The Global Three-Dimensional Structure for the Developmental Phase of ENSO

A Thesis

Presented in Partial Fulfillment of the Requirements for The Degree Masters of Science
in the Graduate School of The Ohio State University

By
Scott Andrew Melaragno, B.A.
Graduate Program in Atmospheric Science

The Ohio State University

2010

Thesis Committee
Dr. Jialin Lin, Advisor
Dr. Jay S. Hobgood
Dr. Jeffery C. Rogers
ABSTRACT

An examination of NCEP reanalysis anomaly data for neutral El Niño-Southern Oscillation (ENSO) phases is conducted in order to portray a three-dimensional view of the global teleconnections associated with this phenomenon. The neutral phase, which occurs when Niño 3.4 sea surface temperatures (SSTs) lack either warm or cold anomalies, precedes both warm and cold ENSO events. Few studies have examined the significance of these phases, usually grouping both warm-to-cold and cold-to-warm phases into one mean state, when in reality these transitional periods are far from neutral. Because of a lack of neutrality seen within NCEP reanalysis data from 1950-2007, the title of “developmental phase” will be given for apparent neutral events leading up to an extreme phase.

During a developmental phase one year before a mature El Niño (December-January-February [-1]), warm SST anomalies bisecting the equator/date line and along 30°S within the eastern Pacific are seen. Increased SSTs also appear in the northern Pacific Ocean, southern Atlantic Ocean, Baffin Bay off the west coast of Greenland, Gulf of Mexico and the eastern Mediterranean Sea. Cold SST anomalies are seen predominantly throughout the Tropical Pacific. Enhanced precipitation and upward motion above warm SST anomalies occurs over the western Pacific, surrounding Indonesia and Papua New Guinea.
Analysis of the zonal mean circulation provides a vertical representation of how the neutral phase affects the three latitudinal circulation cells, along with the horizontal Walker circulation. Symmetric cooling of the tropical troposphere and Northern Hemisphere (NH) midlatitudes can be seen during this phase, with a mid-level warm core above the equator. More vertical warming around the polar regions, especially in the Southern Hemisphere (SH) can be seen during the boreal winter one year before an El Niño. Combining these vertical and horizontal cross-sections shows a weakening and displacement of Hadley cells 20°N and S, with a strong westerly tropical jet positioned directly along the warm core in the mid-to-upper troposphere. Critical in the development and decay of ENSO events, the Walker Circulation appears to be deteriorating, a foretelling sign of an impending El Niño. Even in the polar regions, critical weakening of the polar vortex correlates with neutral conditions.

The teleconnections seen during the neutral phases of ENSO provide new findings that help explain the complex dynamics associated with a coupled ocean-atmospheric system. The timescale of a developmental phase aids in predicting warm and cold events that are potentially one year away from fruition. With the completion of a three dimensional schematic and the corresponding teleconnections associated with a developmental episode, this study provides new methodology in forecasting extreme events throughout the entire ENSO cycle.
DEDICATION

Dedicated to my family, friends, and fiancé for their unconditional support through this two year adventure. I would not be where I am today without these people in my life.
ACKNOWLEDGEMENTS

I would like to extend my thanks to Jialin Lin for all of his help, guidance, and patience throughout the entire construction of my thesis. His introduction of the neutral phases of ENSO to me has proven to be an extremely interesting topic and an important area of future research. Also, special thanks to my committee members Jay S. Hobgood and Jeffery C. Rogers for their classes in Synoptic and Dynamic Meteorology. Their teachings concerning the physics and theories of the atmosphere have played an imperative role in this thesis. Additional thanks to Taotao Qian for her construction of the pre-1948 dataset and her help throughout this process.

This work was supported by NASA Modeling, Analysis and Prediction (MAP) Program, NOAA Climate Prediction Program for the Americas (CPPA), and NSF grant ATM-0745872. The correlation analysis was conducted using online plotting tools developed by NOAA ESRL Physical Science Division (PSD), Boulder Colorado from their website at http://www.esrl.noaa.gov/psd/.

Furthermore, a special acknowledgement to Erik Fraza, Mike Davis, and Meng-Pai Hung for all their support and advice in helping me complete this thesis.
VITA

September 4, 1985 ..........................................Born USAFA, Colorado
May, 2008 ......................................................B.A. Geography and Environmental

Sciences, Miami University-Oxford

FIELD OF STUDY

Major: Atmospheric Sciences
TABLE OF CONTENTS

ABSTRACT ....................................................................................................................... ii

DEDICATION ..................................................................................................................... iv

ACKNOWLEDGEMENTS .................................................................................................. v

VITA ................................................................................................................................... vi

LIST OF FIGURES .......................................................................................................... ix

Chapters

1. Introduction .................................................................................................................. 1
   1.1 General and Historical Background of ENSO ....................................................... 1
   1.2 Post-TOGA Research and ENSO Theories ......................................................... 6
   1.3 Global Circulation Cells during ENSO .............................................................. 9
   1.4 Unanswered Questions and the Purpose of this Study ........................................ 11

2. Data and Methodology ............................................................................................... 15
   2.1 Data ................................................................................................................... 15
   2.2 Methodology ...................................................................................................... 16

3. The Neutral Phases of ENSO: Are They Really Neutral? ........................................ 21
   3.1 Results ............................................................................................................. 21
   3.2 Summary and Discussion .................................................................................. 24
LIST OF FIGURES

Figure 1. The Oceanic Niño Index (ONI). Events are defined as 5 consecutive months at or above the +0.5° anomaly for warm (El Niño) events and at or below the -0.5 anomaly for cold (La Niña) events. The threshold is further broken down into Weak (with a 0.5 to 0.9 SST anomaly), Moderate (1.0 to 1.4) and Strong (≥ 1.5) events. For an event to be weak, moderate or strong it must have equaled or exceeded the threshold for at least 3 months (Image from The Climate Prediction Center (CPC) ENSO Impacts 2010). .......................................................... 14

Figure 2. a) The raw Nino3.4 SST time series (thin line) and smoothed Nino3.4 SST time series (thick line), (b) the spectrum of raw Nino3.4 SST time series (black) and smoothed Nino3.4 SST time series (red), (c) the transition index, and (d) the lag-correlation between the transition index and the smoothed Nino3.4 SST time series. .......................................................... 19

Figure 3. The (a) smoothed Niño 3.4 index and (b) the transition index. Both have the corresponding phases of ENSO, each lasting one year. .................................................. 20

Figure 4. Linear correlation of winter DJF (a) SST, (b) SLP, and (c) 1000 mb zonal wind with transitional Nino 3.4 SST. .................................................................................. 28

Figure 5. Same as Figure 4 but for SLP during (a) JJA (-1.5), (b) SON (-1.25), and (c) MAM (-.75). ................................................................................................................. 29

Figure 6. ER Pre-1948 SLP for (a) DJF and (b) annual using the transitional Nino 3.4 index. ....................................................................................................................... 30

Figure 7. Same as Figure 5, but for SST anomalies.................................................. 31

Figure 8. Schematic of winter (cold to warm) developmental phase (-1). ................ 32

Figure 9. Linear correlation of winter DJF mean zonal mean air temperature with transitional Nino 3.4 SST. .................................................................................. 59

Figure 10. Same as Figure 9 but for geopotential height......................................... 60

Figure 11. Same as Figure 9 but for zonal wind..................................................... 61
Figure 12. Same as Figure 9 but for meridional wind. .............................................. 62

Figure 13. Same as Figure 9 but for vertical pressure velocity. .................................. 63

Figure 14. Same as Figure 9 but for SST. ........................................................................ 64

Figure 15. Same as Figure 9 but for (a) precipitation, and (b) 500mb vertical velocity... 65

Figure 16. Same as Figure 9 but for (a) SLP, (b) 1000 mb zonal wind, and (c) 1000 mb meridional wind. ........................................................................................................ 66

Figure 17. Same as Figure 9 but for 200 mb (a) geopotential height, (b) zonal wind, and (c) meridional wind. ........................................................................................................ 67

Figure 18. Same as Figure 9 but for northern hemisphere DJF mean geopotential height at (a) 10 mb, (b) 100 mb, (c) 500 mb, and (d) 1000 mb. .............................................. 68

Figure 19. Same as Figure 9 but for southern hemisphere DJF mean geopotential height at (a) 10 mb, (b) 100 mb, (c) 500 mb, and (d) 1000 mb. ................................. 69

Figure 20. Schematic depiction of the global 3-D structure of ENSO’s developmental phase. ................................................................................................................................. 70

Figure 21. Schematic depiction of the global teleconnections of ENSO’s winter neutral phase. ................................................................................................................................. 71

Figure 22. Linear correlation of summer JJA mean zonal air temperature with the transition Nino 3.4 SST ........................................................................................................... 104

Figure 23. Same as Figure 22 but for geopotential height................................................. 105

Figure 24. Same as Figure 22 but for zonal wind ............................................................... 106

Figure 25. Same as Figure 22 but for meridional wind ..................................................... 107

Figure 26. Same as Figure 22 but for vertical pressure velocity ..................................... 108

Figure 27. Same as Figure 22 but for SST ....................................................................... 109

Figure 28. Same as Figure 22 but for (a) precipitation, and (b) 500mb vertical velocity. ................................................................................................................................. 110

x
Figure 29. Same as Figure 22 but for (a) SLP, (b) 1000mb zonal wind, and (c) 1000mb meridional wind. .......................................................... 111

Figure 30. Same as Figure 22 but for 200mb (a) geopotential height, (b) zonal wind, and (c) meridional wind. .......................................................... 112

Figure 31. Same as Figure 22 but for northern hemisphere JJA mean geopotential height at (a) 1000 mb, (b) 500 mb, (c) 100 mb, and (d) 10 mb. ......................... 113

Figure 32. Same as Figure 22 but for southern hemisphere JJA mean geopotential height at (a) 1000 mb, (b) 500 mb, (c) 100 mb, and (d) 10 mb. ......................... 114

Figure 33. Schematic depiction of the global 3-D structure of ENSO’s developmental phase. .......................................................... 115

Figure 34. Schematic depiction of the global teleconnections of ENSO’s summer neutral phase. .......................................................... 116
CHAPTER 1
INTRODUCTION

Widely considered the most important controlling mechanism for interannual global climate variability, the El Niño-Southern Oscillation (ENSO) is a genuine ocean-atmosphere phenomenon within the tropical Pacific Basin (Philander 1990; Chang et al. 2006). The mechanisms that dictate the oscillatory nature of ENSO are still not well understood, evident in the overall lack of adequate statistical modeling of this phenomenon (Barnston et al. 1999). Dynamic and complex in nature, producing accurate ENSO forecasts has proven to be a very difficult task. Intricacies within this coupled tropical system have been discovered through analysis of the ever-changing dynamic structure of ENSO; however, due to its immense geographic scope and teleconnected weather patterns, a better understanding is needed in order to better predict future climate impacts.

1.1 General and Historical Background of ENSO

Analyses of the cyclical nature of ENSO and the dynamics that make up the structure of this complex system have been developed not by one scientific “breakthrough”; but instead out of a series of studies spanning a period of more than eight decades (Wallace et al. 1998). The life cycle of ENSO fluctuates around the mean
state of the tropical Pacific coupled system, with average conditions consisting of an east-to-west gradient of sea surface temperatures (SSTs) driving the overlying easterly trade winds. This east-to-west gradient in turn reinforces deep atmospheric convection associated with the western warm pool and large scale descending motion in response to cold SSTs in the eastern Pacific. A positive dynamical feedback is the net end result, with low sea level pressure (SLP) in the western Pacific and high SLP in the eastern Pacific (Chang et al. 2006). Known as the Southern Oscillation (SO), Sir Gilbert Walker first presented this positive feedback of SLP variations in the landmark synthesis of studies during 1924 (Walker 1924). Measurements of SLP differences between Darwin, Australia (12°S, 131°E) and Tahiti (17°S, 150°W) associated with the SO were discovered far before the fundamentals of ENSO.

In another landmark study (Bjerknes 1969), the equatorial relationship, represented by SLP differences of the SO and the Pacific basin-scale SST gradient, was recognized as a coupled ocean-atmospheric feedback that acted as the source of ENSO-related climate variability (Wallace et al. 1998). Now a general structure of the equatorial Pacific could be established, with a vertical circulation around the low (high) pressure system in the western (eastern) Pacific, the horizontal easterly flow dictated by the east-to-west SST gradient, and the elevated westerly return flow in response to the upper-level divergence (convergence) of the deep atmospheric convection in the western warm pool (large-scale subsidence associated with the cold SSTs in the eastern Pacific). Bjerknes named this feature the Walker circulation after Sir Gilbert Walker’s previous findings. The underlying importance of the Walker circulation stems from the
importance of the air-sea interactions along the equator, where any change in the SSTs, wind field, and SLP could weaken the general circulation seen over the entire tropical Pacific, initiating a new warm or cold ENSO event (e.g. Bjerknes 1969). This topic is discussed extensively in section 1.3.

With an understanding of the mean conditions that drive the coupled ocean-atmosphere throughout the equatorial Pacific, a discussion concerning the extreme phases of ENSO can be made. The climatological mean SST conditions of the Pacific consist of a western warm pool, which is separated drastically by the cold pool along the eastern boundary. It is important to note that this stark separation of SSTs within the Pacific basin is driven dynamically by the positive tilting of the subsurface thermocline from west-to-east (Colling 2001). The wind stress associated with the easterly trades acts on the ocean surface, which ultimately causes the thermocline to rise and the cold subsurface waters to upwell in the east (Chang et al. 2006).

Originally used to denote the interannual occurrence of warm ocean temperatures off the west coast of Peru and Ecuador during Christmas, El Niño has been recognized as a climatic feature for hundreds of years. Presently, El Niño represents the basin-scale anomalous warming of the tropical Pacific Ocean and the simultaneous changes to the global climate system. Since the Walker circulation is very susceptible to changes in air-sea interactions (Wang 2002), warming of the eastern Pacific drastically alters the SO and the horizontal and vertical motions of the Pacific. During an El Niño, high SLP develops where the western warm pool originates and low SLP anomalies grow over the southeastern tropical Pacific, which substantially weakens the Walker Circulation.
Because of this dual relationship, the El Niño/oceanic phenomenon directly correlates with the atmospheric/Southern Oscillation. The opposite of El Niño is termed La Niña and represents a strengthening of the Walker Circulation due to increased upwelling in the eastern Pacific, in turn driving strong easterly trades deep into the central and western Pacific. ENSO events last approximately 12-18 months and occur every two to seven years, with the entire life cycle averaging around a four year oscillation, depending on the strength of a given extreme phase.

Figure 1 shows a time series of the Oceanic Niño Index (ONI), which is currently the index NOAA uses for classifying El Niño and La Niña events in the tropical Pacific. The ONI uses a running 3-month mean SST anomaly for the Niño 3.4 region (5°N-5°S, 120°-170°W), and events are defined as five consecutive months of equal or above the positive 0.5° anomaly for warm events (-0.5° anomaly for cold events). Each ENSO extreme event is broken down into Weak (with a 0.5 to 0.9 SST anomaly), Moderate (1.0 to 1.4) and Strong (≥ 1.5) events (NOAA CPC, ENSO Impacts). SST anomalies below the weak category represent the neutral phases of ENSO and will be comprehensively explained in Chapter 2. For a singular event to be classified as weak, moderate, or strong, it must have equaled or exceeded the threshold for at least three months, thus indicating the severity of each phase.

Bjerknes’ (1969) synthesis provided a theoretical renewal in the way ENSO was viewed, and from this time on, many studies utilize this thinking to better understand the convoluted dynamics of this phenomenon. One study that expanded upon Bjerknes’ way of thinking was Wyrtki (1975), which emphasized the importance of local SSTs
responding to a sudden decrease in the easterlies over the equatorial central Pacific. This differed from previous theories, which assumed El Niño warmings are a response to surface wind forcing and decreased upwelling. Rather, initiation of ENSO extreme events hinge on a “buildup phase”, where anomalously strong equatorial easterlies increase the slope of the thermocline and the magnitude of upwelling along the eastern Pacific, which in turn causes warmer SSTs to agglomerate in the western side of the basin (Wyrtki 1975). A breaking point is reached as the strong easterly trades abruptly collapse, ushering in the necessary ingredients for a new El Niño.

Several studies used the findings of Wyrtki (1975) to analyze individual warm episodes and corroborate the influential discovery of equatorial trade wind dampening. In the process of examining singular events, many of these studies (McCrea 1976; Wyrtki 1979; Philander 1981) noted a very systematic progression and phase locking associated with the climatological annual march. It was however, the landmark study of Rasmusson and Carpenter (1982, hereafter given the title of RC) that first described the mean seasonal patterns for El Niño in terms of composite maps, which were based on the six major warm events that occurred between 1949 and 1976. Through these El Niño composite maps, RC concluded the lifecycle of a warm event exhibited a systematic evolution. This signified that once an El Niño had begun, a certain level of predictability could be seen throughout the lifecycle of a given episode.

RC broke the composite maps into five phases following the life cycle: antecedent conditions (September [-1]), onset phase (December [-1]), peak phase (April [0]), transition phase (September [0]), and mature stage (January [+1]), where the index refers
to the year before (-1), during (0), or after (+1) El Niño (RC 1982). Utilization of this timescale will be similar to the way the present study views a life cycle of an extreme phase of ENSO. The major findings of RC agreed with Wyrtki’s study, where composite warm episodes portrayed strengthening easterly wind anomalies pushing to the west of the date line during the antecedent phase leading up to an El Niño. Westerly wind anomalies in the western Pacific then took precedent over the zonal flow during the onset phase, which later spawned large positive SST anomalies in the eastern equatorial Pacific during the peak phase. This pattern intensified, with a westward expansion of warm SSTs proceeding to move away from the western coast of South America, reaching the central Pacific during the transition phase. During RC’s mature phase, the positive SST and rainfall anomalies became focused entirely in the central Pacific, thus causing the equatorially symmetric “Hadley Circulation” to intensify in this region. This created an increased area of low-level convergence and eventually altered the entire three scale global circulation model (Wallace et al 1998). The monumental study of Rasmusson and Carpenter (1982) made a dramatic impact on the field of ENSO research and is an essential reference for this thesis.

1.2 Post-TOGA Research and ENSO Theories

A new era in ENSO research followed the influential findings of RC, and with a renewed way of viewing individual extreme events, the Tropical Oceans-Global Atmosphere (TOGA) program was established. Set up to monitor the varying warm and cold phases of ENSO from 1985-1994, the TOGA program was an international research effort located primarily in the tropical Pacific Ocean. Aiming to better understand the
principle dynamics of ENSO, TOGA used these new findings to better forecast future El Niño events. Widely considered an immensely successful program, TOGA according to Chang et al., “led to improvements in our understanding of how the dynamics of the equatorial waveguide plays in the role of ocean memory in the ENSO cycle,” (2006, p. 5123).

TOGA has also provided advancements in the understanding of how the oceanic mechanism, mentioned by Chang et al. (2006), correlates with ocean-atmosphere feedbacks, leading to a class of coupled modes that are implicit to the comprehension of ENSO physics (National Research Council 1996; Chang et al. 2006). Because of these findings, it is now widely accepted that ENSO can be accurately forecasted to some extent, and a correct estimation of the upper-ocean state in the tropical Pacific was therefore critical to making these forecasts (National Research Council 1996). Presently the TOGA observing system uses a wide array of land-sea monitoring systems to better forecast the evolution of a new El Niño or La Niña and provides detailed analyses for the Climate Variability and Prediction (CLIVAR) Program.

From the influential findings during the TOGA decade, many ENSO theories have been introduced and examined in detail (e.g. Neelin et al. 1998), and are used to explain the quasi-oscillatory nature of this phenomenon. In a mathematical sense, the cyclical behavior of ENSO can be described by a single differential delay equation in terms of a SST anomaly. Widely known as the “delayed oscillator” (Suarez and Schopf 1988; Battisti and Hirst 1989), this mechanism of ENSO emphasizes the importance of free upwelling equatorial Rossby waves, which are forced by the zonal wind stress.
anomaly in the central Pacific during an El Niño. These Rossby waves propagate westward and are reflected by the western boundary and become eastward propagating upwelling Kelvin waves (Wang and Weisberg 2000; Lin 2009). The upwelling cold Kelvin waves then effectively kill the warm SSTs in the eastern Pacific and produce the conditions needed for La Niña cold SST anomalies, leading to an overall oscillating effect (Lin 2009).

Similar to the delayed oscillator, the advective-reflective oscillatory theory (Picaut et al. 1997) instead focuses on free downwelling Kelvin waves forced by the zonal wind stress anomaly in the central Pacific during El Niño conditions. These waves propagate eastward and are reflected by the eastern boundary, in turn creating westward propagating downwelling equatorial Rossby waves (Lin 2009). Warm SST anomalies located in the eastern Pacific are then advected by the returned Rossby waves to the western Pacific, which initiate cold SST anomalies in the eastern boundary associated with a La Niña (Lin 2009).

Jin (1997; Part I and II) proposed a recharge-discharge oscillator model for ENSO, which focuses on SST anomalies in the equatorial eastern Pacific and thermocline depth anomalies seen in the equatorial western Pacific (Wang and Weisberg 2000). The importance of zonal wind anomalies on thermocline heights is summarized as, “Westerly wind anomalies in the equatorial central Pacific deepens (raises) the equatorial thermocline in the east (west),” (Wang and Weisberg 2000). This deepening in the east increases SSTs throughout the equatorial eastern Pacific, inducing a mature El Niño event. Concurrently, Sverdrup transport associated with the wind stress curl during this
warm phase causes heat to flow poleward from the equator, which leads to a transition phase where the entire equatorial Pacific thermocline is anomalously shallow (Wang and Weisberg 2000). Cold subsurface waters, which are attributed to the shallow thermocline and climatological upwelling, eventually decrease SSTs in the equatorial eastern Pacific and induce a La Niña event.

The last ENSO theory pertinent to this study is the western Pacific oscillator (Weisberg and Wang 1997), which focuses on the zonal wind anomalies that occur in the western Pacific. Gill (1980) argued that condensational heating due to convection in the equatorial west-central Pacific induces a pair of off-equatorial anomalous cyclones with westerly wind anomalies on the equator. Weisberg and Wang (1997) noted that these westerly wind bursts deepen the thermocline and increase SSTs in the equatorial central Pacific, thus creating necessary conditions for anomaly growth. These off-equatorial cyclones raise the thermocline via Ekman pumping, creating shallow thermocline anomalies that expand over the western Pacific, which decreases SSTs and increases SLP during El Niño (Wang and Weisberg 2000). High SLP anomalies during a warm event create anomalous easterly flow, which produces upwelling and cold SSTs that spread eastward, effectively killing the current El Niño and leading to La Niña-like conditions.

1.3 Global Circulation Cells during ENSO

The important zonal circulation cell, the Walker circulation, has been discussed regarding its alteration by ENSO events; however, because of increasing signs that these events modulate the upper-level flow throughout the subtropical and extratropical atmosphere (van Loon and Rogers 1981; Trenberth et al. 1998; L’Heureux and
Thompson 2006), the meridional circulation cells have become increasingly important in forecasting the potential impacts seen in the midlatitudes. The Hadley cell and the Ferrel cell, described extensively by Trenberth et al. (2000) are very sensitive to the modulation of convergence zones by ENSO extreme phases. Located in the tropical and subtropical regions, the Hadley circulation cell is thermally driven, comparable to the mechanisms that drive the Walker circulation (Trenberth et al. 1998). Convection caused by a heated/unstable tropical airmass creates rising motion and diverges aloft. Air then flows toward the subtropical region, where it then cools, sinks, and flows back to the tropical region (Wang 2002). The Ferrel cell is an extratropical counterpart to the Hadley circulation, where air converges along the extratropical high-latitudes and descends in the subtropical region similar to the Hadley cell. Wang describes the Ferrel Cell, referencing the dynamics of Holton (1992) stating, “The Ferrel cell is forced mostly by transient baroclinic eddy activity through associated poleward heat and momentum transports,” (2002, p. 399).

During the evolution of ENSO, these meridional circulation cells behave differently than the Walker circulation. Wang (2002) describes these changes utilizing NCEP reanalysis data from 1950-1999 for a wide range of ocean-atmospheric processes. He noted that during the mature phase of El Niño, the eastern Pacific shows air rising in the tropical region, flowing northward in the upper troposphere, eventually sinking in the midlatitudes and returning back to the Tropics in the lower levels of the atmosphere (Wang 2002). The anomalous Hadley cell in the western Pacific has an opposite sign than that of the anomalous Hadley cell in the eastern Pacific. The zonal circulation cells,
(Wang introduces a Midlatitude Zonal Cell [MZC] along with the Walker circulation) are dramatically weakened during the warm phase, with a switching of wind direction opposite of the mean state (opposite being a switch to westerlies at low levels for the Walker circulation and easterlies at low levels for the MZC).

Focused on the teleconnections themselves, Trenberth et al. (1998) notes that a zonal mean temperature increase in the middle to upper tropical troposphere occurs during an El Niño event, which is correlated to enhanced convection and adiabatic heating in the descending branches of the Hadley and Walker circulations. This deep convection is also associated with symmetric upper-level anticyclonic systems along the equator, which are related to the divergence of flow aloft (e.g. Holton 1992). Trenberth et al. (1998) states that the divergent component of the flow seen between these anticyclones provides enough forcing for the production of Rossby waves in the atmosphere, which occurs through the advection of Earth’s vorticity. A wave train of alternating high and low geopotential anomalies acts in response to the Rossby waves, and leads to a southward displacement of the subtropical jet stream, creating an enhanced storm track in this region (refer to schematic seen in Figure 4 of Trenberth et al. 1998). Teleconnections corresponding to the modulation of global circulation patterns from ENSO play a vital role in better predicting and understanding this phenomenon and will be employed extensively throughout this study.

1.4 Unanswered Questions and the Purpose of this Study

Even with the previously presented advancements of the past eight decades, predicting phase changes within the ENSO lifecycle has proven to be a formidable task.
Many underlying questions have yet to be answered. What causes a mode to change from its transition phases to the extreme phases and vice versa? The theories listed in section 1.2 still do not accurately explain why certain El Niño events last longer than others, why they have a shorter to almost nonexistent transition phase, or explain when these phase changes will actually occur. The underlying physical mechanisms dictating the quasi-oscillatory nature of ENSO are unquestionably flawed within global climate models, and until a better understanding of the coupled ocean-atmosphere dynamics is reached, El Niño/La Niña forecasts will continue to be imperfect.

One approach that has been mostly ignored by previous studies is the importance of transitional phases leading up to the extreme modes of ENSO. Transitional phases continue to be grouped within a neutral category, when in reality they are far from neutral. Warm to cold transitional phases exhibit synoptic features much different than the opposite cold to warm transitional episodes, and these variations continue to be erroneously grouped together. The goal of this thesis is to investigate the important ocean-atmospheric interactions that occur during transitional phases of ENSO and to effectively show that these phases are far from neutral. Additionally this thesis seeks to use these developmental phases to answer the following:

1. With a global three-dimensional structure for the developmental phases of ENSO, what large-scale features appear to be occurring leading up to a warm or cold event?

2. What are the corresponding teleconnections seen for the winter and summer one year before warm and cold ENSO events?
3. How does the developmental phase induce extreme ENSO events?

4. With these findings, how can using the developmental phase better predict teleconnected weather patterns associated with ENSO phase changes?

Chapter 2 will describe the data and methodology used for the transitional index of this thesis. The focus of Chapter 3 is the Pacific synoptic events of the developmental phase. Chapter 4 will present the results using NCEP reanalysis data, a schematic of the composite winter neutral phase for El Niño events, and a schematic of teleconnected patterns associated with these events. Chapter 5 will cover the summer equivalent to Chapter 4. Chapter 6 concludes with the main findings of the thesis and introduces potential future research on the teleconnections associated with neutral phases of ENSO.
**Figure 1.** The Oceanic Niño Index (ONI). Events are defined as 5 consecutive months at or above the +0.5° anomaly for warm (El Niño) events and at or below the -0.5 anomaly for cold (La Niña) events. The threshold is further broken down into Weak (with a 0.5 to 0.9 SST anomaly), Moderate (1.0 to 1.4) and Strong (≥ 1.5) events. For an event to be weak, moderate or strong it must have equalled or exceeded the threshold for at least 3 months (Image from The Climate Prediction Center (CPC) *ENSO Impacts* 2010).
CHAPTER 2
DATA AND METHODOLOGY

2.1 Data

All data are taken from the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) Physical Science Division (PSD) using reanalysis fields on a 2.5° latitude \( \times \) 2.5° longitude grid (Kalnay et al., 1996). There exist 18 analysis levels (up to the 200 mb) for the horizontal maps and 27 (up to the 10 mb) for the vertical cross-section and polar stereographic maps (except for omega anomalies, where the 100 mb was the maximum vertical extent). The main variables used in this study include air temperature, SST, precipitation rates, SLP, geopotential height, zonal and meridional winds, and vertical velocity. These variables are model-derived reanalysis fields that use a modernized global data assimilation method.

The NCEP/NCAR reanalysis project began in the early 1990’s with the recovery of land surface, ship, rawinsonde, pilot balloon wind observations (PIBAL), aircraft, satellite and other important ocean-atmospheric data from the past 40 years (Kalnay et al., 1996). This data was then quality controlled, eliminating any perceived climate fluctuations that occurred during this time series. For the first time, researchers had a single outlet to gather global climate data, which was particularly important for a decade where global warming became an apparent concern to the scientific community.
this project, data was difficult to obtain and was often dispersed all over the world. Once implemented, this project even made it easier for foreign nations to collaborate with one another.

Beginning in May of 1994, an NCEP supercomputer started processing one month’s worth of reanalysis data and forecasts in one day (Kalnay et al. 1996). Continuing at this rate, 13 years of data was then complied between May of 1994 through September of 1995. The original reanalysis discussed in Kalnay et al. 1996 only went as far back as 1957; however, with the implementation of the Northern Hemisphere Upper-Air Network in 1946, this data was also added, providing information from 1948-1957 into the reanalysis database.

2.2 Methodology

Similar to the Oceanic Niño Index (ONI), as described in Chapter 1, creating a transitional index requires smoothing the Niño 3.4 SST anomalies, which eliminates interseasonal variability within the index. Therefore from the raw Niño 3.4 SST time series (Figure 2a), two indexes are developed: a smoothed index and a transition index. A 25 month running mean is then applied to the raw time series, creating the smoothed index, and is represented by the thick line in Figure 2a and the life cycle seen in Figure 3a. The transition index is defined as the time derivative of the smoothed index, where the time derivative is calculated using central difference scheme except for the first and last data points, for which forward and backward difference scheme is used, correspondingly (Figure 2c). The transitional index can then be utilized in creating anomaly maps, in turn portraying the oceanic/atmospheric conditions one year before
ENSO extreme phases. Refer to Figure 3 for the definition of each phase. The time (cycle) represents one year for each phase, thus the entire lifecycle of ENSO is around 4 years. When examining Figure 3, the classification of ENSO extreme phases is as follows: warm phases represent El Niño events and cold phases represent La Niña episodes.

The composite structures of ENSO's extreme phases and transition phase are constructed by calculating the linear correlation between the NCEP/NCAR reanalysis data and the ENSO smoothed index and transition index. Zonal mean cross-sections, global horizontal maps and polar stereographic maps of all the different variables were the main graphs analyzed in this thesis. Correlation with the smooth index represents the warm El Niño phase, and if multiplied by -1, the cold La Niña phase, which is explained by the linear nature of the ENSO lifecycle (Chang et al. 2006). Correlation with the transition index represents the cold to warm developmental phase, and if multiply by -1, the warm to cold developmental phase. For correlation with 62 years of data, the 95% confidence level is 0.25.

Using the transitional index defined above for the years 1948-present, analyses can focus on the anomalies occurring during the exact neutrality between extreme warm and cold events. In order to provide an outlook one year before ENSO extreme phases, these reanalysis maps will focus primarily on the winter (DJF) months that occur one year(-1) before an El Niño/La Niña; however, summer (JJA), autumnal (SON), and vernal (MAM) SLP anomalies are used to show the changes seen both before and after this developmental phase.
In order to further solidify these results, the transitional index was also applied to NOAA’s ERSST_V3 dataset provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA [from their Web site at http://www.esrl.noaa.gov/psd/]. ERSST_V3 stands for extended reconstruction sea surface temperature (ERSST) version 3 and is used to make conclusions in the next Chapter. This dataset was created using the most recently available International Comprehensive Ocean-Atmosphere Data Set (ICOADS) SST data and improved statistical methods that allow for an accurate compilation using sparse data (Smith et al. 2008). This monthly analysis begins January 1854, but because of inconsistent data, the analyzed signal is severely dampened before 1880. Therefore, this is the earliest reconstructed date for the present study. The use of 67 more years provides a longer time series (1880-1947), which in turn strengthens the argument of neutral phase impacts on the initiation of El Niño. ERSLP anomaly maps are also discussed in Chapter 3. Further information on this reconstructed dataset can be found in Smith et al. (2008).
Figure 2. a) The raw Nino3.4 SST time series (thin line) and smoothed Nino3.4 SST time series (thick line), (b) the spectrum of raw Nino3.4 SST time series (black) and smoothed
Nino3.4 SST time series (red), (c) the transition index, and (d) the lag-correlation between the transition index and the smoothed Nino3.4 SST time series.

Figure 3. The (a) smoothed Niño 3.4 index and (b) the transition index. Both have the corresponding phases of ENSO, each lasting one year.
CHAPTER 3

The Neutral Phases of ENSO: Are They Really Neutral?

(Results of a paper ready for submission to the Journal of Climate)

3.1 Results

Considering first the oceanic-atmospheric conditions that occur during the boreal winter months (DJF) one year before El Niño, a global snapshot can be made exhibiting the important anomalies responsible for the quasi-oscillatory nature of ENSO. Rasmusson and Carpenter (1982) defined this episode as the “onset phase” and from the neutral phase reanalysis maps (Figure 4), significant features are now recognizable in altering the mean climatologically conditions enough to move the Pacific Basin toward El Niño-like conditions. For the purposes of this section, the winter (DJF) period one year before a warm event will be defined as the developmental phase.

During the developmental phase, the western warm pool has sidled eastward from the mean western location to around the dateline and equator, while cold SSTs occur along the eastern equatorial Pacific, with maximum values around 10°S. Off-equatorial SST anomalies can be seen near the coast of South America, with extremely warm values around 30°S. It is important to note that there are no SST anomalies located within the Niño 3.4 region (120°W-170°W, 5°S-5°N), thus personifying the unnecessary neutrality of the developmental phase. Drastic warming throughout the ocean surface supports
increased atmospheric deep convection, further reinforcing changes in the equatorial atmosphere pressure fields. Therefore SLP anomalies related to these SST maxima are seen basin-wide (Figure 4b), with strong subtropical anomalous cyclones in the northern and southern hemispheres along the dateline and broad areas of high SLP anomalies stretching along 60°N and S. Expanding from these subtropical lows are developing off-equatorial cyclones located around 165 °E over the western Pacific. Tropical in nature and quasi-symmetric along the equator, these anomalous cyclones dictate the zonal wind, in turn reversing the easterly trade winds of the western Pacific to a westerly zonal wind anomaly. Figure 4c portrays a westerly wind burst (WWB) moving over the Islands of Indonesia and New Guinea and ending abruptly before reaching the dateline. Wang and Weisberg (2000) reinforce the importance of WWB utilized in past studies, stating that westerly wind anomalies in the western Pacific induce eastward propagating downwelling Kelvin waves, which herald the beginning of an El Niño event.

Downwelling of the upper ocean surface lowers the thermocline and increases the overall heat content, and the resulting suppression of the thermocline travels east as a Kelvin wave.

To grasp the overall implications of these anomalous off-equatorial low pressure systems, observations of the annual trek of these systems must be made, especially before an extreme event commences. Using the cycle of the transitional index, an overall time scale can be seen leading up to an El Niño. Looking at the summer JJA (-1.5) SLP anomalies (Figure 5a) before the strong SST values reach a threshold of an El Niño, broad subtropical cyclones appear to dominate the western and central Pacific, with the
beginnings of an off-equatorial low pressure system located roughly at 120°E and 10°N. Located well west of the dateline, it is important to note that this feature has little influence on the central Pacific, which becomes important in the initiation of a warm event. Following the annual progression of the developmental phase, a prominent off-equatorial core of low SLP anomalies located along 160°E, 10°N can be seen during the autumn months SON (-1.25). Corresponding to the low pressure feature in the Northern Hemisphere, a tongue of low SLP anomalies appears to be breaking off of the large cyclonic system located along 30°S, becoming elongated toward the equator. Moving from the winter DJF (-1) to the Spring MAM (-.75), prominent symmetric off-equatorial low SLP anomalies have moved east, almost reaching the dateline, in turn bringing the WWB seen in Figure 5c. The annual progression of these quasi-symmetric features indicates an eastward momentum of anomalous westerly winds, which corroborates what previous studies have reported concerning pre-El Niño conditions in the Pacific basin.

In order to establish a more substantial time series for the neutral ENSO events that have occurred before 1948, utilization of the ERSLP and ERSST anomalies allows for key conclusions to be made. First looking at the DJF pre-1948 SLP anomalies (Figure 6a) shows several interesting trends, especially in the western Pacific. According to the pre-1948 data, the northern Pacific appears to be the location of broad low SLP anomalies, differing from the 1948-2008 dataset; however, these two time series converge on the location of the quasi-symmetric off-equatorial cyclones, with the pre-1948 records showing an overall westward location of these features. Although slightly different in placement of large-scale SLP anomalies, the appearance of these off-
equatorial low pressure systems provides sufficient initial evidence that one year before an El Niño event, a semi-coherent synoptic atmospheric pattern is established.

Because of the coupled natured of the ENSO system, investigation of past SST records in theory should agree with the present data concerning the development of a warm event. In Figure 7, widespread warm SST anomalies are evident just west of the dateline with symmetric stretching north and south of the equator. In correspondence to the off-equatorial low pressure systems, these warm SST anomalies provide the ingredients necessary for deep atmospheric convection. Due to the overall importance of the annual progression of these symmetric cyclonic features, examination supplies more evidence of the broad scale warming associated with this developmental phase. With this substantial time series extending back over a century, a definitive synoptic setup can now be related to a developing phase that occurs one year before an El Niño.

3.2 Summary and Discussion

Through examination of the oceanic and atmospheric data and model-derived reanalysis data, the western Pacific is a key region in dictating phase changes for ENSO extreme events. The dynamics of the western warm pool in the production of deep-atmospheric convection create conducive conditions for low pressure systems and increased vertical motion. Off-equatorial anomalous cyclones become fixtures in the western Pacific during neutral conditions, and with the resulting equatorial westerly wind anomalies, a transition in the synoptic scheme of the Pacific Ocean begins to take shape. Rasmusson and Carpenter (1982) first discussed the transition associated with a weakening of the easterly trade winds and the subsequent increase in westerly wind
anomalies to be associated with a ‘transition area’ (refer to page 360 of RC). The authors describe that within the transition area 0-10°N, 130-170°E, the flow is relatively weak, thus allowing for a reverse in sign of the zonal pattern by means of a weak wind anomaly. Therefore, in Rasmusson and Carpenter’s ‘transition area’, the presence of off-equatorial cyclones would allow westerly wind anomalies to displace the climatological easterly trades, consequentially disrupting the coupled oceanic-atmospheric system.

Ultimately, a relaxation in the west-to-east slope of the thermocline and a decrease in the west-to-east SST difference with in the equatorial Pacific from zonal wind anomalies will break the flow needed to sustain the Walker circulation (Chang et al. 2006). The temperature seen throughout much of the Pacific basin dictates the strength of the Walker circulation, and with further eastward transport of warming ocean temperatures, continued suppression of the trade winds will spread into the eastern Pacific. Known as the Bjerknes hypothesis, this feedback revealed from Bjerknes 1969, is the underlying process responsible for the development of extreme ENSO phases.

In relation to the influence of these wind anomalies on the initiation of warm and cold events, many studies have noted that the westerly wind anomalies over the western Pacific induce eastward propagating downwelling Kelvin waves (e.g., Wyrtki 1975; McCreary 1976; Philander 1981). Warming associated with downwelling Kelvin waves disturbs the air-sea relationship feedbacks which concurrently spread high SST anomalies to the east, ushering in a new El Niño event. The strong 1997-98 El Niño provides an accurate example of how these downwelling Kelvin waves can occur during the winter months one year before a peak El Niño event (Wang and Weisberg 2000).
Complementing equatorial Kelvin waves, off-equatorial Rossby waves carry areas of thermocline anomalies of opposite sign to the western Pacific (Chang et al. 2006; Lin 2009). Once a Rossby wave reaches the western boundary, a reflected Kelvin wave with similar characteristics of the parent wave will then propagate eastward, ushering in new phase for the ENSO cycle.

From the modeled reanalysis data and the extensive time series of the developmental phase, a better representation of the dynamics responsible for creating the oscillatory nature of ENSO can be seen. More importantly, a focused snapshot of the ocean-atmospheric environment can now be constructed, which allows for a representation of what the synoptic setup looks like one year before an El Niño. For the purposes of better predicting phase changes within the ENSO lifecycle, a schematic representing the developmental phase for winter DJF (-1) during the period 1950-2007 is shown in Figure 8. The broad scale features occurring throughout the global ocean-atmospheric system are represented in the schematic, with the off-equatorial cyclones just west of the dateline being the key features in this schematic. The anomalous cyclonic flow near the equator appears to be generating westerly wind anomalies (represented by the thick orange arrow along the equator in Figure 8) and conversely driving the mean flow of the trade winds back into the center and eastern Pacific. Previously discussed, the dynamics of this situation provide the necessary means to an end, with the means being the eastward propagating downwelling Kelvin waves carrying upper ocean heat content to the coast of South America and the end representing a new El Niño event.
Figure 8 relies on the accuracy of the data that was used in the reanalysis and the interpretation of the results. ENSO’s dynamics have created problems in the forecasting of new severe events; however, the developmental phase provides new insight to what might be driving this ubiquitous global phenomenon. Using Figure 8 as a tool, one can analyze the current neutral conditions bounded by the inevitable warm and cold events to make conclusions on the potential timing of another phase change. Forecasters should note that the developmental phase schematic acts as a guide and represents all the neutral conditions that have occurred over the last half century. Hence, each El Niño/La Niña event is different (e.g. Trenberth’s [2001] examination of indexing each El Niño and the uniqueness of all ENSO events). Predicting individual events can be an insurmountable task, and these new methods can utilize the developmental phase and the neutral setting that precedes an El Niño in order to better forecast the conditions associated with a given episode.
Figure 4. Linear correlation of winter DJF (a) SST, (b) SLP, and (c) 1000 mb zonal wind with transitional Nino 3.4 SST.
Figure 5. Same as Figure 4 but for SLP during (a) JJA (-1.5), (b) SON (-1.25), and (c) MAM (-.75).
Figure 6. ER Pre-1948 SLP for (a) DJF and (b) annual using the transitional Niño 3.4 index.
Figure 7. Same as Figure 6, but for SST anomalies.
Figure 8. Schematic of winter (cold to warm) developmental phase (-1).
CHAPTER 4
GLOBAL 3-DIMENSIONAL STRUCTURE OF THE TRANSITION PHASE DURING WINTER

4.1 A Three-Dimensional View Using Zonal Mean Cross Sections

The neutral phases used in the NCEP reanalysis data represent the transitional indices occurring between the decay of a La Niña and the onset of an El Niño. Due to the seasonal differences that occur for both hemispheres, an examination of both the boreal winter (December-January-February one year before [-1] an El Niño event), and boreal summer (June-July-August [-1.5]) developmental phases will make the analysis unbiased toward either hemisphere. As discussed earlier, the mature phase of El Niño occurs during the boreal winter months. Because of this phase locking to the annual march, the winter developmental phase will be discussed first, followed by the summer transitional episode. By analyzing the zonal mean cross sections of ocean-atmosphere variables for the entire troposphere(0°-357.5°E, 1000-100 mb), followed by the global distribution of each variable, and then ending with the synoptic characteristics for each field, a global three-dimensional structure of the developmental phase can be made.

The temperature distribution in the atmosphere is critical for defining the thermodynamic state and ultimately the wind structure seen in global circulations for the upper atmosphere (Peixoto and Oort 1992), therefore the first zonal mean cross section
will focus on air temperature (Figure 9). The distribution of absorbed solar radiation and
the associated highest temperatures are focused in the intertropical regions; however, the
zonal mean cross section clearly indicates low temperature anomalies symmetric around
the equator. Strong cooling can be seen throughout the tropical and subtropical
troposphere, with the exception of a warm core aloft, centered on the equator and the
500mb level (more on this warm core in the zonal wind anomaly analysis). These
negative temperature anomalies appear to be confined in the Hadley cell regions (0°-
30°N/S); however, the Ferrel cells (30°-60°N/S) are dominated by weak warm anomalies
at the surface, with quasi-symmetric cores of high temperature anomalies aloft (just
above 200mb). The NH Polar cell exhibits a dual temperature relationship, which is
represented by strong cold anomalies located at the southern-most boundary (60°N) and
weak warm anomalies throughout the troposphere. Within the SH polar cell, increased
warming can be seen at the surface and aloft, directly below the 200mb level. Comparing
the results of Figure 9 to the expected conditions that would occur during a warm event
(high temperatures over the Tropics due to increased convection and condensational
heating), the developmental phase produces an inverse relationship.

Directly related to vertical distributions of temperature, an examination of the
zonal mean cross section for geopotential heights becomes important in creating a
vertical representation of the global atmosphere. Geopotential heights (Z) can indicate
areas of high or low pressure systems, with high (low) Z values representing ridging
(troughing). Predictable geopotential height anomalies are seen in Figure 10, which
corresponds to the previous temperature anomalies. A large boundary located close to
60° latitude in both hemispheres appears to be the most identifiable feature for the geopotential height anomalies. Clearly the summer for the SH is creating large positive Z anomalies during the transitional phase. The Polar cells for both hemispheres portray anomalously high geopotential heights throughout the troposphere, where both the Ferrel and Hadley cells have anomalously low Z values, especially at 45°S and 25°N. Additionally the Ferrel cell in the NH does not blend in with the wide-spread distribution of low geopotential heights, which are ambiguously grouped within the subtropical circulation cells of the SH. A clear strong core of low geopotential heights from 700mb to 300mb around the northern-most boundary is seen, with weaker anomalies surrounding this feature on both sides.

Looking at the zonal mean cross section for zonal wind anomalies (Figure 11), westerly wind anomalies will be labeled by positive values and easterly flow associated with negative values. Mentioned earlier, the strong core of westerly wind anomalies can be seen centered over the equator and the 400mb level, oriented slightly above the warm core of temperature anomalies. Directly below this jet maximum (5°S) are weak easterly wind anomalies, and with this surface return flow, the Walker Circulation can clearly be identified. Even with the small easterly wind anomalies seen along the equator, the Tropics are predominantly westerly in nature, indicating a transition to El Niño-like conditions could be seen in the near future. The other westerly wind anomalies appear in the expected midlatitudes, with strong anomalies seen in the Ferrel Cell of the SH (35°S). Strong negative anomalies associated with normal atmospheric conditions are evident along the polar easterlies (60°N/S) and the subtropical northeast trades (30°N); however,
the trades of the SH are almost non-existent. Piecing together the meridional circulation cells requires an analysis of the meridional wind anomaly cross section (Figure 12).

Positive values represent northerly wind anomalies, whereas negative values portray southerly wind anomalies. The expected position of the Hadley cell is not represented in the meridional cross section for the winter developmental phase. First, the critical region of equatorial convergence is gone, replaced by divergence at the surface and convergence at the 400mb level. Positive northerly anomalies located along the equator are directly north of negative southerly anomalies, signifying an area of divergence, and vice versa for the upper-level conditions over the Tropics. Conversely, areas of convergence are seen at 25°S at the surface with divergence aloft in the mid to upper-levels (especially the 600mb level). Another even stronger area of convergence is seen over the SH midlatitudes, with strong divergence through much of the upper troposphere into the stratosphere. Important in Figure 12 is the lack of any continuity associated with areas of surface convergence or divergence in the North Hemisphere, particularly during the boreal winter where strong midlatitudinal cyclones dictate much of the weather.

The last cross section examined for the winter developmental phase focuses on vertical pressure velocity (\(\omega\)) anomalies (Figure 13). Negative \(\omega\) anomalies represent rising motion, where positive values portray descending air. Further showing the mass divergence seen at the low-latitudes, the equator is dominated by deep atmospheric subsidence. The SH again personifies a very organized longitudinal structure of vertical velocity anomalies, with alternating rising (20°S and 45°S) and sinking (30°S and 60°S)
motions. Differing substantially is the vertical velocities of the NH, where a coherent structure only appears to exist in the Ferrel and Polar cells. The NH Hadley cell region has no definitive rising or sinking; however, aloft (700mb and above) has relatively strong alternating vertical velocities.

Combining the results of Figure 11-Figure 13, the secondary circulations (Holton 1992) can be seen within the typical Hadley and Ferrel cell regions; however, a unique relationship appears to be occurring during the winter developmental phase of ENSO. A reversal in these meridional circulation cells can be seen, with two Ferrel cells straddling the equator, creating the large scale subsidence that is usually seen over the horse latitudes (30°N/S). A more complex meridional circulation scheme arises in the NH subtropics, beginning with the alternation of two small Hadley cells (20-30°N; 35-45°N) between one Ferrel cell (30-35°N) with each cell located around the 800mb level. Therefore most of subtropics exhibit no surface flows, which plays an important role in the distribution of enhanced convection and subsidence. Principally, this substantially alters the storm tracks and upper-level jet stream placement, marking a lack of teleconnected weather patterns leading up to an El Niño event.

4.2 A Global View Using Horizontal Anomaly Maps

With a three-dimensional vertical structure established in the previous section, variables distributed on global horizontal maps for the winter neutral phase can be given. Confined to a vertical cross section of both hemispheres, only secondary circulations could be analyzed, which potentially merges averaged anomalous data from two different longitudes. A global view of variables pertinent to ENSO phase undulation can be given
using the following figures. The importance of warm SST anomalies, concurrent increased convection, and the eventual production of low pressure centers on the fundamental dynamics of ENSO cannot be stressed enough (Gill 1980), hence, leading to the overall importance of Figure 14. The horizontal distributions of SST anomalies located throughout the entire Pacific basin are key to the formation and decay of new El Niño events. During the winter developmental phase, much of the Pacific Ocean is dominated by warm SST anomalies, compared to other oceans dominated by anomalous cooling. The strongest area of warming appears to be situated in the far northern Pacific, bounded by the Aleutian Islands to the north and the Hawaiian Islands to the south. Extratropical in nature, this region is well north of the Tropics, where fluxes in SST drive much of the dynamics within the ENSO (Trenberth 1998). Another large belt of warming appears in the southern Pacific, stretching from Southern Australia east toward the west coast of Chile. Even though the anomalies located off the coast of South America (30°S) appear to be close to having an influence of ENSO dynamics, it still falls outside the tropical spectrum needed to influence phase changes.

On a smaller scale, a relatively strong SST anomaly located just west of the date line along the equator does have the best location to effectively induce a warm or cold event. Located along the eastern extents of the western pacific warm pool, these warm SST anomalies show that a gradual eastward propagation in subsurface temperatures may be occurring. Regarding the western warm pool, Figure 14 shows a diminishing in the areal extent of warm SSTs, which is also seen during an El Niño event (RC 1982).
more important is the production of deep atmospheric convection associated with anomalously warm SSTs and correlated anomalous low pressure production.

Concerning the importance of cold SST anomalies in Figure 14, much of the tropical oceans display globally large scale cooling, especially in the Atlantic Ocean. Large cold SST anomalies explain the low geopotential heights and temperature anomalies in the Tropics (Figure 9-Figure 10). Air-sea interactions limit the temperature and the height fields associated with these regions, which inhibit rising motion and convection associated oceanic heat transfers. Large tropical warming is a signature feature of El Niño events (RC 1982), however, the developmental phase continues to exhibit an inverse relationship through much of the Tropics.

Focusing on the precipitation rates one year before mature El Niño episodes (Figure 15a) will highlight regions of high and low pressure, and respective weak and strong precipitation anomalies associated with these systems. First looking at large-scale features, positive precipitation anomalies appear to be widely distributed just south of the strongest area of SST anomalies (refer to Figure 14) located along 30°N. Strong precipitation anomalies are also occurring in the midlatitudes (between 30-60°N/S) of the Atlantic Ocean, with the North Atlantic exhibiting high anomaly values that do not appear to be correlated to high SSTs (perhaps an NAO signal).

Low precipitation anomalies again appear mostly confined to the equatorial regions, with very low rates seen over the northern Indian Ocean and eastern Pacific Ocean. This reaffirms two conclusions made from the zonal mean cross sections: 1) The apparent weakening of the Walker Circulation and 2) The replacement of Hadley cells at
the equator by Ferrel cells. Noted earlier, the eastern Pacific low precipitation values signal a broad area of subsidence associated with the descending branch of the Walker Circulation. In addition, these weak precipitation rates signify the descending branch of the Ferrel cell, which is usually accompanied by broad areas of high pressure. These conclusions therefore show that the climatological placement of the intertropical convergence zone (ITCZ) over the equator does not appear to be occurring during the developmental phase before an El Niño event.

Looking at the synoptic scale shows strong precipitation rates over much of the western Pacific warm pool, which is associated with the ascending branch of the Walker circulation. Other than over Central Africa, the western warm pool is the only region with strong convection occurring at the equator, and with high precipitation values pushing east of the dateline, conditions are favorable of cyclonic development. The ocean-atmospheric relationship that appears in this region will help portray the dynamics needed to possibly spur a new ENSO phase.

Precipitation rates show the areal coverage of how much convection may be occurring in the atmosphere; however, vertical velocity anomalies (Figure 15b) show how fast this air is rising. In addition, these 500mb ω anomalies represent deep atmospheric convection, a critical component for the ascending branch of the Walker circulation. Key areas of rising motion, denoted by negative values, appear again over the Hawaiian Islands, which relates to the high precipitation values of Figure 15a. Another anomalously strong area of vertical motion appears along 30°N (between 120-90°W), which is dominated by desert conditions associated with the normal subtropical
highs that dwell over these regions. Due to the sensitive nature of deserts toward anomalous precipitation, it is important to note the effects these developmental phases have on subtropical latitudes.

The vertical velocity structures of the Walker circulation are evident in Figure 15b, with anomalously high vertical velocities over the western Pacific and the large area of descending motion over the eastern Pacific. Perhaps representing a weakening of the Walker circulation, the ascending branch is far to the east of its normal position, which is effectively delimiting the distribution of easterly winds at the surface and the westerly winds aloft (Wang 2002). The importance of the Walker circulation cannot be stressed enough, and even slight changes to the system can have dramatic effects on ocean-atmospheric interactions throughout the equatorial Pacific.

Extreme subsidence appears to dominate much of the Indian Ocean, a key region that influences the Madden-Julian-Oscillation (MJO), which is a phenomenon that has been correlated to the birth and decay of ENSO events (Bergman et al. 2001). This large area of strong descending air would indicate the presence of high pressure and warming temperatures. Usually strong convection in the Indian Ocean is associated with increased activity of the MJO’s modulation of SST in the western and central Pacific (Kessler et al. 1995). Cold SST anomalies associated with enhanced evaporative cooling of increased convection create stronger winds, and can potentially excite equatorial Kelvin waves, another important mechanism in triggering extreme phases of ENSO. The Indian Monsoon could be skewing the results of Figure 15, with the associated dry continental
northeast winds influencing these anomalies. The Indian Ocean will be examined extensively in the boreal summer discussion of the developmental phase.

Strong areas of sinking motion located outside of the tropical realm appear over Greenland and Northern Europe. Roughly 75% of Greenland is dominated by this subsidence, which encompasses much of the Arctic Ocean and Scandinavia. Moving to the SH, strong sinking motion can be seen along 60°S, with the strongest core of anomalies located just west of 120°E at this latitude. An interesting pattern appears to be emerging along the northern edge of Antarctica, where alternating areas of rising and sinking motion circumnavigate the continental coast. Figure 14 shows a relatively coherent pattern of warm and cold SST anomalies corresponding to these rising and sinking motions, and could resemble an atmosphere wavelike structure.

Contributing to the vertical characteristics of Figure 15, primary circulations and global scale atmospheric patterns are apparent in Figure 16. Wintertime SLP anomalies (Figure 16a) during the transition phase provide an analysis of why certain zonal and meridional anomalies occur in the atmosphere, and merged with the previously mentioned anomalies, a true global structure can be represented for neutral phases of ENSO.

The global distribution of SLP anomalies should correspond with the precipitation rates, SST anomalies and vertical velocity anomalies from previous figures. Two key features can be seen in the global distribution of SLP. First, looking at the polar regions, positive anomalies dictate much of the SLP distribution for these latitudes. Starting in the NH, strong high SLP anomalies occur over much of Northeast Asia, crossing the
Bering Strait and covering much of northwestern North America. The synoptic
distribution of high SLP in this area diverges with the climatological conditions seen
during the boreal winter months. Usually dominated by the Aleutian Low, which appears
to have disappeared altogether, the North Pacific is instead dominated by high pressure.
In addition to these high SLP anomalies, Greenland, Scandinavia and the Arctic Ocean
all appear to be governed by higher pressure. High SLP anomalies also cover most of the
SH high-latitudes, which is a characteristic that differs from Figure 15. Previous figures
portrayed several areas of strong rising motion and precipitation rates, which do not
correlate with high SLP anomalies. Other ocean atmospheric dynamics may be
occurring, however, are not pertinent to this study. Much of the central and southern
Atlantic also contain relatively high SLP values. In the NH, the central Atlantic high
SLP anomalies correspond to the Azores-Bermuda High, whereas in the SH, high SLP
values correlate with the South Atlantic High. Both of these features appear unaltered by
the developing conditions associated with an El Niño.

The second key feature from Figure 16a looks at the wide allocation of low SLP
anomalies throughout the tropical and subtropical Pacific. The mean location of the
Hawaiian High has been replaced by a deep area of low pressure, with equatorial
extensions of cyclonic anomalies toward the equator. Associated SST, precipitation, and
vertical velocity anomalies also appear in this region of low pressure. The International
Date Line is swathed by low SLP anomalies along the equator and with the eastward
displacement of low pressure, weakening pressure gradients will alter the SO, weaken the
easterly trade winds, and ultimately deteriorating the Walker circulation. Low pressure
can even be seen located east of 120°W, thus showing a synoptic pattern similar to El Niño-like conditions.

Other low pressure areas that appear outside the scope of the tropics, but may be teleconnected to the changes associated with the developmental phase, can be seen over central Asia and the northern Atlantic. Due to the sheer size of the Asian continent, some of the strongest high pressure values can be seen over inland locations that are thousands of miles away from tempered oceans. The normal Siberian High has been displaced by an area of low pressure, centered just east of Mongolia. The Icelandic Low predominantly located over the southern tip of Greenland during the boreal winter has been juxtaposed to the south and appears to be extremely close to Western Europe. Clearly the structure of the Icelandic Low and the Azores-Bermuda High has significantly been altered by the dynamics occurring during the developmental phase. Because the unique relationship between these SLP features control the mean stormtrack for the North Atlantic, the NAO and the teleconnections associated with this phenomenon are altered substantially (Bojariu and Gimeno 2003). Clearly, the scope of the developmental phase cannot be limited to the Tropics, and a certain relationship with other teleconnection patterns (e.g. NAO) may be plausible but are outside the focus of this study.

Moving up in the atmosphere, Figure 17a reconstructs the 200 mb geopotential height field and can help represent upper-level high and low pressure anomalies. Focusing on the global scale circulations, the Hadley cell regions are dominated by low geopotential heights, with the northern Hadley cell exhibiting the most consistent swath of low anomalies. The northern Ferrel and Polar cells have an alternating sequence of
low and high geopotential height anomalies, and due to this characteristic, neither can be
classified as negatively/positively dominated. The southern Ferrel cell appears to be
dominated predominately by negative height anomalies, but with a wave-like pattern
sidling back-and-forth between negative and positive values along 60°S. Finally, the
southern Polar cell clearly is dominated by strong geopotential height anomalies covering
the entire Antarctic continent.

Identifying more synoptic scale features, large bands of low geopotential heights
can be seen over Arabian Peninsula and Southeast Asia, with another strong low Z
anomaly located just west of the Hawaiian Islands. An almost symmetric structure can
be seen over the SH, with two broad areas of low geopotential heights located along the
southern tips of South Africa and Madagascar, with another band of low Z anomalies
spreading along the southern coast Australia. Another interesting series of low
geopotential height anomalies can be seen stacked longitudinally around 30°W. Three
similar anomalies, two in the north and one in the south, create this linear band of upper-
level lows situated through the Atlantic Ocean. The northern most anomalies appear to
be consistent with the SLP anomaly, showing a vertically stacked low situated far south
of its normal location. Other low Z anomalies emerge throughout Figure 17a, however,
are not relevant for ENSO dynamics at this time.

Moving back to the surface, Figure 16 produces a horizontal structure of the lower
troposphere, and the zonal wind anomalies (Figure 16b) are a critical component for this
analysis. Relating more to the Walker circulation, these anomalies provide the best
indication of any weakening associated with the surface branch of this cell. Clearly the
normal easterly winds depicted in the central Pacific has diminished considerably, where a slight bending from the equator to the SH can be seen in the trades from 90°W to 180°/10°S. The movement of the Walker circulation may be a response to the boreal winter climatology and the southward displacement of the ITCZ (Wang 2005). The most important zonal wind anomaly is occurring throughout much of the western Pacific, where westerly wind anomalies appear to dictate the surface flow as far east as date line, representing an eastward shift in the low-level Walker circulation. The zonal wind anomalies of the summer (-1.5) developmental phase (discussed in section 5.2) will supply an alternative view which will validate this eastward progression of westerly wind anomalies.

With the utilization of both Figures 16b and c, areas of broad-scale rotations are made apparent, which signify the general ordination of different pressure systems. Analyzing these features at the global scale, no one cell appears to be dominated by one circulation type (e.g. subtropical high belt, subpolar lows) except between the SH Ferrel and polar cells. The NH surface flows are meandering and inconsistent, where alternating positive and negative anomalies appear in both the zonal and meridional winds, especially over the continents. The SH Ferrel and Polar cells (meandering 45-60°S) do portray a coherent pattern, with what looks like a clear boundary between the cells, which is represented by the change between westerly to easterly flows over a very short distance. Combining the zonal and meridional anomalies produces a pattern of cyclonic circulations circumnavigating the entire SH around 45°S. Also known as the
SH Subpolar lows, these cyclonic low pressure systems are associated with the area of convergence between the Ferrel and Polar cells.

Moving to a synoptic scale, the northern Pacific Ocean has two important rotational features. The first exhibits a cyclonic rotation over the subtropical Pacific due west of the Hawaiian Islands, matching up with the strongest SLP anomaly of Figure 16a. The second feature appears over the Aleutian Sea and with its clockwise rotation, personifies the broad area of high pressure dominating the entire North Pacific. Due to the orientation of these two circulation systems, an enhanced easterly flow along 40°N appears to link the west coast of America directly to the Japanese Islands. This surface flow appears over latitudes that are usually governed by westerly flow.

Two strong circulations can be seen from Figures 10b and c, with the first occurring over central Russia. A geographically large area of easterly winds can be seen over the Kara Sea off the northern coast of central Russia. Alternatively much of southern Russia appears dominated by strong westerly anomalies that stretch from Eastern Europe to central Mongolia. Adding the meridional anomalies to these interchanging flows produces a broad area of cyclonic flow, again corresponding to low a pressure system over Russia seen in Figure 16a. Similar to this feature but stronger in nature is the boundary of strong easterly and westerly flows seen situated within the North Atlantic Basin. Anomalous easterly winds (60°N) appear to connect the United Kingdom with the southern tip of Greenland and Northern Canada. Opposite flow can be seen over the central Atlantic, with a strong core of westerly winds occurring along 30°N. Therefore, north of the westerly wind anomalies, cyclonic circulation is dominating the
general circulation of the North Atlantic. Because of this counter-clockwise flow, a connection of westerly winds stretching from the Northeastern United States all the way to Northern Africa and Southern Europe has been established. Parallel temperatures and other teleconnected features will be translated across the Atlantic Ocean because of this feature.

Lastly, circulations within the Pacific basin are evident with the combination of zonal and meridional anomalies. First, inside the western Pacific warm pool appears a small cyclonic circulation represented by a small core of easterly winds located north of the equator around 20°N and a strong area of westerly winds located along the equator (the western branch of the surface Walker circulation). The SLP anomalies of Figure 16a do not explicitly show the low pressure directing this cyclonic flow, and due to the importance of anomalous low SLP in the western Pacific, locating the cause of a westerly wind burst becomes critical in the understanding of ENSO dynamics.

The second circulation that is not represented well by NCEP SLP reanalysis is associated with the descending branch of the Walker circulation. Located in the eastern Pacific, strong westerly winds are occurring directly south of the equator and stretching from 90°W to the International Date Line. Just south of these anomalies is an area of westerly wind anomalies positively tilted from 40°S/180° toward 15°S/90°W. Combining the northerly and southerly components produces a large area of counter-clockwise rotation which in the SH represents an anti-cyclonic circulation. This large anti-cyclone is important because it correlates with the subsidence associated with the eastern branch of the Walker circulation and is a function of the cold SSTs seen in the eastern Pacific.
Examining the horizontal wind anomalies of the upper troposphere show how global circulations patterns, particularly storm tracks and jet streams, become altered during neutral conditions before an El Niño. Figure 17b and c show the 200mb zonal and meridional wind anomalies, with clear upper-level patterns can be seen from these results. Again examining the global scale features, the NH and SH flow patterns look much more organized than the surface wind anomalies. The upper-level characteristics of the Walker circulation are dominated by a southward displacement of the return flows aloft. For example, looking between 10-15°S, it is apparent that the westerly winds associated with the eastern branch of the Walker circulation are occurring throughout much of the eastern Pacific. Moving due west of these westerly anomalies, however, a transition is occurring over Northern Australia. Upper-level easterly wind anomalies spreading westward toward the Indian Ocean represent the opposite flow of the western branch. The orientation of these zonal wind anomalies signify upper-level divergence along the transition area (10°S/170°W), suggesting that deep atmospheric convection may be occurring at the surface near here, which further shows the eastward progression of low pressure anomalies needed to begin a new El Niño phase.

Again examining the other global scale features, the NH and SH flow patterns look much more organized than the surface wind anomalies. First, a clear alternation between westerly and easterly anomalies is occurring in both hemispheres, beginning with a predominant westerly flow along the equator, and then switching to easterly within subtropical latitudes, with this pattern continuing poleward. The NH does exhibit a more wave-like structure, with westerly ridging over Western Europe, Central Asia, the Bering
Strait and broad troughing over the Caspian Sea, central Pacific, and the North Atlantic Ocean. The SH has a more zonal structure, with strong westerlies seen at 45°S and vigorous easterlies circumnavigating the Antarctic Circle.

Next, focusing on the synoptic scale, several interesting features appear to be occurring. First, the displacement of the polar jet stream in the NH appears to be a key feature of Figure 17b and c. With the mentioned wave-like pattern seen over the NH, certain areas will see troughing cyclonic flow, while others will be dominated by ridging anti-cyclonic circulation. For example, along the west coast of British Columbia, strong ridging associated with the developmental phase of ENSO will move the teleconnected storm tracks to the north and ultimately create calm atmospheric conditions. Alaska, now centered on the displaced storm track receives more potential atmospheric disturbances and rainfall events (as seen in Figure 15b).

An area of strong troughing located over the North Atlantic is another feature that can affect the storm track and the concurrent weather patterns for a given region. Strong upper-level westerlies slightly ridge over the Eastern United States, eventually troughing significantly over the middle of the Atlantic. Expected anomalous weather patterns are then a result of the southward displacement seen in the polar jet stream. Similar to the ridging example, troughing in this location will cause Northern Africa and Southern Europe to be in direct line with this new storm track, and the precipitation rate anomalies of Figure 15b support this conclusion. Therefore, wave-like responses during the winter months will have a predictable pattern associated with the displacement of jet streams and storm tracks during the development of an El Niño event.
Upper-level circulations over the Pacific Ocean can be good indicators of how well-suited an atmosphere is to creating or reducing convection for a given region. Looking at the upper tropospheric circulation patterns, a clear line of rotations can be seen centered along 25-35°S. The first rotation can be seen over Australia, represented by easterly anomalies over the northern coast and westerly flow located along the southern coast. In addition to the meridional flows, this creates a counter-clockwise rotation, which represents anti-cyclonic flow in the SH. The next three features exhibit this same pattern and are centered 25°S/180°, 35°S/130°W, and 30°S/65°W respectively. Each anti-cyclonic circulation corresponds to what look like holes within the negative geopotential height anomalies, thus representing upper-level ridging may be occurring in these areas.

Another key area of circulation can be seen over the subtropics of the central Pacific, located along the strongest core of westerly wind anomalies (10°N). Above what appears to be the subtropical jet stream is a strong core of easterly winds located throughout much of the North Pacific (40°N). The associated branches of northerly and southerly wind anomalies from Figure 17c create what appears to be a large area of cyclonic flow which lines up with the low geopotential heights seen along 30°N and the date line. This stacked upper-level low appears to be dictating the off-equatorial westerly wind anomalies, which is an important area for altering the upper-level Walker circulation. Other upper-level features that were not mentioned here may have been associated with winter developmental phases, however, are not dynamically significant to this study.
4.3 Polar Stereographic Maps

Moving on to a more hemispherical view of the December-January-February anomalies associated with the developmental phase, Figure 18 shows the geopotential height anomalies for the NH. The most important feature of Figure 18 is a dramatic weakening of the wintertime polar vortex from the surface all the way up into the stratosphere. Beginning at the 1000mb level, the geopotential heights of the NH appear to be dominated by low Z values within the tropical and temperate regions, and high Z values represented over the polar regions. The largest negative anomalies appear to be located mainly from the International Date Line spreading east to the Baja Peninsula, and from the equator north to the Hawaiian Islands. Two other low geopotential heights are located more in the high-latitudes but are not nearly as significant as the Pacific anomalies. The first can be seen located just west of the Iberian Peninsula and is the dominate feature for much of the North Atlantic Ocean. Situated over Northern Russia and the Arctic Ocean is another small core of low geopotential heights; however, this feature is completely dominated by the large distribution of positive geopotential heights seen over the high-latitudes. One smaller area of positive Z values can be seen over the Southeastern United States and the central Atlantic, but is less significant moving up in the atmosphere. Covering most of the North Pole, North Pacific and other polar regions is the broad area of high Z anomalies, which appears to have replaced the normal polar vortex associated with wintertime conditions of the NH.

Moving up to the 500mb level, the distribution of low geopotential heights appears to become stronger and delimit the spatial extent of the previously mentioned
positive Z anomalies. The strong swath of low geopotential heights that was originally located in the Tropics and confined to the Pacific has now moved northward and appears to circumnavigate around the entire equatorial regions. Three other low geopotential height anomalies can also be seen over Canada, the North Atlantic, and central Russia, all located close to 60°N. Each one of these features digs into what once was the large allocation of high geopotential height anomalies. The North Pole and the Northern Pacific, however, are still dominated by these high Z values and continues to replace the northern polar vortex. Two smaller positive height anomalies are seen over the Southeastern United States and over the Mediterranean Sea. The high Z anomalies located over the United States have been displaced westward from the original surface location, while the positive geopotential heights located over the Mediterranean appear to have no surface relationships.

Continuing up into the atmosphere, the 100mb height anomalies located within the high-latitudes continue to strengthen. The equatorial distribution of low geopotential heights does show signs of weakening, especially located over the Pacific regions. Two new negative anomalies have strengthened off of the original cells from the 500mb level. One anomalous low has formed over central Canada, apparently breaking off of the original strong low over the North Atlantic. The other area of deepening low geopotential heights can be seen over Southwest Asia, and is an extension of the moderate low Z values of the 500mb level. Even with the strengthening of these low geopotential anomalies, their spatial extent is still trivial to altering the location of high geopotential height anomalies. Although the positive Z anomalies that have dominated
the polar regions appear to have contracted, the overall strength of these heights has increased substantially, particularly over the Bering Strait region.

Finally, the 10mb level encompasses stratospheric characteristics but is still a critical level for analyzing the wintertime polar vortex. Clearly a different relationship is occurring at this level, where only two geopotential height values dominate the upper atmosphere. A large area of low geopotential heights is dominating much of the North Pacific and Northwestern United States. Conversely, an even larger positive geopotential height anomaly can be seen dominating the Northeastern United States, the North Atlantic, and much of northern Eurasia. Neither feature appear to be centered over the polar regions, however, the immense positive Z values seen over the North Atlantic is very close to the North Pole and is significantly stronger then the low Z anomaly over the North Pacific.

Looking at the summertime conditions associated with the boreal winter of the NH, the SH geopotential height anomalies are shown in Figure 19. Again the key feature for Figure 19 is the weakening of the polar vortex throughout the troposphere and the replacing of positive geopotential heights with what are normally low Z values. First, looking at the 1000mb SH view of geopotential height anomalies, two important characteristics can be seen. One key feature is the distribution of low geopotential height anomalies over the extratropical regions of the SH, located along 45°S. An area of opposite characteristics appears over the South Atlantic Ocean, where a broad distribution of positive geopotential heights is the major feature. The strongest negative Z anomalies appear over Southern Australia, the east coast of New Zealand, and the west
coast of southern Chile. A clear boundary along 60°S which separates these strong low geopotential heights from strong positive Z values is seen circumnavigating around the continent of Antarctica. Again these positive geopotential height anomalies have replaced the normal polar vortex located near the South Pole.

Moving further up in the atmosphere to the 500mb level, a general increase in intensity can be seen amongst the positive and negative Z anomalies. For example, the low height anomaly located south of Australia has deepened and increased in size. In addition, two new negative anomalies located over the central and eastern tropical Pacific have taken shape. Another key negative anomaly situated over the east coast of Brazil and the South Atlantic has replaced the broad area of high Z values. Even with hemispheric-wide negative anomalies occurring, the Antarctic continent is still dominated by positive geopotential height anomalies, if not stronger than at the surface. The largest of these positive Z anomalies is occurring along 90°E/ 60°S, and further shows the significant boundary of geopotential heights between the polar regions and the rest of the SH.

At the 100mb level, a general weakening is seen amongst the low geopotential anomalies, however, much of the SH continues to be governed by these Z values. Looking at the region of strongest negative geopotential heights, which was originally located over southern Australia, significant weakening can be seen. On the other hand, the low anomaly originally noticed off the east coast of Brazil (500mb level) appears to have deepened. Again consolidation of the positive Z anomalies is occurring over the Antarctic continent, represented by the strong core of geopotential heights located now
more inland than before. The circular pattern of positive geopotential height anomalies is more evident at this level and further shows the weakening of the SH polar vortex.

Ending at the 10mb level well into the stratosphere, the key feature of this image is the consistent distribution of anomalies throughout the SH. During summertime conditions associated with these neutral ENSO phases, almost the entire SH exhibits negative Z values, except over the South Pole, where no apparent anomalies exist. Therefore throughout all the layers of the examined atmosphere, an overall lack in geopotential anomalies can be seen, signifying the lack of any polar vortex during this time period.

4.4 Presentation of Schematics

Utilization of the previous figures has provided enough information to construct a 3-D structure of the global atmosphere and the associated teleconnections of the winter developmental phase of ENSO. Figure 20 provides a vertical and horizontal structure for the entire Pacific basin, and depicts the major global circulations correlated with the winter developmental phase. The meridional circulation cells for both hemispheres are based off of the zonal mean cross-sections and exhibit alternating Ferrel and Hadley cells, which was discussed from the analysis of previous figures. Two Ferrel-like cells straddling the equator are surrounded on both sides by areas of rising motion associated with Hadley-like circulations. This pattern continues until reaching the two Polar cells signified by strong sinking motions over the northern and southern regions of the planet.

The Walker circulation can also be seen (labeled in red) spanning the entire Pacific basin into the eastern Indian Ocean. Again combining all the anomalous data
associated with the developmental phase, two distinct zonal circulation cells can be seen; one over the western Pacific and the other over the eastern boundary. Concurrent SLP pressure anomalies associated with the mass convergence or divergence of the varying branches of the Walker circulation can also be recognized here. The key area of interest is located along the dateline where a surface low appears to be well east of its normal position. An obvious sign that the Walker circulation is weakening is directly correlated to the position of rising motion, where the typical deep atmospheric convection usually dwells over the western warm pool. The two descending branches also appear situated over areas of low SST anomalies, associated with the cold tongue of cool ocean temperatures along the equatorial eastern Pacific and the broad-scale cooling of the Indian Ocean. It is the varying temperature gradients that dictate the surface flow of the Walker circulation, and as the zonal temperature gradient weakens over the central Pacific, so does the secondary circulation of the Walker cell. With the combination of these zonal and meridional circulations, a global three-dimensional view can be seen during the winter neutral phase before an El Niño.

In order to show the corresponding teleconnections during the winter developmental phase, Figure 21 was created to portray the major precipitation and temperature anomalies distributed around the world. The NCEP reanalysis maps that use the transitional index can effectively portray the mean synoptic set up of atmospheric conditions for every developing El Niño event since 1948. Therefore, precisely one year before peak El Niño conditions, the global distribution of precipitation and temperature anomalies can be forecasted to some extent. During the developmental phase, much of
the central Pacific exhibits wet and warm conditions, a setting very conducive for supporting deep atmospheric convection. In addition, regions far away from the interworkings of the Pacific Ocean and the coupled ENSO phenomenon also see teleconnected weather conditions. For example, much of the Northwestern United States experiences dry and cool conditions during the winter before an El Niño, which could potentially impact this region in a negative way. Due to the massive geographic scope of this analysis, portions of previous maps are not discussed within the paper; however, these areas do play a role in developing the 3D structure of the neutral phases of ENSO.
Figure 9. Linear correlation of winter DJF mean zonal mean air temperature with transitional Nino 3.4 SST.
Figure 10. Same as Figure 9 but for geopotential height.
Figure 11. Same as Figure 9 but for zonal wind.
Figure 12. Same as Figure 9 but for meridional wind.
Figure 13. Same as Figure 9 but for vertical pressure velocity.
Figure 14. Same as Figure 9 but for SST.
Figure 15. Same as Figure 9 but for (a) precipitation, and (b) 500mb vertical velocity.
Figure 16. Same as Figure 9 but for (a) SLP, (b) 1000 mb zonal wind, and (c) 1000 mb meridional wind.
Figure 17. Same as Figure 9 but for 200 mb (a) geopotential height, (b) zonal wind, and (c) meridional wind.
Figure 18. Same as Figure 9 but for northern hemisphere DJF mean geopotential height at (a) 10 mb, (b) 100 mb, (c) 500 mb, and (d) 1000 mb.
Figure 19. Same as Figure 9 but for southern hemisphere DJF mean geopotential height at (a) 10 mb, (b) 100 mb, (c) 500 mb, and (d) 1000 mb.
Figure 20. Schematic depiction of the global 3-D structure of ENSO’s developmental phase.
Figure 21. Schematic depiction of the global teleconnections of ENSO’s winter neutral phase.
CHAPTER 5
GLOBAL 3-DIMENSIONAL STRUCTURE OF THE TRANSITION PHASE DURING SUMMER

5.1 A Three-Dimensional View Using Zonal Mean Cross Sections

With extensive analysis concerning the winter developmental phase, a better understanding of the ocean-atmospheric dynamics before an El Niño has been established. In order to gain continuity between both hemispheres, an examination of the boreal summer (JJA) conditions one and half years before a warm event becomes necessary. Following the structure of chapter 4, different variables that make up the three-dimensional structure of ENSO will be discussed. The main goal of chapter 5 is to create this three-dimensional structure of summertime climate conditions, and to use the main ocean-atmospheric variables of the climate system to provide insight into the general structure of this phenomenon. Beginning with zonal mean cross-sections, followed by global horizontal anomaly maps, and ending with polar stereographic maps, the dynamics of the developmental phase then can be visually seen in a three-dimensional environment.

The first zonal mean cross section that is examined here pertains to the summer distribution of air temperature anomalies, as shown in Figure 22. Each zonal mean cross section examines the entire atmosphere (90°S-90°N, 0°-357.5°E), beginning at the
surface and moving up deep into the stratosphere. The global distribution of air
temperature anomalies during the summer months (-1.5) is clearly dominated by cooling
or negative anomaly trends throughout the atmosphere, especially over the Tropics. The
Hadley cell regions (0°-30°N/S) show the strongest cooling, with the SH cell exhibiting
the strongest negative anomalies. This large-scale cooling is seen throughout the
troposphere, with the largest area of negative anomalies occurring within the upper-
levels. Negative anomalies reach well into the tropopause, finally ending well into
the stratosphere, where weak warming anomalies are seen.

Moving poleward, a transition appears to be occurring within the Ferrel Cell
regions (30°-60°N/S) and is represented by the weak positive temperature anomalies
within these locations. The strongest warming (positive anomalies) located at the surface
along 40°S, showing that during the SH winter of the developmental phase, anomalously
high temperatures can be expected over the midlatitudes. The NH Ferrel cell has weak
positive values reaching up to the 500mb level, which is then replaced by moderate
upper-level cooling. Over the NH Polar cell, (60°-90°N) there is definitive cooling seen
throughout the entire troposphere, with slight positive anomalies seen over the North
Pole. Down in the SH, predominant warming is seen over the high-latitudes. Similar to
the Ferrel cell, the SH Polar cell (60°-90°S) exhibits weak positive anomalies, with a
column of weak cooling seen from 70°-80°S. Similar to the NH, the South Pole also
appears to be contained by warm temperature anomalies, however, the vertical extent of
this warming is far greater here than over the North Pole.
Looking at the zonal mean cross section for geopotential height, a systematic distribution of anomalous Z values is evident in the data. Geopotential height anomalies again can signify the presence of upper-level high and low pressure systems. Beginning over the equator, weak positive geopotential heights appear at the surface; however, moving vertically, a gradual transition is seen from weak high Z anomalies, to weak low geopotential heights, and finally ending at the top of the troposphere with strong low Z values. From the 400-100mb levels, a distinct core of low geopotential heights can be seen with the similar arching shape centered over the equator. This core is located very close to the most negative temperature anomalies from Figure 22, and explains why similar anomalies persist here.

The Ferrel cells of both hemispheres have unique but opposite characteristics. The NH cell is completely under weak positive geopotential anomalies, except within the upper-levels where a transition to cooling can be seen. Over the SH Ferrel cell, a boundary within the geopotential height field appears directly in the center of the circulation (45°S), with a transition from strong negative Z anomalies to the mostly positive Z anomalies. This boundary can be seen vertically throughout the troposphere, which appears to be located directly over the strongest easterly wind anomalies. The Polar cells of each hemisphere exhibit contrasting relationships, with the SH cell dominated by high geopotential values and the NH cell show little to no anomalies during this period. A strong core of low geopotential heights does appear over the troposphere directly above the NH Polar cell, which resembles the location of the normal polar vortex (discussed in section 5.3).
The next zonal mean cross section is focused on the zonal wind anomalies distributed throughout the atmosphere, with positive values representing westerly wind anomalies and vice versa for easterly wind anomalies (Figure 24). Starting with the zonal wind anomalies over the equator, two important conclusions can be made. First, directly off the equator is the presence of weak surface easterlies, which appear separated by a moderate westerly anomaly directly over the equator. During a mature El Niño event, the flow directly over the equator is dominated by very strong westerly wind anomalies, a scenario similar to Figure 24 but much more severe in nature. The second key anomaly located between the tropical Hadley cells is a very strong core of westerly wind anomalies aloft. Located between 500-400mb, these persistent westerly anomalies correlate with the return flow of the Walker circulation and appear directly above the easterly trades at the surface. This jet maximum was also noted during the boreal winter developmental phase, however, the summertime tropical jet appears to be weaker.

Moving poleward, more surface westerly flow is seen within the Hadley cells, with the most significant anomalies occurring over the SH. The westerly winds of the NH Hadley cell are mainly confined to the center of the circulation and tilt equator-ward moving up in the atmosphere. Symmetric to both hemispheres are two very intense easterly anomalies that appear along the boundary between the subtropical Hadley Cell and the mid-latitudinal Ferrel cell. These anomalies appear throughout the entire tropospheric atmosphere, abruptly ending at the 100mb level where the stratospheric environment takes over. Two noticeable differences can be seen between these two hemispheric easterly anomalies: 1) The SH flow appears to be much stronger and more
pronounced than its NH counterpart. 2) The SH easterlies, located along 45°S, appear 15° further south than the easterly flow of the NH, which is located along 30°N.

Another key component of Figure 24 is the strong westerlies seen within the NH Ferrel cell. Potentially important for the location of jet streams and concurrent storm tracks, these westerly wind anomalies are located around 50°N and are significant throughout the entire troposphere and into the stratosphere. A similar westerly jet occurring within the SH Polar cell can be seen between 500 and 200mb aloft. Another key difference between the two hemispheres takes place within these Polar cells. North of dominant midlatitude westerlies of the NH exists an overall lack of anomalous flow. The entire NH Polar cell is dominated by neither easterly or westerly anomalies; however, the SH counterpart has a very strong easterly flow that starts close to the South Pole and stretches vertically until reaching the stratosphere. Perhaps a function of the wintertime conditions associated with the SH during this time period, the placement of these wind anomalies changes with the seasons but clearly can also change due to forcings within ENSO.

Transitioning to the meridional zonal mean cross sections, Figure 25 can be used to show the locations and distribution of the global Hadley, Ferrel, and Polar cells and their equivalent surface and upper-level flows. Similar to the zonal wind anomalies, positive values indicate southerly wind anomalies and negative values are associated with northerly wind anomalies. Starting at the equator, the normal Hadley cell region appears to be again replaced by a Ferrel-like cell, with divergence occurring just south of the equator and convergence at the 500mb level. A relatively disjointed upper-level structure
complicates the flows of this cell. Directly above the equator is where northerly anomalies dominate, represented by cores located along 700mb, 500mb, and 150mb. This relationship creates what looks like deep atmospheric divergence tilting positively from the equator up to the 150mb level over 30°N, represented in Figure 25 by the strong positive anomalies seen within much of the Hadley cell region.

Moving on to the normal Ferrel cell locations, each hemisphere exhibits a similar area of convergence located along the boundary of the Hadley cell. Regions normally dominated by the Subtropical Highs (30°N/S) have been replaced by extensive convergence. Over the NH, the Ferrel cell exhibits a Hadley-like circulation, where a large core of convergence can be seen over the southern branch (25°N) and a broad area of divergence located over the northern branch of the cell (50°N). Looking at the SH Ferrel cell, a comparable region of convergence can be over the northern branch of the circulation around 35°S and widespread divergence can also be seen located over the southern branch (60°S). The only key difference between the two hemispherical Ferrel cells is the intensity of the convergence, with the SH exhibiting very strong southerly anomalies located just south of vigorous northerly winds, whereas the NH experiences a weaker area of convergence. Again the importance of the annual march associated with the boreal summer conditions should provide insight into why the SH convergence area is stronger than in the NH. Lastly, over each area of convergence (divergence) a concurrent region of divergence (convergence) aloft can be seen through the orientation of these meridional wind anomalies.
Ending with the Polar cell, a contrasting relationship between both hemispheres is apparent through the data. The NH Polar cell is clearly dominated by southerly wind anomalies with an overall lack of forcing seen throughout the troposphere. Differing from the NH, the SH Polar cell experiences a weak area of surface convergence located along 75°S and has no apparent upper-level divergence. The thermodynamic structures of each pole will play a role in the zonal and meridional winds that occur during the seasonal differences between the two hemispheres.

The last zonal mean cross section discussed here deals with the omega (ω) anomalies associated with vertical pressure velocities, as shown in Figure 26. The anomaly values represent rising and sinking motions associated with areas of convergence and divergence. Deep atmospheric convection and rising motion is represented by negative ω values, where conversely, positive anomalies represent subsidence and the presence of high pressure systems. Throughout the global structure, alternating areas of positive and negative ω anomalies appear to correspond to the varying branches of each circulation cell. Much of the tropical regions appear to be correlated with the strong divergence seen at the surface, and this is represent in Figure 26 by the deep atmospheric positive ω anomalies. A new feature emerges directly over the equator which was not depicted well in the previous figure, represented by strong negative vertical velocity anomalies over this area. This is important for the evolution of an El Niño event and helps to show that even with predominantly subsiding conditions seen over the Tropics, weak convection is still a characteristic of equatorial climate during the developmental phase.
Moving outside of the Hadley cell region introduces the previously mentioned areas of convergence and associated rising motion. Strong negative anomalies appear over 30°S and 25°N and show that anomalous deep atmospheric convection is occurring over these locations. Especially within the SH Ferrel cell region, these negative anomalies can be seen dominating over the subtropics until the descending branch of the Ferrel cell appears to govern the vertical motions of the midlatitudes. The NH Ferrel cell has an area of weak rising motion occurring over 25°N and becomes stronger aloft, solidifying that deep convection can be seen over this area. The descending branch of the Ferrel cell, however, is much closer to the strong vertical velocities of the ascending branch. Ultimately, this relationship shows that over the NH regions, alternating meridional cells are seen throughout the midlatitudes, with two Hadley-like circulations surrounding one Ferrel cell-like system.

Finishing with the respective Polar cells of each region, an inverse pattern transpires between each hemisphere. The NH Polar cell begins with moderate subsidence over 70°N, which appears to be relatively weak at the surface, and then changes abruptly to negative anomalies moving poleward. Negative \(\omega\) anomalies over the heart of the NH Polar cell have little relation to the surface, only develops above the 800mb level. The northernmost portion of the NH Polar cell resembles the normal sinking associated with the Polar High over the North Pole, and is personified by large-scale subsidence located along 85°N. Switching to the SH Polar cell, an alternate relationship can be seen. First, this cell begins with weak mid-level surface rising motion that is replaced above by anomalous sinking. Directly south of this rising motion is a weak area of surface
subsidence that becomes more pronounced over the mid-to-upper troposphere. Finally, close to the North Pole is an extensive swath of strong rising motion seen throughout the entire column, and is represented by negative anomalies along 85°S, which illustrates the inverse relationship between the two hemispheres.

5.2 A Global View Using Horizontal Anomaly Maps

Next, the following images pertain to the global horizontal structure for the boreal summer associated with the developmental phase before an El Niño. The previous zonal mean cross section images provided a good representation of the meridional and vertical structures for the entire troposphere; however, because these anomalies were averaged longitudinally, examination of horizontal maps is needed to complete the three-dimensional structure. The first figure to be discussed is the distribution of SSTs during June, July, and August, as shown in Figure 27. The key feature of SSTs associated with the summer conditions one and a half years before a warm event is the domination of warm SST anomalies over the Pacific Ocean. A distinct pattern can be seen associated with these anomalies occurring between the Northern and Southern Hemispheres. With what appears to look like symmetric greater than signs (>), warm SST start in the western polar regions of the Pacific, slant to the southeast over the NH (slant to the north east over the SH), and then dramatically change in the other direction close to 30°N (30°S), finally slanting southwestward (northwestward) toward the western warm pool.

Surrounding these symmetric warming pools are varying ranges of cold SST anomalies. However, the eastern Pacific has the most significant cooling throughout the entire basin. With an extensive cold tongue spreading from the west coast of Peru all the
way to the International Date Line, La Niña-like conditions are evident by this feature. Based on the lifecycle of ENSO (Figure 3), these conditions are agreeable due to the fact that the developmental phase used for this NCEP reanalysis is the cold-to-warm transition before an El Niño event. Because the summer neutral period (-1.5) is the beginning season for the entire transition, it will correlate the most with a decaying La Niña event. It is important to note that the summer developmental phase is its own entity and cannot be grouped with either El Niño or La Niña conditions, thus showing why these phases are so important to the understanding of ENSO dynamics. Therefore the key point for Figure 27 is the zonal extent of SST cooling in relation to the western warm pool. When compared to Figure 14 (Winter SST anomalies), the western warm pool (eastern cold tongue) appears confined solely to the far western Pacific (has a much larger spatial coverage and western presence), which are key features that show that equatorial warming has not occurred yet and an impending El Niño is still far away.

Due to the importance of SST divisions over the equatorial Pacific, the Walker circulation will also respond expectedly to strong temperature gradients at the surface. Strong equatorially cooling would resemble an increase in easterly trades and ultimately an overall strengthening of the Walker Circulation. Therefore, this provides another factor that shows the summer developmental phase is far from producing El Niño-like conditions. Based on the lifecycle on ENSO, it would be inaccurate to say that these so-called neutral phases are insignificant to the evolution of a warm event. Clearly a transition is occurring once La Niña conditions withdraw from the Pacific Ocean, ushering in the necessary conditions that will inevitably begin a new El Niño.
Moving to a more synoptic approach, important SST anomalies appear throughout the global oceans. First, a long swath of warm SST anomalies can be seen over the Atlantic Ocean along 30°N. Other than this small band of warm SSTs, much of the Atlantic is filled by negative SST values, especially over the Caribbean, which is an important region for the intensification of tropical cyclones. Over the North Atlantic, weak cold SST anomalies can be seen running up the coast of North America, an area that resembles the Gulf Stream. Transitioning poleward, the Arctic Ocean depicts an overall warming trend, which is intensified by positive SST anomalies stretching along the east coast of Greenland all the way to Northern Russia.

The southern Atlantic resembles its northern counterpart quite well. Tropical cooling along the equator and subtropics shows a similar relationship to what was occurring over the Caribbean. Moving up into the high-latitudes, widespread warming can be seen from 50°S reaching as far south as the coast of Antarctica. This transition is much more severe than the one that took place over the NH, with high levels of warming associated with the entire subpolar South Pacific. Perhaps not as pertinent to ENSO, increasing SST temperatures off the coast of Antarctica do play an important role over longer times scales, particularly when forecasting teleconnections associated with global warming.

Over the Indian Ocean, a critical heat sink to the western warm pool, basin-wide extreme cooling can be seen. The entire coasts of Southwest and Southeast Asia, India, and the Philippines feel the most significant negative anomalies. These negative anomalies act in restricting wide-spread convection, a key component associated with the
MJO. Moving south, these negative anomalies persist throughout the Indian Ocean, where the eastern coast of Africa sees extensive cooling. There does appear to be moderate warming between southern Africa and the coast of Antarctica; however it is fleeting in comparison to massive cooling seen inside the Indian Ocean.

Complementing the SST anomalies seen during neutral summer ENSO are the precipitation and 500mb vertical velocity (ω) anomalies which are shown in Figure 28. Both maps responded according to the warm and cold SST anomalies and further solidify the importance of surface temperature changes over the Pacific Ocean. Starting with Figure 28a, precipitation rates associated with increased SST warming can be seen distributed globally, with some key areas that represent the surface convection that may be occurring during this developmental episode. First, it is apparent that much of the northern Pacific has increased precipitation rates. Positive rates appear directly over the warmest SST anomalies, with some exceptions. The greater than symbol associated with warm SSTs does not transfer over to the precipitation rates, where strong precipitation anomalies are scattered throughout the entire northern extent. An anomalous amount of convection can be seen along the equator from 180° through 120°W that is over the eastern cold tongue of SSTs, an area normally suppressed with dry conditions. A small core of warm SSTs is located along the equator from 150°-120°W, but seems too small to cause the convection seen over the equatorial eastern Pacific. Ultimately, this feature does not transition into the winter teleconnections described in chapter 4, showing that increased precipitation may be a cause of increased warming seen during the boreal summer. One region exhibiting significant drying does appear over the North Pacific and
is confined to the Aleutian Islands and Alaska, an area that was previously associated with heavy precipitation rates during the winter (Figure 15a).

Shifting to the southern Pacific, an extensive band of low precipitation rates takes shape over the extreme SST cooling seen around the eastern Pacific cold tongue. Interestingly, the swath of negative precipitation rates can be seen stretching all the way from 90°W across the entire Pacific Basin along 10°S. The presence of negative precipitation anomalies over the western warm pool indicates that the normal convection seen in this region is suppressed during the summer. Perhaps more important is that these negative anomalies represent areas that allow solar radiation to reach the surface. Thus, warming the equatorial SSTs of this region ultimately leads to increased convection seen during the winter developmental phase (Figure 14–Figure 15 of chapter 4). Much of the western Pacific does exhibit high precipitation rates; however, over the key transition region described by Rasmussen and Carpenter (1982), inhibition of convection is preventing the developing conditions needed to spawn a new warm phase. Pushing further south within the Pacific introduces another large region of high precipitation anomalies, further agreeing with the placement of convection over anomalously high SSTs.

Examining the individual anomalies outside of the Pacific, other important regions can be seen with strong or weak precipitation rates. A distinct structure arises from Figure 28a over the Western and Eastern United States. Governed by negative precipitation anomalies, the Western Divide exhibits strong drying during the summer, whereas the Eastern Seaboard correlated with increased precipitation. The Caribbean and
south-central Atlantic Basin also correlate with negative precipitation anomalies during JJA, which potentially signifies below normal tropical cyclone activity during the much of the Atlantic Hurricane Season. Moving northward from the equatorial Atlantic, a distinct band of high precipitation rates are seen along 30°N for the entire Atlantic Basin. An area of transition north of this region has contrasting negative anomalies over much of the North Atlantic.

The South Atlantic exhibits a different distribution of precipitation rates. Where the equatorial regions, especially off the east coast of Brazil, show strong convection, the subtropical and mid-latitudinal regions display basin-wide dry conditions. Perhaps the most substantial area of high precipitation can be seen located over the southern Atlantic and portions of Antarctica. This contrasts to precipitation rates occurring over Greenland and the Arctic Ocean, where strong negative anomalies appear throughout these regions. During the SH winter, scattered positive precipitation rates appear cross the Antarctic landscape.

Additional key areas of precipitation can be seen over the large continental regions. Bordered by negative anomalies over Siberia and Eastern Europe, much of central Russia correlates with high precipitation rates. Because of the sheer size of Russia, positive precipitation rates are a key teleconnection with what is occurring during a summer developmental phase. Another large swath of positive precipitation rates located over Sudan, Egypt, and Saudi Arabia shows the influence of transitioning episodes toward drought-sensitive regions. Over the southern half of Africa,
predominantly dry conditions prevail, potentially creating more water scarcity issues over a continent riddled by famine.

A recurring theme seen during the developmental phase is the mass cooling, subsidence, and drying observed over the Indian Ocean. This characteristic prevails again and is particularly noticeable over the Indian Peninsula, a coastal region typically known for increased precipitation rates during the moist summer monsoon conditions (Barnett 1983). Significant aridity can be seen over the southern tip of India and spreading into the Arabian Sea. Along the South Indian Ocean, a slightly opposite tendency appears within the data. Focusing on the waters between Australia and Papua New Guinea, a core of strong precipitation values can be seen. These anomalous precipitation values indicate a correlation with weak warm SST anomalies occurring over this region and represent the convection associated with the far western Pacific during normal conditions.

Regarding the continent of Australia, it exhibits an overall drying trend, while the northern and southern boundaries appear covered by high precipitation anomalies. Again, many areas were not discussed concerning potentially important precipitation anomalies; however, the entire global scale was taken into account regarding the teleconnections associated with ENSO.

While Figure 28a provided a general picture of surface precipitation rates, the 500mb omega anomalies will show where deep atmospheric convection is occurring, and provide a better vertical structure for the entire globe. Positive \( \omega \) values correlate with strong subsidence and high pressure, where negative anomalies correlate with deep atmospheric convection, signified by rising motion above the 500mb level, and
corresponding low pressure systems. Beginning with the important circulation cells and their deviations correlated with the summer neutral phase, conclusions can be made concerning the overall structure of these cells. Along the southern equatorial Pacific, the intensity of the Walker circulation is much stronger than the wintertime anomalies seen in chapter 4. This provides further evidence of the gradual weakening of this cell leading up to an El Niño event. Strong descending motion seen throughout the central and eastern Tropical Pacific show that the descending branch of the Walker cell appears much stronger than the spatial small ascending branch over the western Pacific. Subsidence along the equator can even be seen well to the west of the date line, suppressing the necessary convection that will eventually propagate eastward.

Regarding the two Hadley cell regions, consistent sinking motion over the equator is occurring, contradicting the normal ascending motion that is seen over the ITCZ regions. The only two regions of strong atmospheric convection appear over the western warm pool and the central Atlantic. Outside the Hadley cell latitudes, strong convection appears to be the trend within the Ferrel cells. The strongest area of vertical motion is represented by a core of negative anomalies located over the subtropical North Pacific, following the wide swath of warm SST and precipitation anomalies. These strong negative anomalies begin in the western Pacific and branch northeast and southeast in both hemispheres, eventually reaching 120°W. The key feature occurring over the Ferrel cell region is the alternation of positive and negative vertical velocities, representing an overall inconsistent trend in ascending motion. A similar relationship can be seen over both Polar cell regions, where no anomaly dictates the entire circulation.
Focusing on the synoptic regions, corresponding areas of rising and sinking motion continue to correlate with the previous two images. Areas that did not appear as substantial in Figure 28a, stand out through the $\omega$ anomalies that appear over several key regions. First, the intensity of the vertical motion associated with the Eastern United States presents itself through the core of moderate negative anomalies, particularly over the southeastern regions. Another new area of interest arises over Antarctica, centered along 90°W. A strong core of negative anomalies can be seen over this region, while an opposite area of sinking motion appears over much of the southern Pacific, directly to the west of the Antarctic rising motion. Over the Indian Ocean, equatorial subsidence corresponds with negative precipitation anomalies, but increased sinking motion over Madagascar went previously unmentioned due to the weak anomalies of this region. A final area of note that contradicts the low precipitation rates occurring in Figure 28a covers the entire southern tip of Africa. Weak precipitation rates can be seen inland; however, negative $\omega$ anomalies show that rising motion is the key component of South Africa. There are other dynamics which may be the result of inconsistencies in the data. However, these exceed the scope of this thesis.

The surface dynamics and secondary circulation discussed using Figure 27 and Figure 28 have provided information key to the beginnings of the developmental phase. Figure 29 complements these maps by showing the global distribution of primary circulations and concurrent wind anomalies. The SLP anomalies of the winter developmental phase introduced the importance of off-equatorial low pressure systems on westerly wind anomalies and the inducement of basin-wide warmings within the Pacific.
An analysis of global SLP distributions introduces an important pattern occurring during the boreal summer. Four distinct partitions of SLP occur over the entire globe, with the strongest distribution of pressure gradients seen over the Pacific Ocean associated with the Southern Oscillation (SO). The first subdivision of SLP anomalies is confined within the following boundaries: 90°E and 180°; 60°N and 45°S. Strong low SLP anomalies dominate the landscape of this subdivision, with the strongest low pressure values occurring between the two Hadley cell regions of the western Pacific. The counterpart to the western Pacific subdivision is the positive SLP anomalies bounded within 120°-45°W and 60°N-60°S. One area of anomalous low pressure (centered along 30°S/90°W) appears within this boundary. These high pressure anomalies consistently correspond to the land masses of North and South America. The third subdivision exhibits weak low SLP anomalies bounded within the Atlantic Ocean, with four low pressure systems centered over 40°N/30°W, 30°S/15°E, and 60°S/60°W. The last subdivision exhibits moderate high SLP anomalies and appears bounded between the Prime Meridian and 90°E. Each one of these boundaries have small anomalies that oppose the existing pressure field, however, the domination of each region by these respective SLP values is what should be taken away from Figure 29a.

Examining the smaller scale features associated with teleconnected SLP distributions is the next step in this discussion. The first major SLP anomaly feature can be seen in over the entire western Pacific, where symmetric broad-scale low pressure systems dominate the basin. Important in creating the all important WWB that have been previously studied is the strong low pressure anomaly located over the Philippines. Low
pressure in this region creates cyclonic flow and the concurrent westerly flow seen along the equator, a key component in generating equatorial downwelling Kelvin waves. Another potential significant low pressure anomaly appears centered along 25°S/180° and produces the most negative SLP anomalies within Figure 29a. This broad-scale low pressure system predominantly governs over much of the subtropical Pacific. The associated cyclonic flow along the equatorial SH will also contribute to the creation of WWB seen over the western Pacific. The overall impact of these westerly wind anomalies is muted by the fact that cyclonic flow well off of the equator will not provide the necessary conditions to produce a trapped equatorial Kelvin waves.

The lack of cyclonic flow near the equator can be correlated with the placement of high SLP anomalies linked to the eastern Pacific cold tongue. The undeniable influence of cold SST anomalies along the eastern equatorial Pacific is seen with the atmospheric response of positive anomalous SLP. Meandering around 10°S, elongated high SLP can be seen pushing close to the western Pacific, which will continue to subdue any convection along this area. Even more important is that higher SLP anomalies along the equator need to be switched to negative values in order for El Niño conditions to evolve, and during the summer months (-1.5), the transition between a cold to warm event appears to be a gradual process. Only over the far western Pacific does an off-equatorial low pressure system linked with deep oceanic convection emerge as a potential synoptic feature favoring the development of a new El Niño; however, several other obstacles between the ocean-atmosphere systems stand in the way of basin-wide transitioning.
The next variable to discuss is the horizontal distribution of 200mb geopotential heights, as shown in Figure 30a. Analyzing from a global perspective, a clear separation of geopotential height anomalies can be seen between the Hadley cell regions and the Ferrel cells of both hemispheres. The Tropics appear dominated by low geopotential heights at the 200mb level circling across the entire globe. Between the boundaries of the tropical Hadley cell and mid-latitudinal Ferrel cell is a wave like pattern within the negative Z anomalies, where areas of ridging can be seen over high geopotential heights and troughing situated between these features. The Rossby wave pattern appears more pronounced over the NH than the SH, where two large cores of positive geopotential heights control much of the midlatitudes of the SH. Situated along 60°S, these strong positive Z values have no competing low geopotential height anomalies, except over the Antarctic Peninsula. The NH Polar cell exhibits widespread low geopotential heights, where as the SH cell has no significant anomalies to mention.

Smaller-scale anomalies in the geopotential height field can be seen over several regions. One strong negative core of geopotential height is located over Brazil and has the most significant anomalies for the entire map. Another strong area of low geopotential heights can be seen over a smaller spatial extent off the east coast of Hawaii, where a tight core of low Z values may play an important role in the upper level dynamics of this region. An additional interesting feature can be seen over the Continental United States, where a moderate core of low Z anomalies appears confined by weaker anomalies. Almost identical in nature is a long tongue of low geopotential heights situated over the eastern North Atlantic. With almost identical latitudes (45°N)
and spatial magnitudes, an interesting upper-level pattern may be occurring over the midlatitudes between North America and Europe. Lastly, two weak areas of positive geopotential heights appear over the NH comparable to the distribution seen over the SH. One weak area of upper-level ridging appears over Central Asia, while the stronger anomaly emerges over Alaska and the Aleutian Islands. The latter area of positive geopotential heights has ties to the surface, and can be linked to the strong high pressure system over the same region, signifying deep atmospheric ridging and subsidence.

Back at the surface, the distribution of zonal and meridional wind anomalies represent the surface circulation flows, as seen in Figure 29b-c. Concerning the global circulation cells, the Pacific Ocean region of the Hadley cell has two distinct zonal wind anomalies, with the western Pacific dominated by westerly flow and the eastern Pacific showing strong equatorial easterlies anomalies. The spatial extent of easterly wind anomalies over the tropical Pacific appear confined compared to the broad-scale distribution of westerly winds values. The Ferrel cells of each hemisphere show contrasting results. Much of the NH Ferrel cell is disjointed and does not show any continuity between zonal wind anomalies. The SH distribution of zonal winds clearly correlates with strong easterly wind anomalies within the Ferrel cell region, especially along 45°S. Moving closer to the poles, the NH continues to exhibit disorganized surface winds, whereas the SH Polar cell exhibits two unique boundaries of zonal flow. Around 70°S, strong westerly wind anomalies prevail until reaching 80°S, where broken easterly winds can be seen circling the South Pole.
Analyzing both the zonal and meridional anomalies, synoptic-scale circulations in the data become apparent. Beginning over the western Pacific, two small counter-clockwise circulations, signifying cyclonic flow, appear centered along 20°N/150°E and 15°N/125°E respectively. Due to the orientation of these circulations, a strong belt of westerly winds north of the equator flow from Southeast Asia, eventually colliding with the strong easterlies seen over the eastern Pacific. These anomalous winds can unequivocally be linked to the WWB (discussed in Chapter 3) correlated with inducing warm downwelling equatorial Kelvin waves. Comparing with the winter developmental phase, this strong core of westerly winds appears much further west than the previously mentioned zonal wind anomalies, ultimately showing the eastward displacement of the WWB associated with the annual march leading up to a new ENSO event. An increasing number of findings continue to point toward the western Pacific as the key region in the development of warm and cold phases, and this study is not different.

Other strong primary circulations can be seen over the southern Pacific. Beginning close to the equator, elongated anti-cyclonic circulation associated with the equatorial easterly wind anomalies and the strong subtropical westerlies south of this region is evident. Moving south, an opposing cyclonic circulation can be seen from the subtropical westerlies of the Pacific and the intense easterly flow seen over the midlatitudes. Again this counterclockwise flow matches the broad area of low SLP anomalies centered over south-central Pacific. Two strong cyclonic circulations become even more apparent over Asia, with the strongest rotation seen over western Russia. A feature much weaker in Figure 29a than what the zonal and meridional flows portray is
located over the Antarctic Peninsula. Strong westerlies located between the southern tip of South America and the presence of concentrated easterlies over Antarctica, along with prominent northerly and southerly anomalies represents a vigorous cyclonic rotation that appears underestimated within the SLP reanalysis.

Building off of the surface zonal and meridional anomalies, the 200mb upper-level flow patterns (Figure 30b and c) show important characteristics that dictate the placement of jet streams and midlatitude storm tracks. Concerning the zonal wind anomalies, the return flows of the Walker circulation are far more recognizable than the winter upper-level patterns (Figure 17b). The two branches of the cell are evident by the 200mb easterly wind anomalies over the western Pacific and the strong westerly wind anomalies of the central and eastern Pacific. The upper-level area of divergence occurs during the transition of flows, approximately along 10°S and 170°E. The normal conditions of the Walker cell seen in Figure 30b and the orientation of the surface and return flows further agree that little to no weakening in the circulation is evident during the summer developmental phase.

If the Walker Circulation is a tropical phenomenon that occurs within the Hadley cell region, the subtropical and polar jet streams of the upper latitudes can be considered an extra tropical phenomena that occur within the Ferrel Cells. Between the NH Ferrel and Hadley cell regions, easterly wind anomalies dominate the flow. Conversely the polar jet stream, represented by strong westerly anomalies, oscillates in a wave like pattern between the Polar and Ferrel cell regions. Moving to the SH, a boundary between the Hadley and Ferrel cells correlates with both westerly and easterly anomalies. A
transition in the flow occurs along the International Date Line, where predominant westerly flow moves along 30°S from the Prime Meridian to the International Date Line, gradually changing to easterly anomalies through much of the Western Hemisphere. A similar upper-level pattern to the NH prevails over the Ferrel cell region of the SH, however, a more zonal pattern dominates here instead of the wave-like anomalies along the Arctic Circle. Prevalent easterly anomalies can be seen along 45°S, with an abrupt switch to westerlies circumnavigating the Antarctic Circle, and finally ending with a thin band of easterly winds over the South Pole.

Utilizing both Figure 30b and c will help determine if upper-level rotation associated with neutral ENSO conditions is occurring. While geopotential heights may depict high and low pressure anomalies aloft, finding corresponding cyclonic and anti-cycloic circulations will ultimately show the distribution of these features. The following rotations will aid in finding high and low pressure anomalies masked by the negatively biased geopotential height anomalies of Figure 30a. First, the organization of westerlies along 30°S, easterly flow over 15°S, and the orientation of northerly and southerly winds creates anti-cyclonic flow over Australia. This rotation is identified in Figure 30a by a hole in the low geopotential height field centered on 25°S/140°E; however, Australia is still enveloped by weak negative Z anomalies. Another circulation that was previously diluted by biased geopotential height anomalies can be seen over the Southeastern United States. Counter-clockwise rotation is centered along the Eastern Seaboard and undoubtedly represents upper-level ridging and high pressure. A weakening in the anomaly field correlates with this feature, but continues to classify the
Southeastern United States with negative geopotential heights. Lastly, a previously mentioned feature off the east coast of Hawaii appears underestimated not in its intensity, but the overall spatial coverage associated with this anomaly. Strong westerly flow along 10°N, focused easterly anomalies along 30°N, and the distribution of meridional winds creates a significantly wider rotation than what Figure 30a would lead one to believe.

The combination of all three images within Figure 30 creates a global picture of upper-level wind patterns, height anomalies, and associated pressure gradients, providing new insight into the dynamics that dictate the distribution of teleconnections associated with ENSO.

5.3 Polar Stereographic Maps

Finishing with a hemispherical view of the June-July-August anomalies associated with the developmental phase, Figure 31 shows the geopotential height anomalies for the NH. Contrasting to the winter developmental phase, neutral summer conditions correlate with a strengthening in the northern polar vortex. At the surface, two large areas of positive geopotential height anomalies can be seen in Figure 31a, one occurring over North America and the western Atlantic and the other covering much of Europe and Northern Africa. Compared to the distribution of negative Z anomalies, these positive height values appear focused over large land surfaces. The most substantial negative anomalies can be seen spanning much of the Pacific Ocean to portions of Southeast Asia and India, with the deepest low Z anomalies occurring near the equator. Additional small negative anomalies emerge over the North Atlantic, central Russia, and over the Bering Strait. One inappreciable low geopotential height anomaly located close
to the North Pole appears to have a small importance at the surface; however, this feature will play a greater role as the analysis moves up the troposphere into the stratosphere.

Rising into the middle atmosphere, a transition to negative geopotential heights appears to be occurring, replacing the dominant positive Z anomalies seen over North America and Europe. The entire equatorial spectrum of the NH is now fully covered with low geopotential heights, with the maximum negative anomalies residing over the central Pacific. Still, several weak positive anomalies can be seen intermixed with the dominant negative Z anomalies. The western United States, Alaska, Siberia, and Western Europe exhibit these ridging anomalies, but are still only small representations of their original size seen within the 1000mb level. Concerning the location of the weak surface low geopotential height anomaly, a stronger core of negative Z values emerges near the North Pole, centered over the Queen Elizabeth Islands. According to Figure 31, the presence of the polar vortex becomes more apparent at higher levels within the troposphere.

Now within the tropopause (100mb level), the presence of any positive geopotential heights is all but gone, only left by holes of neutral-to-weak negative anomalies seen intermixed by stronger low geopotential heights. Three distinct neutral anomalies can be seen over the high latitudes (Aleutian Islands, Mongolia, and Eastern Europe), but appear insignificant to the overall upper flow. The entire NH is consistently covered by negative Z anomalies, especially along the Tropics spreading up into the Continental United States and the North Pole. Confined by the Arctic Circle are cellular cores of low geopotential height anomalies, with the abovementioned troughing seen over the Queen Elizabeth Islands becoming further pronounced.
Finally, reaching into the middle stratosphere, a key pattern in the geopotential height distributions is established. The Queen Elizabeth Islands’ low geopotential height anomaly now acts as the principal feature of the 10mb level. Clearly, the gradual spreading of weakening circular negative Z anomalies around the core of pronounced low geopotential heights signifies the presence of a strong polar vortex over the NH. These weaker circular height anomalies appear centered around the Queen Elizabeth Islands, further showing the importance of this feature. Therefore, because of increased strengthening of the low geopotential height anomalies seen near the North Pole, the summer developmental phase correlates with a definitive intensification of the NH polar vortex.

The SH winter geopotential height anomalies (Figure 32) provide a further indication that the polar vortex of both hemispheres during the boreal summer neutral phase correlates with intensification over the poles. At the 1000mb level, the distribution of positive Z anomalies appears centered over Antarctica, represented by three distinct cells located over the south-central Pacific, the South Pole, and the south-central Atlantic. Another significant area of positive Z anomalies appears over South America, which is represented well by the SLP anomalies seen in Figure 29a. The strongest negative anomalies linked to the central Pacific emerge as the dominate feature of Figure 32a. Two other low geopotential height values appear over Southern Africa and the Antarctic Peninsula, with the later displaying a more significant role in the upper troposphere.

At the 500mb level, each anomaly begins to condense into stronger cores of high and low geopotential height anomalies. The mid-level allocation of Z anomalies has
created a clear boundary along 45°S, separating the low-latitude negative geopotential heights from the high-latitude positive geopotential heights. The only exception to this trend is over the Antarctic Peninsula, Argentina, and Chile, where an inverse relationship appears confined to these regions. Around the subtropical latitudes is an overall increase in negative geopotential heights, with the strongest anomalies occurring over Brazil and Australia. The positive anomalies over Antarctica have concentrated into two distinct cells, with one covering the southern Pacific and the other dominating the southern Atlantic. Much of the Antarctic continent exhibits an overall lack of anomalies at the 500 mb level, which could potentially allow a decrease in geopotential heights over this region.

The most organized structure of all the levels becomes evident within the 100mb level. A similar pattern persists from the 500mb level and is represented by the consistent separation of negative Z anomalies over the tropical and midlatitudes from the positive height anomalies situated over the high-latitudes. Differing from the mid-levels is the presence of symmetric low geopotential heights centered along 90° west and east. The introduction of these features to the South Pole demonstrates an increase in the upper-level polar vortex. One last note to the 100mb structure of geopotential height anomalies deals with the global strength of the Z values. Most of the SH tropopause correlates with gradual weakening in the strength of anomalies, except for the symmetric lows situated over Antarctica.

Finally, reaching the middle-stratospheric distribution of geopotential heights allows for a clear representation of the SH polar vortex. Almost all of the anomalies
associated with the troposphere have disappeared or weakened substantially, leaving only
two characteristic geopotential heights worth mentioning. A dipole structure appears
with the orientation of a moderate low geopotential height over Eastern Antarctica and a
weak positive Z anomaly covering the southern Atlantic. The location of this core of low
geopotential heights, however, is the key feature of Figure 32, and substantiates the
presence of a moderate SH polar vortex during the boreal winter developmental phase.

5.4 Presentation of Schematics

Organizing each figure pertaining to the summer developmental phase allows for
a three dimensional representation of the global structure of the atmosphere. Using the
main findings presented for each variable, Figure 33 embodies the vertical and horizontal
circulations contained within the entire Pacific basin. The meridional circulation cells for
both hemispheres are derived from the zonal mean cross-sections, and the general
structure of the Hadley, Ferrel, and Polar cells can be seen clearly by the flow patterns at
the surface and aloft. The meridional circulation cells during the boreal summer have
varying sizes and orientation when compared with the winter developmental phase.

Similarly, two Ferrel cells appear just south of the equator, signified by strong subsidence
along 5°S/105°W at the center of these two cells. Moving poleward, two distinct Hadley
cell circulations are represented by the two strong areas of convergence located along the
subtropical latitudes (30°N/S). Here is where the two hemispheres differ in the
distribution of higher latitude meridional circulations. Over the NH, due north of the
subtropical convergence regions is a small cell resembling a Ferrel-like flow, with
divergence at the surface (40°N) and convergence aloft. The diverging surface flow then
travels northward; converging along 60°N, where strong rising motion can be seen and upper-level divergence directs air poleward. Strong sinking motion completes this circulation and exhibits the general structure of the NH Polar cell. The SH meridional cells outside the Tropics begin with focused upper-level divergence directing flow southward, where strong convergence aloft creates large-scale subsidence along 60°S. This diverging air then propagates south, eventually converging, rising, and then diverging toward the poles. Sinking motion at the poles completes this small circulation, resembling a weaker adaptation of the SH Polar cell.

The Walker circulation continues to be a prominent fixture within the Pacific Ocean. Labeled again in red, two distinct branches appear over the entire Pacific Basin. Compared to the winter Walker circulation, the summer counterpart shows a significant placement to the west. Strong easterly winds can be seen spanning the entire eastern and central Pacific, even intruding into the western warm pool across the date line. In addition, the summer Walker Circulation appears almost entirely zonal in nature, unlike the tilting structure seen during the winter developmental phase (Figure 20). Regarding the placement of high and low pressure anomalies, Figure 33 shows the presence of strong high pressure systems over the eastern Indian Ocean and the eastern Pacific Ocean. Over the western Pacific, where strong vertical motion dominates the flow, low pressure anomalies appear disjointed from the ascending branch. Conversely, strong subtropical cyclonic systems appear well off of the equator, with only one system, located over the extreme western Pacific influencing the Tropics. Therefore, the strength
in the zonal flow seen in Figure 33 solidifies that the during the summer developmental phase, the Walker Circulation shows little signs of weakening.

Now that a 3-D representation of the global structure during the summer transitional phase has been created, the concurrent placement of teleconnected weather patterns can be given, as seen in Figure 34. The major precipitation and temperature anomalies created using NCEP reanalysis data show the synoptic set up of atmospheric conditions for every summer neutral phase since 1950. Utilization of Figure 34 provides a global snapshot of the precipitation and temperature anomalies that can occur around one and a half years before a mature El Niño event. Therefore major alterations to mean atmospheric conditions for a given region can be predicted with enough accuracy to prepare for future events.

Once the teleconnections seen in Figure 34 become coherent to the summer developmental phase, an impending El Niño event can be expected within one and half years. For example, the Eastern United States experiences higher precipitation along with pronounced cooling during summer developmental phases. In addition, the Caribbean correlates with regional cooling, whereas the North Pacific shows strong warming one and a half years before a warm phase. Other teleconnections of interest appear over the western Pacific and western Indian Oceans. Large-scale dry and cool conditions from Madagascar to India dominate the western Indian Ocean, whereas the western and north-central Pacific appears dominated by an L-shaped swath of wet conditions. These opposing anomalies aid in the intensification of the Walker circulation, and the displacement or weakening of these teleconnections could signal a disruption in
the dynamics associated with the oscillatory nature of ENSO. With the combination of Figure 21 and Figure 34, a seasonal outlook associated with the summer and winter developmental phases can be used in better predicating the timing and strength of alternating extreme phases of ENSO.
Figure 22. Linear correlation of summer JJA mean zonal air temperature with the transition Nino 3.4 SST
Figure 23. Same as Figure 22 but for geopotential height.
Figure 24. Same as Figure 22 but for zonal wind.
Figure 25. Same as Figure 22 but for meridional wind.
Figure 26. Same as Figure 22 but for vertical pressure velocity.
Figure 27. Same as Figure 22 but for SST.
Figure 28. Same as Figure 22 but for (a) precipitation, and (b) 500mb vertical velocity.
Figure 29. Same as Figure 22 but for (a) SLP, (b) 1000mb zonal wind, and (c) 1000mb meridional wind.
Figure 30. Same as Figure 22 but for 200mb (a) geopotential height, (b) zonal wind, and (c) meridional wind.
Figure 31. Same as Figure 22 but for northern hemisphere JJA mean geopotential height at (a) 1000 mb, (b) 500 mb, (c) 100 mb, and (d) 10 mb.
Figure 32. Same as Figure 22 but for southern hemisphere JJA mean geopotential height at (a) 1000 mb, (b) 500 mb, (c) 100 mb, and (d) 10 mb.
**Figure 33.** Schematic depiction of the global 3-D structure of ENSO’s summer developmental phase.
Figure 34. Schematic depiction of the global teleconnections of ENSO’s summer neutral phase.
CHAPTER 6
Summary and Discussions

6.1 Key Findings

The quasi-oscillatory lifecycle of the El Niño-Southern Oscillation (ENSO) continues to create a complex and convoluted dilemma within the dynamics of global climate forecasting. Even with eight decade’s worth of research, predicting phase changes within ENSO is perpetually misrepresented by even the most sophisticated computer modules. Thus, the ocean-atmospheric formulas interwoven deep within global climate models must be flawed to some extent. One possible problem shown by this study was the combination of both warm-to-cold and cold-to-warm transitional phases into one diluted neutral phase. The neutral phase, which occurs when Niño 3.4 sea surface temperatures (SSTs) lack either warm or cold anomalies, precedes both warm and cold ENSO events; therefore, are of critical importance in better understanding the complex lifestyle of ENSO. Through the use of NCEP reanalysis data from 1948-2007, clear teleconnections during these neutral phases prove to be extremely influential in providing insight into the ocean-atmospheric characteristics before a warm or cold phase. Therefore, the lack of neutrality associated with transitional events shows that these phases are far from neutral, and the title of “developmental phase” is a more appropriate use of this term.
Divided into two seasonal components, the developmental phase has contrasting teleconnections depending on the season. For the winter developmental phase (December-January-February [-1]), warm SST anomalies centered along the equator/International Date Line and over the mid-latitudinal Pacific correlate with increased convection, deep rising motion, and strong anomalous low pressure anomalies. The area of strong low pressure anomalies over the Northern Hemispheric central Pacific appears to have an off-equatorial extension, an imperative feature in creating strong westerly wind bursts (WWB) close to the equator and the date line. The introduction of westerly wind anomalies near the central Pacific, as seen in Figure 4, has been shown to initiate warm downwelling equatorial Kelvin waves. Due to the eastward propagation associated with Kelvin waves, warm SSTs are then carried across the Pacific, eventually colliding with the eastern boundary and inducing an El Niño event. These features are further represented in the Pre-1948 ENSO dataset (Figure 6 and 7), proving the western Pacific is a key region for inducing phase changes within the ENSO lifecycle.

On a broader-scale, the eastward movement of warm SSTs within the central Pacific and the displacement of cold SSTs toward the eastern Pacific concurrently adjust the strength of the Walker circulation. During the winter developmental phase, a weaker temperature gradient seen over the equatorial Pacific in turn deteriorates the easterly trade winds. This ultimately slows down the Walker circulation and disrupts the system altogether. Figure 20 depicts this weakening along with the distribution of the Hadley, Ferrel, and Polar cells. The Hadley cells appear displaced toward the subtropics, where the Ferrel cells now dominate the equatorial regions with large-scale subsidence. In
addition, increased tropospheric warming is seen around the polar regions, where the
tropics appear dominated by colder temperatures. A mid-level warm core does appear
over the equator during the winter developmental phase, and correlates with a strong
westerly jet stream at this same level. Even weakening of the polar vortex of both
hemispheres is seen from the surface to the 10mb level one year before an El Niño.

During the summer developmental phase (June-July-August [-1.5]), the global
three-dimensional structure of the atmosphere correlated with normal conditions. For
example, much of the western Pacific exhibits anomalous warming of SST, where the
central and eastern Pacific correlates with extensive cooling. The strong basin-scale SST
gradient one and a half years before an El Niño reinforce the intensity of the Walker
circulation, which shows no signs of weakening during this phase. In addition, strong
easterly wind anomalies intrude into the western Pacific boundary, suppressing the
development of any WWB. The meridional circulation cells also appear similar to the
normal Three-Cell model, excluding along the equator where Ferrel-like cells continue to
suppress vertical development. The Hadley cells appear along 30°N/S, with a NH Ferrel
cell and SH Polar cell being the only abnormal circulations during this phase. Opposite
to the winter developmental phase, the polar vortex for both hemispheres appears to be
strengthening. Therefore, the summer neutral phase exhibits the most normal global
three-dimensional structure; however, based on the anomalies seen during the winter
months, this timescale still shows that the ocean-atmospheric environment is still in the
process of transitioning to a new episode.
6.2 A New Methodology for Better Predicting ENSO

The main teleconnections for both the winter and summer developmental phases (Figure 8, Figure 21, and Figure 34) provide a new methodology for better predicting new El Niño events. Because of the linear relationship between El Niño and La Niña events, as discussed in Chapter 2, these anomalies can be reversed to additionally acquire the teleconnections one year before a cold event. Therefore, a completion of the entire lifecycle of ENSO and the concurrent teleconnections of each phase is now available. Utilizing the anomalies seen in Figures 8, 21, and 34, a certain level of predictability is possible for all ENSO events. A new methodology in forecasting each phase of ENSO can now be implemented and tested. If the given oceanic and atmospheric conditions line up with any of the presented maps for the winter (summer) developmental phases, the onset of an El Niño or La Niña event can be expected within one year (one and half years) from the time of these observed teleconnections. It is important to note that these results are only meant to be template in better predicating ENSO phase changes, and do not actually validate any one El Niño theory. Consequently, more analysis is needed to prove the effectiveness of this method and is a possible area of future research.

6.3 Future Research

Other future research possibilities may incorporate the influence of other teleconnection patterns. Increased studies (e.g. Kessler et al. 1995; Hendon et al. 1998; Zhang and Dong 2004), have shown that the Madden-Julian oscillation (MJO) can promote El Niño because of its eastward propagating, WWB that excite downwelling Kelvin waves in the equatorial Pacific, which is a similar finding to this thesis. The
results of the present study could provide new insight into the correlations between these
two phenomena, showing how both the MJO and ENSO interact with each other.

Another influential mode of decadal variability that has been connected to ENSO is the
Pacific Decadal Oscillation (PDO). Both exhibit increased SST anomalies over the
central and eastern Pacific during their respective warm phase, with the PDO only
changing phases every 20-40 years (Wallace et al. 1998). Due to the close proximity of
the PDO to the ENSO, information regarding these developmental phases may aid in
better linking these two patterns of climate variability. Lastly, because of the
teleconnections seen over the North Atlantic, especially during the winter developmental
phase, investigation into the correlation between ENSO neutral phases and the North
Atlantic Oscillation (NAO) could provide new insight for these winter-oriented
phenomena.

From the observed results of this thesis, a global three-dimensional structure
during both winter and summer developmental phases of ENSO has been achieved.
Furthermore, these findings incorporate a new methodology in better forecasting extreme
phases and their associated teleconnections. Yet, the completion of the entire ENSO
lifecycle, with the introduction of these developmental phases, is possibly the most
important outcome of this thesis; thus providing continuity into an already convoluted
ocean atmospheric phenomenon.
REFERENCES


Chang et al., 2006: Climate Fluctuations of Tropical Coupled Systems—The Role of Ocean Dynamics. *Journal of Climate-Special Section*, 19, 5122.


Weisberg, R. H., C. Wang, 1997: A Western Pacific Oscillator Paradigm for the El Niño-

Wyrtki, K., 1975: El Niño—The Dynamic Response of the Equatorial Pacific Oceanto
