolan Fu (2007). "Climatic regime shift and decadal anomalous events in China." Climatic Change **84**(2): 167-189.

Wheeler, B. W., J. E. Rigby, et al. (2006). "Pokies and poverty: problem gambling risk factor geography in New Zealand." Health & Place **12**(1): 86-96.

Wong, R. B. (1982). "Food Riots in the Qing Dynasty." The Journal of Asian Studies **41**(4): 767-788.

Ye, D. Z., Huang, R. H. (1996). The Study on Rules and Reason of Flood or Drought in Yangtze River and Yellow River Basins (in Chinese) Jinan: , Science and Technological Press of Shandong Province. pp 61-93.

Zhang, D. E., Ed. (2004). The compendium of Chinese Meteorological records of the Last 3,000 years. (in Chinese). Nanjing, China, Jiangsu Education Publishing House.

Zhang, L. J., H. Q. Bi, et al. (2004). "Modeling spatial variation in tree diameter-height relationships." Forest Ecology and Management **189**(1-3): 317-329.

5 Conclusion

Past climate change can provide the evidence for the study on long-term variations of climate change. While scientists are more interested in the prediction of future climate change and the projection of future scenario, study on past climate change can tell us what happened before and what's the consequences of past climate change on environment, ecosystem and human societies. Moreover, past climate change can not only fill the gap of the instrumental data by reconstructing the past climate change series, but also reveal the relationship between climate change, ecosystem, and human society. One of advantages of historical records is that reconstructed data from historical documents has higher temporal and spatial scale compared with the natural proxy data.

This study adopted information from -- "The compendium of Chinese Meteorological records of the Last 3,000 years (Zhang 2004) which represents the utmost results of recent work on historical records of past climate change in China . The historical records for the last Dynasty of China (Qing Dynasty, 1644-1911) were digitized to recover the information about past climate change and its ecological &social-economic impacts. The dataset contains 85701 records recorded in 1504 counties within the study area. In this study, this valuable information was used to study on the long-term climate change, and the relationship between climate change and environmental conditions, ecosystem and socio-economic consequences.

Only a few studies have addressed the impacts of past climate change due to lack of data. For instance, most of previous studies are relied on information recovered from the special compendiums, which only collected single type of climate event. Therefore, it's hard to conduct analysis on the relationship between different climate related events. The compendium adopted in this study contains the mostly systematic and exhaustive collection of climate related information from the historical documents of China. This effort gives us a great opportunity to solve the issue that previous studies are hard to overcome.

In chapter one, the driven question is "whether the variation of agriculture harvest has been associated with climate change in the past? Among the interested variables, which one is strongest factor which affect the agriculture harvest? Does the relationship between climate change and other events vary across the space?" To answer these questions, correlation analysis and spatial analysis were conducted.

The results of Pearson correlation test showed that temperature has a significant negative relationship with poor harvest at annual scale. The results also showed that temperature is not the strongest factor affecting agricultural harvests. Instead, drought shows strongest effect on agriculture harvest for Qing Dynasty. This indicated that besides the direct effect of cold temperature on crop growth, water deficiency is the most important factor limiting crop yields. The spatial analysis revealed the spatial variation and clustering of the variables.

Since the stationarity is often a basic assumption for some common statistics methods. To reveal the relationship between past climate change and other climate related events, it's important to study whether the assumption of stationarity is met. The two case studies addressed this issue in temporal and spatial scale, respectively. In chapter two, continuous wavelet analysis was used to identify the periodicity of interested variables, such as temperature, precipitation, droughts, flood, locust plagues et al. The aim of the study is to explore the temporal trends and pattern of locust dynamics and climate variables.

The results of the case study revealed that the consistent periodicity of locusts, temperature and drought series are at 80-100 year’s band, which is consistent with previous studies (Weihong Qian 2007; Zhibin Zhang 2009). The consistent associations at coherence at same frequency and time space (1777-1810 around 10 year’s periodicity) between locust and temperature, temperature and drought, locust and drought indicated that there is a possible interlinks of temperature→drought→locust plague.

The last case study conducted spatial analysis on relationship between famine incidence and past climate change variables by using localized model—GWR. The results showed that GWR model significantly improved the global regression model over OLS method. The GWR model provides deep insights into the spatial variations of the famine occurrences pattern. Among the explanatory variables, drought has the strongest negative effect on famine incidence.

Overall, based on the three case studies, the general trend and spatial pattern of several climate related variables were explored, such as drought, flood, poor harvest, locust plague and famine incidence. The impacts of past climate change, in terms of temperature and precipitation on those events were also examine. Based on the findings of the studies, drought showed strongest effect on the ecosystem, and human society. There is also a possible link that cold period may trigger more frequently drought events which has a indirect ecological and social-economic impacts. The effort on improving our understanding of past climate change will help us to understand the current situation and better predict the future. To achieve this goal, the case studies used proxy data which were extracted from China historical documents to examine long term variability and trends of past climate change. This valuable dataset were digitized and hence can be used by research community to provide a foundation for future research on past climate change, with aspects about impacts of past climate change on environment conditions, ecosystem, and human society.

6 Appendix

6.1 Modification of GIS data

- **Study area**

Although the data source of this study—Zhang's compendium was supposed to collect all of documents and records in the China, which means the study area was supposed to cover the whole country, due to the difference between historical administrative boundary and current administrative system, the study area is quite different than the current country boundary of China. Over Qing Dynasty, there were 27 province level districts. Depends on the location and the administration type, the district were called "province" or "General governed district". The provinces are the areas which are dominated by China's main nationalities, while some remote area with less population and dominated by other minor nationalities are called "General governed district". For an example, in 1820 (the 25th year of JiaQing Emperor), there were 27 province level districts in China. Among them, there are 18 provinces which were the administrated area from former Ming Dynasty, three "General governed districts" in the Northeast China are the former area of Mandarin nationality, and six "General governed district" in the Northwest are the former area of dominated by other minor nationalities, such as "Mongolia, Tibet, Uighur, and Hui, etc." (http://q.sohu.com/forum/14/topic/3769455). Because those "General governed districts" are either lack of consistent administration or the main habituated nationality body is not Han, historical records in those area were much less than that of provinces. For instance, most of records collected in the "General governed district" were from "Zouzhe (memorial to the throne)" which is official letters or reports send from local governors to the emperor. Rather than the local gazette which has some special officials or scholar consistently record the meaningful information, those “Zouzhe” has less consistency over time and more biased. Besides the administrative system’s difference, there are some provinces were not controlled by the central government at the beginning of Qing Dynasty. For instance, central government lost control of Xinjiang at the end of 16 century. It was reoccupied by central government to be one province of China until 1884; and Taiwan was belong to the Fujian province until separated to a single province in 1887; three general districts in Northeast (Fengtian, Jilin, Heilongjiang) were set to provinces in 1907. Therefore, those districts and provinces were removed from the study area due to lack of enough information and consistency over Qing Dynasty, the collected records from compendium do cover the all of 30 provinces in China though.

After removing those general districts and provinces, the rest 18 province from former Ming Dynasty were Zhidi (Beijing, Tianjin, Hebei), Jiangsu, Anhui, Shanxi, Shandong, Henan, Shaanxi, Gansu, Zhejiang, Jiangxi, Hubei, Hunan, Sichuan, Fujian, Guangdong, Guangxi, Yunan, Guizhou. Except the “Zhidi” which is equal to three current provinces, all of others have same or similar administrative boundary as previous one.

- **Define the region:**

According to the administrative bureau of China (http://www.xzqh.org/quhua/), the administrative regions were divided into:

- Northern of China: Beijing, Tianjin, Hebei, Shanxi, Inter-Mongolia
- Northern East: Liaoning, Jinlin, Heilongjiang
- East of China: Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong
- South of China: Henan, Hubei, Hunan, Guangdong, Guangxi, Hainan
- Southwest: Chongqing, Sichuan, Guizhou, Yunan, Xizang (Tibet)

- Northwest: Shaanxi, Gansu,Qinghai, Ningxia, Xinjiang
- Others: Hongkong, Macao, Taiwan

Note: Hongkong, Macao are belong to the South of China; while Taiwan is belong to East of China, however, because the historical reason of the colonization, they are not included in the study area. Also, because the historical administration reason mentioned above, the following province are also excluded from the study area:

Northeast: Liaoning, Jinlin, Heilongjiang

North of China: Inter-Mongolia

SouthWest: Xizang

Northwest: Qinghai, Ningxia, Xinjiang

Others: Hongkong, Macao, Taiwan

Finally, the regionalization of study area is modified as following:

1. North of China (4 province-level districts): Beijing, Tianjin, Hebei, Shanxi
2. East of China (6 province-level districts): Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Shandong
3. Middle of China (4 province-level districts): Henan, Hubei, Hunan, Jiangxi
4. South of China (3 province-level districts): Guangdong, Guangxi, Hainan
5. Southwest (3 province-level districts): Sichuan(Chongqing), Guizhou, Yunan
6. Northwest (2 province-level districts): Shaanxi, Gansu

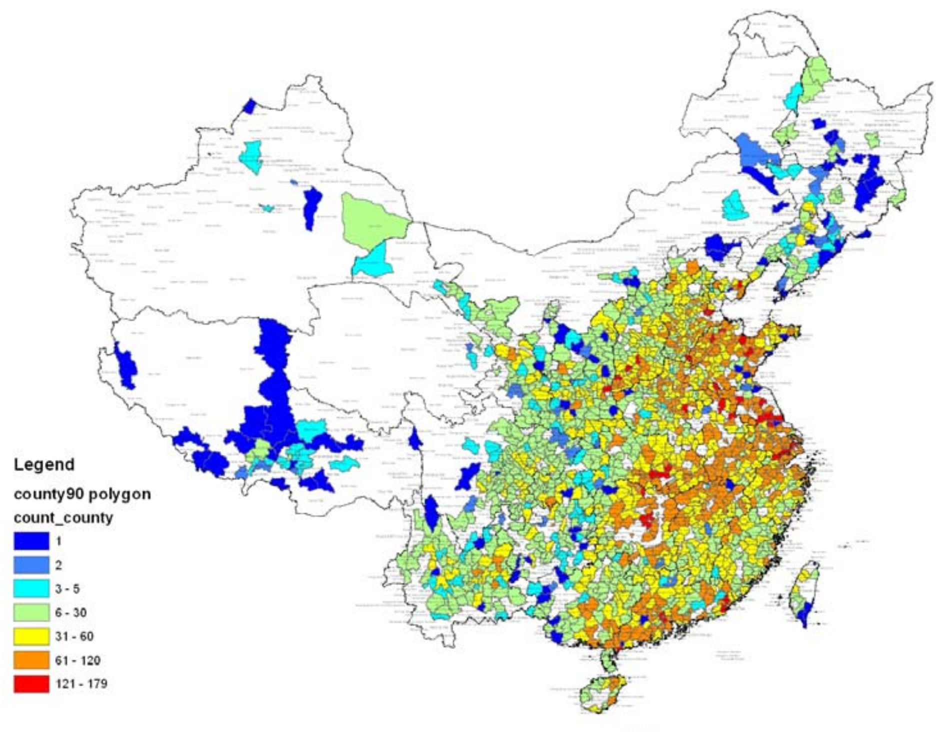
- **Define the boundary of counties**

Since the first Emperor established the county regionalism when he consolidated the whole country in B.C. 221, the county was treated as the basic administrative unit to the present. Therefore, although the boundary of the country changed frequently in history, the counties' boundaries are more stable through history. Because county is the most stable administrative unit of China through the history and most of records collected in the compendium were from local gazettes of corresponding counties, most of those records in the compendium were relocated to the current county by editors as the basic recording location. Because most of compilations were conducted during the last two decades of the 20th century and compilers used the administrative division system in 1990 to relocate the records, the most suitable county level map is county boundary map for 1990, which was used in this study. For most of counties, the boundaries of the county in the map were adopted directly. However, the boundaries of some of counties were modified due to the "Shi-Qu" and "Shi-Xian" issues in the administrative division system of China. In the China's administrative system, "Shi" has both meaning of "municipality" or "county" and "Qu" means "suburban district" within a municipality, while "Qu" is a real county-level district. For instance, one large municipality can contains several "Qu" which each of them equivalent a county-level division. Nevertheless, due to historical reason, those suburban are not a single district unit until they were compartmentalized out of the modern cities. Therefore, in this study, if the "Shi" and "Qu" are in the same municipality, they were regarded as a single county-level division. This method was also applied to the "Shi-Xian" issue. "Xian" means county in Chinese. This issue often happens for some middle-size cities that separated part of the old counties due to city growth or moved the administrative bureau to the vicinity area to establish a new city. However, both "Shi" and "Xian" share the same old cities' name. For an example, "YueYang Shi" and "YueYang Xian" in Hunan province are both county-level divisions in the current administrative system, however, in the history there is only one district for "YueYang County", which was represented in the local gazette. Since there is no way to assign the location of historical records to any of them, the records were regarded as both of them, and the boundaries of those problematic counties were merged to one single unit. Totally, there are 16 “Qu” and 56 “Xian” were modified by this method in the study area. The counties which have no records during the entire Dynasty, which most due to the historical administrative reason, were also excluded from the map. There are 2421 counties in China in 1990 (not including Hongkong and Macao). After remove nine provinces are not included in the study area which due to historical reasons, there are 1897 counties within the study area in1990. Among them, there are 1527 counties which have at least one recorded interesting event over the studying period. Finally, by modifying the boundary of some counties, there are 1504 counties which have the historical records of past climate conditions within the study area.

6.2 The table of brief summary of observed counties in each current province in China

Province Name	# of recorded county	Total # of county	%
Anhui	60	82	73.2
Beijing	15	15	100.0
Fujian	64	70	91.4
Gansu	53	81	65.4
Guangdong	82	95	86.3
Guangxi	68	88	77.3
Guizhou	53	82	64.6
Hainan	13	23	56.5
Hebei	125	150	83.3
Heilongjiang	15	79	19.0
Henan	103	130	79.2
Hubei	73	79	92.4
Hunan	77	104	74.0
Jiangsu	59	75	78.7
Jiangxi	83	90	92.2
Jilin	17	47	36.2
Liaoning	32	61	52.5
Neimenggu	15	88	17.0
Ningxia	20	20	100.0
Qinghai	5	42	11.9
Shaanxi	96	97	99.0
Shandong	97	110	88.2
Shanghai	10	13	76.9
Shanxi	105	106	99.1
Sichuan	136	192	70.8
Taiwan	13	21	61.9
Tianjin	12	12	100.0
Xinjiang	8	88	9.1
Xizang	33	78	42.3
Yunnan	75	125	60.0
Zhejiang	68	78	87.2
Total in China	1685	2421	69.6
Total in study area	1527	1897	80.5

6.3 The map shows the counties which have records during Qing Dynasty.



6.4 The table of brief summary of historical weather documents of China

Dynasty	Period	Name	Description	Application
Shang(yin) Dynasty	18th to 12th century B.C.	Oracle bones inscriptions	Eyewitness records of the weather and forecast	Climate of Northern China (Wittfogel 1940; Hu 1944)
Zhou Dynasty	1111-246 B.C.		Records of unusual weather and general descriptions of some phonological phenomena (blossoming dates of certain flowers, lake or river freezing dates, the arrival dates of swallows	Indirect inference of the general conditions (Wang 1979; Wang 1980)
Qin Dynasty	246-206 B.C.		No significant number of documents, even destroy previous records	
Han Dynasty	206 B.C. -220A.D.	Wu-Xing-zhi (records of five elements) Zai-Yi-Zhi (Records of Disasters and Portents	More standard formats for various records, reprints in Twenty-Five Histories, that are commercially available	
Sung Dynasty	960-1279	Local records	Written by private scholars, not good uniformity, but cover a much-wider area and higher density	Reconstruction of past climate
Ming and Qing Dynasty	-1911	Instrumental measurements staring from 1843 Qing-Yu-Lu (Clear and Rain Records) Yu-Xue-Feng-Cun (Inches of rain and snow)	Measured by Jesuits or missionaries from France, Russia in Beijing, Shanghai, Taiwan. Local official Daily records and reported to the emperor monthly. The entry include: sky conditions, wind directions, precipitation types and duration. 41 places have been found with 4 cities have relative consistent report: Beijing (1724-1903), Nanjing (1723-1798), Suzhou (1736-1806), Hangzhou(1723-1773)	

6.5 The contents of "the compendium of Chinese Meteorological records of the Last 3,000 years".

	Meteorological records	Periods
Volume I	Ancient to Yuan Dynasty	23rd century BC to 1367 AD
Volume II	Ming Dynasty	1368-1643AD
Volume III	Early Qing Dynasty	1644-1795Ad
Volume IV	Later Qing Dynasty	1796-1911AD

6.6 The table of description of index

Variables		English description	Chinese description
Season	1	Spring	春
	2	Summer	夏
	3	Fall	秋
	4	Winter	冬
	5	Spring &Summer	春夏
	6	Summer &Fall	夏秋
	7	Fall &Winter	秋冬
	8	Winter &Spring	冬春
Famine	0	None	无
	1	Famine, rice expensive	饥,米贵，祲
	2	Severe famine, have to eat tree bark and soil	大饥,以树皮,土为食
	3	Starve to death and cannibalism	饿死,人相食
Harvest	-1	Barren or Poor Harvest	荒，歉
	1	Good Harvest	有年
	2	Very Good Harvest	大熟,大有年
	3	Wheat has more than two fringes	麦秀两歧
Plague (Yi)	1	Epidemic disease	疫
	2	Severe epidemic diseases	大疫
	3	Variola	痘疫
	4	Diarrhea	痢疾
	5	Black death (bubonic plague)	鼠疫
Death (Deciles)	-2	Hard to tell how many, >1000	不可胜计
	-1	Very often, >100	死者甚众，枕藉
	1	10 percent	十分之一
	2	20 percent	十有一二
	3	30 percent	十有二三
	4	40 percent	十有三四
	5	50 percent	十有四五
	6	60 percent	十有五六
	7	70 percent	十有六七
	8	80 percent	十有七八
	9	90 percent	十有八九
Locust	0	None	无蝗
	1	Locust, no damage reported	蝗不为灾
	2	Lots of locust, or sky full of locusts	大蝗
	3	Damage reported	蝗灾
	4	Nymph of a locust reported	螟，蝻
	5	Damage reported by nymph of a Locust	螟，蝻为灾
Continuous	0	None	无

raining	1	Continuous raining or cloudy	恒雨，无晴
	2	Precipitation soaked	大雨水
		Continuous raining days	
Rainstorm	1	Rain	大雨，潦
	2	Rainstorm	大雨如注,尺余
	3	Start raining	始雨，始透
	4	Shower	微雨
Snowstorm	1	Snow	雪
	2	Heavy snow or pile up approximately 1chi	大雪, 瑞雪或一尺
	3	Rain snow shower or rain ice	雨雪,或雨冰
	4	Pile up 1chi to 3 chi	大雪一尺到三尺
	5	>3chi	三尺以上
	6	>5chi	五尺以上，丈余
	7	Ice cover the tree	木介,木冰
Frost	1	Frost	霜
	2	Frost damage or early frost	霜灾,伤麦，早霜
Drought	1	Drought	旱,半旱
	2	Heavy drought, damage	大旱,旱灾,伤禾
	3	Precipitation are not on time and not enough	雨旸愆期
	4	Favorable weather; good weather for the crops	雨旸时若，雨水调，夜雨昼晴
		Continuous no rain days	
Flooding	1	Water logging	漫溢,地淹,涝
	2	Dike breaching, big flooding	河决,灾，堤崩,大水,城或屋坏,山洪 (2.5既指2＋4)
	3	Drown to death	人伤（3.5指3＋5）
	4	Mud-rock flow/avalanche	山崩，泥石流
	5	水涌，水啸，水斗	水涌，水啸，水斗
	6	Fountain	泉出
	7	Flooding and avalanche	大水山崩
	8	Avalanche and people die	人死山崩
Sea wave flooding	1	Sea tide overflow the bank, damage cropland	海潮,海溢
	2	Big sea tide overflow,	海潮大,船毁，伤堤
	3	People die	伤人
	4	Salt tide	咸潮
	5	tsunami	海啸
	6	No tide	失潮
	7	3 tides/day	一日三潮
Yellow river flooding	1	Overflow	溢
	2	Bank breaching	决
	3	Change the route	改道
	4	Dry up	断流

Wind	1	Strong wind	大风
	2	Wind damage	大风拨禾,伤人
	3	Dust storm, dust haze	风沙，风霾
	4	Whirlwind	旋风
Wind direction Dust no sunlight Dust comments	1	Dust no sunlight Color	昼晦
Dust Rain	1	Rain dust, mud	雨土
	2	Rain dirty snow	雨黑雪
	3	Dirty frost	黑霜
	4	Salt rain	咸雨，卤雨
Tornado	1	Toledo	飓风
	2	Damage	坏民居,伤禾稼
	3	Tornado	旋风，龙卷风（鱼龙气）
	4	Typhoon	台风
Hot	1	Hot	热
	2	Very hot, animal die	酷热,动物热死
	3	Hot to death	人暍死
	4	Suddenly temperature increasing, abnormally hot	骤热，反常热，如夏
	5	Winter has no snow or ice	冬无雪,无冰
	6	None or few snow and rain	无雨雪，稀少
	7	No frost	秋无霜
Cold	1	Cold, rive ice, plants frostbite	严寒,井冻,花木多枯死,河冰,伤麦
	2	Very cold, tree and animal winter kill	极寒,树木皆冻死、牲畜
	3	Freeze to death	人冻死
	4	Suddenly temperature decreasing, abnormally cold (Counter- season)	骤冷，反常冷，如秋
	5	Whole year is cold	岁寒
Animal epidemic disease	1	General livestock	畜
	2	Cattle	牛
	3	Pig	猪
	4	Sheep	羊

7 CV

EDUCATION

Ph.D, Ecology and Evolution with *Graduate GIScience Certificate,* May. 2010, Rutgers University, New Brunswick, NJ
M.S. Jan 2009, Statistics**, Rutgers University, New Brunswick, New Jersey**
M.S. July 2002, Geography, **Nanjing University, Nanjing, China**
B.S. July 1996, Geography, **Nanjing University, Nanjing, China**

RESEARCH INTERESTS

- Historical climate change and its impacts on environment and ecosystems
- Terrestrial Ecosystem processes and climate interaction, especially energy, water, carbon exchange among soil, vegetation, and atmosphere and terrestrial responses/feedbacks to global climate change
- Ecosystem carbon and nitrogen cycling and global change
- Measuring and modeling ecological patterns and processes from cell to globe
- Applying Remote Sensing and GIS techniques in ecosystem modeling.
- Spatial autocorrelation analysis in land use change modeling

TEACHING EXPERIENCE

- Spring 2007 Laboratory Instructor, "Limnology", Rutgers University, NJ.
- Fall 2006 Laboratory Instructor, "Invertebrate Zoology", Rutgers University, NJ.
- 2005-2006 Laboratory Instructor, "General Biology I&II", Rutgers University, NJ.

RESEARCH EXPERIENCE

- Fall 2009—present Environment Modeler/Analyst, DRBC, NJ.
- Fall 2007--summer 2009 Graduate Assistant, Ecology program, Rutgers University, NJ.
- Fall 2005--summer 2007 Teaching Assistant, Ecology program, Rutgers University, NJ.
- Fall 2003--summer 2005 Fellowship, Graduate Scholl, Rutgers University, NJ.
- Fall 1999--summer 2002 Graduate Assistant, Nanjing University, China.

AWARDS

2003–2005, Graduate School Fellowship, **Rutgers University**

Publication

ZEWEI MIAO, MING XU, RICHARD G. LATHROP JR. & YUFEI WANG (2008). Comparison of the A–Cc curve fitting methods in determining maximum ribulose 1·5-bisphosphate carboxylase/oxygenase carboxylation rate, potential light saturated electron transport rate and leaf dark respiration. Plant, Cell & Environment.
Wang Yufei, Pu Lijie (2002). A Review on the ^{137}Cs Application in the soil Erosion Study in China. Journal of Nanjing University (in Chinese).