Regional Famine Patterns of The Last Millennium as Influenced by Aggregated Climate Teleconnections

by

Michael Melton Santoro

A Dissertation Presented in Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy

Approved April 2017 by the
Graduate Supervisory Committee

Randall S. Cerveny, Chair
Kevin McHugh
Anthony Brazel
Robert C. Balling Jr.

ARIZONA STATE UNIVERSITY

August 2017

ABSTRACT

Famine is the result of a complex set of environmental and social factors. Climate conditions are established as environmental factors contributing to famine occurrence, often through teleconnective patterns. This dissertation is designed to investigate the combined influence on world famine patterns of teleconnections, specifically the North Atlantic Oscillation (NAO), Southern Oscillation (SO), Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO), or regional climate variations such as the South Asian Summer Monsoon (SASM). The investigation is three regional case studies of famine patterns specifically, Egypt, the British Isles, and India.

The first study (published in *Holocene*) employs the results of a Principal Component Analysis (PCA) yielding a SO-NAO eigenvector to predict major Egyptian famines between AD 1049-1921. The SO-NAO eigenvector (1) successfully discriminates between the 5-10 years preceding a famine and the other years, (2) predicts eight of ten major famines, and (3) correctly identifies fifty out of eighty events (63%) of food availability decline leading up to major famines.

The second study investigates the impact of the NAO, PDO, SO, and AMO on 63 British Isle famines between AD 1049 and 1914 attributed to climate causes in historical texts. Stepwise Regression Analysis demonstrates that the 5-year lagged NAO is the primary teleconnective influence on famine patterns; it successfully discriminates 73.8% of weather-related famines in the British Isles from 1049 to 1914.

The final study identifies the aggregated influence of the NAO, SO, PDO, and SASM on 70 Indian famines from AD 1049 to 1955. PCA results in a NAO-SOI vector

and SASM vector that predicts famine conditions with a positive NAO and negative SO, distinct from the secondary SASM influence. The NAO-famine relationship is consistently the strongest; 181 of 220 (82%) of all famines occurred during positive NAO years.

Ultimately, the causes of famine are complex and involve many factors including societal and climatic. This dissertation demonstrates that climate teleconnections impact famine patterns and often the aggregates of multiple climate variables hold the most significant climatic impact. These results will increase the understanding of famine patterns and will help to better allocate resources to alleviate future famines.

DEDICATION

To the many friends and family who loved me over the years:

I dedicate this work to my wife Annie, my lovely daughters Lucy and Hannah, my mother Dr. Shari Melton, my dad Dr. Granger Macy, in loving memory of my father Richard Santoro, and in thanksgiving for the grace and perseverance given to me by God. I am grateful for the love and support you have all given me over the years.

ACKNOWLEDGMENTS

I thank Dr. Randall Cerveny for his instruction, patience and support; without his leadership this dissertation would not be possible. I also thank him for shaping me as a teacher and academic professional.

I thank my committee Dr. Kevin McHugh, Dr. Anthony Brazel, and Dr. Robert Balling Jr. for their assistance and supervisory support of the research included in this work. I thank Dr. Fekri Hassan for his contributions to the initial stages of my research.

Finally, I thank all of those who have sacrificed in order to help me on this journey, including by family, friends, co-workers, and students.

TABLE OF CONTENTS

Page

LIST OF TABLES vii

LIST OF FIGURES viii

LIST OF ABBREVIATIONS x

CHAPTER

1 INTRODUCTION 1

Famine as a Historical Problem 1

Research Question 4

Famines and Climate 7

Statistical Methods 11

Dissertation Framework 13

2 CLIMATE TELECONNECTIONS, NILE RIVER LEVELS, AND EGYPTIAN FAMINE 15

Introduction 16

Study Area and Data 17

Methods 23

Discussion 33

Conclusions 34

3 CLIMATE ATTRIBUTED FAMINES OF THE BRITISH ISLES AND THE NORTH ATLANTIC OSCILLATION 35

Introduction 36

CHAPTER Page

Climate Teleconnections 40

Study Area and Data 44

Methods and Results 51

Discussion and Conclusions 60

4 INDIAN FAMINE AS INFLUENCED BY THE NORTH ATLANTIC OSCILLATION, THE SOUTHERN OSCILLATION AND THE SOUTH ASIAN MONSOON 64

Introduction 65

Climate Drivers and their Reconstructive Proxies 68

Methods and Results 76

Conclusions 95

5 CONCLUSIONS 99

Summary of Results 99

Overall Conclusions 107

Future Research 108

Significance 109

REFERENCES 110

APPENDIX

A BRITISH FAMINE LIST 123

B INDIAN FAMINE LOST 129

BIOGRAPHICAL SKETCH 137

LIST OF TABLES

Table Page

2.1 Egyptian Famine List....31

3.1 Stepwise Discriminant Analysis Statistics (British Famine)....58

3.2 Principal Component Analysis Statistics (British Famine)....60

4.1 Principal Component Analysis Outputs Statistics (Indian Famine)....79

LIST OF FIGURES

Figure Page

1.1 Geographical Areas of Investigation 5

2.1 Time Series of Raw Factor Scores of Principal Component Analysis Climate Teleconnection Eigenvector 25

2.2 Time Series of Detrended Factor Scores of Principal Component Analysis Climate Teleconnection Eigenvector 26

2.3 Egyptian Famine Years and Respective Detrended Factor Scores 29

2.4 Detrended Factor Scores Preceding AD 1200 Egyptian Famine 32

3.1 Atmospheric Effects of the North Atlantic Oscillation 42

3.2 North Atlantic Oscillation Time Series and British Famines 45

4.1 South Asian Summer Monsoon Index Time Series 70

4.2 North Atlantic Oscillation Time Series 72

4.3 Southern Oscillation Index Time Series 74

4.4 Pacific Decadal Oscillation Time Series 75

4.5 Time Series of Principal Component Analysis Climate Teleconnection Eigenvector 80

4.6 Asian 500 hPa Geopotential Heights AD 1992 and 2010 85

4.7 Asian 2 meter Air Temperature AD 1992 and 2010 86

4.8 Asian Precipitation Rate Anomaly AD 1992 and 2010 87

4.9 Asian 500 hPa Geopotential Heights AD 1896-1902 89

4.10 Asian Precipitation Rate Anomaly AD 1896-1902 90

Figure Page

4.11 Time Series of Detrended Principal Component Analysis Climate Teleconnection Eigenvector and Indian Famine Events 95

LIST OF ABBREVIATIONS

AD ..... Anno Domini (Year)

AH ..... Anno Hegirae (Year)

AMO ..... Atlantic Multidecadal Oscillation

BC ..... Before Christ (Year)

DNAO ..... Detrended North Atlantic Oscillation

DSOI ..... Detrended Southern Oscillation Index

ENSO ..... El Niño Southern Oscillation

FAD ..... Food Availability Decline

FED ..... Food Entitlement Decline

hPa ..... hecto-Pascals

ITCZ ..... Inter Tropical Convergence Zone

LIA ..... Little Ice Age

MCA ..... Medieval Climate Anomaly

NAO ..... North Atlantic Oscillation

PCA ..... Principal Component Analysis

PDO ..... Pacific Decadal Oscillation

SASM ..... South Asian Summer Monsoon

SASMI ..... South Asian Summer Monsoon Index

SDA ..... Stepwise Discriminant Analysis

SO ..... Southern Oscillation

SOI ..... Southern Oscillation Index

SST ..... Sea Surface Temperatures

Chapter 1

INTRODUCTION

Famine as a Historical Problem

Human civilization has struggled with food insecurity for thousands of years. Famine is one of the greatest tragedies that could befall a people (O'Grada, 2009). Anecdotal accounts of historical famine are commonplace and found in history textbooks, historical texts, depicted in film and, in sacred scripture. One of the more familiar famine accounts is found in the Bible and tells the story of Joseph in Egypt (Schneider and Mesirow, 1976):

Genesis 41:29-31, 53-57

> *Seven years of great abundance are now coming throughout the land of Egypt; but seven years of famine will rise up after them, when all the abundance will be forgotten in the land of Egypt. When the famine has exhausted the land, no trace of the abundance will be found in the land because of the famine that follows it, for it will be very severe. …When the seven years of abundance enjoyed by the land of Egypt came to an end, the seven years of famine set in, just as Joseph had said. Although there was famine in all the other countries, food was available throughout the land of Egypt. When all the land of Egypt became hungry and the people cried to Pharaoh for food, Pharaoh said to all the Egyptians: "Go to Joseph and do whatever he tells you. "When the famine had spread throughout the land, Joseph opened all the cities that had grain and rationed it to the Egyptians, since the famine had gripped the land of Egypt.*

Indeed, the whole world came to Egypt to Joseph to buy grain, for famine had gripped the whole world.

As Schnieder and Mesirow (1976) noted, famine, particularly from a climatic viewpoint has been a phenomenon of great historical significance. It has been a reoccurring catastrophe for many societies for thousands of years (e.g. Brown and Anderson, 1976; O'Grada, 2009; Schneider and Mesirow, 1976; Nash, 1976; Keys, 1950; Slavin, 2016).

Even today, famines continue to occur globally (Kumar et al., 2005), particularly in areas that struggle with food insecurity such as India and parts of North Africa. As recently as February 2017, the United Nations International Children's Emergency Fund (UNICEF) declared a state of famine in South Sudan, citing war and drought as causes (UNICEF, 2017).

In addition to the understood social causes of famine (e.g. war, politics, social class systems etc.), climate variations are shown to affect famine patterns (e.g. crop loss from flooding, drought, pests etc.). A better understanding of the environmental influence on historical famine will help to more accurately predict future famine events. Determination of the causal impacts of climate on globally significant historical regions can provide valuable information on historical events and, with appropriate intervention, can help avert future disaster.

Past research has indicated that, famine strikes people who struggle with food insecurity or those on the edge of food insecurity for a prolonged period (Sen, 1981). While famine and food shortage are often connected, famine implies a greater severity of societal effects, i.e., famine leads to excessive mortality, whereas a food shortage would

not (Slavin, 2016). Famine implies a deficiency of food of such magnitude and of such an extended time that a collective period of starvation occurs across an entire population for a significant time (Slavin, 2016).

Much of the existing famine research focuses on one of two schools of thought for famine causation: 1) climatic and environmental influences (e.g., Sinha et al., 2007; Hassan, 2007; Engler et al., 2013; Shi et al., 1014; Engler and Werner, 2015; Santoro et al., 2015), or 2) social and societal influences (Malthus, 1798; Sen, 1977; Sen, 1981; Ellman, 2000; Engler, 2012; Rai and Smucker, 2016). However, a growing body of research acknowledges that the deteriorating conditions leading to famine typically involve a combination of societal and environmental actors (Engler, 2012; Adamson, 2014; Slavin, 2016; Kumar, 2016).

The first school of thought, an environmental point of view, suggests that food availability is the key instigator of famine. This theory is known as Food Availability Decline (FAD). FAD is defined as the natural scarcity or non-availability of food (e.g., Sen, 1981; Sen, 1981a; Wolde-Mariam, 1984; Ellman, 2000; Moon, 2009; Slavin, 2016). The causes of FAD may be an issue of population demand exceeding the ability to produce food (Malthus, 1798; Ambirajean, 1976; Weir, 1991; Lima, 2014), or a series of environmental events, such as a climate shock, that reduce the availability of food, for example a frost or drought (Keys, 1950; Kershaw, 1973; Zhang et al., 2007, 2011; Engler, 2012; Slavin, 2016).

The second view of famine's causes attributes famine as the result of the decisions that human beings make with respect to food supply and distribution. Actions such as the hoarding of food and political upheaval can exacerbate, or be a reaction to,

changes in supply or distribution of food (Keys, 1950; Sen, 1981; Slavin, 2016). This means that individuals or segments of society may not have access to an existing food supply. This view on famine is defined in terms of societal influence on food supply and is known as Food Entitlement Decline (FED). If food cannot be accessed, hunger will occur (Sen, 1981; Ellman, 2000; Engler, 2012; Slavin, 2016).

In order to investigate the causes of famine, it is necessary to identify when and where famine has occurred. Historical records of famine, unfortunately, are often scarce and often based on flawed assumptions (O'Grada, 2009). Most famine records are based on a few sources such as Walford's 1879 *The Famines of the world: Past and Present*, or Thomas Short's 1749 *A General Chronological History of the Air, Weather, Seasons, Meteors, etc.* (O'Grada, 2009), these sources are difficult to verify. Despite challenges in the reliability of these historical texts, a review of these historical chronologies, in conjunction with review of famines cited in the modern literature, does allow for the creation of a workable famine chronology.

Consequently, the focus of my research is the study of the environmental and climatological conditions that contribute to famine. I will do this through case study analysis of specific historical famines around the world (Figure 1.1).

Research Question

Famine patterns around the world have been the subject of extensive research including many books, popular media analysis and academic research. This research has contributed to the creation of various warning systems and mitigation measures (e.g., Novella and Thiaw 2012) in an attempt to mediate the affects of food insecurity and

famine. For example, in order to better forecast famine conditions, Novella and Thiaw (2012) developed an African rainfall climatology precipitation monitoring system using a rainfall estimation algorithm based on an existing 29-year precipitation dataset in conjunction with satellite data and real time precipitation data.

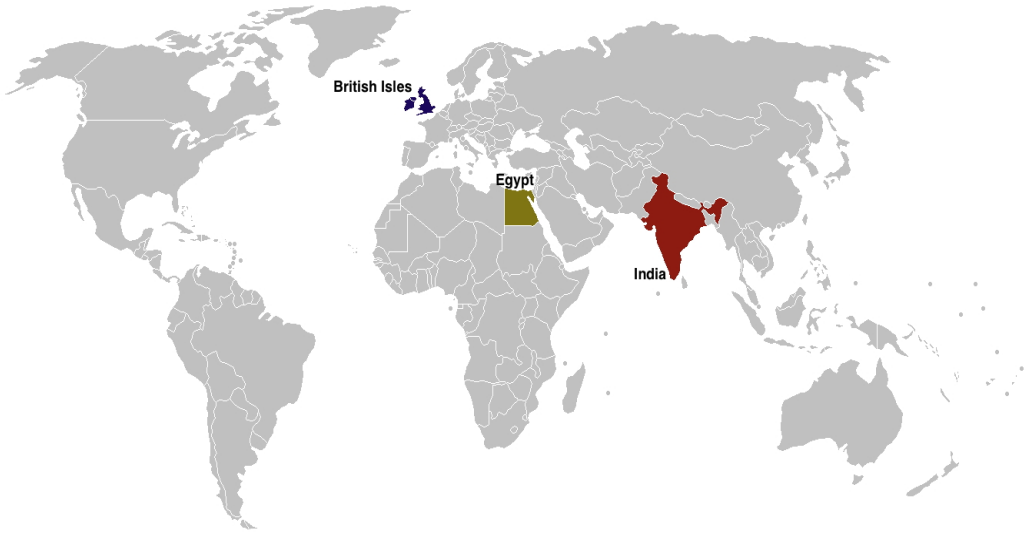


Figure 1.1. The geographic areas of the three regional investigations described in this dissertation (i.e., Egypt (yellow), the British Isles (blue), and India (red)).

Many sources independently address the social or climatological causes of famine (e.g., Sen, 1981, Davis, 2002; Hassan, 2007a; Engler et al., 2013; Shi et al., 1014; Slavin, 2016), but there is still a great deal to learn particularly with respect to the environmental impact on the occurrence of famines throughout history. The bulk of the existing research with respect to climatological phenomena and famine occurrence focus on single climatic teleconnections, such as the North Atlantic Oscillation (NAO) or South Asian Summer Monsoon (SASM) (e.g. Sinha et al., 2007; Shi et al., 1014; Kumar, 2016; Fraser, 2006;

Hassan, 2007a). Teleconnections are multi year Inter-annual Ocean and atmospheric oscillations.

These single relationship studies between teleconnections and climate have often investigated the relationship of famine to large teleconnections such as the North Atlantic Oscillation (NAO) (Hassan, 2007a), El Niño Southern Oscillation (ENSO) (Davis, 2002), or regional climate phenomena such as the South Asian Summer Monsoon (SASM) (Shi et al., 2014), or as specific as a single anomalous season leading to famine such as the severely cold winter prior to the 1740-1741 Irish famine (Engler et al., 2013).

Despite this body of research, there has been little work examining the aggregated effect of climate teleconnections on world famine patterns. Therefore my research addresses the following question:

What is the aggregate influence of climate teleconnections (e.g., the North Atlantic Oscillation, El Niño Southern Oscillation, the Pacific Decadal Oscillation or the Atlantic Multidecadal Oscillation), or regional climate phenomena (such as the South Asian Summer Monsoon) on the historical occurrence of famine around the world?

My hypothesis is that climate, as represented by an aggregated teleconnection variable, incorporating the shared variance of many teleconnections (such as the North Atlantic Oscillation and El Niño Southern Oscillation), will account for a significant amount of variance in the occurrence of specific regional famines (e.g., in Egypt, India or The British Isles) over the last 1000 years. I also hypothesize that

such an aggregated teleconnection will correlate better to those regional famines than will any single climate teleconnection.

Famines and Climate

In order to study the relationship between climate teleconnections and famine, I need to define a set of specific teleconnections and identify famine data for different parts of the world.

Climate Teleconnections

First, I address climate teleconnections. Climate teleconnections are interannual, ocean and atmospheric oscillations of wind, air pressure and ocean temperatures, that can impact the weather in regions far beyond their specific location. They are large-scale, often multi-year, oceanic and atmospheric variations in circulation that can affect weather and climate over large areas of the Earth (e.g., Walker and Bliss, 1932; van Loon and Rodgers, 1978; Lamb and Peppler, 1987; Diaz and Markgraf, 1992; Jones et al., 1997; Trenbreth, 1997; Mantua and Hare, 2002; MacDonald and Case, 2005; Knight et al., 2006; Trouet et al., 2009). Teleconnections should not be considered proxies for the regional weather patterns they influence, but rather contributing factors to the development of those weather patterns (Seager et al., 2003; Ramadan 2012).

The climate teleconnections included in this research are the North Atlantic Oscillation (NAO), El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and Atlantic Multidecadal Oscillation (AMO), each is independently known to affect the climate of geographical areas included in these studies- Egypt, British Isles and

India (Hasternath, 1987; Jones et al., 1997; Kakade and Dugam, 2000; Krishnan and Sugi, 2003; Grey et al., 2004; D'Arrigo and Wilson, 2006; Roy, 2006; Li et al., 2008; Abtew et al., 2009; Jury 2009; Brandimarte et al., 2011; Yan et al., 2011; Shi et al., 2014). A general description of each researched teleconnection is given below; please consult the subsequent chapters for detailed information on each teleconnection.

The North Atlantic Oscillation (NAO) is a major interannual variation of atmospheric circulation in the North Atlantic Ocean that is often characterized by the air pressure difference between Iceland and the Azores (Jones et al., 1997; Lamb and Peppler, 1987; Trouet et al., 2009; Walker and Bliss, 1932). The NAO is known to directly affect the temperature and precipitation patterns of North America and Europe (Jones et al., 1997; Wanner et al., 2001; Visbeck et al., 2001), but may affect circulation patterns for much of the northern hemisphere (Burns et al., 2003; Dugam, 2008, Roy 2011).

The Atlantic Multidecadal Oscillation (AMO) is a long-term (decadal) variation in climate best characterized by sea surface temperature variations across the Atlantic Ocean. It can have a noted effect on the climate over much of the Northern Hemisphere, and may be interrelated to the NAO. (Grey et al., 2004; Knight et al., 2006). The AMO can be represented by an index based on Sea Surface Temperatures (SST) anomalies of the Atlantic Basin. The AMO's known effects include summer rainfall in north Western Europe including the British Isles (Grey et al., 2004; Knight et al., 2006).

El Niño Southern Oscillation (ENSO) is a multi-year ocean-atmospheric oscillation causing changes in precipitation patterns around much of the world (Diaz and Markgraf, 1992). The oceanic component of ENSO is El Niño and is related to equatorial

ocean temperatures across the Pacific Ocean, with the warm phase known as El Niño and the cool phase known as La Niña (Nash, 2002). The Southern Oscillation (SO) is the atmospheric component of ENSO and is characterized by sea level pressure differences between Tahiti and Darwin, Australia (Trenberth, 1997). The Southern Oscillation Index (SOI) serves as an indicator of the phase of ENSO with negative SOI values associated with El Niño, the warm water intrusion into the eastern South Pacific of warm equatorial waters (Diaz and Markgraf, 2000; Yan et al., 2011).

The Pacific Decadal Oscillation (PDO) is a long-term (decadal) oscillation of SSTs and atmospheric circulation in the Northern Pacific Ocean. The positive phase of the PDO is identified by anomalously warm SSTs in the northeastern Pacific and negative PDO is identified by anomalously cool SSTs (MacDonald and Case, 2005; Mantua and Hare, 2002). The PDO is known to affect the intensity of an El Niño event as well as influence circulation and precipitation patterns across the Northern Hemisphere (Mantua and Hare, 2002).

In addition to climate teleconnections, there are regular seasonal variations in climate patterns, such as the South Asian Summer Monsoon, that are similarly identified with famine patterns (Sinha et al., 2007, Shi et al., 2014). The South Asian Summer Monsoon (SASM), also known as the Indian Monsoon, is the annual migration of the Intertropical Convergence Zone (ITCZ) that produces variations in rainfall across India and South Asia (Fleitmann et al., 2007).

Famine Variables

I also need to address the occurrence of specific historical famines. As noted in my research question, I am examining famine events occurring within three major civilizations: Egypt, Britain and India. (Figure 1.1) Historical records of famine for each of these areas are significant, detailed and well researched.

The Egyptian civilization is one of the oldest on earth, and has a history of famine related to climate and the Nile River. Better understanding of the history of this great civilization is of a common good, and may help in understanding the causes and prevention of famine in that region today. Egypt is located in the northeastern Sahara desert and is characterized by an arid climate. Despite the arid climate civilization was able to thrive because of the annual flood of the Nile River (Kondrashov, et al. 2005, and Hassan, 2007a). For historical record and documentation of famine in Egypt, see: the following selected references; Al Latif Al Baghdadi (1204); Samy (1915); Zakry (1926); Keys et al. (1950); Nash (1976); and Hassan (2007a).

The British Isles exists in the mid-latitudes and generally has a temperate climate characterized by moderate temperatures and ample rainfall. Great Britain has an extensive history of famine and past research surrounding specifically British (excluding for example Scotland and Ireland) famine questions if mid-latitude famines have a different climatology than subtropical famines. For historical record and documentation of famine in Britain, see: Short (1749); Walford (1879); Lucas (1930); Keys et al. (1950); Nash (1976); Campbell (2010); Engler (2012); DeWitte (2015); Engler et al (2013); and Slavin (2016).

India may have the most extensive famine history on earth, and may still be prone to localized famine (Kumar, 2016). Understanding the climatology of famine in this region may aid in the prediction and hopeful prevention of future famine. The climate of India is monsoonal which is characterized by intense summer rainfall as a result of the northward migration of the Intertropical Convergent Zone (Fleitmann et al., 2007). Failure of the monsoon in India has been linked to environmental and social difficulties (Sinha et al., 2007; Shi et al., 2014). For historical record and documentation of famine in India, see: Ganguli (1933); Lucas (1930); Keys et al (1950); Sinha et al (2007); O'Grada (2009); and Shi et al (2014).

Statistical Methods

To date the study of climate/famine relationships has focused primarily on a single climate index or reconstruction such as the NAO, SOI or PDO and how that phenomenon affects the regional climatology and famine patterns. Despite the body of research linking the environment to famine patterns, there has been little evaluation of the cumulative effects of multiple aspects of climate, thus the statistical methods used in the subsequent papers include: Principal Component Analysis, the Student's t-test, and Stepwise Discriminate analysis.

The Principal Component Analysis (PCA) is a statistical analysis that transforms a set of potentially correlated observations into a new set of explicitly uncorrelated variables (Rummel, 1970; Jackson, 1991). This is useful in order to identify common variance among a group of variables, such as multiple climate variables.

For the purposes of the research that follows, I used a PCA to identify the aggregated effect of climate on famine. With the goal of identifying how shared variance of climate may impact famine patterns in the three regions studied, a number of climate variables was included in an un-rotated Principal Component Analysis (PCA).

I applied correlation analysis, in particular Student's t-tests, in order to ascertain whether or not the mean of a climate variable is different during famine years than during non-famine years. I chose Student's two-sample t-tests analysis, as it is a difference-of-means test, accessing if the means of two groups significantly vary from one another (Keeping, 1962). The famine data used in the papers that follow are nominative ("yes/no" with descriptors); a basic statistical test such as the two sample Student's t-tests is best suited to demonstrate statistical associations. Generally, the t-tests used in these studies are

Stepwise discriminant analysis is important in my case study analysis because it establishes how accurately and in what order independent variables, such as climate, reclassify nominative groups, such as famine versus non-famine years (Siegel, 1956; Keeping, 1962; Brommer et al., 2003). This is useful in determining which in a set of independent variables may have the most relevance to dependent variables such as famine. When evaluating the famine-climate relationship in Britain, the aggregated climate methodology did not yield significant results; as a result I applied stepwise discriminate analysis.

Dissertation Framework

Given that I am examining the statistical relationship between climate teleconnections and the occurrence of famine, the chapters that follow contain regional case studies for three regions of the world with well-established influences from climate teleconnections and well-documented famine records. In addition to quality climate data, in order to evaluate the environmental impact on famine, I also need good long-term famine records. Therefore I chose three geographic regions with known relationships to regional or global climate variations, and ample famine records to establish a comprehensive list of famine events for that area. These case studies examining the climate famine relationship include Egypt, Britain, and India.

Chapter 2 consists of a research paper that focuses on Egyptian famine. In this paper, I explicitly examine the aggregate affect of the NAO, PDO and SOI climate teleconnections on famine occurrence in Egypt, and the relationship between the Nile River flood failure and the occurrence of famine. A version of this paper was published in the journal *Holocene* on January 16 2015 (872-879) DOI:10.1177/0959683614567880. The authors for this article were Michael Santoro, Fekri A Hassan, MM Abdel Wahab, Randall S Cerveny, and Robert C Balling Jr.

Chapter 3 contains a research paper that investigates the effects of the NAO, AMO, SOI and PDO climate teleconnections on the occurrence of historic British famines over the period AD 1049-1914. In particular the famines included in this study are specifically attributed in the historical texts to weather and climate. The authors for this study were Michael Santoro, Randall S Cerveny, and Robert C Balling Jr. It is to be submitted to the journal *Progress in Physical Geography*.

Chapter 4 discusses the aggregated effect of the NAO, PDO and SOI climate teleconnections on famine occurrence in India over the time period AD 1049 to 1955. This study also addresses the separate influence of a regional climate influence, the South Asian Summer Monsoon. This is a solo authored article to be submitted to the Journal *Annals of the American Association of Geographers*.

Chapter 5 concludes this dissertation. In that chapter, I briefly review my fundamental research question and resultant hypothesis and address the specific findings of each of these three research investigations. I then determine based on these investigations whether or not my hypothesis regarding the influence of climate on famine can be supported. I discuss the areas with potential for further research. Finally, I detail the overall significance of my research on climate and famines.

CHAPTER 2

CLIMATE TELECONNECTIONS, NILE RIVER LEVELS, AND EGYPTIAN FAMINE

This chapter records our investigation of the combined teleconnective influence of the North Atlantic Oscillation, El Niño Southern Oscillation, and Pacific Decadal Oscillation on the Nile River and Famine patterns of Egypt from AD 1049-1921. A version of this chapter titled: *An aggregated climate teleconnection index linked to historical Egyptian famines of the last thousand years* was published in the Journal *Holocene* in January of 2015 doi: 10.1177/0959683614567880. Co-authors include Fekri Hassan, M.M. Abdel Wahab, Randall S. Cerveny, and Robert C. Balling Jr.

Abstract

Variations in the Nile River water level have been historically associated with social development of the Egyptian civilization, particularly through times of famine. In addition, the Nile River water levels have been strongly linked to variations in climate teleconnections, specifically El Niño/Southern Oscillation, the North Atlantic Oscillation and the Pacific Decadal Oscillation. In this paper, we demonstrate that the cumulative effects of these three teleconnections link strongly to the occurrence of famine in Egypt. To create a cumulative response, we employed a principal component analysis (PCA) of the reconstructions of these three climate teleconnections that yielded a composite accounting for sixty-one percent of the total variance in the three datasets. We compared

that analysis to a new compilation of drought and famine in Egypt. Analysis reveals eight of ten major famines in Egypt over the last thousand years correspond to low points or downward movements in a detrended composite eigenvector of the three major climate teleconnections discussed. This SOI-NAO eigenvector has a statistically significant discrimination between the occurrence of famine and non-occurrence of famine ($t = 2.56$; $p = 0.013$). Additionally, the composite climate eigenvector correctly identifies fifty out of eighty events (63 percent) of lesser incident years mentioned in other Arabic texts. While this climate composite teleconnection analysis alone does not explain all famine events in Egypt over the last thousand years, the relative strength of linkage suggests that potential exists to account for even older (e.g., Egyptian Empire) famines as climate reconstructions extending further back n time become available.

Introduction

The Nile River and its flood patterns have had a profound impact on the culture and civilization of northeast Africa (Diaz and Markgraf 1992, Kondrashov et al. 2005, and Hassan 2007a). In particular, the variability of the Nile River has historically been linked to times of prosperity and famine in Egypt. Accounts of famine-based behavior graphically chronicled how closely historical life and death were linked to environmental changes. For example, in an account by Al Baghdadi (1204) in the famine of 1200-1203 AD conditions had deteriorated to an extent that led to cannibalism. Addressing the environmental processes that contribute to famine events aids our understanding of how future climate variations may affect society. Determination of the causal impacts of climate on globally important historical regions can provide valuable information on past

societal impacts. In particular the link between the Nile River and well-known teleconnective climate phenomena such as El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and the North Atlantic Oscillation (NAO) may provide a means of assessing an aspect of the interrelationships between climate and civilization. This study describes these relationships and demonstrates that these teleconnective climate forces have had a direct impact on the historical reoccurrence of Egyptian drought and famine through the use of a new compilation of documented drought and famine records.

Study Area and Data

Nile River Levels

The building of the Aswan Dam reduced the unpredictability of the lower Nile River levels today. Despite the Aswan High Dam the Upper Nile River system still experiences major variations in discharge from year to year (El Din 1977). Some of the Upper Nile River discharge variations are linked to distinct climatic teleconnection locations. Teleconnections such as ENSO, NAO and PDO have been identified as having distinct impacts on Nile River levels (e.g., Bliss 1926, Eltahir 1996, Amarasekera et al. 1997, Kahn et al. 2006, Hassan 2007a, Taye Willems 2011).

Due to the importance of Nile River levels to the Egyptian society, specific heights of the river were historically recorded using devices known as Nilometers. There are several noncontiguous records from Nilometers dating back to 622 AD (Christian Era) (Kondrashov et al. 2005). Several reconstructions of river levels using these historical Nile River or other proxy data have been attempted (Kondrashov et al. 2005,

Hassan 2007a, Wils et al. 2010). The most complete reconstruction to date was compiled using Nile River level data from Rawdah Island, located on the Nile River in central Cairo (Kondrashov et al. 2005). However, due to gaps in the data Kondrashov et al. (2005) have applied advanced spectral analysis methods such as Singular-Spectrum Analysis (SSA) and the Multi-Taper Method (MTM) to fill the gaps and to locate interannual and interdecadal periodicities (Thompson 1982 and Kondrashov et al. 2005). Such methods have yielded a continuous reconstructed record of Nile River levels between the years of 622-1921 AD.

Famine Data

There is an extensive history of famine occurrence in Egypt as early as 2200-2150 BCE associated with the fall of the Old Kingdom in Egypt (Hassan 2007b). Specifically, a long history of famine in the Nile River Valley exists with documentation of specific episodes. Since 1049 AD these occurrences include famines in 1064-1072, 1097, 1200-1202, 1218, 1263-1064, 1372-1373, 1403, 1641, 1792 and 1877 (all dates in AD, with reference from Al Latif Al Baghdadi 1204, Samy 1915, Zakry 1926, Keys et al. 1950, Nash 1976, Hassan 2007a). It is desirable to evaluate climate's influence on the entire famine history of Egypt; however the climate teleconnection reconstructions are limiting at this time, in particular the NAO reconstruction extends only to 1049 AD.

Climate Data

Many different interannual climate teleconnective phenomena impact the weather in areas far beyond their specific location. In particular, a variety of atmospheric

teleconnections are suggested as exerting influences on the watershed associated with the Nile River. One of the earliest studies of ENSO (Bliss 1926) connected variations in the Nile River levels with perturbations of ENSO; the Nile River region is listed as one of the ten geophysical variables that relate to the Southern Oscillation (Eltahir 1996); the Nile River ENSO relationship is one of the oldest and most well-established teleconnective impacts on nature (Diaz and Markgraf 1992).

El Niño / Southern Oscillation (ENSO)

Research of the past few decades has indicated that sea surface temperatures (SST) in the central Pacific ocean can explain 25-40 percent of the variance of Nile River discharge (Eltahir 1996, Amarasekera et al. 1997, Kahn et al. 2006). When the Southern Oscillation Index (SOI) is in the negative phase, it creates changes in global circulation that limit moisture import over the eastern African continent (Seleshi and Demaree 1995) such that higher pressure exists over the Ethiopian and Eritrean highlands, thereby reducing convection and reducing precipitation (Viste and Sorteberg 2013). Since the highlands are the major watershed of the Blue Nile, which contributes a large amount of the Nile's total water flow (Seleshi and Demaree 1995), the entire lower Nile River system is affected by the SOI.

More recently, researchers have examined the Nile/ENSO relationship using a cumulative index of both El Niño and Southern Oscillation (Jury et al. 2002) such that a value of -7 or lower indicates a strong El Niño event and a value of +7 greater indicates a strong La Niña event. Using the Jury et al. (2002) index, a significant relationship

between strong El Niño events and reduced rainfall on the Blue Nile watershed exists at the 90 percent confidence level (Abtew et al. 2009).

We represent the ENSO teleconnection through the use of the Southern Oscillation Index (SOI) based on the alternating variations in atmospheric pressure between the central and western Pacific Ocean. Specifically, the SOI is defined as the sea level pressure difference between Tahiti and Darwin, Australia (Trenbreth 1997). The SOI serves as an indicator of the phase of ENSO with the negative SOI values associated with El Niño (Diaz and Markgraf 2000, Yan et al. 2011).

For this study of historical variations in the Nile River, SOI values extending back over a thousand years were needed. Therefore, we employed reconstructed SOI values using reconstructed Pacific Ocean precipitation levels as a proxy (Yan et al. 2011). A strong and persistent correlation between SOI and precipitation has led researchers to construct a SOI index based on the difference in rainfall between the tropical western Pacific and the equatorial eastern Pacific (Yan et al. 2011).

North Atlantic Oscillation (NAO)

Additionally, other teleconnections have been associated with Nile River levels. In particular, the North Atlantic Oscillation (NAO)—variations in the pressure patterns between Iceland and the Azores (van Loon and Rogers 1978, Lamb and Peppler 1987, Trouet et al. 2009)—has been examined as an influencing factor upon the Nile River. A link exists between the NAO and rainfall in the Nile River watershed, and a direct link between Nile River discharge and Atlantic sea surface temperatures (SST) (Hassan 2007a).

This relationship, however, has not remained constant over the period of reconstructed Nile River levels. Climate reconstructions of the NAO based on oxygen isotopes at Rana, Norway (Baker et al. 2002) and diatom transformations at Voring, Norway (Jansen and Koc 2000) show an inverse relationship between Atlantic SSTs and Nile flood frequency during the early medieval period. The relationship between Atlantic SSTs and flood frequency becomes positive after the year 1000 AD. The apparent oscillatory pattern of the relationship between the NAO and North Atlantic SST is aperiodic over the time period 800-1800 AD. This relationship between North Atlantic SSTs and the NAO is strongly reinforced by proxy speleothem records in the North Atlantic SSTs in the southwest of Scotland (Proctor et al. 2000). The coherence of the relationship between proxy and the Nile flood record is significant, and reflects the oscillatory relationship shown in the Norwegian proxy records (Hassan 2007a).

The NAO is the main synoptic mode of atmospheric circulation in the North Atlantic Ocean and is recognized as the air pressure difference between Iceland and the Azores (Walker and Bliss 1932, Lamb and Pepper 1987, Jones et al. 1997, Trouet et al. 2009). The positive phase of the NAO is associated with higher than usual pressure in the subtropics and lower than normal pressure in the arctic. This results in warm dry winters in southern Europe and wet conditions in northern Europe. The negative phase of the NAO creates opposite conditions over Europe. There is a weak, but positive, correlation between the NAO and precipitation in the Nile River Delta region (Brandimarte et al. 2011). Long-term studies of the Nile River have associated cold conditions in Europe with low Nile River levels throughout the Holocene (Hassan 1981).

As with the reconstructed SOI index, for this study, we required a reconstructed NAO index that extends back for over a thousand years. We employed a NAO reconstruction that was developed from a tree ring drought reconstruction of Morocco and a speleothem-based precipitation proxy from Scotland (Trouet et al. 2009).

Pacific Decadal Oscillation (PDO)

Beyond the NAO's influence on the Nile River, the PDO—long-term variations in North Pacific SST (Taye and Willems 2011)—is also suggested as an influencing factor on Nile River water levels. In particular, a negative correlation exists between PDO, rainfall and flow extremes on the Blue Nile River basin (Taye and Willems 2011). This relationship is reflective of the statistically significant inverse relationship between the PDO and Blue Nile River's rainfall extremes and flow extremes during the June through September dry season (Taye and Willems 2011).

The PDO is a long-term pattern of SST anomalies and atmospheric circulation in the North Pacific. The PDO index is derived from an empirical orthogonal functions analysis (EOF) of SSTs (MacDonald and Case 2005). The positive phase of the PDO is typified by warm SSTs in the northeastern Pacific, whereas cool SSTs are indicative of the negative phase of the PDO (Mantua and Hare 2002, MacDonald and Case 2005). Previous research has noted that the positive phase of the PDO exerts strong climatic influence on precipitation over the Nile River basin (Jury 2009).

The reconstructed PDO dataset is derived using tree ring chronologies from southern California and western Canada. The PDO chronology was calibrated using the

1940-1998 PDO index as a baseline. Reconstructions based on multiple regression analyses of the annual PDO extend from 933-1996 AD (MacDonald and Case 2005).

Methods

Consequent to the available research connecting worldwide climate teleconnections to the climatology of the Nile River, we have selected these three teleconnections, the El Niño -Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), and the Pacific Decadal Oscillation (PDO), to determine if their combined variances might more accurately represent variations in Nile River water levels and, therefore, on famine occurrence in Egypt. While each teleconnection has a complicated and independent relationship with Nile River discharge, their composite relationship has not been previously investigated.

Shared Variances of Teleconnections

Past research indicates that all three major climatic teleconnections have been linked to Nile River variability. Specifically, a significant relationship exists between strong El Niño events and reduced rainfall on the Blue Nile watershed (Abtew et al. 2009). Additionally, a weak but positive correlation between the NAO and precipitation exists in the Nile River Delta region (Brandimarte et al. 2011). Finally, previous research has also demonstrated a relationship between the positive phase of the PDO and precipitation over the Nile River basin (Jury 2009).

While each teleconnection may contribute to Nile River variability, the cumulative or aggregated influence of these three major teleconnections (SOI, NAO and

PDO) with the Nile River has not been addressed. Consequently, we developed a composite teleconnection index that represents the shared variance among the three teleconnections in order to compare the cumulative effect of these teleconnections on the Nile River Basin.

The first step of this project was to extract the shared variance between the three reconstructed teleconnective time series (SOI, NAO and PDO). To that end, we conducted an un-rotated Principal Component Analysis (PCA) on the three reconstructed teleconnection datasets (Jackson 1991) from 1049-1922 AD. Analysis revealed that while the PDO data were normally distributed, the NAO and SOI data displayed slight variations from a normal distribution. However, normality or non-normality of the data does not impact PCA (Rummel 1970).

The first eigenvector demonstrated an inverse relationship with NAO ($r = -0.867$) and positive correlations with SOI ($r = 0.865$) and PDO ($r = 0.581$). The first eigenvector accounted for 61.3 percent of the total variance in the three datasets. The loadings on this eigenvector are strongly NAO and SOI; therefore we will call this the NAO-SOI factor. It is speculated in previous research that the NAO and the SOI have a combined impact on the climatology of the Nile River watershed (Toker et al. 2012).

The second eigenvector is heavily PDO related and demonstrated an inverse relationship with NAO ($r = -0.269$) and positive correlations with SOI ($r = 0.277$) and PDO ($r = 0.814$). The second eigenvector was of less significance explaining 27.1 percent of the total variance of the three datasets and the remaining eigenvectors significantly less. Consequently, we focus our attention on the first eigenvector as representative of the aggregated effects of the SOI/PDO/NAO indices.

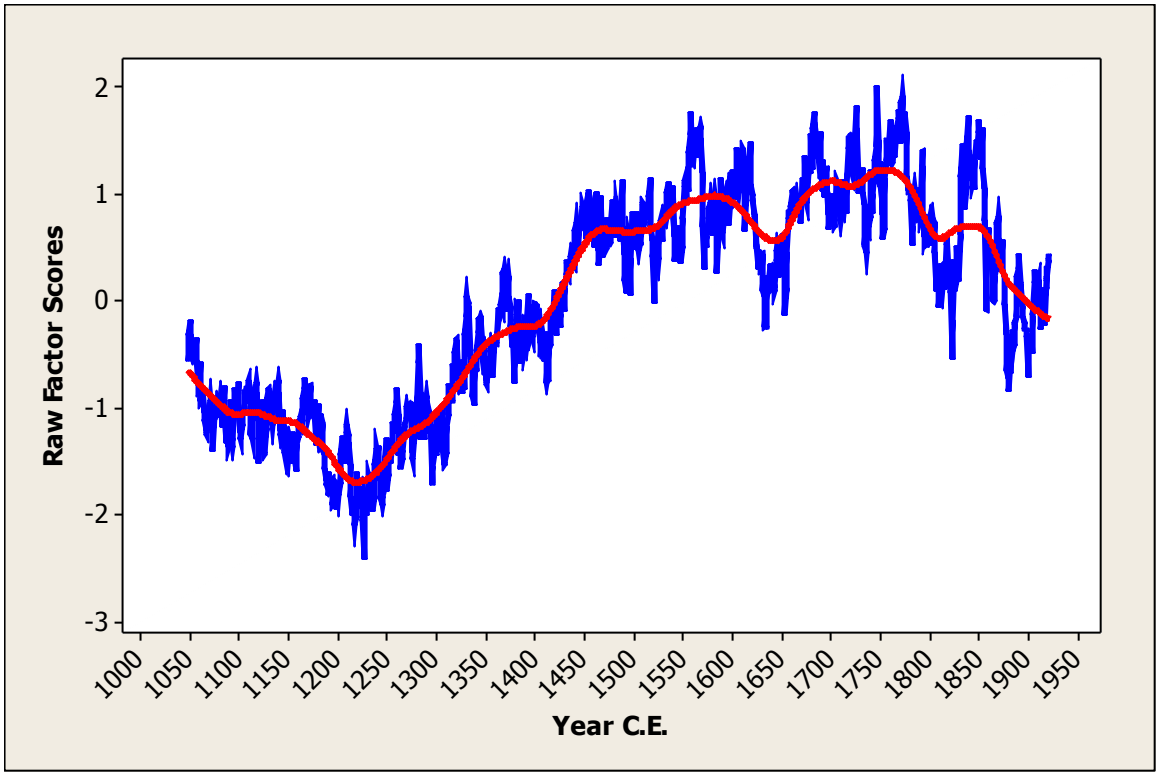


Figure 2.1. Raw factor scores (in blue) associated with the NAO-SOI eigenvector of the three climate teleconnections (SOI, NAO and PDO) with smoothed fit line (produced by a locally weighted scatterplot smoothing algorithm) in red. Years are expressed in (AD)

Since the year-to-year variability of the NAO-SOI eigenvector is highly variable, in order to make a more visually clear time series we employed a LOWESS (locally weighted scatter plot smoothing) algorithm (Cleveland and Devlin 1988). For each data point, the statistical algorithm performs a weighted linear regression, giving the greatest weight in the smoothing to points closest to each x-value and limiting the influence of outliers. A smoothed fit line of the NAO-SOI eigenvector indicates ten minima in the factor scores of the NAO-SOI eigenvector (Figure 2.1 and 2.2).

The plotted factor scores associated with the NAO-SOI eigenvector display a marked long-term positive trend over the last 1000 years (Figure 2.1). As this long-term trend potentially obscures identification of individual Egyptian famine periods embedded

in the data, we extracted this long-term variability from the factor scores of the NAO-SOI eigenvector using a third-order polynomial regression analysis. A smoothed fit line of the residuals from the regression analysis indicates ten distinct minima in the factor scores of the NAO-SOI eigenvector (Figure 2).

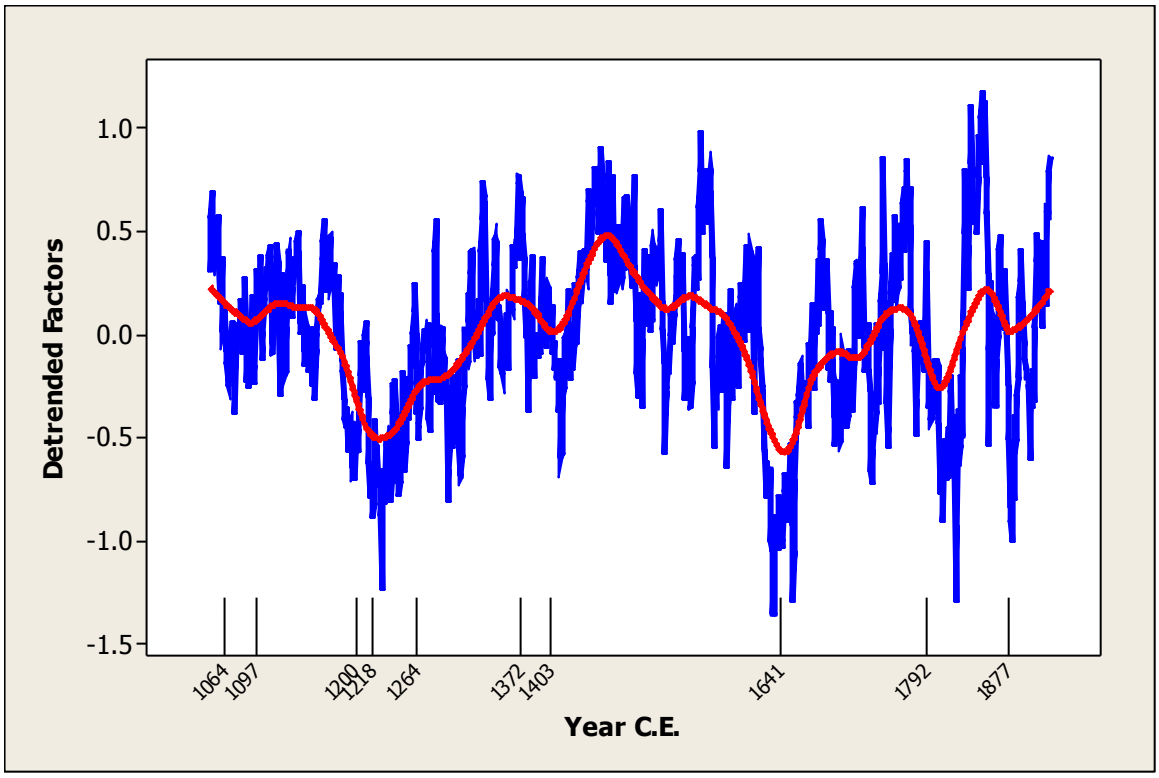


Figure 2.2. Detrended (third-order polynomial regression analysis) factor scores associated with the NAO-SOI eigenvector of the three climate teleconnections (SOI, NAO and PDO) with smoothed fit line (produced by a locally weighted scatterplot smoothing algorithm) in red with specific dates of recorded historical famine years labeled on x-axis. Years are in (AD)

The centennial scale trend apparent in the raw factor scores (Figure 2.1) may hinder the ability to see other decadal scale trends but is a feature that should not to be completely ignored. The lowest raw factor scores occurred between 1200 and 1225 AD. This is concurrent with the 1200-1202 AD and the 1218 AD famine. It is also concurrent

with the transition between the Medieval Climate Anomaly (MCA) and the Little Ice Age (LIA) (Esper et al. 2002). A substantial shift in the effects of the NAO as seen in proxy records in Scotland and Morocco also occurred during this transition (Trouet et al. 2009). It may be of interest in the future to analyze the effects of the MCA-LIA transition on the Nile River basin.

Although the direct linear correlation between the NAO-SOI eigenvector and the reconstructed Nile River levels is not significant at the 90 percent confidence level, the extremes (times of highest and lowest water levels) of the reconstructed Nile River are well-identified by the NAO-SOI eigenvector. Specifically, when the reconstructed Nile River values are classified into two classes, i.e., "high," river values as higher than one standard deviation of the mean (n = 116 out of 873 years) and "low," river values as lower than one standard deviation from the mean (n = 94 out of 873 years), the NAO-SOI eigenvector significantly discriminated between those two classes at the 99.9 percent confidence level ($t = 4.87$; $p = 0.0001$).

As a corollary independent test, we conducted a complementary statistical analysis such that we divided the aggregated teleconnection index into two extremes, i.e., "high," yearly index values higher than one standard deviation of the mean (n = 131 out of 873 years) and "low," yearly index values lower than one standard deviation from the mean (n = 136 out of 873 years). Lower reconstructed river levels were linked with the low extreme class of the aggregated teleconnective index at the 99.9 confidence level ($t = 4.52$; $p = 0.0001$). Significant results achieved by both analyses would indicate more robust confidence (Balling and Cerveny 1996) in the potential relationship between the aggregated teleconnective index and the reconstructed Nile River. Consequently, these

two statistical tests indicate that the aggregated teleconnective index does significantly distinguish high water and low water extremes of the Nile River levels. Since we have shown that Nile River extremes—particularly low extremes—are associated with occurrence of regional famine, a direct comparison of the NAO-SOI eigenvector and famine occurrence in Egypt without the intermediary of the Nile River water levels may prove enlightening. It should be noted that we did attempt to investigate these relationships against modern meteorological data. Unfortunately secular meteorological datasets for the study area over the last century are fragmentary and a comprehensive analysis using monthly data was not possible. As high-quality climate reanalysis data becomes available for this region, this analysis can hopefully be attempted.

Climate Teleconnection Composite and Famines

Historically notable droughts and famine in Egypt have been documented; since 1049 AD these occurrences include the famines of 1064-1072, 1097, 1200-1202, 1218, 1263-1264, 1372-1373, 1403, 1641, 1792 and 1877 (all dates in AD, with reference from Al Latif Al Baghdadi 1204, Samy 1915, Zakry 1926, Keys et al. 1950, Nash, 1976, Hassan 2007a).

When the dates of the NAO-SOI eigenvector's factor score minima are compared to the dates of historical famines occurring since 1049 AD, a close visual similarity between dates of the NAO-SOI eigenvector factor score minima and dates of famine occurrence in Egypt is evident (Figure 2.2). This suggests that the NAO-SOI eigenvector composite does a good job identifying individual famine dates from decadal-scale variability in the factor scores.

Eight of the ten famines correspond to low points or downward trends in this detrended NAO-SOI eigenvector. In addition to the strong relationship between Egyptian famines and Nile River levels (discussed above), it appears that the detrended climate composite is also a good predictor of famine in Egypt.

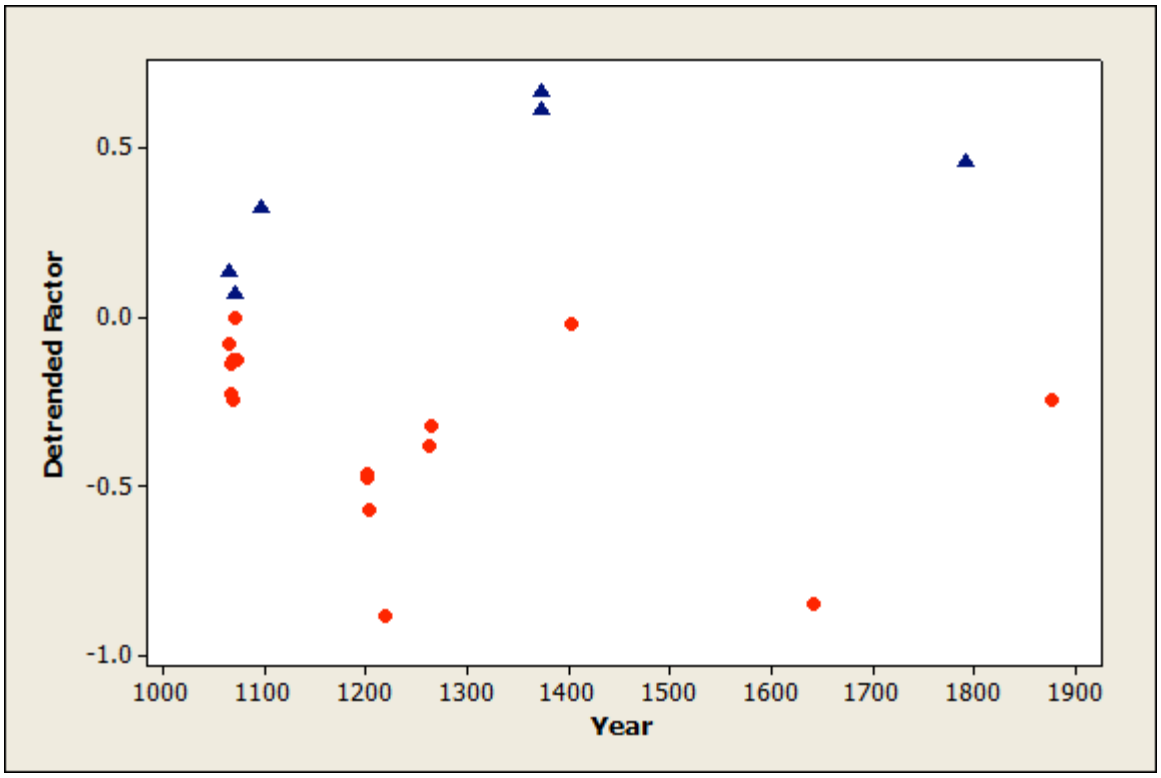


Figure 2.3. Individual years of famine and their detrended factor scores. This includes all years of famine so while there were 10 famines included in this study there were a total of 22 years in which famine was occurring because some of the famines extended beyond one year. Included here are each of the factor scores positive factor scores are depicted as blue triangles and negative factor scores are depicted as red dots.

To assess the statistical validity of this visual relationship, we conducted a set of Student's t-tests on the detrended residuals. The first t-test separated only the listed famine years into one group "famine years" and all others into another group "non-famine years". The detrended factor scores of the individual famine years can be seen in

Figure 2.3. This classification resulted in a weak statistical distinction with a t-value 1.51 (p = 0.146). However separating the five years before each famine into the "famine years" group and all other years into the "non famine years" group captured cumulative effects of climate that may lead to famine conditions. The resultant t-value 2.57 (p = 0.012) shows that there is a significant statistical difference in the factor scores of the cumulative teleconnection composite associated with Egyptian famine years as opposed to non-famine years. Further t-tests incorporating the ten and fifteen years preceding a famine into the "famine years" group yielded similar results with t-values of 3.33 (p = 0.001) and 3.84 (p = 0.000) respectively. This indicates that the aggregated climate teleconnection index not only captures the occurrence of famine events over the last thousand years of Egyptian records, but also indicates that there may be a decadal-scale effect on climate that can lead up to and contribute to severe famine.

Many of the times of extremely low river levels are associated with the worst famines (Table 2.1). However, Nile-linked climate change does not appear to be the sole cause in some famines. Specifically, three of the ten identified famines, the famines of 1264, 1792, and 1877 AD, occurred on years with Nile River floods within one standard deviation of the mean and the 1097 AD famine occurred during an above average flood.

In addition to the well-documented severe famines listed above, numerous instances of stress to the ancient Egyptian population have been recorded due to poor or short Nile River floods (Samy 1915 and Zakry 1926*)*. These sources, in Arabic, contain detailed information about famine, drought, and other times of economic or social stress in the Nile River valley; they have previously been unavailable to most western sources.

Table 2.1. Dates of Egyptian Famines, Nile River flood maximum, listed date and flood level are of the lowest flood if the famine extended beyond one year, and literary reference information for famine occurrence. Dates are given in (AD) with the Islamic year or Anno Hegirae (AH) in brackets.

Famine Date [AH]	Nile River Flood Maximum: given in Centimeters and year of lowest flood for multiple year famines	Literary Reference for Event
1064-1072 [456-465]	792 (1066)	*(Zakry 1926), (Samy 1915), (Keys et al., 1950) and (Nash 1976)*
1096-1097 [489-490]	725 (1096)	*(Zakry 1926) and (Nash, 1976)*
1200-1202 [596-599]	687 (1200)	*(Al Latif Al Baghdad 1204), (Zakry 1926), (Samy 1915), (Keys et al., 1950), (Nash 1976), and (Hassan 2007a)*
1218 [615]	845	*(Nash 1976)*
1263-1264 [661-662]	900	*(Zakry 1926) and (Nash, 1976)*
1372-1373 [772-775]	931 (1372) 447 (1373)	*(Samy 1915) and (Hassan 2007)*
1403 [806]	856	*(Hassan 2007a)*
1641 [1051]	703	*(Zakry 1926)*
1792 [1207]	869	*(Zakry 1926) and (Nash 1976)*
1877 [1294]	896	*(Samy 1915), (Zakry 1926), (Nash 1976)*

Famines mentioned within the Samy (1915) and Zakry (1926) texts can be categorized as years of: (a) low flood where prices increased, (b) low flood not noted by historians, (c) short flood where prices increased, (d) drought, increasing prices, and death due to very low flood, (e) years of marginally shortened flood, (f) severe decline of flood, (g) late flood, and (h) when the Nile River was scarce. Within these categories, there were eighty recorded years, several of which are referenced above (1064-1072, 1200, 1372-1373, 1403, 1877; all dates AD).

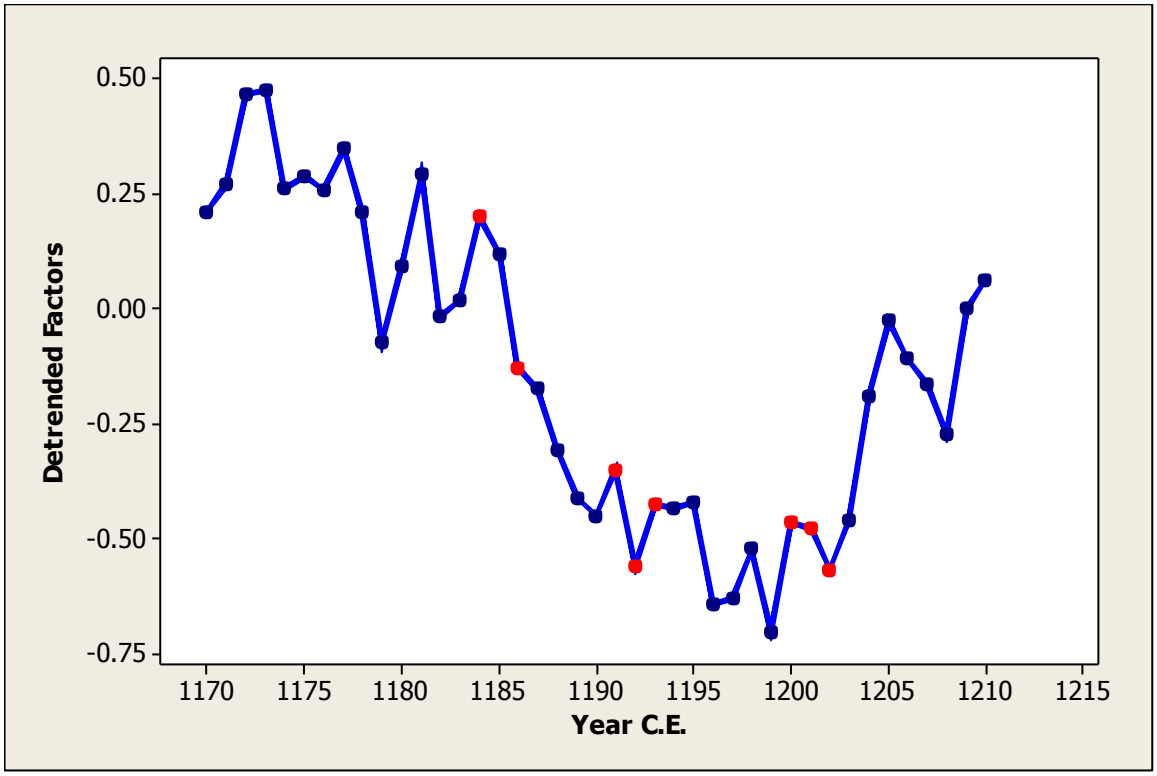


Figure 2.4. Detailed section of the detrended (third-order polynomial regression analysis) factor scores associated with the NAO-SOI eigenvector of the three climate teleconnections (SOI, NAO and PDO) for the years 1170-1210 AD Individual years are in blue and the connect line is blue. There were years (in red) of increased prices and deaths due to shortages in the years 1184, 1186, 1191, 1192, and 1193 in the years leading up to the disastrous famine of 1200-1202. Years are given in (AD)

Of the eighty incident years, fifty events (63 percent) were associated with a general decline of the teleconnection composite index (Figure 2.4). Many of these minor disruptions are associated with, or leading to, more serious famine. For example, five of the fifteen years leading up to the disastrous famine of 1200-1202 AD were associated with increasing food prices or even deaths because of low Nile River levels. Additionally, these years saw dramatic decreases in the climate composite index (Figure 2.3). While many of these incidents were of relatively minor impact, this is a further indication of the strength of the teleconnection composite index's relationship with Nile River civilization. It appears that there is a decadal-scale buildup of the conditions combined with extreme low flood years of the Nile that contribute the incidence of severe famine.

Discussion

The statistical aggregation of three climate teleconnections, the SOI, NAO, and PDO with well-established connections to the Nile River has produced an eigenvector that explains over 60 percent of the shared variance and which is strongly influenced by variations in SOI and NAO. This eigenvector shows distinct centennial-scale trend near the MCA-LIA transition that may obscure finer-scale decadal trends in the data. Detrending of the long-term variability in this SOI-NAO eigenvector clearly shows these decadal-scale variations.

These variations are not strongly correlated to the Nile River annual flood variations as a whole, but rather are strongly correlated to the extremes, specifically the high and low extremes, associated with the Nile floods or failures. These decadal variations in the eigenvector are also strongly related to the incidence of famine. Eight of

ten major famines of the last millennia are associated with the decadal scale downward trends of the SOI-NAO eigenvector. Documentation of other near-famine events noted to Egyptian society also coincided with these downward trends with 50 events of the 80 supplemental events, or 63 percent, associated with a general decline of the teleconnection composite index. Fundamentally, the decadal-scale buildup of global conditions (e.g., NAO and SOI) combined with extreme low flow years of the Nile contribute to the incidence of severe famine.

Conclusions

This research has demonstrated a relationship between aggregated climate teleconnections and a new compilation of famines over the last millennium. The decadal-scale buildup of global conditions (e.g., NAO and SOI) combined with extreme low flow years of the Nile contribute to the incidence of severe famine. Beyond the analyses of famines over the last thousand years in Egypt, there are records of famines for thousands of years with some dating as early as 2200-2150 BCE associated with the fall of the Old Kingdom in Egypt; for example, texts by the ancient Egyptian Ipuwer describe a famine catastrophe (Hassan 2007b). However, at the present time, comprehensive reconstructions of climate teleconnections do not extend far enough back to allow detailed analysis of the global climate's impact onto time periods associated with ancient famines. The relative strength of the climate/famine linkage established in this analysis suggests the potential exists to address climate's impact on ancient (e.g., Old Kingdom) famines at a future time when climate teleconnection indices can be reconstructed into the distant past.

CHAPTER 3

CLIMATE ATTRIBUTED FAMINES OF THE BRITISH ISLES AND THE NORTH ATLANTIC OSCILLATION

This chapter investigates the influence of teleconnections including the of the North Atlantic Oscillation, El Niño Southern Oscillation, Pacific Decadal Oscillation, and the Atlantic Multidecadal Oscillation on the Famine patterns of the British Isles from AD 1029-1914. A version of this chapter titled: *Historic Famine in the British Isles as Influenced by Global Climate Teleconnections* is to be submitted to the journal *Progress in Physical Geography*. Co-Authors include Randall S. Cerveny and Robert C. Balling Jr.

Abstract

The occurrence of famine is the result of a complex set of societal and environmental factors with many famines attributed in part to certain 'climate shocks." Since AD 1049, sixty-two famines in the British Isles have been historically attributed to anomalous weather. The weather of the British Isles has been strongly linked to various climate teleconnections including the North Atlantic Oscillation (NAO), and the Atlantic Multi-Decadal Oscillation (AMO). We show that these weather-related famines are statistically related to the positive phase of reconstructed NAO and to AMO when compared to non-weather-related famines. The positive relationships of the NAO and the AMO to famine are stronger when compared to all other years, and include a significant negative relationship to the PDO (suggesting a joint interbasin Pacific-North Atlantic influence on historic famine in the British Isles. Utilizing these teleconnections through stepwise discriminant analysis can successfully classify 75.4% of weather-related famines in the British Isles from 1049 to 1914. Five-year lagged NAO demonstrates the strongest relationship to famine and indicates that the historical occurrence of weather-

related famines is most likely initiated during times of extended positive NAO. Ultimately, we show statistically that many—but not all—famines over the British Isles in the last millennia can be accurately classified by a set of global climate teleconnections. This research underlines the critical importance that climate often can play in influencing these horrific societal catastrophes of famine.

Introduction

Famine is a phenomenon that has affected human kind for thousands of years. Many civilizations have well-documented reoccurrence of famine, including that of Ancient Egypt (Hassan, 2007; O'Grada, 2009; Santoro et al., 2015), whose famines are chronicled in research and historical texts, such as the Bible. Similarly, North Africa (e.g., Keys et al., 1950; Hassan, 2007; Slavin, 2016), India (e.g., Keys et al., 1950; O'Grada, 2009; Slavin, 2016), China (e.g., Keys et al., 1950; O'Grada, 2009; Zhang et al., 2007; Zheng, 2014) and Europe (e.g., Keys et al., 1950; O'Grada, 2009; Engler, 2012; Slavin, 2016) have documented regular occurrence of famine over the course of human history. The historical famine patterns of the British Isles are particularly well documented over the past thousand years (e.g., Short, 1749; Walford, 1879; Lucas, 1930; Keys et al., 1950; Nash, 1976; Campbell, 2010; Engler, 2012; DeWitte, 2015; Engler et al., 2013; Slavin, 2016). In addition to the occurrence of these famines, the historical texts also include detailed political, social, and environmental conditions of the times leading up to the famine events.

For example, the Great Famine of, 1315-1317 is widely considered to be one of the deadliest famines in European history, killing millions (Walford, 1879; Lucas, 1930; Keys, 1950; Kershaw, 1973; Nash, 1976; O'Grada, 2009). This famine is thought to have

started with a "Climate Shock" (Slavin, 2016) associated with a particularly cold winter and spring of, 1315, which set into motion a series of causal events, both natural and human in origin (Kershaw, 1973; Slavin, 2016). Similarly, it was thought that the Irish Famine of, 1740-1741 was primarily initiated by the harsh weather of the, 1739-1740 winter (Luterbacher et al., 2004; Xoplaki, 2005; O'Grada, 2009; Engler et al., 2013). These historical accounts illustrate the need to understand the environmental as well as cultural impact of famine on society throughout history, particularly as environmental and climatic forces can affect famine patterns.

Prior to exploring the climatic influences on famine, it is crucial to define "famine." While famine and food shortage are often connected, famine implies a greater severity of societal effects; famine leads to excessive mortality, whereas a food shortage would not (Slavin, 2016). For example, Slavin, (2016) defines famine as: "*a condition of collective starvation occurring in years/periods of extreme and omnipresent deficiency of food resources, in relation to the sheer levels of population"* (p. 434) and food shortage as: "*localized and partial deficiency of food resources"* (p. 434).

Unfortunately, not all scholarly literature agrees on a precise definition—as Engler (2012) argues, a single unequivocal definition of famine has thus far eluded the scientific community. Existing scholarly definitions of famine do, however, include several common terms, separated into two causal schools of thought: environmental and human.

First, many scholars defining famine from an environmental viewpoint commonly use a terms referring to the natural scarcity of food supply or the non-availability of food. These are commonly referred to by the defining phrase Food Availability Decline (FAD)

(e.g., Sen, 1981; Sen, 1981a; Wolde-Mariam, 1984; Ellman, 2000; Moon, 2009; Slavin, 2016). Additionally, "the scarcity of food supply" is commonly defined either by availability or distribution of food (e.g., Sen, 1981; Ellman, 2000; Engler, 2012; Slavin, 2016). The non-availability of food, or FAD, occurs simply when the needs of the local or regional population exceeds food availability (e.g., Sen, 1981; Ellman, 2000; Engler, 2012; Slavin, 2016). These terms represent a supply side theory that is not always considered sufficient to cause famine, but seek to identify potential natural drivers of famine (Engler, 2012; Slavin, 2016).

As one of those natural drivers, climate can lead to a variety of environmental disasters that lead to food shortages. Long-term deterioration of climate conditions (Kershaw, 1973) as well as short-term or even singular bad weather events can contribute to a further break down of environmental conditions (Fraser, 2007). These include crop and livestock loss due to frost, blight, infection and direct mortality. The food shortages weaken individual health and put populations at higher risk of starvation and infection. For example, the Black Death plague (1347-1351) which killed as many as half of London's population (DeWitte, 2012) was preceded by a weakening of the population in part from famine associated with cooler and rainier climates at the end of the Medieval Climate Anomaly. The end of the Medieval Climate Anomaly brought a rapid cooling at the beginning of the 13th century (DeWitte, 2015). The increase in famines coinciding with this cooling and excessive summer rainfall was blamed for crop failures due to mold and blight (Dark and Gent, 2001; Dawson et al., 2007; DeWitte, 2012). Severe winter conditions and late frosts are blamed for a severe famine in the 1140's (Short, 1749; Nash, 1950).

Furthermore, undesirable conditions lead to increased migration that leave people susceptible to new, otherwise unfamiliar pathogens. Many of these conditions are initially attributed to adverse climate conditions such as flooding, frost, increased humidity, or other climate variables (e.g., Galloway, 1986; Lenihan, 1997; Slavin, 2012; DeWitte and Slavin, 2013). Climate in conjunction with other social and demographic variables such as war, excessive taxation, and food distribution difficulties leaves people more vulnerable to excessive starvation and death which are aspects of famine (e.g., Lamb, 2002; Jordan, 1997; Briggs, 2005; Campbell, 2010; Slavin, 2012; DeWitte, 2015).

Second, scholars defining famine from a human causal viewpoint commonly use Food Entitlement Decline (FED) as a defining concept. This abstraction addresses famine causation from the perspective of human decisions and behavior (e.g. hoarding, diverting food supplies, social or political upheaval) that affect food distribution and supply (Nash, 1950; Sen, 1981; Slavin, 2016). FED is a reference to the ability of an individual to procure food using the rights and opportunities available to them (Sen, 1981; Ellman, 2000; Engler, 2012; Slavin, 2016).

It is tempting to view these as two separate and isolated schools of scholarly thought: a) those who believe that famine is merely a response to natural forces (FAD) and b) those who believe that people make decisions during times of scarcity that ultimately result in famine. A middle ground position argues that the juxtaposition of both environmental and human components create the conditions necessary for the occurrence of famine (Engler, 2012; Slavin, 2016). This theoretical construct that naturally-caused, vis-à-vis climate, food shortages, in conjunction with human interference of natural market forces, is a cause of famine is not a new one. For example,

Key (1950) documents over, 2,000 years of famine and defines the cause of famines as follows: “The primary cause of most famines has been simply crop failure engendered by unfavorable weather…but the resulting suffering has been determined in large measure by prevailing methods of distribution” (Key, 1950, p.1278). Although the occurrence of famine is a complex combination of natural and human factors, climate, through so-called “climate shocks” (Chen, 2015; Slavin, 2016) has been widely considered an important initial driver to most famines (e.g., Campbell, 2010; Engler, 2012; Engler et al., 2013; Dewitte, 2015; Toohey et al., 2016; Slavin, 2016).

This paper focuses on a potential major weather cause, or initial climate shock, across documented famines in the British Isles. The generator of climate shocks is proposed to be the interrelationship of known climatic oscillations. Specifically, this study will assess the occurrence of British Isles famines historically linked to weather the phase of two critical climatic oscillations: the North Atlantic Oscillation and the Atlantic Multi-Decadal Oscillation. We suggest that these climate shocks may contribute to the occurrence and severity of famine, but clearly famine is a complex phenomenon that involves many interrelated causes including climate.

Climate Teleconnections

Climate teleconnections, such as the well-known El Niño Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), the Pacific Decadal Oscillation (PDO) and the Atlantic Multi-Decadal Oscillation (AMO), are large-scale often multi-year oceanic and atmospheric variations in circulation that can affect weather and climate over large areas of the Earth (e.g., Walker and Bliss, 1932; van Loon and Rodgers, 1978;

Lamb and Peppler, 1987; Diaz and Markgraf, 1992; Jones et al., 1997; Trenbreth, 1997; Mantua and Hare, 2002; MacDonald and Case, 2005; Knight et al., 2006; Trouet et al., 2009). Climate teleconnections are known to have an influence on climate patterns around the world but are not to be thought of as proxies for weather patens but rather a contributing factor into the complex reasons why those weather patterns exist (Seager et al., 2003; Ramadan 2012).

Climate teleconnections may be connected to the climate shocks that are believed to contribute to the cause of famine (e.g., Fraser, 2007; Hassan, 2007; Sinha et al., 2007; Elagib, 2014; Shi et al., 2014), even in famines associated with wild animal populations (Wright et al., 1999). Climate teleconnections, including the PDO, ENSO, and the NAO, have been associated with weather variations and the occurrence of famine in places such as Egypt, Ethiopia, India, and China (e.g., Fraser, 2006; Hassan, 1981; Sinha et al., 2007; Elagib, 2014; Shi and Wilson, 2014; Santoro, 2015). The impact of climate teleconnections of society has included famine, but also large-scale population migrations and the collapse of the Roman Empire (Drake, 2017). Shifts from a strongly positive NAO to a weakly positive NAO is thought to have contributed to cooling and drying trends in northeastern Europe, the resulting food shortages led to as many as four different migration pulses from northeastern Europe to Roman territory between 113 BC and AD 600 (Drake, 2017). This implies that climate teleconnections such as the NAO can be drivers of societal events.

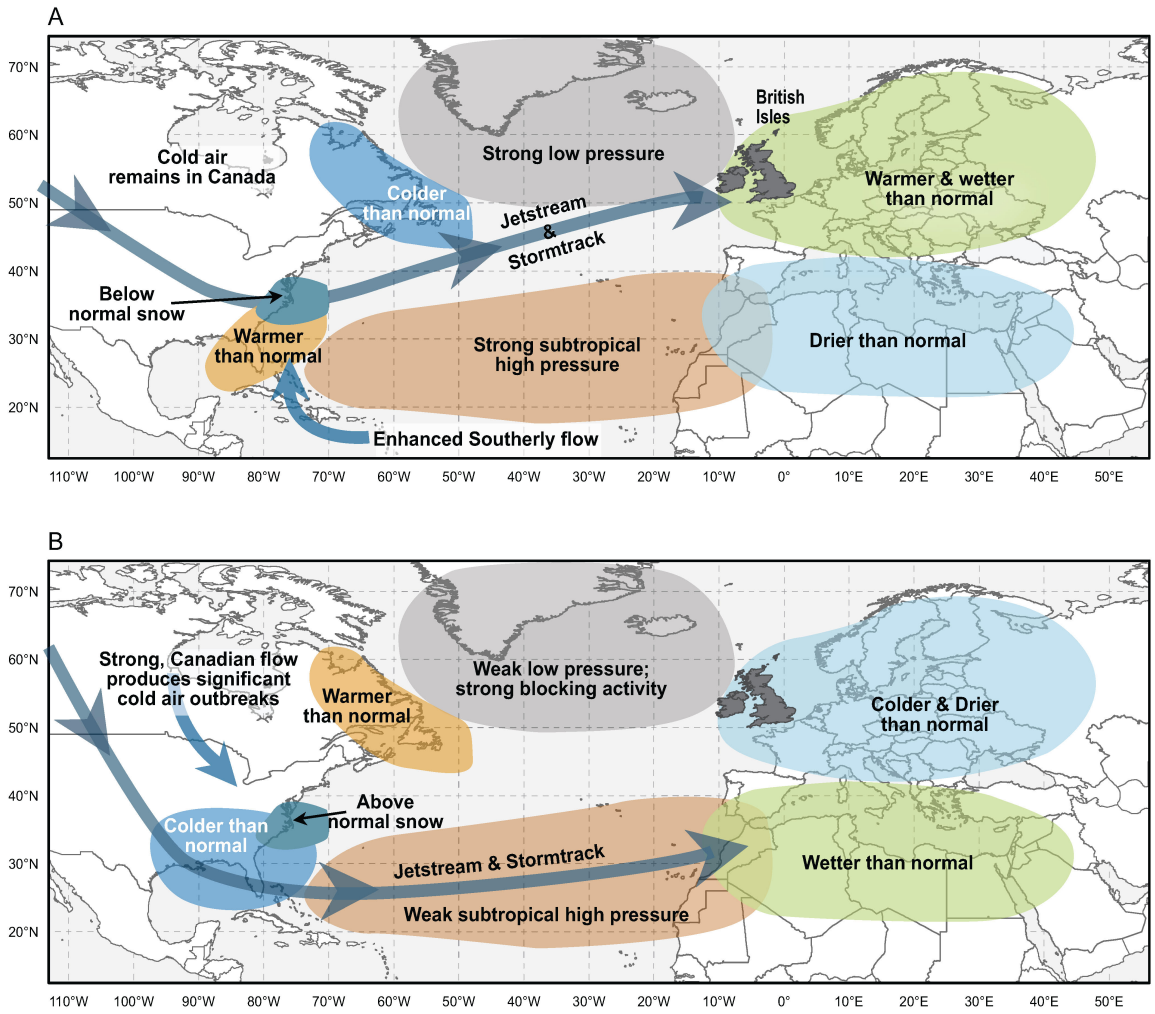


Figure 3.1. The atmospheric effects of the NAO (a) the positive phase of the NAO is associated with a stronger Icelandic Low and Azores High and a resultant strength of the westerlies carrying storm tracks towards the British Isles, (b) the negative phase of the NAO is associates with a weakened Icelandic Low and Azores High and a resultant weakening of the westerlies allowing storm tracks to trend towards southern Europe and the Mediterranean. Our study area, the British Isles, is shaded in dark grey.

North Atlantic Oscillation (NAO)

The NAO is a major interannual variation of atmospheric circulation in the North Atlantic Ocean that is often characterized by the air pressure difference between Iceland and the Azores (Jones et al., 1997; Lamb and Peppler, 1987; Trouet et al., 2009; Walker and Bliss, 1932). The positive phase of the NAO is associated with a well-developed

Azores High and a well-developed Icelandic Low, whereas the negative phase of the NAO is characterized as a weak Azores High and Icelandic Low (Wanner et al., 2001). (Figure 3.1) The result of a positive NAO is a well-developed westerly wind, which results in anomalously cool and dry winters in southern Europe and the Mediterranean and wet and warm conditions in northern Europe including the British Isles. The negative phase of the NAO weakens the westerlies and creates warm, wet winters in southern Europe and cool, dry conditions in northern Europe (Figure 3.1) (Jones et al., 1997; Wanner et al., 2001; Visbeck et al., 2001).

Atlantic Multidecadal Oscillation (AMO)

As opposed to the NAO, the AMO is a long-term (decadal) variation in climate best characterized by sea surface temperature variations across the Atlantic Ocean. It can have a noted effect on the climate over much of the Northern Hemisphere. The cause in variability in sea surface temperatures (SSTs) is thought to be the result of changes in strength of the thermohaline circulation (Grey et al., 2004; Knight et al., 2006). The AMO can be represented by an index based on SST anomalies of the Atlantic Basin. The AMO's known effects include summer rainfall in north Western Europe including the British Isles (Grey et al., 2004; Knight et al., 2006). A positive AMO Index is associated with a warm SSTs anomaly and is linked with decreased mean sea level pressure. This atmospheric circulation is related to increased rainfall over northwest Europe (Grey et al., 2004; Knight et al., 2006).

The Southern Oscillation (SO)

The SO is the accepted measure of a major interannual climate variation of the South Pacific atmosphere/ocean termed "El Niño Southern Oscillation" (ENSO). The Southern Oscillation Index (SOI) is characterized by sea level pressure differences between Tahiti and Darwin, Australia (Trenberth, 1997). The SOI serves as an indicator of the phase of ENSO with negative SOI values associated with El Niño, the warm water intrusion into the eastern South Pacific of warm equatorial waters (Diaz and Markgraf, 2000; Yan et al., 2011).

The Pacific Decadal Oscillation (PDO)

The PDO is a long-term (decadal) oscillation of SSTs and atmospheric circulation in the Northern Pacific Ocean. The positive phase of the PDO is identified by anomalously warm SSTs in the northeastern Pacific and negative PDO is identified by anomalously cool SSTs (MacDonald and Case, 2005; Mantua and Hare, 2002).

Study Area and Data

The geographic area for this study includes the extent of the British Isles: commonly known as the United Kingdom & Ireland (Figure 3.2). The temporal range of this study is AD 1049 to 1914. For data comparison, we employed the following: (a) three paleoclimatic reconstructions of the NAO and a reconstruction of the AMO known to have an established strong climatic impact on the British Isles (Lamb and Peppler, 1987; Knight et al., 2006), a reconstruction of ENSO (Yan et al., 2011), a reconstruction of the PDO (MacDonald and Case, 2005), and (b) an extensive historical record of

famines for the region (e.g. Short, 1759; Walford, 1879; Anonymous, 1930a; Anonymous, 1930b; Keys et al., 1950; Nash, 1976; Hallem, 1984; and Engler et al., 2103; Engler and Werner, 2015).

With regards to terminology, the temporal breadth of the available famine record for the British Isles extends before the formation of Great Britain. Consequently, in the historical record, there are terms used to describe this archipelago including the British Isles, Britain and Ireland, or increasingly the Atlantic Archipelago. For the purposes of this study, we will refer to the geographical area of these famines as the British Isles (Figure 3.2).

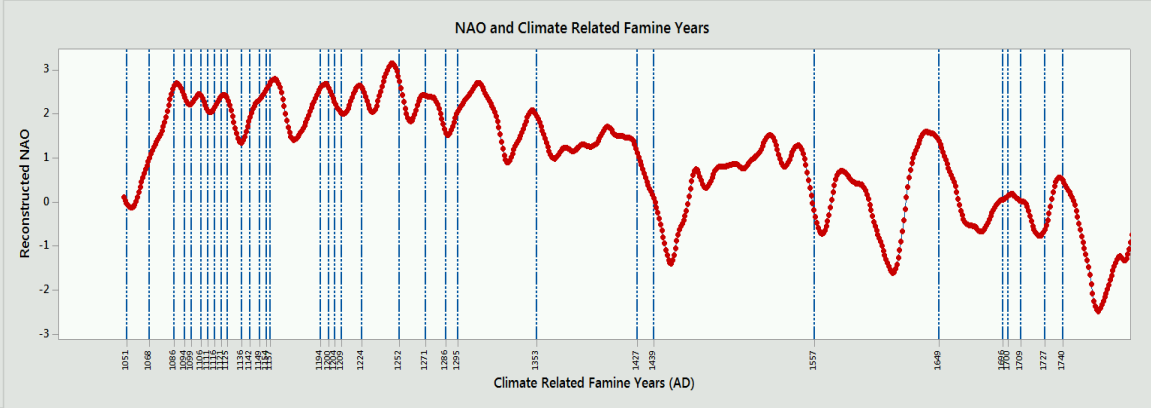


Figure 3.2. Time series showing the Trouet et al. (2009) NAO reconstruction (in red) with climate-related famines events indicated by the blue dotted lines. Note that famine events that spanned multiple years are indicated as a single event.

Famines

The chronology of famines used in this study is a compilation from many sources (Appendix A), but relies heavily on Keys (1950) and includes information from Short, 1759; Walford, 1879; Anonymous, 1930a; Anonymous, 1930b; Keys et al., 1950; Nash, 1976; Hallam, 1984; and Engler et al., 2013; Engler and Werner, 2015. In particular,

Key's (1950) *The Biology of Human Starvation* is a detailed exposition of the history and causes of human starvation; its compilation of worldwide famines incorporates eight major historical texts. This extensive list includes famines occurring globally, including occurrences within the British Isles. Keys' compilation is one of the most complete lists of famines available; however, since 1950 other sources have corroborated many of these events and identified additional famines (Appendix A). Reported climate conditions are compiled from original sources such as Short (1749) and Walford (1879), as well as contemporary general sources such as Nash (1976).

From AD 1049 to present there are at least 172 documented famines associated with the British Isles. The geographical extent and death toll of these famines vary greatly; some famines were fairly local with low mortality rates, were others lasted for many years across the region and lead to the death of tens of thousands. Many of these famines were directly attributed to specific causes including war, civil and political unrest, plague, crop failure and climate.

Sixty-two of these 172 documented famines were directly attributed to anomalous climate conditions during or leading up to the famine. The description of the famine's climate conditions would often be very simple, such as harsh winter, floods, summer heat, crop failure due to frost, or drought, some were attributed to a couple of climatic abnormalities, such as frost followed by flooding, hot dry summer. For example; the Irish famine of 1588 is listed in Keys (1950) as; "*Famine: Ireland, 2 years, cannibalism" (p. 1250)*, and in Nash (1976) as; "*Another famine which forced cannibalism" (p. 731)*. The 1739-1741 Irish famine is listed in Keys (1950) simply as; "*Ireland, 2 years*" (p. 1250), but in Nash (1976) as; *"Frost destroyed potato crop, price of wheat soared" (p732)*.

Engler et al. (2013) described the same famine as being caused by the "Great Frost" of 1740.

Recent study and modern famines are typically associated with semi-arid climates (e.g., Ethiopia, or India) and are therefore commonly associated with drought conditions (Slavin, 2016; Sinha et al., 2007; Elagib, 2014), however this is not the case with famine in the British Isles, where wet and cool conditions are more commonly associated with famine. These cool conditions were often described with respect to long cold winters or late frosts that may have damaged crops (Toohey et al., 2016; Slavin, 2016; Engler et al., 2013). Appendix A categorizes the famines used in this study, listing historical single word descriptors based on the accountings of weather conditions with each famine. Specific descriptors include: "cold" (16 events), "hot" (3 events) and "drought" (9 events), "hail" (1 event) and "wet," which was linked to "cold" (9 events) and to "hot" (3 events). This indicates that 46 of the 172 total famines were related to combinations of cold, and/or wet conditions and only 12 famines were attributed to combinations of heat and/or drought.

In addition to these 62 climate related famines, 110 famines were not attributed to climate causes. These famines were attributed in the historical record to occurrences such as "war," "civil unrest," "plague," "crop failure," or there was no reason specified. Famine documentation of the British Isles extends much further than those included in this study and it would be desirable to evaluate this further history of famine, but this study is constrained by the extent of the NAO and AMO reconstructions that extend to AD 1049 and AD 1572 respectively. The entire chronology of famines used in this study is given in Appendix A.

North Atlantic Oscillation reconstruction

We employ the commonly used and longest annual NAO reconstruction (Trouet et al., 2009). Additional analysis included two recent (Faust et al., 2016; Ortega et al., 2015) NAO reconstructions. First, we used a commonly accepted proxy-based reconstruction that was developed from a tree ring drought reconstruction of Morocco and a speleothem-based precipitation proxy from Scotland and extends from AD 1049 through AD 1995 (Trouet et al., 2009). The Scotland speleothem record is a reconstruction of winter precipitation and the Morocco tree ring record is a reconstruction of the Palmer Drought Severity Index (Trouet et al, 2009). This reconstruction is significant for its length and its identification of persistent positive NAO during the Medieval Climate Anomaly (MCA) (Trouet et al, 2009). Consequently, the Trouet et al. (2009) reconstruction has been a widely used proxy record (e.g. Holmes et al., 2016; Styllas et al., 2016).

However recent reconstruction analysis (Ortega et al., 2015) has been critical of the Trouet et al (2009) persistent positive NAO results during the MCA. To compensate for this potential bias, the Ortega et al. (2015) approach was to create an ensemble of 48 existing NAO reconstructions employing a Principal Component Regression process. Ortega et al. (2015) argue that the ensemble is a better reflection of historical NAO values. This ensemble reconstruction extends from AD 1049-1969.

Additionally, a recent NAO reconstruction (Faust et al., 2016) suggests that Norwegian sediment variations represent temperature and precipitation patterns that are good proxies for the NAO. This climate reconstruction extends 834 BC-AD 1914. Therefore, we have elected to compare the famine record to variations in these three

reconstructions (Trouet et al., 2009; Ortega et al., 2015; and Faust et al., 2016) constrained to the years AD 1049-1914. These datasets are designated as NAO1 (Trouet et al., 2009), NAO2 (Ortega et al., 2015), and NAO_3 (Faust et al., 2016) in the statistical analyses. Because of potential lag-effects between climate teleconnections and famine, we have created a second set of NAO reconstructions with a five-year and 10-year lag for comparison to famine occurrence. These lagged datasets are designated as NAO_1 Lag-5, NAO_2 Lag-5 and NAO_3 Lag-5, and NAO_1 Lag-10, NAO_2 Lag-10 and NAO_3 Lag-10 respectively.

Additional non-annual NAO reconstructions of a 10-100 year resolution do extend much further than AD 1049. For example Olsen et al. (2012) created a 5200-year reconstruction based on isotopic analysis of the sediments of southern Greenland dimictic lakes. The resulting decadal scale reconstruction would be appropriate for evaluating social and environmental trends; however evaluating the reconstructed NAO to specific annual or near-annual events, such as famine, is better served using annual datasets such as the Trouet et al. (2009) dataset. In general, there is correspondence between the Trouet et al. and Olsen et al. datasets. In a test of correspondence, we selected the 49 Olsen et al. data points that occur during the timeframe of the Trouet et al. reconstruction, these 49 data points show a moderate Pearson correlation value of 0.467, p=0.001. This moderate correlation is likely the result of the decadal rather than annual resolution present in the Olsen et al. reconstruction. However, in the development of the reconstruction, Olsen et al. used the Trouet et al. dataset as comparison because it was the best and longest NAO reconstruction available up to that point (Olsen et al., 2012). Therefore, employing the

Trouet et al. dataset will yield the best results because of its high quality and length as noted by Olsen et al.

Atlantic Multidecadal Oscillation reconstruction

A recent AMO reconstruction consists of twelve tree ring reconstructions (extending from AD 1567- 1990) surrounding the North Atlantic Ocean including samples obtained in eastern North America, Europe, Scandinavia, and the Middle East (Gray et al., 2004). The analysis of tree ring samples demonstrates a moderate to strong correlation to North Atlantic SSTs (Gray et al., 2004). A resulting AMI index was created by a 10-year running average of the reconstructed SSTs yielding an AMO index extending from AD 1572-1985, we include the years AD 1572-1914 in our analysis. In the statistical analyses, this dataset is designated as AMO. Like the NAO we have created a second set of AMO reconstructions with five-year and 10-year lags. The lagged datasets will be defined as AMO Lag-5 and AMO Lag-10.

Southern Oscillation Index reconstruction

We employed an SOI reconstruction consisting of instrumental and reconstructed Pacific Ocean precipitation levels as a proxy (Yan et al., 2011). Because of a persistent and strong correlation between the Pacific Ocean precipitation and the SOI researchers were able to construct an SOI index based on the rainfall difference between the equatorial eastern pacific and the tropical western pacific (Yan et al., 2011). The complete dataset extends from AD 50-AD 1955, however since our NAO reconstructions are more limited we employ only the AD 1049- AD 1914. This dataset is designated as

SOI in the statistical analyses. Lagged versions of the data are set at five-year and 10-year lags and are defined as SOI Lag-5 and SOI Lag-10 respectively.

Pacific Decadal Oscillation reconstruction

The PDO reconstruction we included is derived from living and dead tree ring chronologies from western Canada and southern California (MacDonald and Case, 2005). The trees used from these locations are considered to be an opposite ends of the PDO dipole and should create a robust reconstruction of the PDO based on precipitation and stream flow variability captured in the tree ring data. Their multiple regression based reconstruction of the tree ring data was then calibrated to previous PDO reconstructions and the 1940-1998 PDO index and created a PDO reconstruction extending from AD 993-1996 (AD 1049-1914 employed for our analysis). In the statistical analyses, this dataset is designated as PDO. Corresponding five-year and ten-year lagged version of this dataset are designated as PDO Lag-5 and PDO Lag-10.

Methods and Results

Data reduction

Due to (a) the established relationship between teleconnections including the NAO and the AMO to the climate of the British Isles (Lamb and Peppler, 1987; Knight et al., 2006) and (b) the influence of climate on famine (e.g., Lamb, 2002; Jordan, 1997; Briggs, 2005; Campbell, 2010; Slavin, 2012; DeWitte, 2015), we analyzed the direct relationship between climate teleconnections and historical famines of the British Isles. Because of the nominative nature of the famine data ("yes/no" with descriptors), we

selected basic statistical tests as best suited to demonstrate any associations. In this case, we employed two tests, first a difference-of-means test, and second, a stepwise discriminant analysis. With regard to the first, we specifically used the two-sample Student's *t*-test (Keeping, 1962). This test analyzes the difference-of-means of two independent samples, e.g., the NAO in weather or climate related famine years (Famine $_{WX}$) years vs. the NAO in non-weather or climate famine years (Famine $_{Non\text{-}WX}$). The null hypothesis is that there is no difference in the means of the climate values of the two groups. Assumption of normality is preferred for a difference-of-means test, but not essential (Pearson, 1931; Barlett, 1935; Geary, 1947; Sawilowsky and Blair, 1992), as long as the assumption of equal variance is maintained (Welch, 1937; Horsnell, 1935).

Each of the climate teleconnections (including AMO, PDO, SOI, and the three NAO reconstructions) was analyzed for its possible relationship with famine with a set of two sample *t*-tests. The sample categories (based on the historical texts) were set as follows: All Famine (Famine $_{All}$), All Non-Famine (Non-Famine $_{All}$), Weather or Climate Famine (Famine $_{WX}$), and All Non-Weather or Climate Famines (Famine $_{Non\text{-}WX}$).

Consequently, the t-tests were conducted based on grouping the variables by the occurrence of famine against (a) the famine descriptor (Famine $_{WX}$ or Famine $_{Non\text{-}WX}$), and (b) aggregated lag times (specifically, periods of five- and ten-year) leading up to climate attributed famines. If the teleconnections are influencing the occurrence of these weather related famines, the expectation is to reject the null hypothesis when comparing weather famine groups to non-weather groups and to confirm the null hypothesis when comparing famine to non-famine years.

North Atlantic Oscillation.

Given that the NAO reconstruction extends to 1049, our study period is constrained to the period AD 1049 – 1914. During that period, there were 172 incidences of recorded famine, 62 of which were attributed to weather (Figure 3.2). These famine occurrences were compared against the three NAO reconstructions (Trouet et al., 2009; Ortega et al., 2015; and Faust et al., 2016).

Initially, we classified the three NAO reconstruction datasets into years with weather-related famines (Famines $_{WX}$ n=62) and years of non-weather related famines (Famines $_{Non\ WX}$ n=110). Exceeding the α= 0.01 confidence level, the NAO_1 and NAO_3 *t*-test results rejected the null hypothesis and successfully discriminated between the Famine $_{WX}$ and Famine $_{NON\ WX}$ years (NAO_1, t=3.47; *p*=0.001 and NAO_3, t=2.99; *p*=0.003). However the same analysis using the Ortega et al. (2015) NAO_2 reconstruction failed to reject the null hypothesis (t=1.90; *p*=0.059). Furthermore, when NAO values for Famine $_{WX}$ years were classified with respect to all other years (n=803) the difference between the two sets was better using the Trouet et al. (NAO_1) and the Faust (NAO_3) reconstruction (NAO_1, t=5.52; *p*<0.001 and NAO_3, t=2.91; *p*=0.005). This indicates surprisingly that the reconstruction that incorporated persistent positive NAO during the Medieval Climate Anomaly (MCA) NAO_1 (Trouet et al., 2009) better discriminated between famine $_{WX}$ and famine $_{Non\ WX}$ or non-famine years than the more recent NAO reconstruction, NAO_2 (Ortega et al., 2015) which adjusted for such persistence in the MCA and an alternative reconstruction NAO_3 (Faust) which was based on Norwegian sediment variations.

The 5-year lags t-tests produced similar and even more significant results for the NAO_1 and NAO_3 reconstructions. The 5-year lag consists of the NAO reconstruction value five years prior to the actual famine event inserted into the t-test in place of the original NAO value the year of the famine $_{WX}$. Similarly, exceeding the α= 0.005 confidence level, NAO_1 Lag-5 and NAO_3 Lag-5 *t*-test results rejected the null hypothesis and successfully discriminated between the lag-5 years and famine $_{Non\ WX}$ years (NAO_1, t=3.95; $p<0.0001$ and NAO_3, t=2.84; $p=0.005$). These analyses indicate that the NAO_1 reconstruction performed best at identifying famine periods from AD 1049–1914 and is the NAO (and NAO lag-5) dataset used in the discriminant analyses described below.

Given the significant results of the t-test indicating that famine $_{WX}$ are associated with positive NAO values we were left with the curiosity of how to explain the famine $_{WX}$ events associated with cold weather. Therefore an additional t-test was conducted separating famines into cold and non-cold classes. The t-test for the NAO Lag-5 the successfully discriminated between the two classes (t=-2.69 $p=0.01$) indicating that cold famine events are more likely to occur after less positive NAO conditions than warm and or wet famine events.

Although we chose to employ the Trouet et al. dataset for the statistical analysis, the Olsen et al. (2012) dataset did provide an initial measure of significance. Three of the famine events AD 1137, 1649, and 1696 in our dataset do correspond to specific data points in the Olsen et al. reconstruction, the reconstructed NAO values are 1.64, 0.95, and 1.04 respectively. The mean of the NAO for these famine years is 1.21 and is more positive than the 0.875 mean of the entire reconstructed dataset. However, further

examination of the Olsen et al. reconstruction relative to our famine list is problematic due to the decadal rather than annual resolution of that reconstruction.

Atlantic Multidecadal Oscillation.

In contrast to the NAO reconstructions discussed above, the AMO reconstruction (Gray et al., 2004) only extends back to 1572 and therefore only includes 39 of the total famines and 13 of the weather-related famines. As in the previous analysis, we classified the AMO reconstruction by weather-related famines (Famines $_{WX}$ n=13) and years of non-weather related famines (Famines $_{Non\ WX}$ n=39).

When the AMO reconstruction values associated famines were classified into years with weather-related famines (Famines $_{WX,}$ n=13) and years of non-weather related famines (Famines $_{Non\ WX,}$ n=39) the *t*-test results rejected the null hypothesis and successfully discriminated between the two classes the α= 0.005 confidence level (t=2.98; *p*=0.005). As with the NAO, values for Famines $_{WX}$ years were classified with respect to all other years (n=330) the difference between the two sets were even more significant (t=4.12; *p*=0.001).

Lags for the AMO generally showed diminishing significance but were still able to discriminate between the classes. In particular the Lag-5 of NAO and the Famine $_{NON\ WX}$ classes were successfully discriminated (t=2.96 p=0.011). However, for the discriminant analysis discussed below, we omitted the AMO due to the reconstruction being so much shorter than the NAO or PDO (e.g., beginning in 1572 compared to 1049).

Southern Oscillation Index.

The SOI reconstruction (Yan et al., 2011)) extends back to 1049 and therefore includes 172 of the total famines and 62 of the weather-related famines. The SOI t-tests were unable to reject the null hypothesis under any two classes with the exception of All Famine Years (Famine $_{all}$) vs. All Non-Famine (Non-Famine $_{all}$) Years (t=-3.11 p=0.002). None of the SOI tests that included lags were statically significant. Consequently, the SOI was not employed in the discriminant analyses described below.

Pacific Decadal Oscillation.

The PDO reconstruction (MacDonald and Case, 2005) extends back to 1049 and therefore includes 172 of the total famines and 62 of the weather-related famines. Surprisingly, when the PDO was classified into the famine categories, the t-tests were able to successfully discriminate between many of the classes, however with a negative relationship, most notably the All Famine (Famine $_{all}$) (n=172) and All Non-Famine (Non-Famine $_{all}$) (N=694) classes (t=-4.43 p<0.001). Lag analysis showed increasing significance for some of the famine variables, exceeding the α= 0.005 confidence level, PDO Lag-5 *t*-test results reject the null hypothesis and successfully discriminated between the lag-5 years and All Non-Famine years (PDO, t=-4.96; p<0.001). Consequently, the PDO and PDO lag-5 was employed in the discriminant analyses described below.

Stepwise discriminant analysis

Stepwise Discriminant Analysis (Siegel, 1956; Keeping, 1962; Brommer et al., 2003) is used to assess to what degree that variables, in this case climate teleconnection parameters, can successfully segregate between groups, in this study, the occurrence of famine. Following the data reduction discussed above, four independent variables remain for inclusion into our discriminate analysis, specifically NAO_1 and NAO_1-Lag 5 (based on the Trouet et al., 2009 reconstruction) and PDO and PDO Lag-5 (based on the MacDonald and Case, 2005 reconstruction). As mentioned above, we omitted the AMO variable due to that reconstruction being so much shorter than the NAO or PDO, and we omitted the SOI reconstruction because its lack of statistical significance in the initial Student's *t*-tests with famine.

To begin our analyses, we tested our four independent variables for normality (a Gaussian distribution) using the standardized coefficients of skewness and kurtosis, the Kolmogorov-Smirnov one-sample test, and inspection of normal QQ plots. We did not find substantial deviations from normality that would violate assumptions of our statistic tests thereby producing spurious results. The NAO data over the period A.D. 1049 to A.D. 1914 had a one-year serial correlation coefficient of 0.43 while the PDO data showed a serial correlation of 0.07 over the same period. The intercorrelation matrix showed that no two variables shared more than 35% variance over the study period.

Stepwise discriminant analysis establishes how accurately and in what order do the four independent variables reclassify the nominative groups of Famine $_{WX}$ versus non-famine years. As seen in Table 3.1, NAO_1 Lag-5 is the strongest predictor of famine alone able to correctly classify 73.8% of Famine $_{WX}$ over the study period (45 out of 61).

The sign of the standardized canonical coefficient for NAO_1 Lag-5 indicates that the positive phase of NAO is significantly linked to the occurrence of famine in Britain. The positive phase of the NAO is typically associated with wetter than normal conditions in the British Isles (Jones et al., 1997).

Table 3.1. Stepwise Discriminant Analysis: Classification percentage and Canonical Coefficients for each of the included variables NAO-1 refers to the Trouet et al. (2009) NAO reconstruction. NAO -1 (5 year lag) refers to the five year lagged Trouet et al. (2009) NAO reconstruction PDO refers to the MacDonald and Case (2005) reconstruction. PDO (5 year lag) refers to the five year lagged MacDonald and Case (2005) reconstruction.

Step	Variable Entered	Correctly Classified (Percentage)	Correctly Classified (Actual)	Final Standardized Canonical Coefficients
1	NAO-1 (5 yr. lag)	73.8	45/61	-0.844
2	NAO-1	73.8	45/61	-0.800
3	PDO (5 yr. lag)	73.8	45/61	0.667
4	PDO	75.4	46/61	0.625

Adding the NAO_1, PDO and PDO Lag-5 to the stepwise discriminant analysis improves the classification, but only to 75.4% (46 out of 61). However, the two PDO variables (PDO and PDO Lag-5) both enter the stepwise discriminant equation at a high level of statistical significance (<0.01 level of confidence), but their addition to the discriminant function only increases the classification skill by 1.6%.

Interestingly, the signs of the PDO standardized canonical coefficients also indicate a slight potential for famine occurrence in the British Isles to occur immediately after a transition from positive to negative PDO, the opposite of the transition associated with the NAO and famine. Such a dichotomy in timing between phase transition of PDO and NAO potentially emphasizes the overall importance of the Northern Hemispheric

circumpolar vortex. Past analyses of NAO and PDO values over time show that the two teleconnections are often out of phase (Muller et al., 2008, Schwing et al., 2003). Researchers have speculated that the extra tropical Pacific may have an impact on Atlantic teleconnections (such as the NAO) by modifying the Rossby Wave circulation patterns (Muller et al., 2008). Our finding supports the conclusions of Muller et al. (2008) regarding the existence of a combined interbasin Pacific-North Atlantic teleconnection.

In order to establish the robustness of these discriminant results, we used a principal components analysis (PCA) to re-write the data as four orthogonal (uncorrelated) components (Table 3.2). The rotated solution (2) shows that each variable loads highly on one component, and when combined, the four components explain 100% of the variance in the original matrix. When these independent components are entered into a stepwise discriminant analysis, the resultant component scores combine to correctly classify 75.4% (46 out of 61) of the Famine $_{WX}$ years. For example the famines of 1694-1698 are not well predicted by this analysis and occur during times of weakly positive NAO (NAO average 0.056) and are preceded by negative NAO (NAO Lag-5 average -0.081), and these famines occur during negative PDO (average -0.275) they are preceded by weakly positive PDO (average 0.167). However the model correctly predicts the Great Famine of 1315-1317 showing markedly positive and persistent NAO (NAO average, 2.415 and NAO Lag-5 average, 2.696) and is preceded by a negative PDO (PDO average 0.361 PDO Lag-5 average -0.398). Consequently, these results indicate that our initial classification results are robust against any multicollinearity issues with our original four independent variables (NAO_1 Lag-5, NAO_1, PDO and PDO Lag-5).

Table 3.2. Principal Component Analysis correlation matrix; NAO-1 refers to the Trouet et al. (2009) NAO reconstruction. NAO -1 (5 year lag) refers to the five year lagged Trouet et al. (2009) NAO reconstruction PDO refers to the MacDonald and Case (2005) reconstruction. PDO (5 year lag) refers to the five year lagged MacDonald and Case (2005) reconstruction. PCA component 1 is primarily loaded on the PDO, component, 2 is primarily loaded on the 5 year lagged PDO, component 3 is primarily loaded on the 5 year lagged NAO and component 4 is primarily loaded on the NAO.

Variable	NAO-1	NAO-1 Lag	PDO	PDO Lag
NAO-1	1.00	0.59	-0.29	-0.38
NAO-1 Lag		1.00	-0.16	-0.29
PDO			1.00	0.04
PDO Lag				1.00

Variable	PCA Component 1	PCA Component 2	PCA Component 3	PCA Component 4
NAO-1	0.31	-0.20	-0.16	0.92
NAO-1 Lag	-0.06	0.01	0.99	-0.13
PDO	0.95	-0.13	-0.06	0.29
PDO Lag	-0.12	0.98	0.01	-0.16

Fundamentally, these results indicate a strong degree of association between the occurrence or non-occurrence of famine across the British Isles and specific large-scale climate teleconnections, specifically the North Atlantic Oscillation and, to a lesser degree, the Pacific Decadal Oscillation such that for the period from AD 1049 – 1914, famines were correctly identified using climatic teleconnections with 75.4% accuracy (46 out of 61 famine events).

Discussion and Conclusions

The famines of the British Isles, as with famines throughout the world, are the result of a complex combination of natural and human events. However, many famines appear to be initiated by environmental events often referred to as “climate shocks”

(Slavin, 2016). Many of the mid-latitude famines recorded in history have been attributed to anomalous climatic events, especially "wet" conditions that result in blight and the destruction of crops. This reduction of food availability then becomes an additional driver in the occurrence of famine. Our statistical analyses of climate reconstructions including the North Atlantic Oscillation (NAO), the Atlantic Multi-Decadal Oscillation (AMO) and the Pacific Decadal Oscillation (PDO) to famine occurrence reveal that these natural climate oscillations are related to many of these famine-initiating climate shocks for the British Isles over the last thousand years.

We find that many British Isles famines historically attributed to climate are associated with the positive phases of the NAO and AMO, both of which are attributed to increased rainfall over Northwest Europe. Given that the positive phases of the NAO and AMO tend to result in atmospheric circulations that produce increases in rainfall over the British Isles Europe (Jones et al., 1997; Wanner et al., 2001; Visbeck et al., 2001; Grey et al., 2004; Knight et al., 2006), we see that possible physical linkages may exist between the positive phases of the NAO and AMO and many of the historical accounts of famine. We find that this enhanced wetness under positive NAO/AMO conditions has been explicitly associated with the occurrence of some famines across the British Isles. We find that the reconstructed Trouet et al. (2009) NAO index associated with this AD 1193-1196 famine was markedly positive, with a value of, 2.554 in 1193, Short (1749) described the famine of AD 1193-1196:

"This year there was terrible dearth in France, and Flanders, and England, from excessive and unseasonable rains from years past; hence an epidemic and acute fever. This dearth began some years before, and continued four years together; from which great mortality, that there not being living and healthy enough to bury the dead. Funerals were neglected; the dead were thrown on heaps in pits. Most of the vulgar died of the famine, then came the plague."

Additionally, a negative PDO relationship to the occurrence of Famine $_{WX}$ may be surprising at first glance, but is in agreement with research demonstrating that the NAO and PDO are often out of phase and possibly linked (Muller et al., 2008; Schwing, 2003). Recent and extensive research (e.g., Muller et al., 2008; Pinto et al., 2012; Marini and Frankignoul, 2014; Santos et al., 2013) has attempted to ascertain the nature of the juxapositional relationships between the Pacific and Atlantic teleconnections. Various explanations have been supposed including, for example, cycles in sea surface temperatures (Marini and Frankignoul, 2014; Muller et al., 2008), and atmospheric circulation changes in the form of variations of the polar jet (Santos et al., 2013). While the exact nature of the relationship between Pacific and Atlantic teleconnections is complex and not yet entirely clear, our conclusions lend credence to the idea of an interbasin Pacific-North Atlantic teleconnection.

Many of the famines have also attributed to anomalously cold temperatures, which are not associated with positive phase NAO or AMO in the British Isles. For example, the Great Famine of 1315-1317, which some have attributed to a "Climate

Shock" associated with a particularly cold winter and spring of 1315 (e.g. Walford, 1879; Keys, 1950; Kershaw, 1973; Nash, 1976; O'Grada, 2009; Slavin, 2016). However many of these cold weather famines occurred during times that the NAO, while still positive, significantly less positive than the wet weather famine events, such as the famines of the AD 1694-1698, which encompassed an extended cold period where reconstructed NAO readings (Trouet et al., 2009) averaged out to 0.0562. In contrast, the famines of AD 1193-1196 occurring during an extended wet period where reconstructed NAO readings (Trouet et al., 2009) averaged out to, 2.623.

Although these statistical linkages between teleconnection phases and famines do not explain all of the climate conditions that can create climate shocks, we have demonstrated that, with over 75 percent accuracy, times of increased occurrence of famine in the British Isles have tended to coincide with persistent to positive NAO. Consequently, this research reinforces the fact that the environmental and social conditions that lead to historical famine over the British Isles are incredibly complex. Ultimately, we show statistically that many—but not all—famines over the British Isles in the last millennia can be accurately classified by a set of global climate teleconnections. This research underlines the critical importance that climate can play in influencing the complex causes of these horrific societal catastrophes of famine.

CHAPTER 4

INDIAN FAMINE AS INFLUENCED BY THE NORTH ATLANTIC OSCILLATION, THE SOUTHERN OSCILLATION AND THE SOUTH ASIAN MONSOON

This chapter chronicles the teleconnective influence of teleconnections including the of the North Atlantic Oscillation, El Niño Southern Oscillation, Pacific Decadal Oscillation, as well as the regional climate variation the South Asian Summer Monsoon on the Famine patterns of the India from AD 1029-1955. A version of this chapter titled: *Historical Indian Famine and Climate: A Multi-Phenomena Approach* is to be submitted to the Journal *Annals of the American Association of Geographers*. This is a solo publication.

Abstract

Famine is the result of a complex set of environmental and societal factors. Climate has long been considered a driver of the environmental contributions to the cause of famine. The Indian sub-continent saw 70 identified famines between AD 1049-1955, resulting in 220 famine years of the 907 years in the timeframe. The climate of India is been linked to climate teleconnections such as the North Atlantic Oscillation (NAO), Southern Oscillation (SO), and the Pacific Decadal Oscillation (PDO), as well as regional climate variations such as the South Asian Summer Monsoon (SASM). To identify aggregated climate response, I have employed a principal component analysis (PCA), including the four reconstructed climate variables. The PCA yielded two factors accounting for 70.5 percent of the total variance within the four climate datasets. The first factor is a NAO and SOI teleconnection factor, and the second factor is an orthogonal South Asian Summer Monsoon Index (SASMI) factor. A series of t-tests, including the

four reconstructed climate variables and the two factors, show that famine in India is statistically related to the positive phase of the reconstructed NAO and the negative phase of the reconstructed Southern Oscillation Index (SOI) and SASMI. A Reanalysis depiction of such a positive NOA/negative SOI pattern shows that mid-tropospheric flow over India moves well south of the Indian sub-continent with dry continental warm air advected from the arid regions to the northwest. The NAO-famine relationship is consistently the strongest; 74 of the 87 years (85%) of major famine and 181 of the 220 (82%) years of all famines occurred during positive NAO years. This research demonstrates that along with the complex societal causes of famine, global climate teleconnections such as the NAO and SOI have an influence on the famine pattern that is distinct and independent from the influence of regional climate patterns such as the SASMI.

Introduction

Famine, and its patterns of occurrence around the world are well documented in the academic literature (e.g. Short, 1749; Walford, 1879; Lucas, 1930; Keys et al., 1950) including the historical famines of India (e.g., Ganguli, 1933; Sinha et al., 2007; O'Grada, 2009; Shi et al., 1014). Much of the early research around the Indian famine focused on two influencing factors: a) climatic and environmental relationships (e.g., Sinha et al., 2007; Shi et al., 1014) or b) social/societal influences (Sen, 1977; Sen 1981; Ellman, 2000; Engler, 2012; Rai and Smucker, 2016). More recently there is a growing body of literature investigating famine as a function of both of these factors, society and environment (Engler, 2012; Adamson, 2014; Slavin, 2016; Kumar, 2016).

In the past, one of the predominant theories of famine origin is Food Availability Decline (FAD). Food Availability Decline is defined as the natural scarcity or non-availability of food (e.g., Sen, 1981; Sen, 1981a; Wolde-Mariam, 1984; Ellman, 2000;

Moon, 2009; Slavin, 2016). The availability of food as a cause of famine can be seen as a Malthusian issue of population demand exceeding the ability to produce food (Malthus 1798; Ambirajean, 1976; Weir, 1991; Lima, 2014), or a series of environmental events that reduce the availability of food, such as a frost or drought (Keys, 1950; Kershaw, 1973; Zhang et al, 2007, 2011; Engler, 2012; Slavin, 2016). For example, the fourteenth century "Great Famine" of Europe was caused by climate deterioration in the form of cooling during the transition from the Medieval Warming Period to the Little Ice Age (Lima, 2014). The cooling resulted in a reduction in the agricultural carrying capacity, causing FAD and famine (Zhang et al, 2007, 2011; Lima, 2014).

A second view on famine defines famine in terms of societal influence as Food Entitlement Decline (FED). This concept attributes famine to the decisions that human beings make with respect to food supply and distribution. Actions such as hoarding food and political upheaval can exacerbate or be a reaction to changes in supply or distribution of food (Keys, 1950; Sen, 1981; Slavin, 2016). In other words, FED is the change in a person's ability to produce or procure food in relation to the rights and abilities available to that individual. These rights and abilities may limit access to food, even if there is ample food supply; if food cannot be accessed hunger will occur (Sen, 1981; Ellman, 2000; Engler, 2012; Slavin, 2016). Anecdotally, Keys (1950) noted that a short 1527 famine in Sind, India was created by the destruction of grain supplies as a defensive measure. More recently the deadly Bengal Famine of 1942-1943 was not caused by any decline on the production of grain, but rather a combination of social impacts including the diversion of supplies for World War II, administrative chaos, and panic buying (Sen 1981; O'Grada 2009).

The complexity of the environmental and social causes of famine gives rise to the idea that climate shocks, such as a drought, frost or some combination of climatic oscillations, in conjunction with social causes may be the driver for famine events (e.g., Campbell, 2010; Engler, 2012; Engler et al., 2013; Chen, 2015; Dewitte, 2015; Toohey et al., 2016; Slavin, 2016), and that societal response to climate shocks, in particular the market response of grain prices, are the drivers to famine (Campbell, 2010; Adamson, 2014). The Irish famine of 1740-1741 followed one of the coldest winters on record (1740). Subsequent widespread crop failure (FAD), exacerbated by a dramatic increase in food prices (FED), caused difficulty throughout Europe and a severe famine in Ireland (Engler et al., 2013).

Much of the climatic influence on Indian famine is attributed to variations in the South Asian Summer Monsoon (Sinha et al., 2007; Shi et al., 1014; Kumar, 2016). This annual warm and wet period and its variability are understood to have an important historical impact on the peoples of India and the occurrence of famine. Disagreement exists on the extent to which famine is influenced more by natural events such as climate (Fraser, 2006; Campbell, 2010) or more as the result of human decisions and errors (Dando, 1980; Sen, 1981a). It is likely both play key roles in the occurrence and severity of famine around the world and in India (Adamson, 2014; Slavin 2016). While acknowledging the complex social/ environmental causes of famine, this paper focuses on some of the environmental conditions that may contribute to a state more conducive to the occurrence of famine.

Climatic Drivers and their Reconstructive Proxies

Various interannual variations in Earth's atmosphere and oceans have been long known to influence the weather and climate around the planet far beyond their immediate location. Some of these phenomena, known as teleconnections, include the Southern Oscillation (SO), the North Atlantic Oscillation (NAO), and the Pacific Decadal Oscillation (PDO). They are large-scale, often multi-year, oceanic and atmospheric variations in circulation that can affect weather and climate over large areas of the Earth (e.g., Walker and Bliss, 1932; van Loon and Rodgers, 1978; Lamb and Peppler, 1987; Diaz and Markgraf, 1992; Jones et al., 1997; Trenbreth, 1997; Mantua and Hare, 2002; MacDonald and Case, 2005; Knight et al., 2006; Trouet et al., 2009).

Climate teleconnections such as the NAO have a well-documented impact on the environment and society. Not limited to famine, the NAO has been linked to large-scale population migrations and the collapse of the Roman Empire (Drake, 2017). NAO shifts from strongly positive to weakly positive have been associated with cooling and drying of northeastern Europe, these trends have been thought to lead to food availability decline and a resulting mass migration towards Roman territory (Drake, 2017). As many as four migration pulses may have occurred between 113 BC and AD 600, implying that teleconnections such as the NAO may be significant drivers of societal events.

Climate teleconnections are not to be thought of as proxies for regional weather patterns but rather contributing factors to the development of those weather patterns (Seager et al., 2003; Ramadan 2012). Additional climate variations may be more regionalized such as the South Asian Summer Monsoon (SASM), a seasonal shift of the Intertropical Convergence Zone (ITCZ) causing a pronounced late summer rainy season

for much of South Asia. Despite it's regional effect, climate drivers such as the (SASM) still affect large areas of the Earth and a quarter of the world's population (Fleitmann et al., 2007; Sinha et al., 2007; Shi et al., 2014).

South Asian Summer Monsoon (SASM)

The South Asian Monsoon (SASM), also known as the Indian Monsoon, is an annual summer season increase in rainfall as a result of the northward migration of the Intertropical Convergence Zone (ITCZ) (Fleitmann et al., 2007). The ITCZ is a narrow band of wind convergence and precipitation than migrates north and south associated with the intense solar radiation of the summer season (Fleitmann et al., 2007). Nearly 80% of the rainfall for South Asia is received during the monsoon (Sihna et al., 2007).

Variations in the SASM (Figure 4.1) are documented through the use of a tree ring reconstruction based upon 15 tree-ring datasets distributed throughout the Asian continent with date ranges from AD 896 though 2010. Shi and colleagues (2014) produced an index that recreates many of the variations evident in the SASM. Extremely low values of the SASMI imply a failure in the monsoon, and many of the recorded Indian famines established by Shi et al. (2014) as "major famines" corresponded to extreme low SASMI events. The famines included in Shi et al. (2014) were separated into before and after 1658 due to a shift in the SAMSI time series values. Little explanation is given for possible reasons for this shift, but shifts in climate are a common occurrence (Rodionov, 2004). Eight of nine (AD 896-1658) and 10 of 17 (AD 1659-2000) famines were found to be in the extreme lowest SASMI values. The Shi famine list were only

major famines as historical famine can often be difficult to verify due to the scarcity of historical information (Loveday, 1914; Shi et al., 2014).

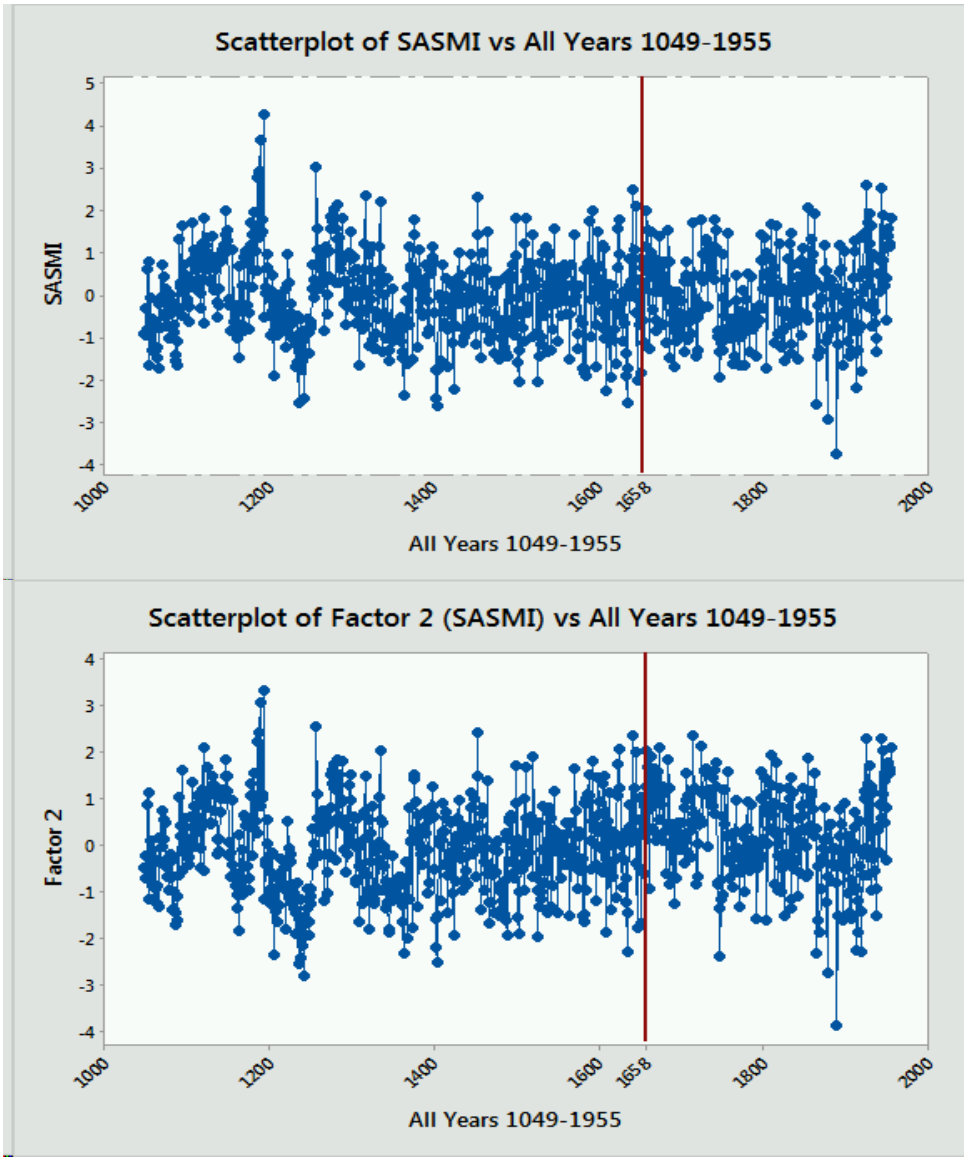


Figure 4.1. Top: A time series of the SASMI from 1049-1955 in blue with the red line indicating the shift noted by Shi et al. (2014) in 1658. Bottom: A time series of the PCA factor 2 which is heavily SASMI loaded from 1049-1955 in blue with the red line indicating the shift noted by Shi et al. (2014) in 1658.

North Atlantic Oscillation (NAO)

The North Atlantic Oscillation (NAO) (Figure 4.2) is the major interannual variation of atmospheric circulation in the North Atlantic Ocean and is measured by the air pressure difference between Iceland and the Azores (Jones et al., 1997; Lamb and Peppler, 1987; Trouet et al., 2009; Walker and Bliss, 1932). The positive phase of the NAO is associated with a well-developed Azores High and a well-developed Icelandic Low, whereas a weak Azores High and Icelandic Low indicate the negative phase of the NAO (Wanner et al., 2001). The NAO reconstruction employed is based on a tree ring drought reconstruction from Morocco and a speleothem based rainfall reconstruction from Scotland and includes annual NAO values extending from AD 1049-1995 (Trouet et al., 2009).

Several different NAO reconstructions exist including a 5200-year reconstruction based on isotopic analysis of the sediments of southern Greenland dimictic lakes (Olsen et al., 2012). However the resolution of these longer reconstructions is decadal rather than annual. This makes them problematic for use in evaluating a list of discrete events such as famines. The uncertainty associated with decadal resolution of this reconstruction makes statistical linkage to specific events difficult. Consequently, the Trouet et al. dataset is used for this analysis because of its length and quality as noted by Olsen et al. (2012).

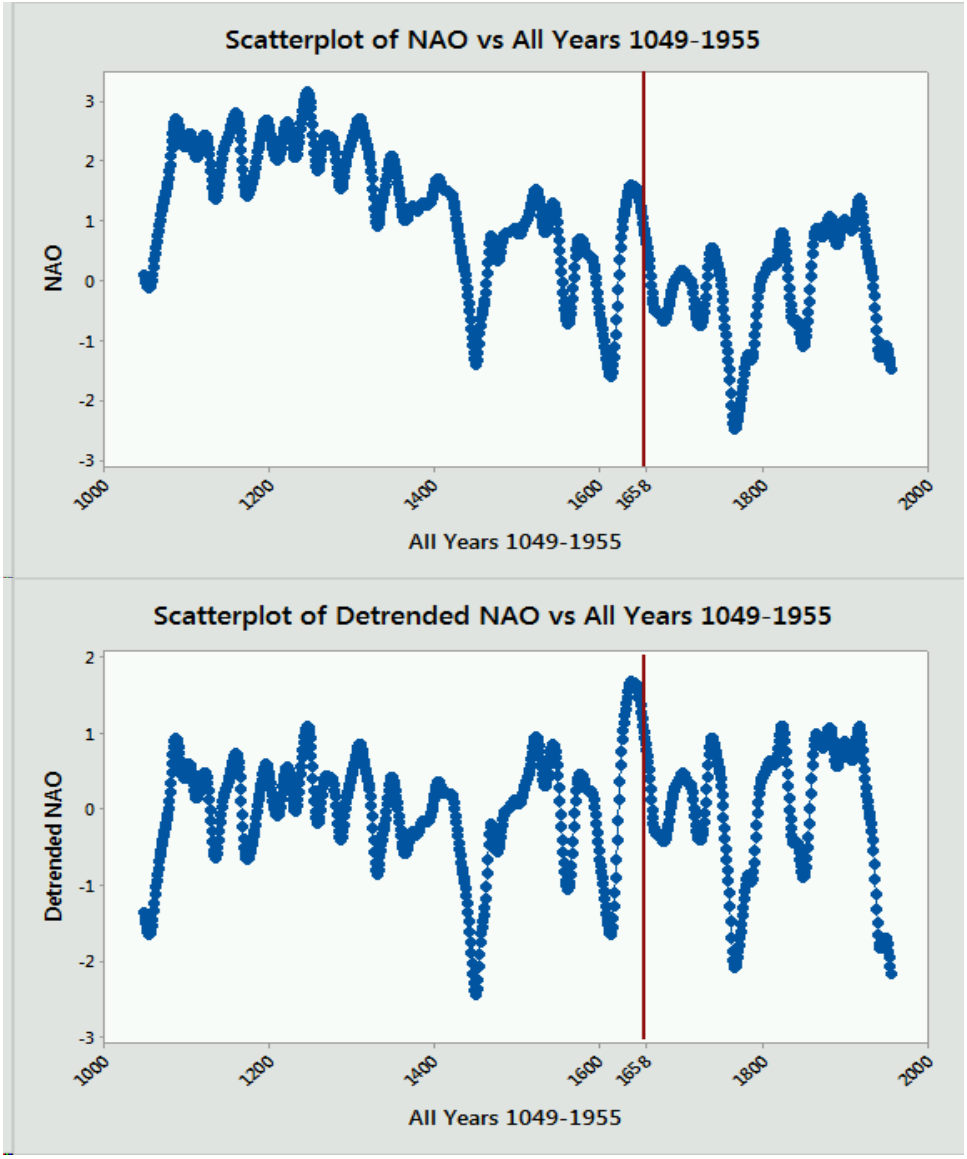


Figure 4.2. Top: A time series of the NAO from 1049-1955 in blue with the red line indicating the shift noted by Shi et al. (2014) in 1658. Note that most of the trend is before the break at 1658. Bottom: A time series of the detrended NAO from 1049-1955 in blue with the red line indicating the shift noted by Shi et al. (2014) in 1658.

The Southern Oscillation Index (SOI)

The Southern Oscillation Index (SOI) (Figure 4.3) describes the condition of the Southern Oscillation (SO) and is an accepted measure of the major interannual climate modification of the South Pacific atmosphere and ocean termed "El Niño Southern

Oscillation" (ENSO). Most of the studies on teleconnections with ENSO related anomalies use the SOI as the scale of reference (Caviedes, 2001). The SOI is represented by sea level pressure differences between Tahiti and Darwin, Australia (Trenberth, 1997). The SOI serves as an indicator of the phase of ENSO with negative SOI values associated with El Niño, the intrusion into the eastern South Pacific of warm equatorial waters, and positive SOI values associated with La Niña, anomalously cold waters off the South American coast (Nash, 2002, Diaz and Markgraf, 2000; Caviedes, 2001; Yan et al., 2011).

This research employed a SOI reconstruction consisting of instrumental and reconstructed Pacific Ocean precipitation levels as a proxy (Yan et al., 2011). Previous research has been able to construct a Southern Oscillation Index based on the rainfall difference between the equatorial eastern Pacific and the tropical western Pacific because of a persistent and strong correlation between the Pacific Ocean precipitation and the SOI (Yan et al., 2011). The complete dataset extends from AD 50-1955; however since the NAO reconstructions are more limited I employ only the time period AD 1049- 1955.

The Pacific Decadal Oscillation (PDO)

The Pacific Decadal Oscillation (PDO) (Figure 4.4) is the long-term (decadal) variation of Sea Surface Temperatures (SST) and atmospheric circulation in the Northern Pacific Ocean. The positive phase of the PDO is identified by anomalously warm SSTs in the northeastern Pacific and anomalously cool SSTs indicate a negative PDO (MacDonald and Case, 2005; Mantua and Hare, 2002).

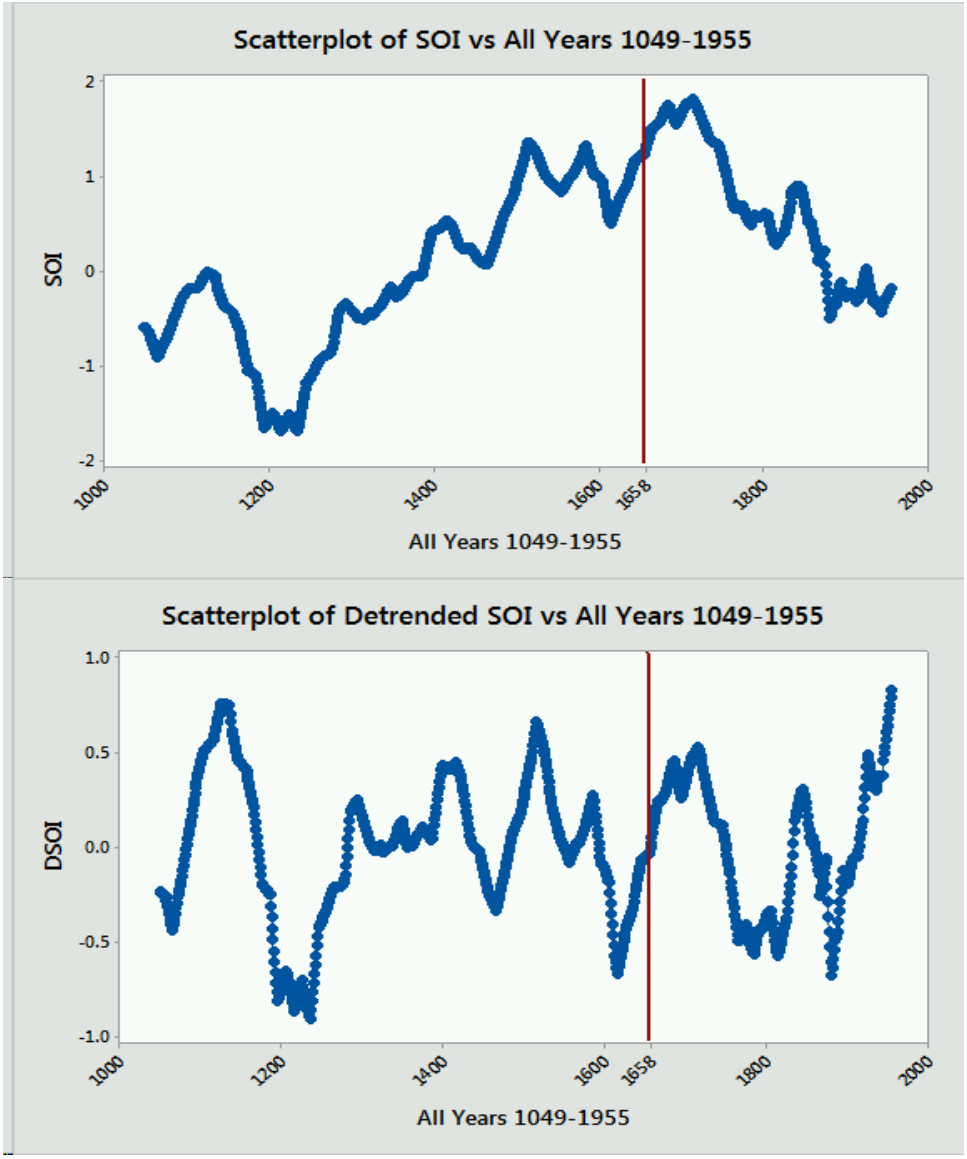


Figure 4.3. Top: A time series of the SOI from 1049-1955 in blue with the red line indicating the shift noted by Shi et al. (2014) in 1658. Bottom: A time series of the detrended SOI from 1049-1955 in blue with the red line indicating the shift noted by Shi et al. (2014) in 1658.

The PDO reconstruction derived from living and dead tree ring chronologies from western Canada and southern California (MacDonald and Case, 2005). The trees used from these locations are considered to be on opposite ends of the PDO dipole and create a robust reconstruction of the PDO based on precipitation and stream flow variability

captured in the tree ring data. Their multiple regression based reconstruction of the tree ring data was then calibrated to previous PDO reconstructions and the measured 1940-1998 PDO values and created a PDO reconstruction extending from AD 993-1996 (AD 1049-1955 employed for our analysis).

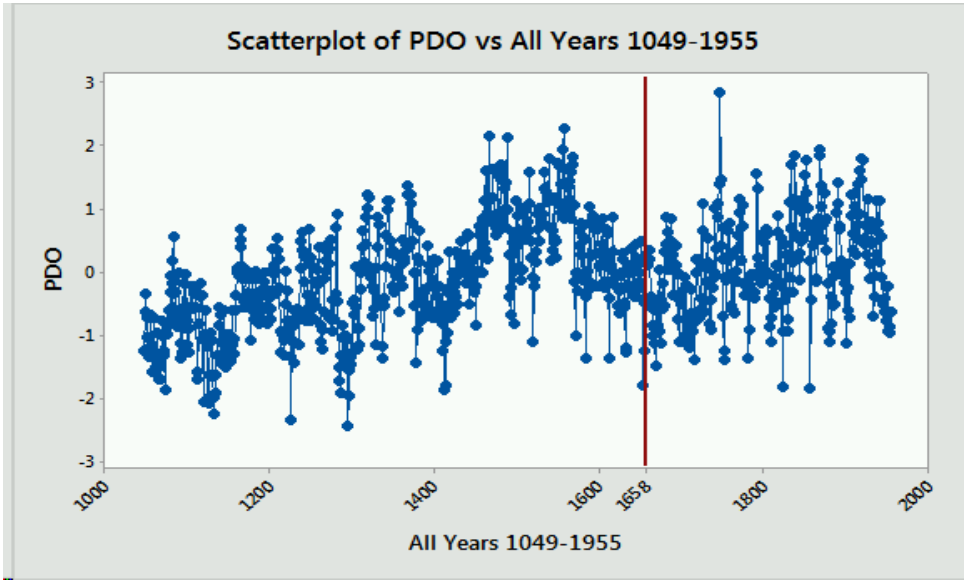


Figure 4.4. A time series of the PDO from 1049-1955 in blue with the red line indicating the shift noted by Shi et al. (2014) in 1658.

Famine

Unfortunately, famine in India has occurred frequently over the past thousand years with famine occurring somewhere in India several times a century since AD 1049 (Appendix B). While Shi et al. (2014) employed a list of 26 famines from AD 896 to 2000; this study expands the list of known Indian famines from those cited by Shi et al. (2014). Here, I expand Shi and colleagues' number of famines to seventy (70) occurring from AD 1049 to 1955. Twenty-one of these famines were deemed by Shi et al. (2014) to be "major famines." The specific criteria that Shi et al. (2014) used to establish these

famines as "major," are not addressed by those authors in their article. Many of the 70 famine events identified occurred over the course of multiple years, so one method of evaluating historical famine is to differentiate all of the years in which famine occurred and those years in which famine did not occur. Of the 907 years between AD 1049 and 1955, 220 years have famine occurring somewhere in India, 87 of the famine years were major famine years according to Shi et al. (2014). The historical references to these 70 famine events and 220 famine years are disparate and sometimes difficult to verify. To be included on the famine list for this study, I verified each event by at least two independent sources (Appendix B).

Methods and Results

The 70 Indian famines from AD 1049 to 1955 were categorized by time and severity. The three time categories included for analysis span (1) the entire study period (AD 1049-1955), (2) "A Years" (those famines between AD 1049-1658) and (3) "B Years" (those occurring between 1659-1955). This segregation into two time periods follows Shi and colleagues' (2014) observation that a major shift occurred in the SASMI in AD 1658 (Shi et al. 2014). Additionally, two categories of famine severity have been identified; specifically, (a) the 70 total famine events, and (b) the 21 famines that were defined as "major" by Shi et al. (2014). As seen in Appendix B, these major famines are longer in duration and identified by more sources than the remaining 49 famines. As stated above, the specific criteria that Shi et al. (2014) used to establish these famines as "major," are not addressed by those authors, but other sources (e.g., Loveday, 1914;

Bhatia, 1967; Parthasarath, et al., 1987; Sen, 1991; Davis, 2001; Kumar, 2005, Grove, 2007) do agree that those famines were markedly deadly.

The statistical influence of climate on famines can be analyzed by computing the number of years in which famine occurred. For the purposes of this study I will analyze the dataset of Indian famine including a) the complete list of years of famine (220) and b) the list of "major" famine years (87) (Appendix B). These lists were then segregated into two time periods (A: 1049-1658 and B: 1659-1955). In order to establish the degree of influence of climate drivers on famine in India, a variety of Student's t-tests were conducted to test the difference of means between famine and non-famine years of climate data. All results are considered significant at the ($p<0.05$) confidence level. The climate teleconnections associated with the year of famine were compared against all years in the dataset domain. This yielded six sets of results. Climate variables included in these tests include NAO, PDO, SOI, SASMI, and the two aggregated indices of these teleconnections discussed below.

Aggregated Indices

Santoro et al. (2015) demonstrated that single climate teleconnections did not display as strong of a statistical relationship to Egyptian famine as did the aggregation of NAO, PDO, and SOI onto a single climate index. Consequently, I developed a similar climate statistical aggregation to evaluate the combined effect of large-scale climate fluctuations on Indian famine. This aggregated index combined the effects of the NAO, PDO, SOI, and SASMI, each of which has been independently identified as influencing Indian climate (e.g. Hasternath, 1987; Kakade and Dugam, 2000; Krishnan and Sugi,

2003; D'Arrigo and Wilson, 2006; Roy, 2006; Li et al., 2008; Shi et al., 2014). The time period in which values of all four indices are available is AD 1049-1955.

Given the number of climate variables and the goal of identifying how their shared variance may impact famine patterns, the climate data were included in an un-rotated Principal Component Analysis (PCA). The PCA is a statistical analysis that transforms a set of potentially correlated observations into a new set of explicitly uncorrelated variables (Rummel, 1970; Jackson, 1991).

Following Shi et al. (2014), the time period was split into "A Years" (specifically 1049-1658) and "B Years" (1659-1955), given their observed shift in the SASMI that occurred in 1658 as well as "All Years" (1049-1955). The PCA was conducted for each of the three time intervals. The results for all three PCAs were similar with the first component factor heavily loading on NAO and SOI, while the second factor heavily loaded on SASMI (Table 4.1). For "All Years," the first factor (Figure 4.5) explained 44.9% of the total variance and loaded heavily negative on NAO (-0.844) and positive on SOI (0.841). The second factor explained 25.6% of the total variance and heavily loaded on SASMI (0.933). These first two factors consequently explained 70.5% of the total variance.

The PCA results were very similar for "A Years" (1049-1658) with the first factor explaining 48.2% of the variance and primarily loading on NAO (-0.822) and SOI (0.841), but with addition of the PDO (0.714) showing relevance. The second factor explained 24.8% of the total variance and loaded heavily on SASMI (0.971). These two factors explain a combined variance of 73%.

Table 4.1. Correlation matrix for PCA including: All Years, A Years, and B Years.

Principal Component Factor Analysis of the Correlation Matrix (All Years)

Unrotated Factor Loadings and Communalities

Variable	Factor 1	Factor 2	Factor 3	Factor 4
NAO	-0.844	-0.168	-0.246	-0.446
SOI	0.841	0.205	0.224	-0.447
PDO	0.593	-0.288	-0.752	0.004
SASMI	-0.154	0.933	-0.326	0.019
Variance	1.7952	1.0231	0.7821	0.3996
% Variance	0.449	0.256	0.196	0.100

Principal Component Factor Analysis of the Correlation Matrix (A Years)

Unrotated Factor Loadings and Communalities

Variable	Factor 1	Factor 2	Factor 3	Factor 4
NAO	-0.822	-0.114	-0.364	-0.423
SOI	0.841	0.175	0.201	-0.470
PDO	0.714	-0.079	-0.692	0.078
SASMI	-0.190	0.971	-0.135	0.042
Variance	1.9294	0.9938	0.6691	0.4078
% Variance	0.482	0.248	0.167	0.102

Principal Component Factor Analysis of the Correlation Matrix (B Years)

Unrotated Factor Loadings and Communalities

Variable	Factor 1	Factor 2	Factor 3	Factor 4
NAO	0.655	-0.365	0.509	-0.423
SOI	-0.759	0.175	0.048	-0.625
PDO	0.626	0.387	-0.586	-0.340
SASMI	-0.150	-0.866	-0.466	-0.100
Variance	1.4189	1.0632	0.8229	0.6950
% Variance	0.355	0.266	0.206	0.174

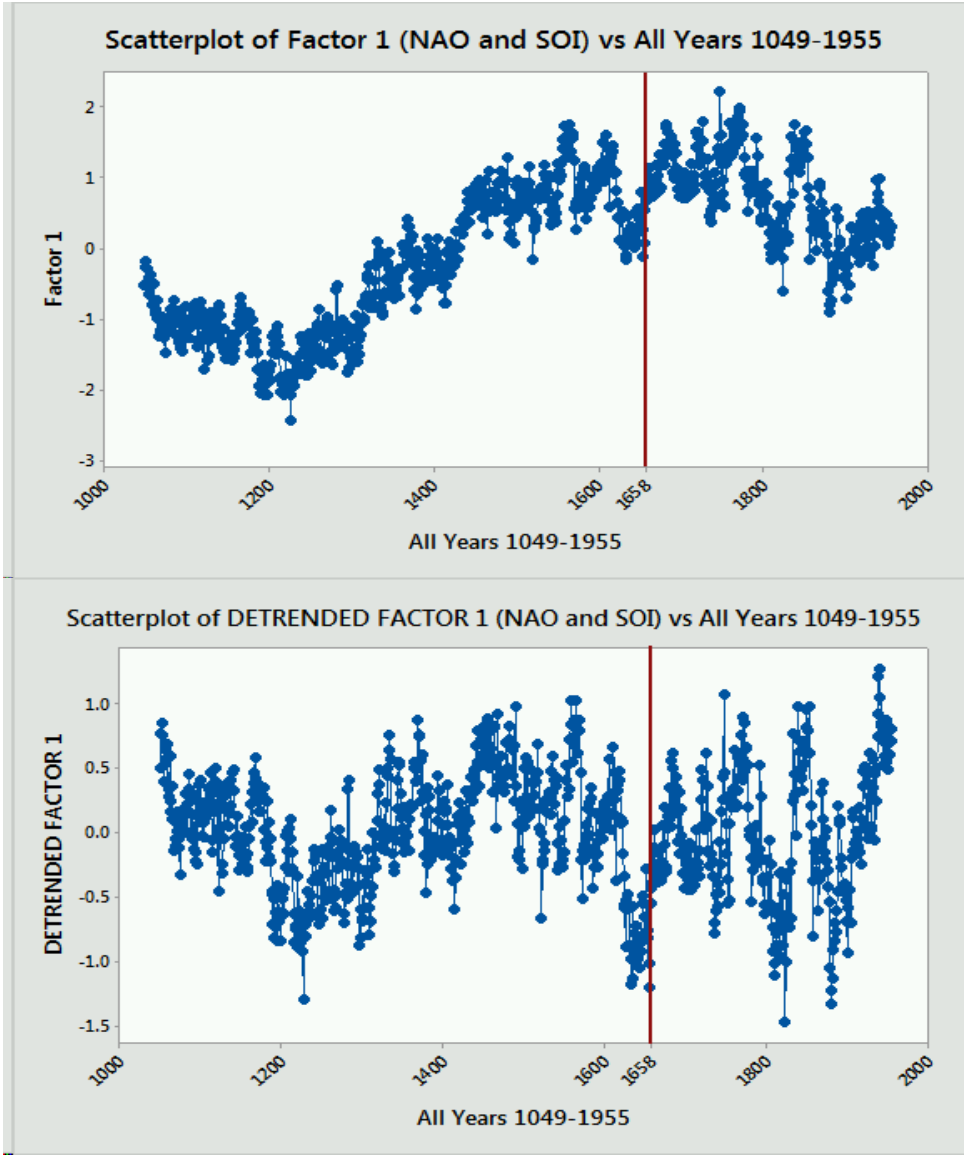


Figure 4.5. Top: A time series of the Factor 1 (NAO and SOI) from 1049-1955 in blue with the red line indicating the shift noted by Shi et al. (2014) in 1658. Bottom: A time series of the detrended Factor 1 (NAO and SOI) from 1049-1955 in blue with the red line indicating the shift noted by Shi et al. (2014) in 1658.

However, the PCA analysis results for the more current "B Years" (1659-1955) time period were surprisingly different. The first factor explained a smaller amount (35.5 %) of the total variance than did the early time period or the whole period, but, more surprisingly. the NAO (0.655) and SOI (-0.759) loadings were inverse to the sign of the

early “A” time period, and the PDO (0.626) loadings were almost as strong as the NAO. The second factor explained 26.6% of the variance and was also (-0.866), but again the sign is inverted, with the first two factors explaining a combined 62.1% of the total variance. This may be a result of the phase shift identified in the SASMI by Shi et al. (2014).

The first factor is a combined factor weighing on NAO and SOI variable, termed in the discussion “Factor 1 (NAO and SOI)”, and the second factor weighing primarily on SASMI, termed in the discussion “Factor 2 (SASMI)”. From each respective time interval, these two new climate aggregates are added to the list of climate variables included in the round of t-tests.

Climate and Famine

It is reasonable to test for a direct statistical relationship of these climate variables to the occurrence of famine given: (1) that climate teleconnections such as the NAO, PDO, and SOI, and seasonal variations such as the SASMI, have an established influence on the climate of India (e.g. Hasternath, 1987; Kakade and Dugam, 2000; Krishnan and Sugi, 2003; D’Arrigo and Wilson, 2006; Roy, 2006; Li et al., 2008; Shi et al., 2014), and (2) that these climate variables have been linked to the quality of agriculture and societal patterns of India (Krishna Kumar et al., 2004, Sinha et al., 2007), which are known to influence famine patterns (Sen, 1981).

Since the famine data are normative (“yes/no” with descriptors), a basic statistical test, in this case a set of two sample Student’s t-tests, is best suited to demonstrate statistical associations. The two-sample t–test is a difference-of-means test, accessing if

the means of two groups significantly vary from one another (Keeping, 1962); in this case ascertaining whether or not the mean of a climate variable is different during famine years than during non-famine years. Included in the t-test analyses are indices of the climate teleconnections NAO, PDO, SOI, SASMI, and the two factors from the PCA, Factor 1 (NAO and SOI) and Factor 2 (SASMI).

In order to account for the possible influence of trend, I detrended the NAO, SOI, and Factor 1 (NAO and SOI) variables through a third order polynomial regression and included in the t-test analyses these detrended variables, labeled as DNAO, DSOI, and Dfactor 1 (NAO and SOI), respectively. Consequently, I tested nine climate variables against famine occurrence including NAO, SOI, PDO, SASMI, Factor 1 (NAO and SOI), Factor 2 (SASMI, DNAO, DSOI, and Dfactor 1 (NAO and SOI).

The climate variables are differentiated as "famine" years (those years in which famine is documented to have occurred in India) and "non-famine" years (those years in which no famine was recorded in India). Additionally, the "famine" years were further classified into "all famine" years and "major famine" years. "Major famines," as discussed above, are defined as longer duration famines documented with multiple sources.

The time frame of the famines are segregated into three datasets; the entire study period "All Years" (AD 1049-1955), "A Years" (those famines between AD 1049-1658) and "B Years" (those occurring between 1659-1955). This results in six sets of t-tests, explicitly using an "All Famine" and Major Famine" analysis for each of the three time periods described above. This set of six t-tests was conducted for using each of nine

climate variables, for a total 54 separate t-tests. Results were assessed using a confidence level of $\alpha = 0.05$.

When I classified the time period "All Years (1049-1955)"into "All Famine Years" (n=220) and "Non-famine Years" (n=687), I found that the independent variables DNAO, DSOI, SASMI, Dfactor 1(NAO and SOI), and Factor 2 (SASMI) each successfully discriminate between the famine and nonfamine years at the $\alpha = 0.05$ confidence level. Specifically, DNAO famine/nonfamine discrimination is the best of all climate parameters, with $t=-5.48$, $p<0.001$. Dfactor 1 (NAO and SOI) produces the next most significant discrimination, $t=4.68$, $p<0.001$. The detrended Southern Oscillation variable, DSOI, achieves significant discrimination with $t=2.40$, $p=0.017$, SASMI $t=2.92$, $p=0.004$, and composite PCA Factor 2 (SASMI) also produces significant results, $t=2.79$, $p=0.005$. The sign of the relationship suggests that the DNAO is positive during famine years.

In contrast, the sign of the DSOI, SASMI, Dfactor 1 (NAO and SOI) and Factor 2 (SASMI) are negative during famine years. This means that the SOI and the SASMI are likely to be in the negative phase during famine events. Factor 1 (NAO and SOI) is negatively loaded onto the NAO and positively loaded onto the SOI, which, with the means that the NAO is still indicated to be in a positive phase, and the SO is still indicated to be in a negative phase during famine years. A positive NAO is characterized by higher than usual pressure in the subtropical Atlantic Ocean and lower than normal pressure in the Arctic Ocean (Jones et al. 1997). A negative SOI is identified by below normal air pressure in Tahiti and above normal air temperatures in Darwin. This phase of the SO is associated with El Niño, the warm water intrusion into the eastern South Pacific

of warm equatorial waters (Diaz and Markgraf, 2000; Yan et al., 2011). Overall, this suggests a consistent global circulation pattern for the occurrence of famine in India with a positive NAO, and a negative SOI) and SASMI conditions being indicators of famine in India.

One means of visualizing such a set of global conditions is through the use of so-called "Reanalysis" data. Reanalysis data, such as taken from the 20th Century Reanalysis Dataset (Compo et al., 2011), are a product of entering all available weather data for a particular time period into a weather model and setting the model to an initial time of 0. The Reanalysis yields an output that represents what the actual conditions likely were at the time of the available observations. Consequently, Reanalysis data are not a forecast, but rather a simulation of the real atmospheric conditions based on the available data (Compo et al., 2011).

Use of the 20th Century Reanalysis allows a first-approximation comparison of the Indian surface and atmospheric conditions between the apparent famine-contribution teleconnection (as represented by conditions in July 1992) and non-famine-contributing atmospheric conditions (as represented by conditions in July 2010). Specifically, this comparison demonstrates the synoptic differences possible with a positive NAO coupled with a negative SOI (1992) or conversely a negative NAO coupled with a positive SOI (2010).

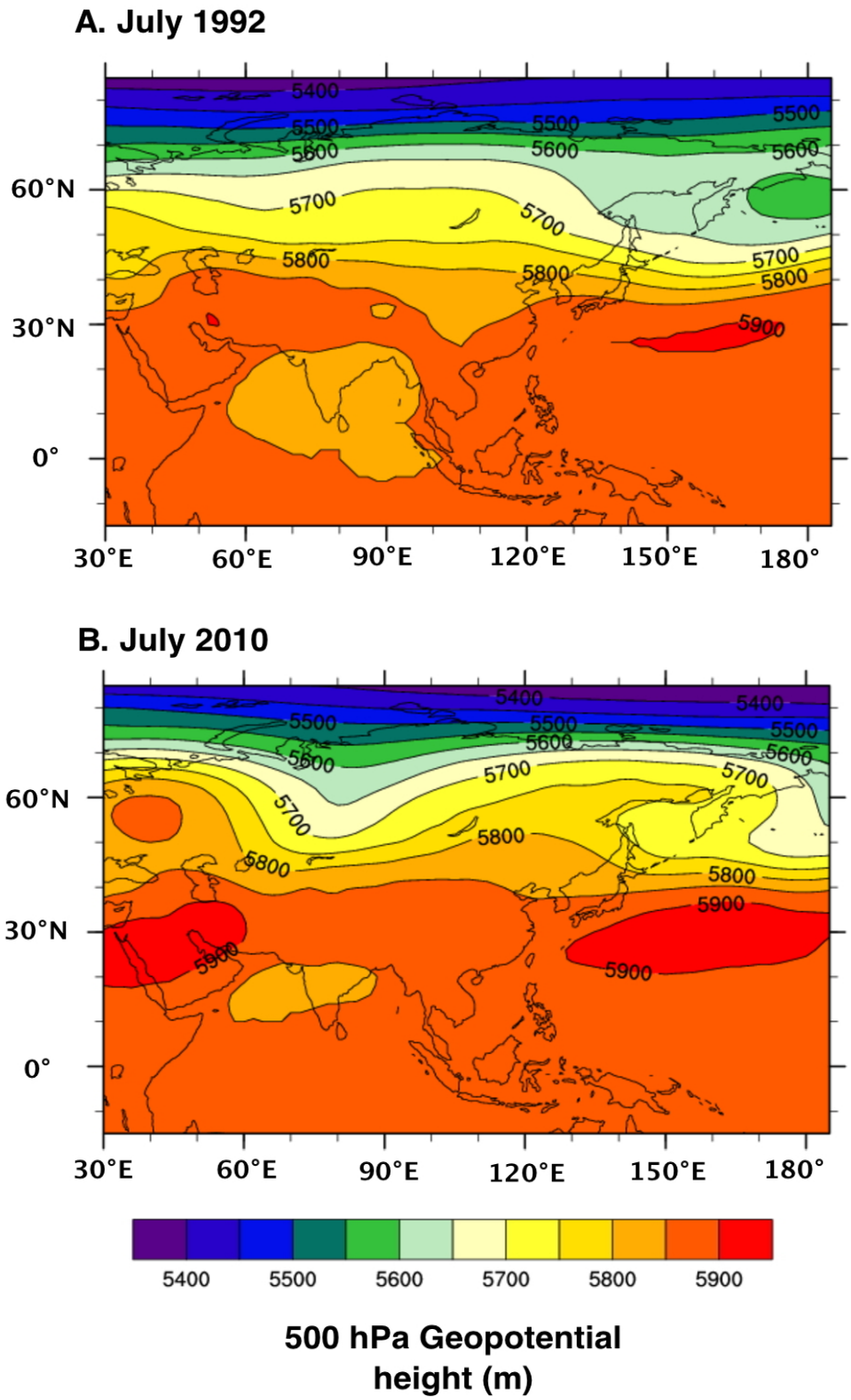


Figure 4.6. For the Asian continent region, 20th Century V2 plots of 500hPa geopotential height (m) for two contrasting situations A. July 1992 (NAO, +1.04; SOI, -0.63) and B. July 2010 (NAO, +0.06; SOI, +1.95).

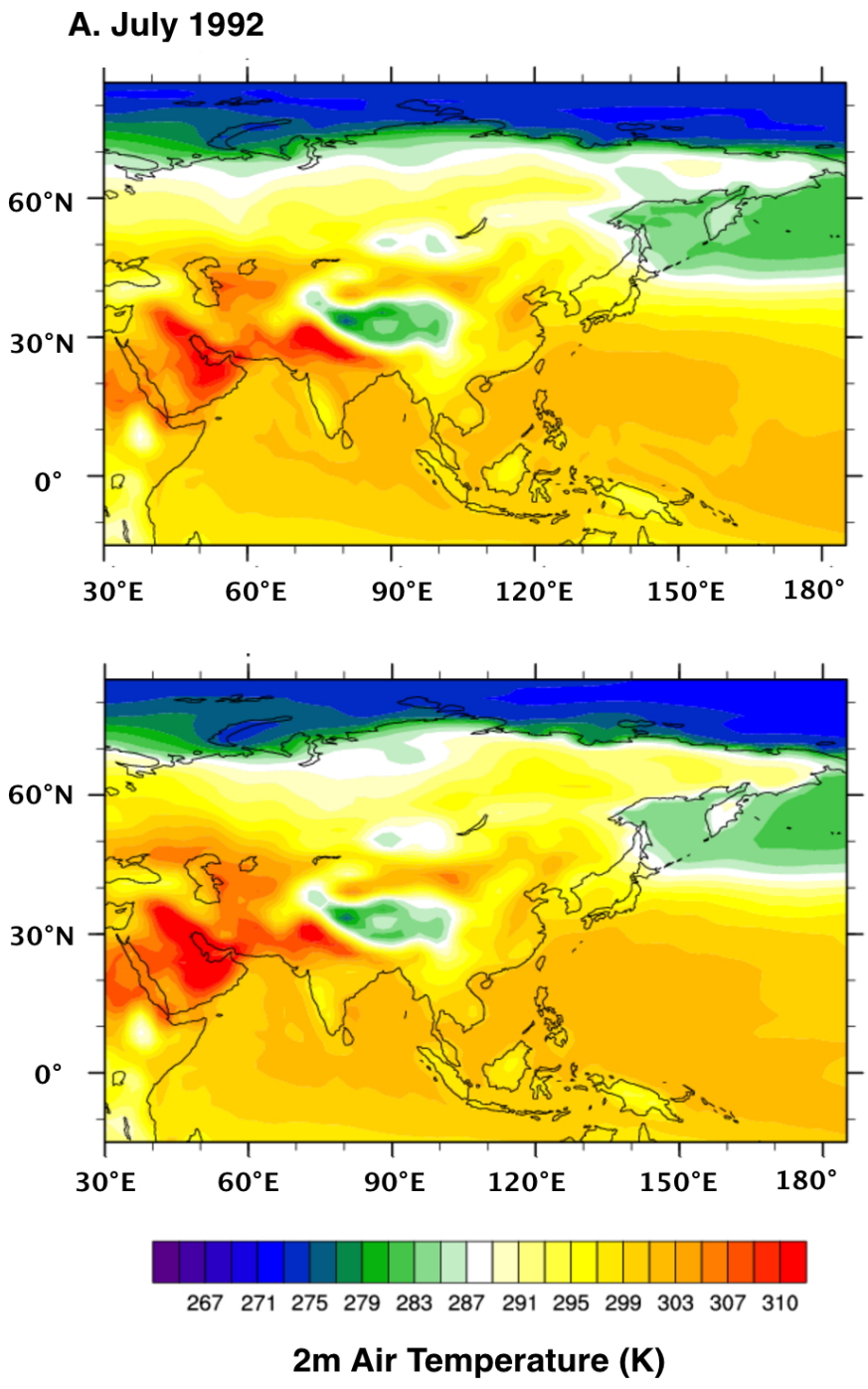


Figure 4.7. For the Asian continent region, 20th Century V2 plots of 2-meter air temperature in Kelvin A. July 1992 (NAO, +1.04; SOI, -0.63) and B. July 2010 (NAO, +0.06; SOI, +1.95).

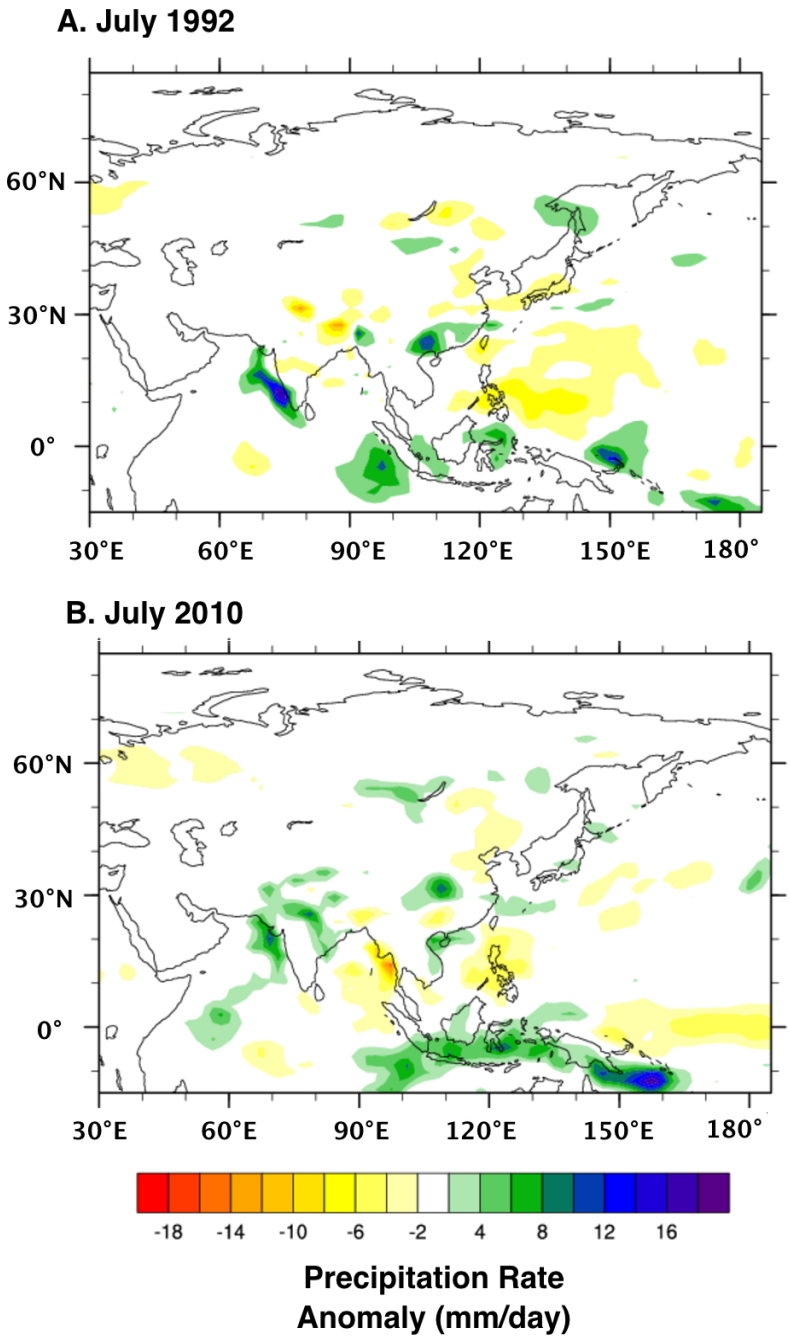


Figure 4.8. For the Asian continent region, 20th Century V2 plots of precipitation rate anomaly (mm/day) A. July 1992 (NAO, +1.04; SOI, -0.63) and B. July 2010 (NAO, +0.06; SOI, +1.95).

July 1992 and July 2010 are two recent examples representing large contrasts between the NAO and SOI. The upper air circulation (500 hPa, mid-tropospheric) pattern displayed by July 1992 conditions has an NAO value of+1.04 and an SOI value of -0.63. Mid-tropospheric flow over India in July 1992 moves well south of the Indian sub-continent (Figure 4.6a). Additionally, the northwesterly surface flow in 1992 (as a result of the upper air low) likely draws dry continental warm air directly from the arid regions to the northwest (Figure 4.7a). The combination of upper circulation diverting moisture to the south and surface flow advecting dry air from more arid regions would result in reduced precipitation on the Indian subcontinent (Figure 4.8a). Although this 1992 situation was not a time of notable famine in India, it does illustrate a likely synoptic weather scenario that could (perhaps in conjunction with other factors) contribute to famine conditions.

In contrast, the July 2010 500 hPa circulation associated with high SOI/low NAO values moves maritime tropical air from Gulf of Aiden directly into India leading to conditions that promote precipitation over India (Figure 4.6b). Furthermore, the likely southwesterly surface flow would in this scenario draw cooler and wetter maritime air that would lead to decreased temperatures (Figure 4.7b) and increased rainfall (Figure 4.8b) relative to the 1992 conditions.

As an example, a severe famine in 1896-1902 shows similar extremes in teleconnections to the 1992 situation in atmospheric conditions. Across the 1896-1902 time period the NAO average is 0.984 and the SOI is -0.244. Consequently, the 20th Reanalysis data for that time period has for the July months of 1896-1902 a well-developed upper air anticyclone over the Arabian Peninsula. The resulting northerly flow

in India would have been unseasonably dry (Figure 4.9) in a fashion similar to 1992. However, it should be noted that uncertainty in the Reanalysis dataset is higher in this earlier (1800s) period of the Reanalysis dataset (Compo et al., 2011). Additionally, the Reanalysis depiction of the July 1896-1902 precipitation rate anomaly shows drier than normal conditions across much of India (Figure 4.10). Historically, the 1890s were a time of documented drought and crop failure in parts of India (McAlpin, 1979) and the atmospheric conditions such as identified here likely contributed to the famine of 1896-1902.

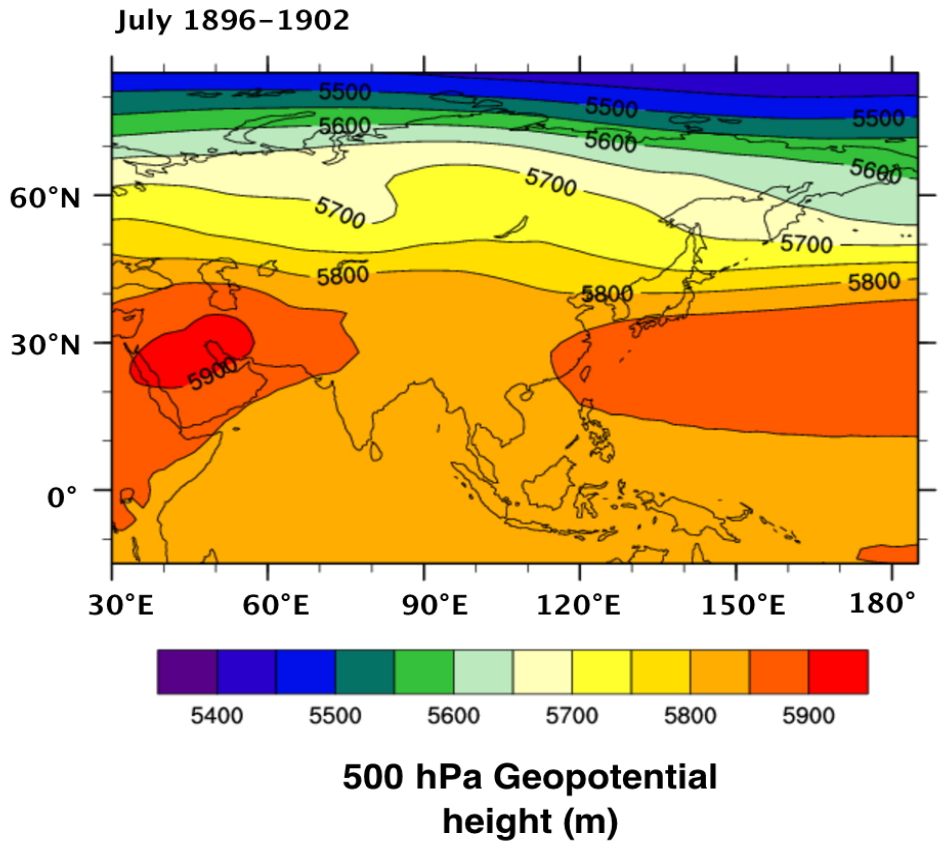


Figure 4.9. The 20th Century V2 plots of 500hPa geopotential height (m) July 1896-1902 (NAO, +0.984; SOI, -0.244) for the Asian continent region.

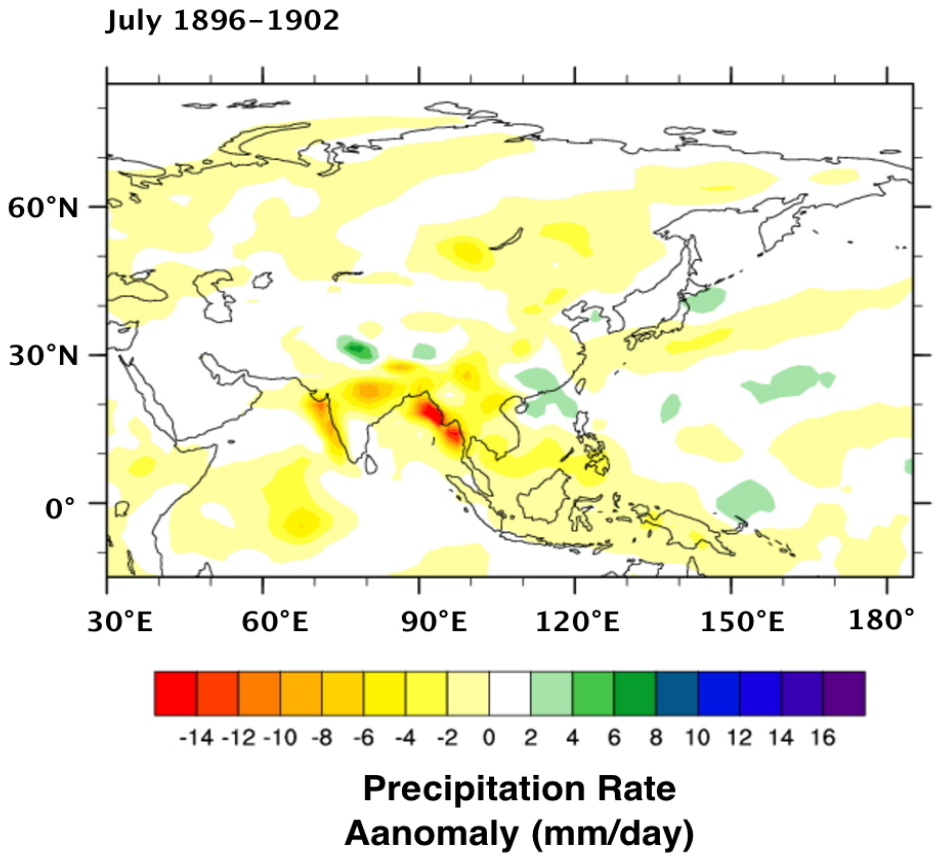


Figure 4.10. 20th Century V2 plots of precipitation rate anomaly (mm/day) July 1896-1902 (NAO, +0.984; SOI, -0.244) for the Asian continent region.

The Pacific Decadal Oscillation (PDO) results, however, indicated no significant difference between "All Famine Years" and "Non-famine Years" (t=0.00, p=0.997). This is in contrast to the significant PDO results with respect to Major Famines as described above and indicates that despite the established PDO/ Indian climate teleconnection, the impact of Northern Pacific SST variations associated with the Pacific Decadal Oscillation on Indian Famine appears to be inconsistent.

Next I classified the time period "Major Famine Years"(n=87) and "Non-Famine Years" (n=820) and this produced similar results as with the "All Famine Years." As with

the analysis of "All Famine Years", the DNAO, DSOI, SASMI, Dfactor 1(NAO and SOI), Factor 2 (SASMI) display significant discrimination for "Major Famine Years" versus "Non-Famine Years". The most significant result was the DSOI ($t=5.63$, $p<0.001$). The next strongest discriminator of major famine was the DNAO ($t=-5.05$, $p<0.001$), followed by the Dfactor 1(NAO and SOI) ($t=3.96$, $p<0.001$), Factor 2 (SASMI) ($t=3.80$, $p<0.001$), and SASMI ($t=-2.57$, $p=0.012$). The phase of these climate teleconnections during "Major Famine Years" is consistent with the phase discussed with "All Famine Years."

However, in contrast to the "All Famine Year" results, the PDO variable produced significant discrimination of "Major Famines Years" and "Non-Famine Years" (t=-2,57 p=0.012). The t-test results indicate that the phase of PDO positive during "Major Famine" years. A positive PDO is identified by anomalously warm SSTs in the northeastern Pacific (MacDonald and Case, 2005; Mantua and Hare, 2002).

As a whole the results for the time period "All Years" show consistent statistically significant relationships between famine and the associated climate variables, with the exception of the PDO. The DNAO, DSOI, SASMI, Dfactor 1(NAO and SOI), Factor 2 (SASMI) display significant discrimination of famine and non-famine years across the entire time series for both famine categories. Additionally the phase of these climate teleconnections during "Major Famine Years" is consistent with the phase discussed with "All Famine Years," suggesting that the mode of the climate famine relationship is also consistent. Specifically, the sign of the t-tests imply that the NAO was more likely to be positive and the SOI and SASMI were more likely to be negative during famine years.

Ocean and atmospheric conditions during the positive NAO and negative SOI (as described above) are illustrated in Figure 4.6 and 4.7.

Following Shi and colleagues' (2014) observation of a major shift in SASMI in AD 1658, I applied the suite of t-tests of climatic parameters to each of the two time periods (i.e., "A Years", those famines between AD 1049-1658 and "B Years", those occurring between 1659-1955). The t-tests for the "A Years" yielded fewer significant results in discriminating famine by climate parameters than seen for "All Famine Years". When the early "A Years" were discriminated into "All Famine Years" (n=134) and "Non-Famine Years" (n=476) four variables produce statistically significant results, explicitly, the NAO, DNAO, and Dfactor 1(NAO and SOI) (NAO t=-2.20, p=0.029, DNAO t=-2.99, p=0.003, and Dfactor 1(NAO and SOI) t=2.70, p=0.008). Additional subdivision of the dataset for this shorter time period into "Major Famine Years" (n=37) and "Non-Famine Years" (n=573) yields only the NAO as a significant variable (t=-2.10, p=0.041). The consistent climate for this shorter early time period is a positive NAO pattern during famine years.

In contrast to the sparse significance of climate variables during the early "A Years" time period, the "B Years" (1659-1955) t-tests resulted in most of the climate variables displaying significant differences between famine and non-famine years. The "All Famine" (n=86) and "Non-Famine" (n=211) analysis produced significant differences of means using the NAO, SOI, SASMI, Factor 1 (NAO and SOI) and Dfactor1 (NAO and SOI). The strongest discriminator between famine and non-famine years being Factor 1 (NAO and SOI) t=-3.96, p<0.001. The second strongest famine year discriminator being the NAO t=-3.24, p=0.002, followed by the SASMI t=2.93, p=0.004,

Dfactor 1 (NAO and SOI) t=-2.64, p=0.009, and SOI t=2.25, p=0.025. In a similar fashion, segregation by "Major Famine" (n=50) and "Non-Famine" (n=247) during the B year time frame produced results with large numbers of significant climate variables including the NAO, SOI, DSOI, SASMI, Factor 1 (NAO and SOI), Dfactor 1 (NAO and SOI), and Factor 2 (SASMI). The best discriminator of famine was the Factor 1 (NAO and SOI) t=-4.51, p<0.001, followed by DSOI t=4.26, p<0.001, SASMI t=3.91, p<0.001, SOI t=3.79, p<0.001, Dfactor 1 (NAO and SOI) t=-2.98, p=0.004, NAO t=-2.86, p=0.006, and Factor 2 (SASMI) t=-2.46, p=0.017. As with the All Years time period the cumulative results indicate that famine, both "All Famine" and "Major Famine" are more likely to occur during a positive NAO and a negative SOI and SASMI. As described above a positive NAO is occurs when higher than usual pressure in the subtropical Atlantic Ocean and lower than normal pressure in the Arctic Ocean (Jones et al. 1997). A negative SOI is characterized by below normal air pressure in Tahiti and above normal air temperatures in Darwin. This phase of the SO is associated with El Niño, the warm water intrusion into the eastern South Pacific of warm equatorial waters (Diaz and Markgraf, 2000; Yan et al., 2011).

Overall, these results, point towards the NAO as being the most important global climatic influence on the occurrence of Indian famine. The phase of the NAO for each time period during famines is indicated to be positive. This is still significant when the persistent positive trends in the NAO dataset are accounted for by employing a detrended NAO dataset.

Of the three time periods studied (All, "A" and "B"), the "B Years" is the only time period in which the raw NAO outperforms the detrended DNAO in the t-tests. This

is because NAO time series shows much less trend in the "B Years" than the "A Years" or the "All Years" time series (Figure 4.2). In general, the underlying phases of the teleconnections (positive NAO and negative SOI) remains constant, with the addition that the SASMI is negative during the famine years. This implies that the atmospheric circulation modifications by a positive NAO and negative NAO, and the reduced monsoon precipitation on the Indian Sub-Continent during the negative SASMI years, affecting the occurrence of famine. The orthogonal nature of their respective component factors suggests that the affects on famine from the teleconnections NAO and SOI are independent from the affects of the SASMI.

In summary, across the three different time periods, famine years in general tend to occur during the positive phase of NAO, and when the SOI and SASMI are negative. The NAO-famine relationship is consistently the strongest; the NAO is indicated as significantly more positive for both "Major Famines" and "All Famine years" in all time categories. Specifically, 74 of the 87 years of "Major Famine" and 181 of the 220 years of "All Famine" occurred during positive NAO years, that is 85% and 82% respectively (Figure 4.11). The second strongest climate/famine relationship is the SASMI; it is indicated to be strongly negative during most famine years indicating that famine in India is associated with the failure of the monsoon. The South Asian Monsoon is a particularly strong indicator of "Major Famine," with "Major Famine" years having a markedly reduced monsoon index, as noted by Shi et al. (2014).

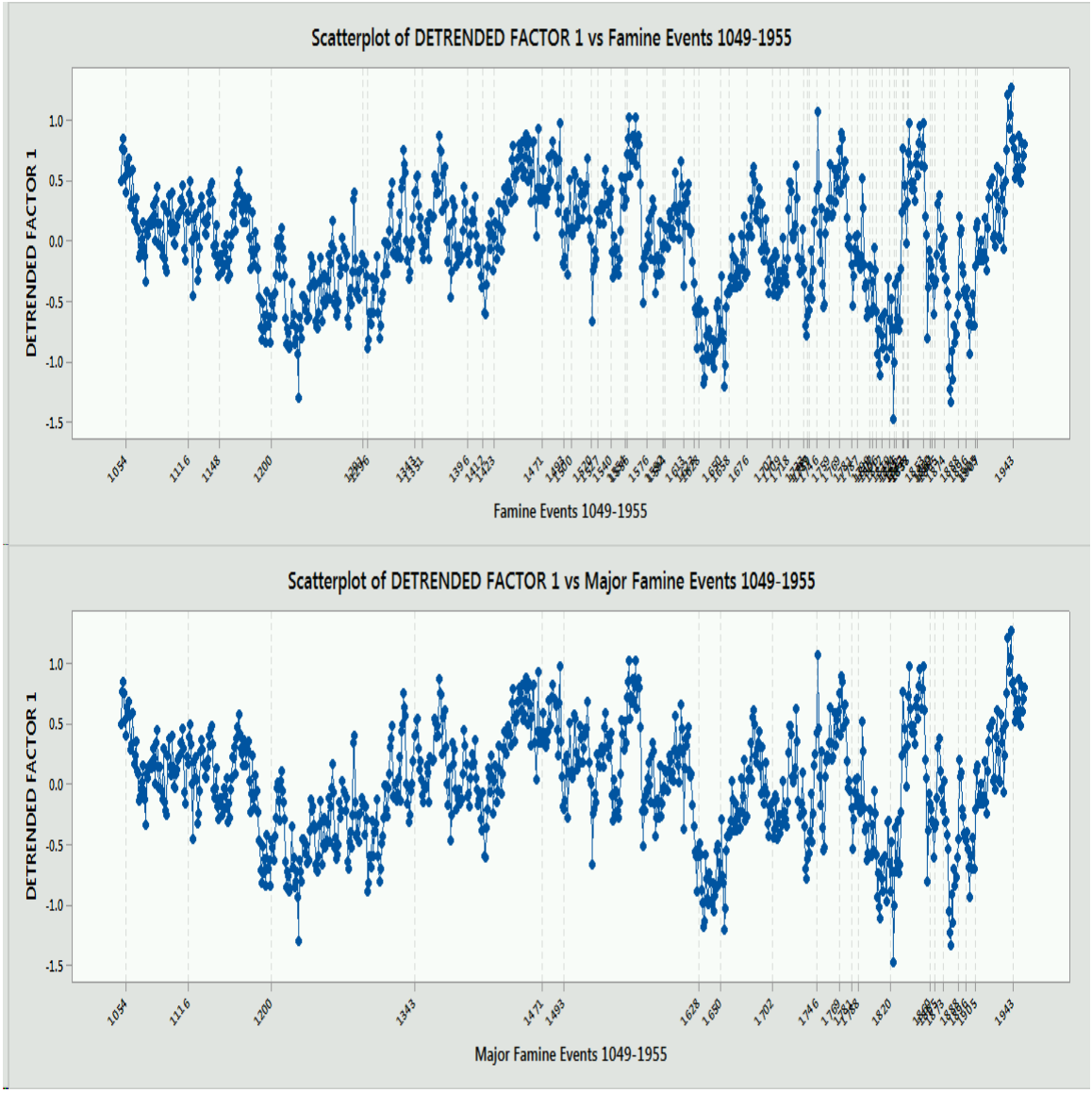


Figure 4.11. Top: Detrended Factor 1 in blue and the first year of 60 famine events in dashed vertical lines. Some famines starting in consecutive years were omitted for the sake of clarity on the figure reducing the number depicted from the 70 total famine events. Bottom: Detrended Factor 1 in blue and the first year of 21 major famine events in dashed vertical lines.

Conclusions

The occurrence of famine has been shown to be the result of a complex set of natural and human factors; Indian famine is no exception. To study the climatic influence on Indian famines, I identified 70 Indian famines from AD 1049 to-1955 and categorized

them by time and severity. I selected four interannual variations in our atmosphere and oceans, the teleconnections termed the Southern Oscillation (SOI), the North Atlantic Oscillation (NAO), the Pacific Decadal Oscillation (PDO) and the South Asian Summer Monsoon (SASM) to use as potential discriminators of Indian famine. In addition, following Santoro et al. (2015), I constructed a set of composite teleconnections using Principal Component Analysis. I then used t-tests do discriminate against the occurrence of famine by year with respect to each climate index.

This research indicates that famine in India occurs during the positive phase of the North Atlantic Oscillation. A positive NAO is characterized by higher than usual pressure in the subtropical Atlantic Ocean and lower than normal pressure in the Arctic Ocean (Jones et al. 1997). Possible explanations for this teleconnective phenomenon include positive NAO causing a more zonal flow in Asia (Chang et al., 2001), or changes to the tropospheric temperature gradients (Goswami et al., 2006).

In accord with a positive NAO pattern, famine in India is statistically linked to a negative Southern Oscillation teleconnection pattern. Overall, this suggests a consistent global pattern for the occurrence of famine in India with a negative SOI is identified by below normal air pressure in Tahiti and above normal air temperatures in Darwin, Australia (Diaz and Markgraf, 2000; Yan et al., 2011). A Reanalysis depiction of a positive NAO/negative SOI pattern shows that mid-tropospheric flow over India moves well south of the Indian sub-continent. Additionally, the northwesterly surface flow (as a result of an upper air low) likely draws dry continental warm air directly from the arid regions to the northwest. This was identified in two recent situations (1992 and 1896-1902).

Not surprisingly, the failure of the South Asian Monsoon, a specifically regional climate control, is statistically linked to the occurrence of famine in India. My results indicate that the South Asian Monsoon Index is significantly lower for famine years, and particularly for "major famine" years (as defined by Shi et al., 2014). This monsoonal influence likely manifests in a direct reduction of agricultural capacity and by extension a food availability decline. Although the Pacific Decadal Oscillation produces less consistent results, there is a significant discrimination of "Major Famines Years" with more positive values during the "All Years" time frame. Such a phase has is identified by anomalously warm SSTs in the northeastern Pacific (MacDonald and Case, 2005; Mantua and Hare, 2002).

There is a strong body of literature linking the conditions in the North Atlantic Ocean to the Asian Monsoon, especially the Indian Monsoon (e.g. Dugam et al., 1997, Kakade and Dugam, 2000, Hong et al., 2003; Burns et al., 2003; Wang et al., 2005; Goswami et al., 2006, Dugam, 2008, Roy 2011, Viswambharan and Mohanakumar 2014). However, the results from this analysis reveal that the relationship between the global and regional climate phenomena may be more complex. Specifically, the NAO, SOI, and SASMI were subjected to principal component analysis and their respective factor loadings resulted in an inverse NAO and SOI factor, and then a second SASMI factor. Because these two factors are orthogonal, this implies that, while NAO may contribute to the Asian Monsoon, there is variance in the Southeast Asian Monsoon that is not related to NAO.

The t-test results further indicate that these factors, and their constituent climate variables successfully discriminate famine years from non-famine years. Therefore, a

reasonable conclusion is that the NAO and SOI impact on famine can be independent from the SASMI impact of famine. The rationale for such a conclusion is that, first, the indices reconstructed to represent the SASM, the NAO and the SO are not exactly the same at the index, nor are the factors created by a PCA using these reconstructions. As a result of these differences there exists the possibility of a variable results. Second, and most importantly, NAO and SO are fundamentally different phenomena than the SASM. The NAO and SO are broad-based interannual variations in the state of the atmosphere and ocean with global ramifications (Jones et al., 1997; Diaz and Markgraf, 2000; Caviedes, 2001; Yan et al., 2011), whereas the SASM is a seasonal variation in the regional climate of South Asia (Sinha et al., 2007; Shi et al., 2014). Therefore potential effects of these teleconnections, in the context of Indian famine, can be independent, without fundamentally contradicting the existing literature suggesting linkages between the teleconnections.

Fundamentally, this study's identification of a strong statistical link between the North Atlantic Oscillation and Indian famine, beyond the direct association between famine and the South Asian Summer Monsoon, indicates the strength of influence by global climate phenomena on specific regional areas. Famines continue to be experienced in India in recent decades (Kumar et al., 2005), therefore continued study of the global climate's influence on India may aid in the prediction and hopeful prevention of famine based on climate conditions corroborative development of regional famine.

CHAPTER 5

CONCLUSIONS

Summary of Results

The threat of famine has been an existential threat to civilizations throughout the world for thousands of years and famine still threatens people today. Much of the existing famine research has focused on one of two schools of thought for famine causation: 1) social and societal influences, or 2) climatic and environmental. The first involves social causes, such as war, politics, social class systems, which link to famine by either limiting peoples access to food through what is know as Food Entitlement Decline (FED), or by limiting the supply of food through what is know as Food Availability Decline (FAD). The second factor involves climate variations as influencing famine patterns, such as crop loss from flooding, drought, and pests, which can contribute to FAD. Given the significance of climate on famine, it is likely that a better understanding of the environmental influence on historical famine would aid in the more accurate prediction of future famine events. Determination of the causal impacts of climate on globally significant historical regions can provide valuable information on historical events and, with appropriate intervention, can help avert future disaster. Consequently, the focus of this dissertation has been the study of the environmental and climatological conditions that contribute to famine. I have undertaken this research through case study analysis of three historical famine regions around the world. My specific research question is phrased as follows:

What is the aggregate influence of climate teleconnections, such as the North Atlantic Oscillation, El Niño Southern Oscillation, the Pacific Decadal Oscillation or the Atlantic Multidecadal Oscillation, or regional climate phenomena such as the South Asian Summer Monsoon on the historical occurrence famine around the world?

This research question leads to my primary research hypothesis:

Climate, as represented by an aggregated teleconnection variable, incorporating the shared variance of many teleconnections (such as the North Atlantic Oscillation and El Niño Southern Oscillation), will account for a significant amount of variance in the occurrence of specific regional famines (e.g., in Egypt, India or The British Isles) over the last 1000 years. I also hypothesize that such an aggregated teleconnection will correlate better to those regional famines than will any single climate teleconnection.

My research has been rooted in two primary constructs: 1) The existence of a relationship between climate and weather elements and the occurrence of famine, and 2) Documentation of impact on global weather and climate patterns by climatic teleconnections (e.g. North Atlantic Oscillation (NAO) or El Niño Southern Oscillation (ENSO)).

Climate teleconnections are interannual, ocean and atmospheric oscillations of wind, air pressure and ocean temperatures, that can impact the weather in regions far

beyond their specific location. They are large-scale, often multi-year, oceanic and atmospheric variations in circulation that can affect weather and climate over large areas of the Earth. I have explicitly included the following climate teleconnections in this research:

(1) The North Atlantic Oscillation (NAO) is a major interannual variation of atmospheric circulation in the North Atlantic Ocean that is often characterized by the air pressure difference between Iceland and the Azores.

(2) The Atlantic Multidecadal Oscillation (AMO) is a long-term (decadal) variation in climate best characterized by sea surface temperature variations across the Atlantic Ocean.

(3) El Niño Southern Oscillation (ENSO) is a multi-year ocean-atmospheric oscillation in the equatorial Pacific Ocean that caused changes in precipitation patterns around much of the world.

(4) The Pacific Decadal Oscillation (PDO) is a long-term (decadal) oscillation of SSTs and atmospheric circulation in the Northern Pacific Ocean.

In addition to these climate teleconnections, I included in one of the case studies, a regular seasonal variations in climate patterns, the South Asian Summer Monsoon. The South Asian Summer Monsoon (SASM), also known as the Indian Monsoon, is the annual migration of the Intertropical Convergence Zone (ITCZ) that produces variations in rainfall across India and South Asia.

These teleconnections and regional phenomenon provided the foundation for each of my three regional studies, Egypt, Great Britain and India.

Egyptian Famine and Aggregated Climate Indices

To address the question of how aggregated climate teleconnections may have impacted famine patterns in Egypt, I led a study comparing an aggregate of a set of climate teleconnections to a newly formed list of Egyptian famines and recorded Nile River levels. The comprehensive list of famines, compiled from a collection of historical texts or first-hand accounts, established ten major famines and several minor events between the years AD 1049-1922. Nile River level information utilized for that study were based on measurements on devices known as Nilometers. Climate reconstructions including: 1) the North Atlantic Oscillation (NAO), using a reconstruction by Trouet et al. (2009) based on a tree ring drought reconstruction from Morocco, and a speleothem precipitation reconstruction from Scotland, 2) the El Niño / Southern Oscillation using a reconstruction of the Southern Oscillation Index (SOI) by Yan et al. (2011) developed from reconstructed precipitation levels of the equatorial Pacific Ocean, 3) the Pacific Decadal Oscillation (PDO) using a reconstruction by MacDonald and Case (2005) derived using tree ring chronologies from Southern California and Western Canada. The teleconnections combined to provide a timeline extending AD 1049-1922. The climate reconstructions of the NAO, SOI, and PDO were subjected to a Principal Component Analysis (PCA) yielding a NAO and SOI aggregate data set. A Student's t-test utilizing the NAO and SOI aggregate failed to discriminate between famine and non-famine years however, examining the time period immediately preceding a famine year was more significant.

In order to capture the cumulative effects of climate leading up to famine conditions, this study established categories for the t-tests including; the five, 10, and 15

years before each recorded famine into the "famine years" group and all other years into the "non-famine years" group. The resultant t-values were 2.57 (p = 0.012), 3.33 (p = 0.001), and 3.84 (p = 0.000) respectively. These results indicate that the aggregated climate index captures the occurrence of Egyptian famine events by showing a possible decadal-scale effect on climate that can create conditions that lead up to and contribute to severe famine. When the reconstructed Nile River values are classified into high river values and low river values (defined higher than or lower than one standard deviation of the mean river level), the NAO-SOI eigenvector significantly discriminated between high and low levels at the 99.9 percent confidence level (t = 4.87; p = 0.0001). In addition to the documented famine years, there were 80 incidents of stress to the Egyptian people related to Nile River levels; of the 80 incident years, 50 events (63%) were associated with a general decline in the aggregated teleconnection index and many of the minor events are associated with, or leading to, more serious famine events.

These results affirmed my primary hypothesis that the aggregate of climate teleconnections (in this case, a NAO and SOI aggregate data set) was a better predictor of historical famine in Egypt than any single climate variable. In addition to the statistical significance of these results, the creation of the comprehensive Egyptian famine list for the period AD 1049 to 1922 was a singular accomplishment; as such a complete list had not been previously assembled.

Historical British Famine and Weather Attributed Famines

In order to continue to address the question of how well aggregated climate teleconnections influence regional famines, I led a study that assessed the influence of

climate teleconnections on a time series of historical British famines. I complied the chronology of famines from a variety of historical texts and chronologies. The famine history of the British Isles was extensive, including 172 famines that occurred between AD 1049 and 1914, Sixty-two of these famines were explicitly attributed to weather or climate in the historical texts. I then compared these weather-attributed famines to the climate teleconnections including: 1) the Trouet et al. (2009) North Atlantic Oscillation (NAO), 2) the El Niño / Southern Oscillation using the Yan et al. (2011) reconstruction of the Southern Oscillation Index (SOI), 3) the Pacific Decadal Oscillation (PDO) using the reconstruction by MacDonald and Case (2005), and 4) Atlantic Multidecadal Oscillation (AMO) using a reconstruction by Gray et al. (2005) based on twelve tree ring samples surrounding the North Atlantic for the years AD 1049-1914.

The aggregate method discussed in the previous section for the Egyptian study failed to yield significant results for the British Isles. I then compared the famines to the climate teleconnections through a series of Student's t-tests that included real time and lagged time comparisons of five and ten years preceding a famine. Several of the individual climate variables and lagged climate variables showed significant t-test results, specifically the NAO, NAO-Lag 5, PDO and PDO Lag-5.

In order to rank the importance of these results I employed the use of a Stepwise Discriminant Analysis (SDA), in this case to establish how accurately, and in what order the four independent variables reclassify the nominative groups of weather-attributed famine versus non-famine years. The NAO Lag-5 was the strongest predictor of famine and was alone able to correctly classify 73.8% of the weather-attributed famines over the study period (45 out of 61 incidents). The addition of the NAO, PDO and PDO Lag-5 to

the SDA only marginally improved the classification to 75.4% of weather-attributed famines.

These results failed to confirm the hypothesis that the aggregation of climate teleconnections would be a primary predictor of famine in the British Isles. Possible reasons for this include: 1) Geographically the British Isles are a mid-latitude region, where as Egypt and India (described in the next section) are sub-tropical, the aggregated climate impact may be different or non-existent at these latitudes. 2) The NAO is the primary climatic predictor of British famine, and a significant portion of the variance captured in the factors determined to be of importance for Egypt and India, and since the NAO's influence in Europe is so strong, and its geographic proximity so close, the NAO's influence may overwhelm the significance of the other teleconnections. The SDA did reveal influence by the PDO, but it was an order of magnitude less impactful than the NAO. Despite the failure to confirm the original hypothesis, these results do suggest that the lagged NAO's effect on the British Isles is strongly related to those specific famines attributed to weather and climate.

Indian Famines and the NAO, SOI and SASMI

As a third test of how well do aggregated climate teleconnections represent regional famines, I undertook a study that assessed the influence of climate teleconnections to a time series of historical famines in India. First, I compiled a list of famines through various sources for AD 1049 to AD 1955 and then statistically compared them to climate teleconnections, using the Trouet et al. (2009) North Atlantic Oscillation (NAO), the El Niño / Southern Oscillation using the Yan et al. (2011) reconstruction of

the Southern Oscillation Index (SOI), and the Pacific Decadal Oscillation (PDO) using the reconstruction by MacDonald and Case (2005). Additionally, I included the South Asian Summer Monsoon Index (SASMI), a regional annual climate phenomenon. The reconstruction of the SASMI by Shi et al. (2014) was developed using tree ring reconstructions from India and China.

My famine list was compiled from various historical texts and chronologies and included 220 famines, 87 of which are considered severe famines. I then conducted a Principal Component Analysis (PCA) of the climate reconstructions of the NAO, SOI, and PDO. The PCA produced two factors, the first primarily based on NAO and SOI such that the component loadings for the SOI and NAO were negatively loaded onto the NAO and positively loaded onto the SOI. The second PCA factor was an orthogonal component primarily loaded onto the SASMI.

These two aggregate indices, along with the independent NAO, SOI, and SASMI were subjected to a series of Student's t-tests. The results of the t-tests indicate, through the NAO and SOI factor, that a positive NAO and negative SOI are cumulatively the best predictor of famine. The second and independently related factor is the SASMI, which is likely to be negative during famine conditions. Previous research notes a shift in SASMI patterns in the year 1659 (Shi et al., 2014); taking this into account, the famine events were separated into two time periods, before AD 1659 and after 1659. This separation did not change the fundamental results of a positive NAO and negative SOI and independently the negative SASMI as the best predictors of famine.

These results for India support the hypothesis that an aggregated climate teleconnection can be a better predictor of famine than a single climate variable. They

also suggest that, despite a link between the NAO and South Asian Summer Monsoon (SASM), that their specific effects on regional famine are independent from one another. These results are of value to a global region that still experiences a form of famine.

Overall Conclusions

These three studies of regional famine produced mixed results with regard to my research hypothesis. While the Egyptian and Indian studies do indicate that aggregated climate teleconnections created through statistical analysis can perform significantly better than individual teleconnections in identifying famines, the British study did not support my hypothesis. This could be due to the mid-latitude location of the British Isles relative to the sub-tropical latitudes of Egypt and India. Another possibility is that the British Isles proximity to the physical processes of the NAO may result in the NAO overwhelming the impact of the other teleconnections. Thirdly, the data employed in these analyses are reconstructions, and reconstructions are not the same as the actual index, and so there exists the possibility of variable results. As described in the next section, this apparent contradiction is in need of further research.

Consequently, I can fundamentally conclude that climate elements such as teleconnections, in conjunction with social elements, can have a significant impact of famine patterns in Egypt, the British Isles, and India, and that the aggregate of climate teleconnections is often a better predictor of famine than any one element of climate.

Future Research

My research indicates that, for the majority of my regional sites, the cumulative effects of global climate are likely to have greater influence on the famine patterns than any single teleconnection or weather component. However, based on past literature, it is clear that environmental impacts do not act alone in creating the conditions for famine. A combination of environmental and social causes ultimately leads to famine.

These conclusions lead to additional opportunity and need for research. First, this dissertation only evaluated the famines of three geographical areas. Regions, such as Continental Europe, China and East Asia, and other parts of Africa, also have experienced ruinous historical famines; indeed, some of these locations continue to experience famine in modern times. These geographical locations have also been identified with climate teleconnection influences. Consequently, I would suggest that these areas should be examined for similar aggregate climate/famine relationships.

Second, as addressed above, further investigation is needed to understand why the famines of the British Isles did not show as strong of a relationship with the aggregates of climate compared to the relative impact of aggregated climate on Egyptian and Indian famines.

Third, the interrelationship between the environmental and social causes of famine must be better understood.

Fourth, as climate reconstructions are improved and extended further back into history, the opportunity will exist to reevaluate and extend the analyses discussed in this dissertation.

Significance

Famine can have catastrophic consequences. Historically, it has taken the lives of millions of people. The importance of understanding the causes of famine is reflected in the wealth of literature on the subject. However, despite this wealth of research, the understanding of the complex environmental and social causes of famine is still not completely understood. This dissertation has addressed on primary influence on famine, climate. I have statistically established that in locations such as Egypt, the British Isles, and India the environmental contributions to famine patterns are complex and can often be the result of multiple components of climate. Through the compilation of famine records and the analysis of these famines with respect to environmental conditions, I have demonstrated that climate, particularly the combined variances of climate teleconnections, can be a primary factor in the occurrence of famine.

Fundamentally, my work has emphasized the importance of climate as one the principal components contributing to famine. Through increased knowledge of the precise effects of climate on famine, I hope that this research may help save future lives by prediction of the antecedent conditions of future famine events, and thus allowing for appropriate advanced preparations or resource allocation.

REFERENCES

Abtew W, Melesse AM and Dessalenge T (2009) El Niño Southern Oscillation link to the Blue Nile River Basin hydrology. *Hydrolgical Processes* 23: 3653-3660 DOI:10.1002/hyp.7367

Adamson, G. C. (2014). Institutional and community adaptation from the archives: A study of drought in western India, 1790–1860. *Geoforum*, *55*, 110-119.

Al Baghdadi A (1204) Kitab Al-Ifada wa'l Itibar [the Eastern Key] (Kamal, H. Z., and Videan J. A. Videan I. E. Trans. 1964) George Allen and Unwin Ltd., London

Amarasekera KN, Lee RF, Williams ER et al. (1997) ENSO and the natural variability in the flow of tropical rivers. *Journal Hydrology* 200:24-39

Ambirajan, S. (1976). Malthusian population theory and Indian famine policy in the nineteenth century. *Population Studies*, *30*(1), 5-14.

Anonymous (1930a). Historic Natural Event. *Nature*, 125(3149, 3150, 3152, 3153), 396, 432, 512, 548

Anonymous (1930b). Historic Natural Event. *Nature*, 126(3188, 3190), 901, 974

Baker A, Proctor CJ, Barnes WL (2002) Stalagmite lamina doublets: a 1000-year proxy record of severe winters in northwest Scotland? *International Journal of Climatology* 22:1339-1345. DOI:10.1002/joc.800

Balfour, E. (1885) The Cyclopædia of India and of Eastern and Southern Asia: Commercial, Industrial and Scientific, Products of the Mineral, Vegetable, and Animal Kingdoms, Useful Arts and Manufactures (Vol. 3). B. Quartitch.

Balling RC and Cerveny RS (1995) Influence of lunar phase on daily global temperatures. *Science* 267:1481-1482 DOI: 10.1126/science.267.5203.1481

Bartlett, M. S. (1935). The effect of non-normality on the t-distribution. Proceedings of the Cambridge Philosophical Society, 31, 223-231.

Bhatia, B. M. (1967). Famines in India; a study in some aspects of the economic history of India, 1860-1965.

Bliss EW (1926) The Nile flood and world weather. *Memoir Royal Meteorological Society* 1: 79-85

Brandimarte L and Baldassarre GD (2011) Relation between the North Atlantic Oscillation and hydroclimatic conditions in the Mediterranean areas. *Water Resource Management* 25:1269-1279 DOI:10.1007/s11269-010-9742-5

Brewis, G. (2010). 'Fill Full the Mouth of Famine': Voluntary Action in Famine Relief in India 1896–1901. *Modern Asian Studies*, 44(04), 887-918.

Briggs, C. (2005). Taxation, warfare, and the early fourteenth century 'crisis' in the north: Cumberland lay subsidies, 1332–13481. *The Economic History Review*, 58(4), 639-672. DOI: 10.1111/j.1468-0289.2005.00317.x

Brommer, D. M., Balling, R. C., & Cerveny, R. S. (2003). Local and Regional Discriminators of Mesoscale Convective Vortex Development in Arizona. *Monthly Weather Review*, 131(8).

Burns, S. J., Fleitmann, D., Matter, A., Kramers, J., & Al-Subbary, A. A. (2003). Indian Ocean climate and an absolute chronology over Dansgaard/Oeschger events 9 to 13. *Science*, *301*(5638), 1365-1367.

Butler, S. H. (1908). Famine. The Imperial Gazetteer of India. The Indian Empire. Economic, 3, 475-502.

Campbell, B. (2010). Nature as historical protagonist: environment and society in pre‐industrial England. *The Economic History Review*, 63(2), 281-314. DOI: 10.1111/j.1468-0289.2009.00492.x

Caviedes, C. (2001). El Niño in history: storming through the ages. University Press of Florida.

Chang, C. P., Harr, P., & Ju, J. (2001). Possible roles of Atlantic circulations on the weakening Indian monsoon rainfall–ENSO relationship. *Journal of Climate*, *14*(11), 2376-2380.

Chen, Q. (2015). Climate Shocks, State Capacity and Peasant Uprisings in North China during, 25–1911 CE. *Economica*, 82(326), 295-318. DOI: 10.1111/ecca.12114

Cleveland WS and Devlin SJ (1998) Locally weighted regression: An approach to regression analysis by local fitting. *Journal of the American Statistical Association* 83:596-610

Collier, M., & Webb, R. H. (2002). Floods, droughts, and climate change. University of Arizona Press.

Compo, G. P., Whitaker, J. S., Sardeshmukh, P. D., Matsui, N., Allan, R. J., Yin, X., Gleason, B. E., Vose, R. S., Rutledge, G., Bessemoulin, P., Brönnimann, S., Brunet, M., Crouthamel, R. I., Grant, A. N., Groisman, P. Y., Jones, P. D., Kruk, M. C., Kruger, A. C., Marshall, G. J., Maugeri, M., Mok, H. Y., Nordli, Ø., Ross, T. F., Trigo, R. M., Wang, X. L., Woodruff, S. D. and Worley, S. J. (2011), The Twentieth Century Reanalysis Project. *Quarterly Journal of the Royal Meteorological Society*, 137: 1–28. doi:10.1002/qj.776

Currey, B., & Hugo, G. (Eds.). (2012). Famine: As a geographical phenomenon (Vol. 1). Springer Science & Business Media.

D'Arrigo, R., & Wilson, R. (2006). On the Asian expression of the PDO. *International Journal of Climatology*, *26*(12), 1607-1617.

Dando, W. A. (1980). The geography of famine. *Scripta Series in Geography*.

Dark, P., & Gent, H. (2001). Pests and diseases of prehistoric crops: a yield 'honeymoon'for early grain crops in Europe?. *Oxford Journal of Archaeology*, *20*(1), 59-78.

Dawson, A. G., Hickey, K., Mayewski, P. A., & Nesje, A. (2007). Greenland (GISP2) ice core and historical indicators of complex North Atlantic climate changes during the fourteenth century. *The Holocene*, 1*7*(4), 427-434.

Davis, M. (2002). Late Victorian holocausts: El Niño famines and the making of the third world (p. 529). London: Verso.

Derbyshire, I. D. (1987). Economic Change and the Railways in North India, 1860–1914. Modern Asian Studies, 21(03), 521-545.

DeWitte, S. N. (2012). Sex differences in periodontal disease in catastrophic and attritional assemblages from medieval London. *American journal of physical anthropology*, 1*49*(3), 405-416.

DeWitte, S. N. (2015). Setting the stage for medieval plague: Pre‐black death trends in survival and mortality. *American Journal of Physical Anthropology*, 158(3), 441-451. DOI: 10.1002/ajpa.22806

DeWitte, S., & Slavin, P. (2013). Between famine and death: England on the eve of the Black Death—evidence from paleoepidemiology and manorial accounts. *Journal of Interdisciplinary History*, 44(1), 37-60. doi:10.1162/JINH_a_00500

Diaz, H. F., & Markgraf, V. (1992). El Niño: historical and paleoclimatic aspects of the Southern Oscillation. Cambridge: Cambridge University Press.

Diaz, H. F., & Markgraf, V. (2000). El Niño and the Southern Oscillation: multiscale variability and global and regional impacts. Cambridge: Cambridge University Press.

Drake, B. L. (2017). Changes in North Atlantic Oscillation drove Population Migrations and the Collapse of the Western Roman Empire. *Scientific Reports*, *7*(1), 1227.

Dugam, S. S. (2008). Use of interactions between NAO and MJO for the prediction of dry and wet spell in monsoon season. *Journal Earth Sciences India*, *111*, 219-228.

Dugam, S. S., Kakade, S. B., & Verma, R. K. (1997). Interannual and long-term variability in the North Atlantic Oscillation and Indian summer monsoon rainfall. *Theoretical and Applied Climatology*, *58*(1-2), 21-29.

Elagib, N. A. (2014). Development and application of a drought risk index for food crop yield in Eastern Sahel. *Ecological Indicators*, 43, 114-125. DOI: 10.1016/j.ecolind.2014.02.033

El Din SS (1977) Effect of the Aswan High Dam on the Nile flood and on the estuarine and coastal circulation pattern along the Mediterranean Egyptian coast. Limnology and Oceanography, 22: 194-207.

Ellman, M. (2000). The 1947 Soviet famine and the entitlement approach to famines. *Cambridge Journal of Economics*, 24(5), 603-630. doi: 10.1093/cje/24.5.603

Eltahir EAB (1996) El Niño and the natural variability in the flow of the Nile River. *Water Resource Research* 32: 121-137

Engler, S. (2012). Developing A Historically Based" Famine Vulnerability Analysis Model"(Fvam)—An Interdisciplinary Approach. *Erdkunde*, 157-172. DOI: 10.3112/erdkunde.2012.02.05

Engler, S., Luterbacher, J., Mauelshagen, F., & Werner, J. (2013). The Irish famine of 1740–1741: causes and effects. *Climate of the Past Discussions*, *9*(1), 1161-1179.

Engler, S., Mauelshagen, F., Werner, J., & Luterbacher, J. (2013). The Irish famine of 1740–1741: famine vulnerability and" climate migration". *Climate of the Past*, 9(3), 1161-1179. DOI:10.5194/cp-9-1161-2013

Engler, S., & Werner, J. P. (2015). Processes prior and during the early 18th Century Irish famines—Weather extremes and migration. *Climate*, 3(4), 1035-1056. doi:10.3390/cli3041035

Esper J, Cook ER, and Schweingruber FH (2002) Low-Frequency signals in long tree-ring chronologies for reconstructed past temperature variability. *Science* 295 2250- 2253

Faust, J. C., Fabian, K., Milzer, G., Giraudeau, J., & Knies, J. (2016). Norwegian fjord sediments reveal NAO related winter temperature and precipitation changes of the past, 2800 years. *Earth and Planetary Science Letters*, 435, 84-93. DOI: 10.1016/j.epsl.2015.12.003

Fleitmann, D., Burns, S. J., Mangini, A., Mudelsee, M., Kramers, J., Villa, I., & Matter, A. (2007). Holocene ITCZ and Indian monsoon dynamics recorded in stalagmites from Oman and Yemen (Socotra). *Quaternary Science Reviews*, *26*(1), 170-188.

Fraser, E. D. (2006). Food system vulnerability: Using past famines to help understand how food systems may adapt to climate change. *Ecological Complexity*, 3(4), 328-335.

Fraser, E. D. (2007). Travelling in antique lands: using past famines to develop an adaptability/resilience framework to identify food systems vulnerable to climate change. *Climatic Cha*nge, 83(4), 495-514. DOI: 10.1007/s10584-007-9240-9

Fukazawa, H. (1982). Agrarian Relations and Land Revenue: The Medieval Deccan and Maharashtra. *The Cambridge economic history of India*, 1, 249-60.

Galloway, P. R. (1986). Long-term fluctuations in climate and population in the preindustrial era. *Population and Development Review*, 1-24. DOI: 10.2307/1973349

Ganguli, R. (1933). Famine in Ancient India. *Annals of the Bhandarkar Oriental Research Institute*, *15*(3/4), 176-197.

Geary, R. C. (1947). Testing for Normality, *Biometrika*, 34, 209-242.

Goswami, B. N., Madhusoodanan, M. S., Neema, C. P., & Sengupta, D. (2006). A physical mechanism for North Atlantic SST influence on the Indian summer monsoon. *Geophysical Research Letters*, *33*(2).

Grove, R. H. (2006). The great El Niño of 1789–93 and its global consequences: Reconstructing an extreme climate event in world environmental history. *The Medieval History Journal*, *10*(1-2), 75-98.

Gray, S. T., Graumlich, L. J., Betancourt, J. L., & Pederson, G. T. (2004). A tree‐ring based reconstruction of the Atlantic Multidecadal Oscillation since 1567 AD. *Geophysical Research Letters*, 31(12). DOI: 10.1029/2004GL019932

Hallam, H. E. (1984). The climate of eastern England, 1250-1350. *The Agricultural History Review*, 32(2), 124-132.

Hassan FA (1981): Historical Nile floods and their implications for climatic change. *Science*, 212:1142-1145 doi:10.1126/science.212.4499.1142

Hassan, F. A. (2007a). Extreme Nile floods and famines in Medieval Egypt (AD 930–1500) and their climatic implications. *Quaternary International*, 173, 101-112. DOI: 10.1016/j.quaint.2007.06.001

Hassan FA (2007b) Droughts, famine and the collapse of the Old Kingdom: re-reading Ipuwer In: Hawass ZA, Richards J (ed) The archaeology and art of ancient Egypt: Essays in honor of David B. O'Connor Conseil Supreme Des Amiquites De L'egypte, Le Caire, pp. 357

Hastenrath, S. (1987). On the prediction of India monsoon rainfall anomalies. *Journal of climate and applied meteorology*, *26*(7), 847-857.

Holmes, N., Langdon, P. G., Caseldine, C. J., Wastegård, S., Leng, M. J., Croudace, I. W., & Davies, S. M. (2016). Climatic variability during the last millennium in Western Iceland from lake sediment records. *The Holocene*, doi: 10.1177/0959683615618260.

Hong, Y. T., Hong, B., Lin, Q. H., Zhu, Y. X., Shibata, Y., Hirota, M., ... & Wang, H. (2003). Correlation between Indian Ocean summer monsoon and North Atlantic climate during the Holocene. *Earth and Planetary Science Letters*, *211*(3), 371-380.

Horsnell, G. (1953). The effect of unequal group variances on the F-test for the homogeneity of group means. *Biometrika,* 40(1/2), 128-136.

Jackson, J.E. (1991) A user's guide to principal components. Hoboken: Wiley and Sons

Jansen E, Koc N (2000) Century to decadal scale records of Norwegian Sea surface temperature variations of the past 2 millennia. Pages/ Clivar Newsletter 8:13-14

Jones, P.D., Jonsson, T., Wheeler. D. (1997) Extension of the North Atlantic Oscillation using early instrumental pressure observations from Gibraltar and South-West Iceland. *International Journal of Climatology* 17:1433-1450

Jordan, W. C. (1997). The Great Famine: Northern Europe in the early fourteenth century. Princeton: Princeton University Press.

Jury MR, Enfield DB, Mélice J (2002) Tropical monsoons around Africa: Stability of El Niño-Southern Oscillation associations and links with continental climate. *Journal of Geophysical Research* 107: 3151-3168 DOI:10.1029/2000JC000507

Jury MR (2009) Ethiopian decadal climate variability. *Theoretical and Applied Climatology* 101:29-40 DOI:10.1007/s00704-009-0200-3

Kahn S, Ganguly AR Bandyopadhyay S et al. (2006) Nonlinear statistics reveals stronger ties between ENSO and the tropical hydrological cycle. *Geophysical Research Letters* 33: L24402 DOI:10.1029/2006GL027941

Kakade, S. B., & Dugam, S. S. (2000). The simultaneous effect of NAO and SO on the monsoon activity over India. *Geophysical research letters*, *27*(21), 3501-3504.

Keeping, E. S. (1962) Introduction to Statistical Inference.(Vol.26), 1962 Courier Corperation, New York

Kershaw, I. (1973). The great famine and agrarian crisis in England 1315-1322. *Past & Present*, (59), 3-50.

Keys, A., Brožek, J., Henschel, A., Mickelsen, O., & Taylor, H. L. (1950). The biology of human starvation. 1950 University of Minnesota Press

Knight, J. R., Folland, C. K., & Scaife, A. A. (2006). Climate impacts of the Atlantic multidecadal oscillation. *Geophysical Research Letters*, 33(17). DOI: 10.1029/2006GL026242

Kondrashov D, Felkis Y and Ghil M (2005) Oscillatory modes of extended Nile River records (A.D. 622-1922). *Geophysical Research Letters* 32: L10702 DOI:10.1029/2004GL022156

Krishna Kumar, K., Rupa Kumar, K., Ashrit, R. G., Deshpande, N. R., & Hansen, J. W. (2004). Climate impacts on Indian agriculture. *International Journal of Climatology*, *24*(11), 1375-1393.

Krishnan, R., & Sugi, M. (2003). Pacific decadal oscillation and variability of the Indian summer monsoon rainfall. *Climate Dynamics*, *21*(3-4), 233-242.

Kumar, R. H., Venkaiah, K., Arlappa, N., Kumar, S., Brahmam, G. N. V., & Vijayaraghavan, K. (2005). Diet and nutritional situation of the population in the severely drought affected areas of Gujarat. *Journal of Human Ecology*, *18*(4), 319-326.

Kumar, M. (2016). Vagaries of Monsoon, Resilience of Society: Revisiting Nature of Socio-political Structures in Early-modern Rajasthan. *Studies in History*, *32*(2), 209-230.

Lamb, H. H. (2002). Climate, History and the Modern World., 2002, Routledge, London.

Lamb PJ, and Peppler RA (1987) North Atlantic Oscillation: Concept and Application. *Bulletin of the American Meteorological Society* 68: 1218-1225

Lenihan, P. (1997). War and population, 1649–52. *Irish Economic and Social History*, 1-21.

Li, J., Yu, R., & Zhou, T. (2008). Teleconnection between NAO and climate downstream of the Tibetan Plateau. *Journal of Climate*, *21*(18), 4680-4690.

Lieberman, V. (2009). Strange Parallels: Volume 2, Mainland Mirrors: Europe, Japan, China, South Asia, and the Islands: Southeast Asia in Global Context, C. 800-1830 (Vol. 2). Cambridge University Press.

Lima, M. (2014). Climate change and the population collapse during the "Great Famine" in pre-industrial Europe. *Ecology and evolution,* 4(3), 284-291.

Loveday, A. (1914). The history and economics of Indian famines. G. bell and sons ltd.

Lucas, H. S. (1930). The great European famine of 1315, 1316, and 1317. *Speculum*, 5(04), 343-377.

Luterbacher, J., Dietrich, D., Xoplaki, E., Grosjean, M., & Wanner, H. (2004). European seasonal and annual temperature variability, trends, and extremes since 1500. *Science*, 303(5663), 1499-1503. DOI: 10.1126/science.1093877

MacDonald GM and Case RA (2005) Variations in the Pacific Decadal Oscillation over the past millennium. *Geophysical Research Letters* 32: L08703 doi:10.1029/2005GL022478

Malthus, T. R. (1798). An Essay on the Principle of Population, as it Affects the Future Improvement of Society: With Remarks on the Speculations of Mr. Godwin, Mr. Condorcet, and Other Writers.

Mantua NJ and Hare SR (2002) The Pacific decadal oscillation. *Journal of Oceanography* 58:35-44 doi:10.1023/A:1015820616384

Marini, C., & Frankignoul, C. (2014). An attempt to deconstruct the Atlantic Multidecadal Oscillation. *Climate Dynamics*, 43(3-4), 607-625. DOI: 10.1007/s00382-013-1852-3

McAlpin, M. (1979). Dearth, Famine, and Risk: The Changing Impact of Crop Failures in Western India, 1870–1920. *The Journal of Economic History, 39*(1), 143-157. doi:10.1017/S0022050700096352

Miller F. P., Vandome A. F., John M.B. (2010). Famine in India. VDM Publishing.

Moon, W. J. (2009). Origins of the Great North Korean Famine: Its Dynamics and Normative Implications. *North Korean Review*, 5, 105. DOI: 10.3172/NKR.5.1.105

Müller, W. A., Frankignoul, C., & Chouaib, N. (2008). Observed decadal tropical Pacific–North Atlantic teleconnections. *Geophysical Research Letters*, 35(24). DOI: 10.1029/2008GL035901

Murton, B. (1984). Spatial and temporal patterns of famine in southern India before the famine codes. In Famine (pp. 71-90). Springer Netherlands.

Nash, J. R. (1976). Darkest Hours: a narrative encyclopaedia of worldwide disasters from ancient times to the present. Chicago: Nelson-Hall.

Nash, M. (2002). El Niño: unlocking the secrets of the master weather-maker. FNAL (Fermi National Accelerator Laboratory (FNAL), Batavia, IL (United States)).

ÓGráda, C. (2009). Famine: a short history. Princeton: Princeton University Press.

Olsen, J., Anderson, N. J., & Knudsen, M. F. (2012). Variability of the North Atlantic Oscillation over the past 5,200 years. *Nature Geoscience*, *5*(11), 808-812.

Ortega, P., Lehner, F., Swingedouw, D., Masson-Delmotte, V., Raible, C. C., Casado, M., & Yiou, P. (2015). A model-tested North Atlantic Oscillation reconstruction for the past millennium. *Nature*, 523(7558), 71-74. doi:10.1038/nature14518

Parthasarathy, B., Sontakke, N. A., Monot, A. A., & Kothawale, D. R. (1987). Droughts/floods in the summer monsoon season over different meteorological subdivisions of India for the period 1871–1984. *Journal of Climatology*, *7*(1), 57-70.

Pearson, E. S. (1931). I. Note on Tests for Normality. *Biometrika*, 22(3-4), 423-424.

Pinto, J. G., & Raible, C. C. (2012). Past and recent changes in the North Atlantic oscillation. Wiley Interdisciplinary Reviews: *Climate Change*, 3(1), 79-90. DOI: 10.1002/wcc.150

Proctor CJ, Baker A Barnes WL, Gillmour MA (2000) A thousand year speleothem proxy record of North Atlantic climate of Scotland. *Climate Dynamics* 16:815-820.

Rai, P., & Smucker, T. A. (2016). Empowering through entitlement? The micro-politics of food access in rural Maharashtra, India. *Journal of Rural Studies*, *45*, 260-269.

Ramadan, H. H., Ramamurthy, A. S., & Beighley, R. E. (2012). Inter-annual temperature and precipitation variations over the Litani Basin in response to atmospheric circulation patterns. *Theoretical and Applied Climatology*, *108*(3-4), 563-577.

Rathore, N. S. (2011). A Historical Perspective of the Development of Rain Water Harvesting Techniques in the Mewar Region, Udaipur, Rajasthan, India. International *Journal of Water Resources & Arid Environments*, 1(4), 285-94.

Raychaudhuri, T., & Habib, I. (1982). Cambridge Economic History Of India Vol-1 (Vol. 1). Orient Blackswan.

Rodionov, S. N. (2004). A sequential algorithm for testing climate regime shifts. *Geophysical Research Letters*, *31*(9).

Roy, S. S. (2006). The impacts of ENSO, PDO, and local SSTs on winter precipitation in India. *Physical Geography*, *27*(5), 464-474.

Roy, S. S. (2011). The role of the North Atlantic Oscillation in shaping regional-scale peak seasonal precipitation across the Indian subcontinent. *Earth Interactions*, *15*(2), 1-13.

Rummel, RJ (1970). Applied Factor Analysis. Evanston, Northwestern University Press, P 13

Sami, L. (2002). Gender Differentials in Famine Mortality: Madras (1876-78) and Punjab (1896-97). *Economic and Political Weekly*, 2593-2600.

Samy [Pasha], Amin (1915) (2009 reprint) Taqueem el-Nil (Nile Almanac) Cairo Government Press, Cairo P 35

Santoro, M. M., Hassan, F. A., Wahab, M. A., Cerveny, R. S., & Balling, R. C. (2015). An aggregated climate teleconnection index linked to historical Egyptian famines of the last thousand years. *The Holocene*, 25(5), 872-879. DOI: 10.1177/0959683614567880

Santos, J. A., Woollings, T., & Pinto, J. G. (2013). Are the Winters, 2010 and, 2012 Archetypes Exhibiting Extreme Opposite Behavior of the North Atlantic Jet Stream?. *Monthly Weather Review*, 141(10), 3626-3640.

Sawilowsky, S. S., & Blair, R. C. (1992). A more realistic look at the robustness and Type II error properties of the t test to departures from population normality. *Psychological Bulletin*, 111(2), 352. doi.org/10.1037/0033-2909.111.2.352

Schwing, F. B., Jiang, J., & Mendelssohn, R. (2003). Coherency of multi‐scale abrupt changes between the NAO, NPI, and PDO. *Geophysical Research Letters*, 30(7). DOI: 10.1029/2002GL016535

Seager, R., Harnik, N., Kushnir, Y., Robinson, W., & Miller, J. (2003). Mechanisms of hemispherically symmetric climate variability. *Journal of Climate*, *16*(18), 2960-2978.

Seleshi Y and Demaree GR (1995) Rainfall variability in the Ethiopian and Eritrean highlands and its links with the Southern Oscillation Index. *Journal of Biogeography* 22: 945-952

Sen, A. (1977). Starvation and exchange entitlements: a general approach and its application to the Great Bengal Famine. *Cambridge Journal of Economics*, *1*(1), 33-59.

Sen, A. (1981). Ingredients of famine analysis: availability and entitlements. *The Quarterly Journal of Economics*, 433-464.

Sen, A. (1981a). Poverty and Famines: an essay on entitlement and deprivation. Oxford: Oxford University Press.

Sen, A. (1991). Public action to remedy hunger. *Interdisciplinary science reviews*, *16*(4), 324-336.

Shi, F., Li, J., & Wilson, R. J. (2014). A tree-ring reconstruction of the South Asian summer monsoon index over the past millennium. *Scientific Reports*, 4. DOI:10.1038/srep06739

Siegel, S. (1956). Non-Parametric Statistics. 1956. McGraw-Hill, London

Sinha, A., Cannariato, K.G., Stott, L.D., Cheng, H., Edwards, R.L., Yadava, M.G., Ramesh, R. and Singh, I.B (2007). A 900‐year (600 to 1500 AD) record of the Indian summer monsoon precipitation from the core monsoon zone of India. *Geophysical Research Letter*s, 34(16). DOI: 10.1029/2007GL030431

Short, T. (1749). A General Chronological History of the Air, Weather, Seasons, Meteors, &c. in Sundry Places and Different Times, More Particularly for the Space of, 250 Years, Together with Some of Their Most Remarkable Effects on Animal (especially Human) Bodies, and Vegetables (Vol., 2). London: T. Longman and A. Millar.

Slavin, P. (2012). The Great Bovine Pestilence and its economic and environmental consequences in England and Wales, 1318–501. *The Economic History Review*, 65(4), 1239-1266. DOI: 10.1111/j.1468-0289.2011.00625.x

Slavin, P. (2016). Climate and Famines: a historical reassessment. *Wiley Interdisciplinary Reviews: Climate Change*, 7(3), 433-447. DOI: 10.1002/wcc.395

Styllas, M. N., Schimmelpfennig, I., Ghilardi, M., & Benedetti, L. (2015). Geomorphologic and paleoclimatic evidence of Holocene glaciation on Mount Olympus, Greece. *The Holocene*, doi: 10.1177/0959683615618259

Taye MT and Willems P (2011) Influence of climate variability on representative QDF predictions of the upper Blue Nile basin. *Journal of Hydrology* 411: 355-365 DOI:10.1016/j.jhydrol.2011.10.019

Thompson JD (1982), Spectrum estimation and harmonic analysis, Proceedings of theIEEE, 70: 1055-1096.

Toker E, Sivan D, Stern E, et al. (2012) Evidence for centennial scale sea level variability during the Medieval Climate Optimum (Crusader Period) in Israel, eastern Mediterranean. *Earth and Planetary Sciences Letters* 315: 51-61 DOI: 10.1016/j.epsl.2011.07.019

Toohey, M., Krüger, K., Sigl, M., Stordal, F., & Svensen, H. (2016). Climatic and societal impacts of a volcanic double event at the dawn of the Middle Ages. *Climatic Change*, 1-12. DOI: 10.1007/s10584-016-1648-7

Trenberth K (1997) The definition of El Niño. *Bulletin of the American Meteorological Society* 112: 326-332

Trouet V, Esper J, Graham NE, et al. (2009) Persistent positive North Atlantic Oscillation mode dominated the medieval climate anomaly. *Scienc*e. 324: 78-80 doi:10.1126/science.1166349

van Loon, H., & Rogers, J. C. (1978). The seesaw in winter temperatures between Greenland and northern Europe. Part I: General description. *Monthly Weather Review*, 106(3), 296-310.

Visbeck, M. H., Hurrell, J. W., Polvani, L., & Cullen, H. M. (2001). The North Atlantic Oscillation: past, present, and future. *Proceedings of the National Academy of Scien*ces, 98(23), 12876-12877. doi: 10.1073/pnas.231391598

Viste E and Sortenberg A (2013) Moisture transport into the Ethiopian highlands. *Intentional Journal of Climatology*. 33: 249-263 DOI:10.1002/joc.3409

Viswambharan, N., & Mohanakumar, K. (2014). Modulation of Indian summer monsoon through northern and southern hemispheric extra-tropical oscillations. *Climate dynamics*, *43*(3-4), 925-938.

Walford, C. (1879). The Famines of the World: Past and Present. London: E. Stanford.

Walker GT and Bliss EW (1932): World Weather V. *Memoirs of the Royal Meteorological Society* 36: 53-84.

Wang, Y., Cheng, H., Edwards, R. L., He, Y., Kong, X., An, Z., ... & Li, X. (2005). The Holocene Asian monsoon: links to solar changes and North Atlantic climate. *Science*, *308*(5723), 854-857.

Wanner, H., Brönnimann, S., Casty, C., Gyalistras, D., Luterbacher, J., Schmutz, C., Stephenson, D.B. and Xoplaki, E., (2001). North Atlantic Oscillation–concepts and studies. *Surveys in Geophysics*, 22(4), 321-381. DOI: 10.1023/A:1014217317898

Weir, D. R. (1991). Malthus's Theory of Population. In *The World of Economics* (pp. 401-406). Palgrave Macmillan UK.

Welch, B. L. (1937). On the z-test in randomized blocks and Latin squares. *Biometrika,* 29(1/2), 21-52.

Wils THG, Robertson I, Eshetu Z, et al. (2010) Towards a reconstruction of Blue Nile baseflow from Ethiopian tree rings. *The Holocene* 20:837-848 DOI: 10.1177/0959683610365940

Wright, S. J., Carrasco, C., Calderon, O., & Paton, S. (1999). The El Niño Southern Oscillation, variable fruit production, and famine in a tropical forest. *Ecology*, 80(5), 1632-1647. 10.1890/0012-9658(1999)080[1632:TENOSO]2.0.CO;2

Wold-Mariam, M. W. (1984). Rural vulnerability to famine in Ethiopia: 1958-1977.

Xoplaki, E., Luterbacher, J., Paeth, H., Dietrich, D., Steiner, N., Grosjean, M., & Wanner, H. (2005). European spring and autumn temperature variability and change of extremes over the last half millennium. *Geophysical Research Letters*, 32(15). DOI:10.1029/2005GL023424

Yan H, Sun L, Wang Y, et al. (2011) A record of the Southern Oscillation Index for the past, 2000 years from precipitation proxies. *Nature Geoscience* 4: 611-614 doi: 10.1038/NGEO1231

Zakry, Antoun (1926). The Nile during the times of the Pharaohs and Arabs (in Arabic). Cairo: Matbaet Al-Maref.

Zhang, D. D., Brecke, P., Lee, H. F., He, Y. Q., & Zhang, J. (2007). Global climate change, war, and population decline in recent human history. *Proceedings of the National Academy of Sciences*, 104(49), 19214-19219. DOI: 10.1073/pnas.0703073104

Zhang, D. D., Lee, H. F., Wang, C., Li, B., Pei, Q., Zhang, J., & An, Y. (2011). The causality analysis of climate change and large-scale human crisis. *Proceedings of the National Academy of Sciences*, *108*(42), 17296-17301.

Zheng, J., Xiao, L., Fang, X., Hao, Z., Ge, Q., & Li, B. (2014). How climate change impacted the collapse of the Ming dynasty. *Climatic Change*, 127(2), 169-182. doi:10.1007/s10584-014-1244-7

APPENDIX A

BRITISH FAMINE LIST

Year	Climate	Sources
1741	Cold	(Keys et al., 1950), (Wolford, 1979), (Short, 1749), (Engler et al., 2015), (Engler et al., 2013a), (Engler et al., 2013b)
1740	Cold	(Keys et al., 1950), (Wolford, 1979), (Short, 1749), (Engler et al., 2015), (Engler et al., 2013a), (Engler et al., 2013b), (Nash, 1976)
1728	Cold and Flood/ Rains	(Keys et al., 1950), (Short, 1749), (Engler et al., 2015), (Nash, 1976)
1727	Cold and Flood/ Rains	(Keys et al., 1950), (Short, 1749), (Engler et al., 2015), (Nash, 1976)
1709	Cold and Flood/ Rains	(Keys et al., 1950), (Wolford, 1979), (Short, 1749), (Anonymous, 1930b)
1700	Cold and Flood/ Rains	(Keys et al., 1950), (Wolford, 1979), (Short, 1749)
1698	Cold	(Keys et al., 1950), (Wolford, 1979), (Short, 1749)
1697	Cold	(Keys et al., 1950), (Wolford, 1979), (Short, 1749)
1696	Cold	(Keys et al., 1950), (Wolford, 1979), (Short, 1749)
1695	Cold	(Keys et al., 1950), (Wolford, 1979), (Short, 1749)
1694	Cold	(Keys et al., 1950), (Wolford, 1979), (Short, 1749)
1650	Flood/ Rains	(Keys et al., 1950), (Short, 1749)
1649	Flood/ Rains	(Keys et al., 1950), (Wolford, 1979), (Short, 1749)

Year	Climate	Sources
1558	Heat and Flood/ Rains	(Keys et al., 1950), (Wolford, 1979), (Short, 1749)
1557	Heat and Flood/ Rains	(Keys et al., 1950), (Wolford, 1979), (Short, 1749)
1556	Heat and Flood/ Rains	(Keys et al., 1950), (Wolford, 1979), (Short, 1749)
1439	Flood/ Rains	(Keys et al., 1950), (Short, 1749)
1427	Flood/ Rains	(Keys et al., 1950), (Wolford, 1979), (Short, 1749), (Anonymous, 1930b)
1353	Drought	(Keys et al., 1950), (Short, 1749), (Nash, 1976)
1317	Cold	(Keys et al., 1950), (Kershaw, 1973), (Lucas, 1930), (Nash, 1976)
1316	Cold	(Keys et al., 1950), (Nash, 1976)
1315	Cold	(Keys et al., 1950), (Short, 1749), (Nash, 1976)
1295	Hail	(Keys et al., 1950), (Wolford, 1979), (Short, 1749), (Nash, 1976)
1286	Drought	(Keys et al., 1950), (Short, 1749), (Hallam, 1984)
1271	Flood/ Rains	(Keys et al., 1950), (Hallam, 1984), (Nash, 1976)
1252	Drought	(Keys et al., 1950), (Wolford, 1979), (Hallam, 1984), (Anonymous, 1930a), (Nash, 1976)

Year	Climate	Sources
1224	Drought	(Keys et al., 1950), (Nash, 1976)
1209	Cold and Flood/ Rains	(Keys et al., 1950), (Wolford, 1979), (Nash, 1976)
1204	Flood/ Rains	(Keys et al., 1950), (Short, 1749), (Nash, 1976)
1203	Flood/ Rains	(Keys et al., 1950), (Wolford, 1979), (Short, 1749), (Nash, 1976)
1200	Cold	(Keys et al., 1950), (Wolford, 1979), (Nash, 1976)
1196	Flood/ Rains	(Keys et al., 1950), (Wolford, 1979), (Short, 1749), (Nash, 1976)
1195	Flood/ Rains	(Keys et al., 1950), (Wolford, 1979), (Short, 1749), (Nash, 1976)
1194	Flood/ Rains	(Keys et al., 1950), (Wolford, 1979), (Nash, 1976)
1193	Flood/ Rains	(Keys et al., 1950), (Wolford, 1979), (Nash, 1976)
1157	Flood/ Rains	(Keys et al., 1950), (Nash, 1976)
1154	Cold and Flood/ Rains	(Keys et al., 1950), (Wolford, 1979), (Short, 1749)
1150	Cold and Flood/ Rains	(Keys et al., 1950), (Short, 1749), (Nash, 1976)
1149	Cold	(Keys et al., 1950), (Short, 1749), (Anonymous, 1930a), (Nash, 1976)

Year	Climate	Sources
1143	Cold	(Keys et al., 1950), (Short, 1749), (Nash, 1976)
1142	Cold	(Keys et al., 1950), (Short, 1749), (Nash, 1976)
1141	Cold	(Keys et al., 1950), (Short, 1749), (Nash, 1976)
1137	Drought	(Keys et al., 1950), (Wolford, 1979), (Short, 1749), (Nash, 1976)
1136	Drought	(Keys et al., 1950), (Wolford, 1979), (Nash, 1976)
1135	Drought	(Keys et al., 1950), (Wolford, 1979), (Nash, 1976)
1126	Flood/ Rains	(Keys et al., 1950), (Wolford, 1979), (Nash, 1976)
1125	Cold and Flood/ Rains	(Keys et al., 1950), (Wolford, 1979), (Short, 1749)
1122	Cold	(Keys et al., 1950), (Wolford, 1979), (Nash, 1976)
1121	Cold	(Keys et al., 1950), (Wolford, 1979), (Nash, 1976)
1117	Flood/ Rains	(Keys et al., 1950), (Wolford, 1979), (Short, 1749), (Nash, 1976)
1116	Flood/ Rains	(Keys et al., 1950), (Short, 1749), (Nash, 1976)
1111	Cold	(Keys et al., 1950), (Wolford, 1979), (Short, 1749), (Nash, 1976)

Year	Climate	Sources
1106	Drought	(Keys et al., 1950), (Wolford, 1979), (Short, 1749), (Nash, 1976)
1099	Flood/ Rains	(Keys et al., 1950), (Wolford, 1979), (Short, 1749), (Nash, 1976)
1096	Flood/ Rains	(Keys et al., 1950), (Wolford, 1979), (Short, 1749)
1095	Flood/ Rains	(Keys et al., 1950), (Short, 1749), (Nash, 1976)
1094	Flood/ Rains	(Keys et al., 1950), (Short, 1749), (Nash, 1976)
1093	Cold and Flood/ Rains	(Keys et al., 1950), (Short, 1749), (Nash, 1976)
1086	Flood/ Rains	(Keys et al., 1950), (Wolford, 1979), (Short, 1749), (Nash, 1976)
1068	Cold	(Keys et al., 1950), (Wolford, 1979), (Nash, 1976)
1051	Drought	(Keys et al., 1950)

APPENDIX B

INDIAN FAMINE LIST

Date	Famine events/Locality	Source
1052-1059	Hindustan	(Keys et al., 1950), (Nash, 1976)
1054	Famines in Alangudi and Tanjore	(Keys et al., 1950), (Murton, 1984), (Currey and Hugo, 1984)
1116-1119	Famine in Deccan	(Keys et al., 1950), (Loveday, 1914), (Ganguli, 1933), (Loveday, 1914), (Murton, 1984)
1148-1159	General India	(Keys et al., 1950), (Walford, 1879)
1200-1211	Famines in Tiruppamburam and Tanjore	(Keys et al., 1950), (Loveday, 1914), (Murton, 1984)
1259	Bombay	(Keys et al., 1950), (Loveday, 1914)
1291	Delhi	(Keys et al., 1950), (Loveday, 1914), (Walford, 1879), (Ganguli, 1933)
1296-1317	Delhi	(Keys et al., 1950), (Loveday, 1914)
1343-1345	Great famine	(Keys et al., 1950), (Loveday, 1914), (Walford, 1879), (Ganguli, 1933), (Sen, 1991), (Nash, 1976)
1351-1363	Kashmir	(Keys et al., 1950), (Loveday, 1914)
1396-1408	Deccan	(Keys et al., 1950), (Loveday, 1914)

Date	Famine events/Locality	Source
1412-1413	Ganges	(Keys et al., 1950), (Walford, 1879), (Nash, 1976)
1423	Deccan	(Keys et al., 1950), (Loveday, 1914)
1471-1472	Bijapur famine	(Keys et al., 1950), (Loveday, 1914), (Walford, 1879), (Ganguli, 1933), (Nash, 1976)
1493-1494	Bombay famine	(Loveday, 1914), (Murton, 1984)
1494	Delhi	(Keys et al., 1950), (Loveday, 1914)
1495	Hindustan	(Walford, 1879), (Nash, 1976)
1500	Delhi	(Keys et al., 1950), (Loveday, 1914)
1520	Bombay	(Keys et al., 1950), (Loveday, 1914)
1521	Sind	(Walford, 1879), (Nash, 1976)
1527	Sind	(Keys et al., 1950), (Loveday, 1914), (Ganguli, 1933)
1540	Coromandel Coast	(Keys et al., 1950), (Loveday, 1914)

Date	Famine events/Locality	Source
1540-1543	Sind	(Keys et al., 1950), (Loveday, 1914), (Walford, 1879), (Ganguli, 1933), (Nash, 1976)
1554-1555	Delhi, Agra, Bajama District	(Keys et al., 1950), (Loveday, 1914), (Ganguli, 1933)
1556	Hindustan	(Keys et al., 1950), (Loveday, 1914), (Ganguli, 1933)
1576	Delhi	(Keys et al., 1950), (Loveday, 1914), (Ganguli, 1933)
1577	Kutch	(Keys et al., 1950), (Loveday, 1914)
1592	Sholapur District	(Keys et al., 1950), (Loveday, 1914)
1594-1598	Central India, Hindustan	(Keys et al., 1950), (Loveday, 1914), (Ganguli, 1933), (Nash, 1976)
1613-1615	Punjab	(Keys et al., 1950), (Loveday, 1914), (Ganguli, 1933)
1623	Gujarat, Ahmedabad	(Keys et al., 1950), (Loveday, 1914), (Ganguli, 1933)
1628-1632	Famines in Deccan, Gujarat ,and Hoozoor	(Keys et al., 1950), (Loveday, 1914), (Walford, 1879), (Ganguli, 1933), (Miller et al., 2010), (O' Grada, 2007)
1650-1661	Famines in Ahmedabad, Bengal and Bombay	(Keys et al., 1950), (Loveday, 1914), (Walford, 1879), (Ganguli, 1933), (Rathore, 2011), (Nash, 1976)

Date	Famine events/Locality	Source
1676-1677	Hyderbad	(Keys et al., 1950), (Loveday, 1914), (Ganguli, 1933)
1685	Hyderbas, Deccan	(Keys et al., 1950), (Loveday, 1914), (Ganguli, 1933)
1702-1704	Famine in Bombay, Deccan	(Keys et al., 1950), (Loveday, 1914), (Walford, 1879), (Ganguli, 1933), (Fukazawa, 1982), (Nash, 1976)
1709	Bombay	(Keys et al., 1950), (Loveday, 1914)
1718	Bombay	(Keys et al., 1950), (Loveday, 1914), (Ganguli, 1933)
1733	NW Povinces	(Walford, 1879), (Nash, 1976)
1737	Bombay	(Keys et al., 1950), (Loveday, 1914)
1739	Delhi	(Keys et al., 1950), (Loveday, 1914), (Walford, 1879), (Nash, 1976)
1746-1747	Famine in Bombay, Kutch	(Keys et al., 1950), (Loveday, 1914), (Walford, 1879), (Ganguli, 1933), (Nash, 1976)
1759	Bombay	(Keys et al., 1950), (Loveday, 1914), (Ganguli, 1933)
1769-1770	Bengal famine	(Keys et al., 1950), (Loveday, 1914), (Walford, 1879), (Ganguli, 1933), (Miller et al., 2010), (Nash 2002), (Collier and Webb 2002), (Leiberman, 2003), (Nash, 1976)

Date	Famine events/Locality	Source
1781-1784	Madras city and surrounding areas, Bombay, Bengal, Bellry, United Provences, Kashmir, Rajputana, Chalisa famine	(Keys et al., 1950), (Loveday, 1914), (Walford, 1879), (Ganguli, 1933), (Loveday, 1914) 17 (Nash, 1976)
1787	South Mahratta	(Keys et al., 1950), (Loveday, 1914), (Walford, 1879), (Ganguli, 1933)
1788-1794	The Doji Bara or Skull famine, East India Drought	(Keys et al., 1950) 6 (Walford, 1879), (Ganguli, 1933), (Grove, 2007), (Nash, 1976)
1799-1801	Northwest Provences, Bombay, Central India	(Keys et al., 1950), (Loveday, 1914), (Ganguli, 1933)
1802-1804	Rajputana, Bombay	(Keys et al., 1950), (Loveday, 1914), (Walford, 1879), (Ganguli, 1933), (Nash, 1976)
1806-1807	Widespread	(Keys et al., 1950), (Loveday, 1914), (Walford, 1879), (Ganguli, 1933), (Nash, 1976)
1812-1813	Bomby, Agra, Madras	(Keys et al., 1950), (Loveday, 1914), (Walford, 1879), (Ganguli, 1933), (Nash, 1976)
1819-1820	NW Provences, Rajputana, Deccan, Broach	(Keys et al., 1950), (Loveday, 1914), (Walford, 1879), (Nash, 1976)
1820-1822	Upper Sind famine	(Keys et al., 1950), (Walford, 1879), (Ganguli, 1933), (Loveday, 1914), (Balfour, 1885), (Nash, 1976)
1824-1825	Deccan, Bombay, Madras, parts of NW Provences	(Keys et al., 1950), (Loveday, 1914), (Walford, 1879), (Ganguli, 1933), (Nash, 1976)
1826-1828	Rangoon	(Keys et al., 1950), (Walford, 1879)

Date	Famine events/Locality	Source
1832-1833	Sholapur	(Keys et al., 1950), (Loveday, 1914), (Ganguli, 1933), (Nash, 1976)
1833-1834	Gujarat, Kandish, northern Deccan	(Keys et al., 1950), (Loveday, 1914), (Walford, 1879), (Nash, 1976)
1837-1838	NW India	(Keys et al., 1950), (Walford, 1879), (Nash, 1976)
1838	Bombay	(Keys et al., 1950), (Walford, 1879), (Nash, 1976)
1853-1855	Bellary, southern Madras, Deccan, Rajputana, Bombay	(Keys et al., 1950), (Loveday, 1914), (Walford, 1879), (Ganguli, 1933), (Nash, 1976)
1860-1861	Upper Doab famine	(Keys et al., 1950), (Loveday, 1914), (Walford, 1879), (Ganguli, 1933), (Derbyshire, 1987), (Butler, 1908), (Nash, 1976)
1862	Deccan	(Keys et al., 1950), (Loveday, 1914), (Walford, 1879), (Ganguli, 1933)
1865-1870	Famines in Orissa and Rajputana	(Keys et al., 1950), (Loveday, 1914), (Walford, 1879), (Ganguli, 1933), (Butler, 1908), (Raychaudhuri and Habib, 1982), (Nash, 1976)
1874	Bengal	(Keys et al., 1950), (Loveday, 1914), (Walford, 1879), (Ganguli, 1933)
1873-1878	Southern India famine	(Keys et al., 1950), (Loveday, 1914), (Walford, 1879), (Miller et al., 2010), (Nash, 2002), (Butler, 1908), (Parthasarathy et al., 1987), (Sami, 2002)

Date	Famine events/Locality	Source
1888-1889	Late Victorian droughts	(Keys et al., 1950), (Loveday, 1914), (Walford, 1879), (Ganguli, 1933), (Davis, 2001)
1896-1902	Famine in India	(Keys et al., 1950), (Loveday, 1914), (Walford, 1879), (Ganguli, 1933)(Collier and Webb 2002), (Butler, 1908), (Sami, 2002), (Brewis, 2010), (Nash, 1976), (Brewis, 2010)
1905-1906	Famines in Bombay	(Raychaudhuri and Habib, 1982), (Nash, 1976)
1906-1907	Darbhanga District (floods)	(Keys et al., 1950), (Loveday, 1914), (Ganguli, 1933), (Nash, 1976)
1907	United Provences	(Keys et al., 1950), (Loveday, 1914), (Ganguli, 1933), (Nash, 1976)
1943-1944	Bengal Famine	(Miller et al., 2010), (Raychaudhuri and Habib, 1982), (Nash, 1976)

BIOGRAPHICAL SKETCH

Michael Santoro is a PhD candidate at the School of Geographical Sciences and Urban Planning at Arizona State University. He also received his Master's Degree at the School of Geographical Sciences and Urban Planning at Arizona State University in 2009 with his thesis titled "Antecedent Climate and North Central Arizona Wildfire Variability." He is residential faculty of geoscience at Chandler Gilbert Community College and a proud husband and father. He has been interested in weather and climate since he was a small child, and those around him recognized his potential for teaching long before he did. He is excited to be living out his dreams of career and family.