DETECTING ENSO PERIOD CHANGES IN A PROXY RECORD SPANNING THE LAST MILLENNIUM

A Thesis in
Geosciences
by
Joshua N. Dorin

© 2008 Joshua N. Dorin

Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science

August 2008
The thesis of Joshua N. Dorin was reviewed and approved* by the following:

Klaus Keller
Associate Professor of Geosciences
Thesis Advisor

Michael Mann
Associate Professor of Meteorology

James Kasting
Distinguished Professor of Geosciences

Sridhar Anandakrishnan
Associate Professor of Geosciences

Katherine H. Freeman
Professor of Geosciences
Associate Department Head of Graduate Programs

* Signatures are on file in the Graduate School
Abstract

Anthropogenic activities have increased radiative climate forcings, causing widespread changes to the climate system. The future response of the climate to anthropogenic forcing depends on the responses of the various components of the climate system. One such component is the El Niño-Southern Oscillation (ENSO). The recent occurrence of several ENSO events with increased period raises the question whether anthropogenic climate forcing has changed ENSO. Detecting anthropogenic ENSO period changes requires an estimate of the natural variability (defined here as the unforced variability). Most ENSO change detection studies use instrumental records that have limited ability to capture the full natural variability. Here we analyze ENSO period changes in a published fossil coral record spanning the last millennium. We find a decrease in ENSO period from the pre-1850 to post-1850 intervals, which is significantly (p < 0.1) outside the range of natural variability as approximated by a control run of a global climate model. This result is consistent with anthropogenic ENSO modulation, however, natural forcings need to be considered for a formal attribution test.
Table of Contents

List of Figures ..................................................................................................................... v
Preface ............................................................................................................................... vi
Acknowledgements ......................................................................................................... vii

Chapter 1: Introduction .................................................................................................... 1
  Introduction ................................................................................................................ 2
  References ................................................................................................................. 13

Chapter 2: Detecting ENSO Period Changes in a Proxy Record Spanning the Last Millennium ................................................................. 16
  Abstract .................................................................................................................... 18
  Introduction .............................................................................................................. 19
  Data .......................................................................................................................... 23
  Methods .................................................................................................................... 25
  Results and Discussion ............................................................................................. 26
  Caveats ..................................................................................................................... 29
  Conclusions .............................................................................................................. 30
  Acknowledgements .................................................................................................. 31
  Appendix .................................................................................................................. 32
  References ................................................................................................................ 35

Chapter 3: Conclusions and Future Work .................................................................... 40
  Conclusions .............................................................................................................. 41
  Future Work ............................................................................................................. 42
  References ................................................................................................................ 44
List of Figures

Chapter 1

Figure 1-1: Bjerknes feedback .................................................................5

Chapter 2

Figure 2-1: Raw data and wavelet analysis of the Palmyra coral record ..............24
Figure 2-2: Estimated ENSO periods from 30-year sections of the Palmyra corals ......27
Figure 2-3: Detection of anthropogenic ENSO period changes ...............................28
Figure 2-4: Performance of different methods in estimating ENSO period .................34
Preface

The contents of this thesis include a multi-authored manuscript (Chapter 2) that has been submitted to the Journal of Climate. Joshua N. Dorin, the candidate for Master of Science, is the first author. The thesis advisor, Klaus Keller, is the senior (last) author. Brian C. Tuttle contributed to the methodological development, provided essential insights and discussions, and is listed as the second author. The contents of the manuscript are the product of the research efforts of Joshua N. Dorin during his time as a graduate student in the Department of Geosciences at The Pennsylvania State University.
Acknowledgements

I am greatly indebted to many people for their help in the completion of this thesis. First and foremost, Klaus Keller gave me his sagacious advice and unrelenting encouragement. I also thank my committee members for fruitful discussions that improved this thesis. Finally, my fellow students and friends provided me with unconditional support and happiness.
Chapter 1: Introduction
Introduction

Anthropogenic greenhouse gas emissions have resulted in considerable increases in radiative forcings, which have already caused “discernable human influences” on the climate (IPCC 2007). The future response of the climate system to anthropogenic forcing is deeply uncertain. This uncertainty results from our currently incomplete understanding of (i) key components of the climate system and (ii) their complex interactions. This thesis focuses on the El Niño – Southern Oscillation (ENSO), one specific component of the climate system.

ENSO is the largest global climatic oscillation on interannual time scales (Cane 2005). The widespread effects of ENSO include devastating floods and droughts (Cane 2005), as well as changes in surface temperature (Diaz et al. 2001) and Atlantic hurricane activity (Landsea 2000). It was only recently, however, that scientists had a mechanistic understanding of ENSO, or even an idea of the global impact that ENSO has on the climate. In fact, prior to the 20th Century, “El Niño” referred to the semi-regular appearance of a warm current off the coast of Peru around Christmas (Philander 1990). Around 40 years ago, scientists realized that this warm water was associated with a warming of the entire eastern and central tropical Pacific Ocean and a change in the tropical atmospheric circulation. From then on, “El Niño” became associated with these large-scale changes in the ocean and atmosphere.

The groundwork for understanding the fully coupled system began at the end of the 19th Century in response to the failures of several Indian monsoons, which resulted in droughts and famines, causing the deaths of millions of people (Davis 2001). This work was initiated by Sir Gilbert Walker, who hoped to be able to predict the interannual
variability of the monsoons by studying atmospheric data from stations around the world (Philander 1990). In these data, Walker found that surface pressures in the Pacific Ocean and the Indian Ocean were inversely related, a phenomenon he termed the Southern Oscillation. He worked on this problem through the 1930s, examining correlations between the Southern Oscillation and variables including surface pressure, precipitation and surface temperature around the world. Although he was unable to predict the monsoon behavior successfully, Walker had found patterns in the climate system that would help motivate the further study of this phenomenon in the future. This work, however, failed to gain the acceptance of his contemporaries because the results were based on correlations rather than mechanistic reasoning, thereby leaving ENSO largely forgotten for several decades.

During the late 1950s, ENSO reemerged in the scientific community, due in large part to the initiation of the International Geophysical Year of 1957-58 campaign to collect global atmospheric and oceanographic observations (Philander 1990). Incidentally, there was a strong El Niño during these years, bringing attention to the fact that the sea surface temperatures (SSTs) in the tropical Pacific were unusually high, the trade winds were very weak and the central tropical Pacific, normally a dry region, featured intense rainfall. Walker had shown that trade wind intensity and precipitation in this region were correlated, but SST had not been analyzed because of limited data availability (Philander 1990). The observations collected during the 1950s and 1960s showed that El Niños were separated by periods when the tropical Pacific was in the opposite phase, namely when SSTs in the central and equatorial Pacific were cooler,
precipitation was lower and the trade winds were stronger. These events became known as La Niñas.

The currently prevailing mechanistic explanation for the occurrences of El Niños and La Niñas was proposed by Bjerknes (1969). He first observed that the coupling of the ocean and atmosphere in the tropical Pacific could explain the mean state of the region. Easterly trade winds drive oceanic currents that move surface waters to the western basin. These waters become very warm due to the direct solar radiation received year-round, resulting in a relatively deep thermocline in the west. The thermocline remains shallow in the east. This tilt of the thermocline is reflected in the temperature of the water brought to the surface by equatorial and coastal upwelling induced by the trade winds. In the central and eastern Pacific, upwelling brings colder waters from below the shallow thermocline to the surface. In contrast, the thermocline in the west is too deep to allow for the entrainment of cold waters from below the thermocline. The resulting zonal SST gradient drives the zonal atmospheric circulation (named the Walker circulation by Bjerknes): air rises over the warm western Pacific, flows eastward, sinks over the cooler eastern Pacific and flows westward along the ocean surface, reinforcing the trade winds. This coupling process between the ocean and the atmosphere became known as the Bjerknes feedback.

Bjerknes then explained how El Niños and La Niñas develop from trade wind anomalies that strengthen and stabilize by the Bjerknes feedback (Bjerknes 1969, Cane 2005) (Figure 1-1). If the trade winds collapse or weaken slightly, then both the rate of upwelling decreases and the western warm pool flows eastward, reducing the upwelling of cold waters and depressing the thermocline in the central and eastern equatorial Pacific. Both effects contribute toward a reduced zonal SST gradient, weakening the
Walker circulation and the trade winds. This situation describes an El Niño. Similarly, if there was a slight strengthening of the trade winds, then the zonal SST gradient increases, reinforcing the winds. This event is known as a La Niña.

Figure 1-1. Bjerknes feedback: Originally from Bjerknes (1969); modified from Kump et al. (1999)

Although Bjerknes was able to explain why El Niños and La Niñas are the two preferred states of the tropical Pacific, he could not explain why the system oscillates between them on interannual timescales (Cane 2005). Over the next several decades, theories for the presence of an interannual oscillation would arise through the development of coupled ocean-atmosphere ENSO models. These models contained a set of mathematical equations describing the oceanic and atmospheric dynamics in the
tropical Pacific. By the mid-1980s, these models were able to simulate the oscillatory ENSO behavior, thus giving scientists insight into the mechanisms that govern ENSO (Zebiak and Cane 1987).

One commonly accepted theory for the presence of an interannual oscillation that came about through the development of these models is based on the propagation of waves across the tropical Pacific Ocean and their reflection at continental boundaries (Philander 1990). During the initiation of an El Niño, when the trade winds weaken, two types of ocean waves are generated: a westward-propagating cold-water (upwelling) Rossby wave and an eastward-propagating warm-water (downwelling) Kelvin wave (Suarez and Schopf 1988). The Kelvin wave acts to deepen the thermocline in the central and eastern equatorial Pacific Ocean, thus increasing SSTs, leading to an El Niño. The Rossby wave reflects off the western boundary as an eastward-propagating cold-water (upwelling) Kelvin wave. The Kelvin wave travels eastward and acts to shoal the thermocline and reverse the SST anomalies in the central and eastern equatorial Pacific Ocean, leading to a La Niña.

If the transit times of the Kelvin and Rossby waves were the only factors determining the oscillatory behavior of the system, ENSO would oscillate on timescales similar to the time needed for the waves to cross the Pacific (< 1 year). ENSO oscillates, however, on interannual timescales (Cane 2005). The longer timescale is hypothesized to result from the interactions of the Bjerknes feedback with the equatorial ocean dynamics (Cane 2005). On one hand, the Bjerknes feedback acts to lock the tropical Pacific into one of the two ENSO phases, thus, extending the period of the oscillation. On the other
hand, equatorial waves act to switch the system from one ENSO phase to the other on
subannual timescales.

One common approach towards understanding the oscillatory behavior of ENSO
has been the development of a simple mathematical model that describes the changes in
SST induced by the Bjerknes feedback and equatorial wave dynamics (Battisti and Hirst
1988). This model, known as the delayed oscillator, has the form:

\[ \frac{dT}{dt} = cT - bT(t - \tau) \]

where \( T \) is the SST in the eastern equatorial Pacific Ocean, \( t \) is time, \( b \) and \( c \) are
coefficients (discussed below), and \( \tau \) is a time lag constant (the time needed for a Rossby
wave to travel from its origin in the central Pacific to the western boundary and return to
the eastern Pacific as a reflected Kelvin wave) (Battisti and Hirst 1988). The first
coefficient, \( c \), represents the growth of SST anomalies by the Bjerknes feedback. The
second coefficient, \( b \), represents the suppression of SST anomalies by Kelvin waves.
Although \( \tau \) is well constrained from the known speeds of Rossby and Kelvin waves and
the geometry of the Pacific basin (\( \tau \approx 180 \) days), the values of \( b \) and \( c \) are poorly
constrained because they depend on processes that are not well understood, such as the
atmosphere-ocean coupling strength and the effects of the Kelvin waves on the
thermocline depth (Battisti and Hirst 1988). A sensitivity analysis by Battisti and Hirst
(1988) shows how different values of these parameters affect the period of the
oscillations generated by the delayed oscillator. In particular, the period is shown to be
positively correlated with \( c \) and negatively correlated with \( b \). Furthermore, the period in
the delayed oscillator model is longer than the time lag constant \( \tau \). The delayed oscillator
model, hence, provides a simple example of how the Bjerknes feedback and equatorial wave dynamics can act together to set the ENSO period to timescales longer than \( \tau \).

Although the development of a complete theory of ENSO is an area of active research, the use of the delayed oscillator equation, as well as other more complex models, have suggested that the properties of ENSO are determined in large part by the background state of the tropical Pacific Ocean. In particular, the thermocline depth in the eastern equatorial Pacific and the trade wind intensity are believed to be two very important variables (Fedorov and Philander 2000). One property that is of key importance is the period of ENSO. Fedorov and Philander (2001) show that a deepening of the thermocline or weakening of the trade winds increases ENSO period. A shoaling of the thermocline or strengthening of the trade winds decreases ENSO period.

Current projections of how ENSO period may respond to anthropogenic climate forcing are deeply uncertain (Fedorov and Philander 2000; Fedorov et al. 2006). One group of studies (Fedorov and Philander 2000, 2006) hypothesizes that increased radiative forcing will increase ENSO period while an adaptation of another study (Cane et al. 1997) hypothesizes the opposite response. Both hypotheses relate the effects of anthropogenic activities to changes in ENSO period through changes in the thermocline depth and trade wind intensity in the tropical Pacific.

The first hypothesis, proposed by Fedorov and Philander (2000) and Fedorov et al. (2006), predicts that ENSO period will increase in response to anthropogenic climate forcing. This response is a result of two factors: (i) increased temperatures and (ii) increased precipitation. Both factors act to deepen the thermocline and weaken the trade winds in the tropical Pacific.
The first factor, increased surface air temperatures (SAT), will increase ENSO period by restructuring the global oceanic heat budget (Fedorov and Philander 2000; Fedorov et al. 2006). In the tropical Pacific Ocean, there is a net heat gain, which is strongest in regions where there is equatorial upwelling of colder waters from below the thermocline. At higher latitudes, there is a net heat loss from the ocean where cool air blows over the warm Kuroshio current. This meridional heat flux differential contributes to the poleward heat transport from the tropics to higher latitudes. If anthropogenic greenhouse gas emissions warm the atmosphere at higher latitudes, then the heat lost from the ocean to the atmosphere will decrease. This reduction in heat loss will weaken the poleward heat transport from the tropics, increasing the amount of heat in the tropics, or equivalently, deepening the thermocline. By the Bjerknes feedback, the trade winds will weaken (Bjerknes 1969). In summary, increasing SAT will act to deepen the thermocline and weaken the trade winds, which then act to increase ENSO period.

The second factor, increasing precipitation in the subtropical oceans, will increase ENSO period by weakening the shallow overturning circulation (Fedorov and Philander 2000; Fedorov et al. 2006). In the midlatitude Pacific Ocean, water is forced below the surface by the winds and flows equatorward along isopycnals. Once the water reaches the equator, upwelling brings it to the surface. The water then travels to higher latitudes by Ekman transport completing the circulation loop. The entire shallow overturning circulation contributes to the poleward heat transport. If anthropogenic climate forcing increases precipitation in the mid-latitude oceans, then the density gradient between the mid-latitude and the tropical ocean will decrease. This decreased density gradient acts to weaken the shallow overturning circulation, reducing the poleward heat transport. The
excess heat in the tropics implies a deeper thermocline, thus weaker trade winds by the Bjerknes feedback (Bjerknes 1969), acting to increase ENSO period (Fedorov and Philander 2001).

The second hypothesis, adapted from Cane et al. (1997), predicts that anthropogenic climate forcing will decrease ENSO period. This response is driven by the ocean dynamical thermostat (Clement et al. 1996). If the tropical Pacific Ocean is heated uniformly, the SST will respond differently in the west than in the east. In the west, the surface waters will warm because the deep thermocline prevents the upwelling of cold waters. In the east, however, the trade winds bring cold water from below the shallow thermocline to the surface, counteracting the warming. This response of SST due to the ocean dynamical thermostat is, hence, that the zonal SST gradient increases, strengthening the trade winds and reducing the thermocline depth by the Bjerknes feedback (Bjerknes 1969), acting to decrease ENSO period (Fedorov and Philander 2001).

These two hypotheses predict different responses of ENSO period to anthropogenic climate forcing. Whether anthropogenic activities have already changed ENSO period by either of these mechanisms is an open question.

Several studies have examined whether recent anomalously long ENSO events were statistically unusual given the instrumental record, but have come to conflicting conclusions (Harrison and Larkin 1997; Rajagopalan et al. 1997; Solow 2006; Trenberth and Hoar 1996; Trenberth and Hoar 1997). Trenberth and Hoar (1996) conclude that the 1990-95 El Niño was unexpected given an instrumental record of atmospheric ENSO behavior. Rajagopalan et al. (1997), on the other hand, conclude that it cannot be
determined at this time whether the event is outside the range of natural variability. Although these papers were groundbreaking towards determining the effect of anthropogenic climate forcing on ENSO, they are silent on several key questions: (i) What is the ENSO period variability over the last millennium? (ii) Has there been a statistically significant change in ENSO period from the pre-anthropogenic interval (pre-1850) to the anthropogenic interval (post-1850)? (iii) Is this shift outside the range of natural variability? (iv) Which hypothesis, as presented above, is more consistent with the observations? Chapter 2 addresses these questions by a statistical analysis of the observation record of Cobb et al. (2003).

Detecting anthropogenic ENSO period changes asks the question whether observed ENSO behavior over the anthropogenic interval is outside the range of natural variability. It, hence, requires an estimate of the natural variability of ENSO period (Hergerl et al. 2007). Unfortunately, the tropical Pacific varies on multi-decadal to centennial timescales (Zhang et al. 1997), while the instrumental record covers mostly the past century (Trenberth and Stepaniak 2001), providing little evidence to characterize the natural variability. Therefore, the analysis of proxy ENSO records is necessary for the detection of potential anthropogenic ENSO changes.

One proxy record that may provide useful observational constraints to test the two hypotheses is an oxygen isotope record derived from fossil corals at Palmyra Island (Cobb et al. 2003). Palmyra Island is located in the central equatorial Pacific near the boundary of the cold tongue that extends off the South American coast. During an El Niño, the cold tongue retracts back to the South American coast and the western warm pool moves eastward. SST and precipitation anomalies increase around the island,
resulting in negative isotopic oxygen anomalies. The situation reverses during a La Niña, resulting in positive isotopic oxygen anomalies.

Here we analyze the Palmyra coral record for trends in ENSO period. The central question to be addressed is 'Do we detect anthropogenic ENSO period changes in the Palmyra coral record over the last millennium?' We show that there is a statistically significant decrease in ENSO period that is unexplained by the natural variability. This finding supports the mechanistic hypothesis adapted from Cane et al (1997).
References


Chapter 2: Detecting ENSO Period Changes in a Proxy Record

Spanning the Last Millennium
Detecting ENSO Period Changes in a Proxy Record Spanning the Last Millennium

Joshua N. Dorin¹*, Brian C. Tuttle² and Klaus Keller¹

¹Department of Geosciences, Penn State University, University Park, PA
²Graduate Program in Acoustics, Penn State University, University Park, PA

*corresponding author e-mail: jdorin@geosc.psu.edu

In review as a note in the

Journal of Climate

Running Title:

DORIN ET AL.: DETECTING ENSO PERIOD CHANGES
Abstract

The recent occurrence of El Niño – Southern Oscillation (ENSO) events with increased period raises the question of whether anthropogenic climate forcing is modulating ENSO. Detecting past anthropogenic ENSO changes requires a quantitative understanding of the ENSO variability prior to significant anthropogenic forcing. Most ENSO change detection studies focus on instrumental records. Here we analyze ENSO variability in a published high-resolution fossil coral record spanning the last millennium that may provide a more robust characterization of pre-anthropogenic variability than the instrumental record. We test for potential ENSO changes by applying a time series model to this proxy coral record and using a model control simulation to approximate unforced ENSO behavior. Based on the analyzed ENSO record and the adopted method, we find a statistically significant (p < 0.1) decrease in ENSO period from pre- to post-1850. This finding is consistent with anthropogenic modulation, but other explanations (e.g., natural forcing variations) would have to be considered before one could formally attribute these ENSO period changes to anthropogenic forcing.

Keywords: El Niño – Southern Oscillation, ENSO, anthropogenic climate change, climate change detection
Introduction

The El Niño-Southern Oscillation (ENSO) is the dominant source of global climate variability on interannual timescales, affecting temperature, precipitation, ecosystem dynamics, and livelihoods worldwide (Cane 2005; Philander 1990). The occurrence of an unusually long El Niño from 1990-95 has intensified the debate about a change in ENSO behavior (Cane 2005; Fedorov and Philander 2000). This observation, as well as model simulations (Collins 2005; Lin 2007; Timmermann et al. 1999), suggest the tantalizing possibility that ENSO might be modulated by anthropogenic climate forcing.

Detecting potential anthropogenic ENSO changes addresses the question of whether the recent ENSO behavior is outside the range of natural variability (defined here as the unforced or internal variability) (Barnett et al. 2001; Hegerl et al. 2007; Santer et al. 1995). Most ENSO change detection studies focus on the instrumental record (e.g., Harrison and Larkin 1997; Rajagopalan et al. 1997; Solow 2006; Trenberth and Hoar 1996; Trenberth and Hoar 1997). These studies break important new ground, but face the potential problem that the instrumental ENSO record is relatively short compared to the decadal-to-centennial timescale of natural variability of the tropical Pacific Ocean (Zhang et al. 1997). The relatively short length of the instrumental record may explain some of the contradicting conclusions of these studies (Harrison and Larkin 1997; Rajagopalan et al. 1997; Trenberth and Hoar 1996; Trenberth and Hoar 1997). In addition, these studies examined atmospheric ENSO records, which have a lower signal-to-noise ratio than oceanic-derived ENSO records (Rasmusson and Carpenter 1982). Here we address these
two potential problems by analyzing an oceanic proxy record spanning the last millennium.

The detection of anthropogenic climate change requires an estimate of the natural variability (Hasselmann 1993; Hegerl et al. 1997). Climate change detection studies typically estimate this natural variability by analyzing records before anthropogenic climate forcing became significant (Hegerl et al. 1997). While precisely identifying this separation date is difficult ((Cane 2005; Ruddiman 2003), the year 1850 is often used (Hegerl et al. 2007), and we adopt this date as an approximation for the boundary between the pre-anthropogenic and anthropogenic intervals.

We focus on analyzing ENSO period changes because theoretical analyses suggest that this property may be modulated by radiative climate forcing. ENSO period is largely dependent on the background state of the tropical Pacific Ocean, as described by the spatially averaged depth of the thermocline in the eastern equatorial Pacific and the intensity of the time-averaged trade winds (Fedorov and Philander 2000). Sensitivity analyses show an increased ENSO period for a deepening of the thermocline or a weakening of the trade winds (Fedorov and Philander 2001). A shoaling of the thermocline or strengthening of the trade winds results in a decreased ENSO period.

How anthropogenic climate forcing may affect ENSO period is a deeply uncertain question (Fedorov and Philander 2000; Fedorov et al. 2006). One hypothesis proposed by Fedorov and Philander (2000) and Fedorov et al. (2006) predicts that anthropogenic climate forcing results in an increase in ENSO period through a restructuring of the oceanic heat budget and resulting changes to the thermocline depth and trade wind intensity in the tropical Pacific. Specifically, anthropogenic greenhouse gas emissions
increase surface air temperatures at high latitudes, causing a decrease in the local oceanic heat loss to the atmosphere. Additionally, precipitation decreases in the subtropics, resulting in a weakening of the shallow overturning circulation (cf. Fedorov et al. 2004). Both effects reduce the poleward heat transport from the tropics, implying a deeper thermocline in the equatorial Pacific. Sea surface temperatures (SST) in the western tropical Pacific are less affected by vertical movements of the thermocline compared to the eastern tropical Pacific due to the thermocline tilt. An increase in the thermocline depth in the tropical Pacific would, hence, decrease the zonal SST gradient, thereby weakening the trade winds through the Bjerknes feedback (Bjerknes 1966; Bjerknes 1969) and increase ENSO period.

An alternative hypothesis adapted from Cane et al. (1997) predicts the opposite response, where anthropogenic climate forcing results in a decreased ENSO period. The mechanism driving this response is the ocean dynamical thermostat (Clement et al. 1996) in which a uniform heating of the tropical Pacific Ocean induces a non-uniform response of tropical Pacific SSTs. Specifically, the eastern equatorial Pacific warms less than the western equatorial Pacific due to the upwelling of colder waters, which counteracts the warming effect of increased radiative forcing (Clement et al. 1996; Sun and Liu 1996). The increased zonal SST gradient causes a strengthening of the trade winds by the Bjerknes’ feedback (Bjerknes 1966; Bjerknes 1969), which results in a shoaling of the thermocline in the east. As a result, the ENSO period decreases (Fedorov and Philander 2001).

These two hypotheses make contradicting predictions about the response of ENSO period to anthropogenic greenhouse gas emissions. We can use the ENSO record
to test which hypothesis is more consistent with the observations. Specifically, we test
whether the observed ENSO period after 1850 is statistically different from the
observed ENSO period before 1850 and whether this difference is outside the range of
natural variability. We apply several statistical techniques to estimate changes in the
mean period of ENSO as recorded in an ENSO proxy record. In particular, we (i) use
positive controls to examine the abilities of several methods to extract period shifts and
to show that the resolution of ENSO records affects the skill of the methods (see
Appendix), (ii) calculate the observed ENSO period shift in the proxy record and (iii)
estimate the distribution of natural variability of ENSO period shifts to allow for the
potential detection of anthropogenic changes. We find a statistically significant
decrease in observed ENSO period from pre-1850 to post-1850 which is outside our
estimate of the natural variability. Our findings provide support in favor of the
hypothesis adapted from Cane et al. (1997).
Data

a) Proxy record

We analyze the published Palmyra Island fossil coral record (Cobb et al. 2003) (Figure 2-1a). The monthly resolved oxygen isotope record consists of four 60- to 150-year-long intervals between 1149 and 1998 over the last thousand years (inclusion of the published interval from the 10th Century does not affect our conclusions). The corals at Palmyra Island provide a promising ENSO record as they are located in the central tropical Pacific Ocean, at the edge of the cold tongue that extends off the coast of South America. During an El Niño, the cold tongue retracts and the western warm pool moves eastward. The associated positive SST and precipitation anomalies result in negative $\delta ^{18}$O anomalies in the Palmyra corals. During a La Niña, the situation reverses, resulting in positive $\delta ^{18}$O anomalies.
Figure 2-1. Raw data and wavelet analysis of the Palmyra coral record: (a) raw data from Cobb et al. (2003) and (b) the wavelet power spectrum using a Morlet wavelet transform. The y-axis is the Fourier pseudo-period (years). A 50-year-long window was applied to smooth the power spectrum. The marginal wavelet power spectrum of the Palmyra coral record for the pre-1850 and post-1850 intervals is shown in panel (c).

b) Model simulations

We approximate the natural variability of ENSO by the variability of the 1000-year-long NINO3.4 index in the control simulation (1850-level forcings) of the GFDL2.1 general circulation model (Delworth et al. 2006). This model approximates observed ENSO behavior with reasonable skill (Wittenberg et al. 2006). As the NINO3.4 index of the control run is just one realization of natural ENSO behavior in the model, we create 100 realizations using a bootstrap resampling method. Specifically, we break the NINO3.4 index into 30-year sections and randomly select from them. This procedure also removes the effects of potential model drift.
Methods

We estimate ENSO period changes in the observational record by applying a simple time series model (see Appendix) to 30-year sections of the Palmyra coral record. We test for a statistically significant change in mean ENSO period from pre-1850 to post-1850 using a two-sided t-test and a bootstrap resampling technique.

To determine whether the ENSO period shift observed in the Palmyra corals is outside the range of natural variability, we generate the distribution of ENSO period shifts expected in the corals due to natural variability. To this end, we develop a statistical relationship between the instrumental NINO3.4 index and the Palmyra corals over the interval 1950-93. We apply this relationship to the 100 realizations of the control NINO3.4 index to create 100 realizations of the Palmyra corals (hereafter called ‘pseudocorals’) that approximate the natural ENSO variability. This statistical model approximately accounts for complications of the relationship between ENSO and the corals introduced by observation error (Cobb et al. 2003), vital effects of the coral (Leder et al. 1996) and other climate variability (Cobb et al. 2003). We subsample the pseudocorals at the time intervals at which the Palmyra coral observations exist and use the simple time series model to extract the pre-1850 to post-1850 ENSO period shift for each of the pseudocoral realizations. We construct the cumulative distribution function of ENSO period shifts and compare the resulting 90% confidence intervals to the observed shift in the Palmyra corals. The data and implementation of the methods are available from the authors upon request.
Results and Discussion

A Morlet wavelet analysis (Torrence and Compo 1998) of the Palmyra coral record (Figure 2-1b) shows some evidence for increased ENSO periods during the pre-1850 interval and decreased periods during the post-1850 interval. The marginal distribution of the wavelet power spectrum (Figure 2-1c) shows a clearer signal for a decrease in ENSO period, but the statistical significance of this shift is difficult to assess. The time series model analysis of the Palmyra corals shows ENSO period changes that are similar to the broad patterns observed in the wavelet analysis (Figure 2-2). ENSO periods are generally higher during the pre-1850 interval ($\mu = 6.4$ years, $\sigma = 1.9$ years, $N = 9$), while periods post-1850 are lower ($\mu = 4.0$ years, $\sigma = 0.60$ years, $N = 4$). This 2.4-year decrease in ENSO period from pre-1850 to post-1850 is statistically significant ($p < 0.1$). In particular, three of the four estimated ENSO periods in the post-1850 interval are at or below the lower limit of periods observed pre-1850.
Figure 2-2. Estimated ENSO periods from 30 year sections of the Palmyra corals. The dashed lines are the mean ENSO periods for the pre-1850 and post-1850 intervals.

The width of the 90% confidence interval for ENSO period changes derived from the pseudocorals is 3.3 years, considerably wider than the 90% confidence intervals of 2.5 years derived from the NINO3.4 realizations (Figure 2-3). This widening is due to the consideration of observation error and vital effects of the coral. The estimated ENSO period decrease of 2.4 years is outside the 90% confidence interval of the estimated unforced ENSO variability in the pseudocorals. As a result, we detect a statistically significant decrease in ENSO period of 2.4 years in the Palmyra coral. The observed decrease in ENSO period is consistent with the hypothesized ENSO response to anthropogenic climate forcing adapted from Cane et al. (1997).
**Figure 2-3.** Detection of anthropogenic ENSO period changes: Cumulative distribution functions derived from the 100 realizations of the pseudocorals (red) and the NINO3.4 index (blue) from the GFDL2.1 control simulation. The 90% confidence intervals are shown at the top. The vertical green line shows the observed shift in ENSO period in the Palmyra corals (*cf.* Figure 2-2).
Caveats

Our results hinge on several assumptions. First, we approximate anthropogenic changes by analyzing the difference between mean ENSO periods in the pre-1850 and post-1850 intervals. Second, we consider only a single ENSO proxy record. Third, we assume that the relationship between ENSO and the isotopic oxygen values of the fossil corals has remained stationary over the last millennium. Fourth, we neglect the effects of natural forcing on ENSO behavior. Last, but not least, we neglect potentially important effects of structural and parametric uncertainties of our statistical analysis.

One strategy to reduce the uncertainty about anthropogenic ENSO modulation is to expand the observational record with longer continuous records of ENSO behavior over the last millennium. In particular, coral records from the eastern and central tropical Pacific Ocean, of similar abilities in capturing ENSO dynamics to Cobb et al. (2003), seem likely to be useful additional constraints. In addition, model simulations of natural (as opposed to unforced or internal) ENSO behavior over the last millennium are needed to better characterize the full range of variability of ENSO period changes. For example, Adams et al. (2003) and Mann et al. (2005) show that natural forcing (volcanic and solar forcing) can explain a sizable fraction of ENSO variability over the last millennium in proxy records and model simulations. We hypothesize that the consideration of natural forcing will widen the distribution of ENSO period changes compared to those shown in Figure 3.
Conclusions

Given our assumptions and caveats, we draw two main conclusions. First, we detect a statistically significant decrease (p < 0.1) in ENSO period in the Palmyra coral record between pre- and post-1850. This result is consistent with the hypothesis of anthropogenic ENSO modulation and the mechanism adapted from Cane et al. (1997). It is important to note, however, that we do not address the attribution of the observed ENSO period changes to anthropogenic forcing. Second, we show that neglecting uncertainties due to confounding effects, such as observation error and vital effects of the coral in the analysis of proxy records can result in the overconfident detection of ENSO period changes.
Acknowledgements

We thank Axel Timmermann, George Philander, Richard Tol and Michael Mann for helpful discussions. Thomas Delworth and Andrew Wittenberg provided the GFDL 2.1 data. We gratefully acknowledge support from the National Science Foundation. Opinions, findings, potential errors and conclusions expressed in this work are those of the authors alone, and do not necessarily reflect the views of funding entities.
Appendix: Comparison of several methods considered to estimate ENSO period

This appendix (i) describes two methods considered in our analysis to estimate ENSO period and (ii) evaluates their skill by applying each method to positive control time series.

The first method is a Fourier analysis using a Fast Fourier Transform (FFT) algorithm where the ENSO period is assumed to be the period between 2 and 10 years that has the most spectral power (Trenberth 1984). The second method, referred to as the time series model, is based on a Fourier series, but uses an optimization technique to determine the best parameters to fit the series to the data. Specifically, we first apply a low-pass filter to the time series to remove oscillations with period less than 1.5 years to increase the signal to noise ratio (Trenberth 1984). We then fit the following model to the observations

\[ Y(t) = \sum_{i=1}^{N} a_i \sin\left(\frac{2\pi}{b_i} t + c_i \right) \]

where \(a_i\), \(b_i\) and \(c_i\) are the amplitude, period and phase shift of each sine function, respectively. The ENSO period is the \(b_i\) between 2 and 10 years (Trenberth 1984) with the largest amplitude \(a_i\). The value of \(N\) determines the model complexity (we show results for the time series model with \(N = 2\) and \(N = 3\)). We use a numerical optimization method to determine model parameter values that minimize the root mean square error (RMSE) of the residuals between the model output and the observations. To overcome the problems introduced by non-smooth gradients and local minima in the RMSE objective function, we implement the global optimization algorithm Differential Evolution (DE) (Storn and Price 1997) to solve this non-convex optimization problem. DE is a genetic algorithm that uses a sequence of mutation and selection to minimize an
objective function. In order to show the convergence to a close approximation to the
optimal parameters of the time series model, we run the DE algorithm with two sets of
random initial conditions and compare the optimal solutions. If the amplitudes and
periods for each run differ by less than 1.0%, the two solutions are for practical purposes
identical and are considered a good approximation to the global minimum. In case this
approach does not lead to convergence, we discard the solutions and reinitialize the
process. This procedure is continued until the convergence criteria are satisfied.

To evaluate the skill of these methods in estimating ENSO period, we construct
1400 30-year-long positive control time series, each the sum of an ENSO oscillation, an
annual cycle, three other oscillations with periods between 2 and 20 years and AR(0)
noise. The ENSO oscillation is the strongest oscillation with period between 2 and 10
years in the time series (Trenberth 1984). The periods, amplitudes and phase shifts of the
different oscillations are known and vary between the 1400 time series. We also construct
these time series with different resolutions (1, 3, 4, 6 and 12 months) to determine if they
limit our abilities to estimate the correct ENSO period.

We evaluate the accuracy and precision of two different statistical methods to
estimate period changes from time series mimicking ENSO dynamics. We apply these
different methods to our positive control ENSO records to (i) examine their skill in
estimating the correct ENSO periods and (ii) determine whether certain temporal
resolutions of the records limit the abilities of the different methods. The skill is defined
as the RMSE of the calculated and known ENSO periods.

For each resolution of the positive control ENSO records, both the time series
models considered outperform the FFT method in estimating ENSO period (Figure 2-4).
We hypothesize that this is due to the fact that the choice of frequency and phase shift in the time series model is continuous and not prescribed by the time resolution of the data, as in the case with an FFT. Furthermore, the resolution affects the abilities of each of the methods. In those time series with a resolution coarser than six months, the accuracy of all considered methods drops considerably. The RMSE derived from the time series model increases by a factor of three when the resolution drops from monthly to annual values.

**Figure 2-4.** Performance of different methods in estimating ENSO period: Root mean square error (RMSE) of the estimated ENSO periods and the known ENSO periods for 1400 self-constructed time series as a function of the temporal resolution of the time series for the Fast Fourier Transform (FFT) and the Fourier-based time series model (N=2 and N=3) analyses.
References


Ginoux, A. Gnanadesikan, C. T. Gordon, S. M. Griffies, R. Gudgel, M. J.
Harrison, I. M. Held, R. S. Hemler, L. W. Horowitz, S. A. Klein, T. R. Knutson,
C. D. Milly, V. Ramaswamy, J. Russell, M. D. Schwarzkopf, E. Shevliakova, J. J.
Zeng, and R. Zhang, 2006: GFDL's CM2 global coupled climate models. Part I:
Formulation and simulation characteristics. Journal of Climate, 19, 643-674.

2002.
——, 2001: A stability analysis of tropical ocean-atmosphere interactions: Bridging

Fedorov, A. V., R. C. Pacanowski, S. G. Philander, and G. Boccaletti, 2004: The effect of
salinity on the wind-driven circulation and the thermal structure of the upper

Fedorov, A. V., P. S. Dekens, M. McCarthy, A. C. Ravelo, P. B. deMenocal, M. Barreiro,
R. C. Pacanowski, and S. G. Philander, 2006: The Pliocene paradox (mechanisms


Hasselmann, K., 1993: Optimal Fingerprints for the Detection of Time-Dependent

Hegerl, G. C., K. Hasselmann, U. Cubasch, J. F. B. Mitchell, E. Roeckner, R. Voss, and
J. Waszkewitz, 1997: Multi-fingerprint detection and attribution analysis of
greenhouse gas, greenhouse gas-plus-aerosol and solar forced climate change.

*Climate Dynamics*, **13**, 613-634.


Chapter 3: Conclusions and Future Work
Conclusions

We draw three main conclusions from the analysis in Chapter 2. First, we detect a statistically significant ($p < 0.1$) shift in ENSO period between the pre- and post-1850 intervals as recorded in the Palmyra coral record. This result is consistent with the hypothesis of anthropogenic ENSO modulation and the mechanism adapted from Cane et al (1997). Second, we show that neglecting observation error and vital effects of the coral in the analysis of the proxy record can result in overconfident detection capabilities. Finally, we show that the temporal resolution of an ENSO proxy record can affect the skill of different methods in estimating ENSO period.

The contributions of this analysis are twofold. First, our detection study extracts a signal from the proxy record that can be used to improve our understanding of the relationship between ENSO and (anthropogenic) climate forcing. As ENSO is the largest global climatic oscillation on interannual timescales, anthropogenic modulation of ENSO can have nontrivial effects on natural ecosystems and human welfare. Second, we give an estimate of ENSO period changes over the last millennium as recorded in a proxy record. These estimates can be assimilated into climate models to constrain hindcasts and make more skillful probabilistic predictions of future ENSO behavior.
Future Work

Two avenues to improve the analysis detailed in Chapter 2 merit further discussion. First, we analyze a single ENSO proxy record, which covers the last thousand years only intermittently. A continuous record of ENSO behavior over the last millennium with similar high fidelity to the Palmyra coral record would help to reduce the current uncertainty surrounding possible anthropogenic ENSO period changes. Second, we neglect the effects of natural forcing on ENSO behavior. Studies have shown that both volcanic and solar forcings can explain a sizeable fraction of the reconstructed ENSO variance over the last millennium (Adams et al. 2003; Mann et al. 2005). Incorporating an estimate of ENSO behavior from a model simulation that accounts for volcanic and solar forcing would likely improve our detection analysis.

These two extensions of the current work focus on the detection of anthropogenic ENSO changes. Detection, however, concerns the past. Decision makers are mostly concerned about the future and require predictions of ENSO behavior. Current predictions about the response of ENSO to anthropogenic climate forcing are highly uncertain and subject to several methodological caveats. Collins (2005), for example, predicts how the mean ENSO state will change by weighting different global climate models (GCM) based on their “ENSOness”. The resulting ENSO predictions are highly uncertain and include both El Niño-like or La Niña-like responses to anthropogenic forcing. The most likely response based on the weightings is no shift. Another study, van Oldenborgh et al. (2005), analyze changes in both El Niño variability and the mean ENSO state. Most models in this study show an El Niño-like response in the mean state, but changes in ENSO variability are mixed.
These ENSO prediction studies break important new ground, but neglect useful information contained in ENSO proxy records. One extension of the analysis described in Chapter 2 is to use the estimates of ENSO period variability found in the Palmyra corals to derive likelihoods for the ENSO models used in Collins (2005) and van Oldenborgh et al. (2005). These predictions can then be combined using Bayesian Model Averaging (Hoeting et al., 1999) to derive potentially improved ENSO projections.

While the proposed analysis above examines climate model structural uncertainty, it neglects uncertainty in model parameters. Addressing how uncertainty in key climate model parameters affects predictive skill is complicated by the tension between computational efficiency and model complexity. A model needs to be computationally fast enough to explore the entire parameter space, yet complex enough to include key processes and feedbacks needed to simulate ENSO accurately. Although the GCMs used in the previous ENSO prediction studies simulate ENSO with reasonable skill, they are too slow to explore the parameter space. One possible approach to solve this problem is to couple an ENSO model (e.g., the Zebiak-Cane model [Zebiak and Cane, 1987]) to an Earth System Model of Intermediate Complexity (EMIC) that is much faster than a GCM. This approach would enable the fusion of a large ensemble of simulations with the proxy record analyzed in Chapter 2.
References


