An Overview of El Niño-Southern Oscillation Understanding

By

Chunzai Wang [1]

and

Joel Picaut [2]

[1] NOAA Atlantic Oceanographic and Meteorological Laboratory (AOML)

Miami, Florida

[2] Institut de Recherche pour le Développement (IRD)

Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (LEGOS)

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Abstract

Since the TOGA (Tropical Ocean and Global Atmosphere) program, and in particular the maintenance of its observing system in the tropical Pacific, significant progress has been made in the understanding of the El Niño-Southern Oscillation (ENSO) phenomenon. Occurrence of ENSO has been explained as either a continual and self-sustaining mode or a stable mode triggered by stochastic forcing. The difference between a self-sustaining cyclic mode and a stable non-cyclic mode is that for a stable non-cyclic mode each El Niño is independent of the next but depends on stochastic forcing for its initiation, whereas for a self-sustaining cyclic mode each El Niño is related to the next events of La Niña and El Niño. Whatever the case, El Niño is growing up with warm sea surface temperature (SST) anomalies in the equatorial central/eastern Pacific. After an El Niño reaches its mature phase, negative feedbacks are required to terminate growth of the warm SST anomalies. Four major negative feedbacks have been proposed: wave reflection at the ocean western boundary, discharge process, western Pacific wind-forced Kelvin wave, and anomalous zonal advection. These negative feedbacks may work together for terminating El Niño warming, and their relative importance may be time-dependent.

Variability with frequency higher and lower than ENSO timescale has been identified to play roles in ENSO. The seasonal cycle can contribute to the irregularity and phase-locking of ENSO, and the intraseasonal variability can be a source of both ENSO's variability and irregularity. Topical Pacific decadal-multidecadal variability and warming trends modulate ENSO and its predictability. Many mechanisms have been proposed to explain tropical Pacific decadal-multidecadal variability, being categorized as tropical origins and tropical-extratropical connections. Mechanisms of the tropical origins include stochastic forcing, interactions between the seasonal and interannual cycles, internal nonlinear concept of homoclinic-heteroclinic orbits, nonlinearity between El Niño and La Niña, and local ocean-atmosphere interaction, while those of the tropical-extratropical connections involve oceanic bridges, wave propagation, and atmospheric bridges. Difficulties and uncertainties on studies of low-frequency variability and interpretation of warming trends, global warming, and ENSO are also discussed.

1. Introduction

At the end of the 19th century, the term El Niño was used to denote the annual occurrence of a warm ocean current that flowed southward along the west coast of Peru and Ecuador around Christmas. The Peruvian geographers noted that in some years the onset of warm conditions was stronger than usual and was accompanied by unusual oceanic and climatic phenomena. Starting with the arrival of foreign-based scientific expeditions off Peru in the early 20th century, the concept gradually spread through the world's scientific community that El Niño referred to the unusual events. The annual occurrence was forgotten. It wasn't until the 1950s/1960s that scientists realized that El Niño is far more than a coastal phenomenon, and that it is associated with basin-scale warming in the tropical Pacific Ocean. Sir Gilbert Walker in the 1920s and 1930s found that notable climate anomalies occur around the world every few years, associated with what he called the Southern Oscillation [*Walker*, 1923, 1924; *Walker and Bliss*, 1932]. The Southern Oscillation is characterized by an interannual seesaw in tropical sea level pressure (SLP) between the Western and Eastern Hemispheres, consisting of a weakening and strengthening of the easterly trade winds over the tropical Pacific. *Bjerknes* [1969] recognized a connection between El Niño and the Southern Oscillation. Subsequently, scientists treat El Niño and the Southern Oscillation as simply aspects of the same phenomenon of the ocean-atmosphere system and then study them together in what we now call "El Niño-Southern Oscillation", or ENSO.

Bjerknes [1969] first recognized the importance of interaction between the tropical Pacific Ocean and atmosphere for ENSO. He hypothesized that a positive ocean-atmosphere feedback involved the Walker circulation is a cause of ENSO. *Bjerknes* viewed that an initial positive sea surface temperature (SST) anomaly in the equatorial eastern Pacific reduces the east-west SST gradient and hence the strength of the Walker circulation, resulting in weaker trade winds around the equator. The weaker trade winds in turn drive the ocean circulation changes that further reinforce SST anomaly. This positive ocean-atmosphere feedback leads the equatorial Pacific to a warm state, i.e., the warm phase of ENSO (El Niño). During that time, *Bjerknes* did not know what causes a turnabout from a warm phase to a cold phase, which has been recently named La Niña.

Since *Bjerknes'* hypothesis, ENSO has not been intensively studied until the 1980s. The intense warm episode of the 1982-83 El Niño, which was not noticed until it was well developed, galvanized the scientific community to understand and predict ENSO. The 1982-83 El Niño was not consistent with the "buildup" of sea level in the western Pacific by stronger than normal trade winds prior to 1982, presumed to be a necessary precursor of El Niño [*Wyrtki*, 1975]. Also, there was no warming off the west coast of South America in early 1982, considered to be part of the normal sequence of events characterized the evolution of El Niño [e.g., *Rasmusson and Carpenter*, 1982]. This motivates a ten-year international Tropical Ocean-Global Atmosphere (TOGA) program (1985-1994) to study ENSO. TOGA builds an ocean observing system in the tropical Pacific Ocean, conducts theoretical and diagnostic studies of the ENSO phenomenon, and develops a sequence of coupled ocean-atmosphere models to study and predict ENSO. A special volume of the Journal of Geophysical Research (volume 103, June 1998) provided a comprehensive review of observations, theory, modeling, and predictability of ENSO during the TOGA decade (also see ENSO reviews of *Philander* [1990]; *McCreary and Anderson* [1991]; *Battisti and Sarachik* [1995]). The present paper reviews progress in ENSO understanding, with a major focus on the development after the TOGA decade. However, for the sake of continuity it also briefly summarizes the progress made before and during the TOGA decade.

ENSO's low-frequency modulation and high-frequency influence on ENSO are newly and recently developed research topics of ENSO. The 1997-98 El Niño is characterized by exceptionally strong high-frequency wind variability during the onset phase. Numerical models, which succeeded in predicting the onset of the 1997-98 El Niño, were unable to forecast its intensity [e.g., *Barnston et al*., 1999; *Landsea and Knaff*, 2000] until the March 1997 westerly wind burst was incorporated. This may suggest the importance of high-frequency variability forcing, stimulating scientists to further investigate roles of high-frequency variability in ENSO. This paper briefly reviews impacts of high-frequency variability on ENSO. *Lengaigne et al*. [2004, this volume] provide a review of influence of westerly wind events on ENSO, and *Rothstein and Kochurov* [2004, this volume] investigate the ocean response to an idealized atmospheric westerly wind burst using an oceanic GCM.

ENSO is a very irregular oscillation, both in frequency and amplitude. Its frequency varies usually between two to seven year^{-1}, and sometime in a way that it appears modulated on decadal and multidecadal timescales [e.g., *Mokhov et al*., 2000]. In terms of amplitude, there are decades (or multi-decades) where El Niño and/or La Niña (i.e., ENSO amplitude) is/are more or less energetic, while there are decades where El Niño is more common than La Niña (e.g., since the mid 1970s) and vice versa. Such feature can be viewed as a nearly regular ENSO oscillation superimposed on natural decadal and multidecadal oscillations and on a warming trend [*Lau and Weng*, 1999; *Cai and Whetton*, 2001a; *Philander and Fedorov*, 2003]. Decadal-multidecadal variability of ENSO appears to influence the global atmospheric circulation [*Diaz et al*., 2001], and thus the climate over many parts of the world, going from Australia [*Power et al*., 1999], India [*Torrence and Webster*, 1999], Africa [*Janicot et al*., 2001], and North America [*Gershunov and Barnett*, 1998]. Such variability appears to alter the ocean productivity of the

Pacific Ocean [*Chavez et al*., 2003] and ENSO predictability. Indeed, most coupled models of ENSO exhibit a decadal modulation in their prediction skills [e.g., *Balmaseda et al*., 1995; *Flugel and Chang*, 1998; *Kirtman and Schopf*, 1998]. Such feature holds for ENSO-based statistical predictability of precipitation such as over U.S. [*Gutzler et al*., 2002]. Therefore, many studies have recently focused on ENSO low-frequency modulation, especially after the TOGA decade. This paper also provides a review of ENSO low-frequency modulation. *Schneider and Latif* [2004, this volume] give an overview of Pacific decadal variability.

The present paper is organized as follows. Section 2 briefly describes observations of ENSO. Section 3 reviews our present understanding of ENSO mechanisms. Section 4 briefly summarizes effects of high-frequency variability on ENSO. Section 5 reviews a newly and recently developed facet of ENSO, its low-frequency modulation. Finally, Section 6 provides a summary.

2. Observations of ENSO

2.1. The ENSO Observing System

The backbone of the ENSO observing system (Fig. 1) is the TAO (Tropical Atmosphere Ocean) array of about 70 moored buoys [*Hayes et al*., 1991]. Most of them are equipped with a 500-m thermistor chain and meteorological sensors. At the equator several moorings are equipped with ADCP (Acoustic Doppler Current Profiler) and current meters [*McPhaden*, 1993]. Developed during TOGA as a multinational program between France, Japan, South Korea, Taiwan, and United States, this array is now supported by US with the dedicated R/V Ka'imimoana and by Japan with their TRITON program (hence the official name of TAO/TRITON since January 1st, 2000). The ocean observing system is completed by a

Voluntary Observing Ship (VOS) program, an island tide-gauge network, and a system of surface drifters. All the data are transmitted in near-real time to the Global Telecommunication System, for research and prediction purposes. A suite of meteorological and oceanographic satellites completed all these measurements, with in particular the TOPEX/Poseidon altimeter that appears most useful in observing and analyzing tropical ocean variability [*Picaut and Busalacchi*, 2001]. Details about the TOGA ENSO observing system can be found in *McPhaden et al*. [1998].

The obvious parameters for observing the ENSO coupled phenomenon are surface wind stress and SST (through a combination of satellite and in situ data). The basic 2-7 year period of ENSO is set by the thermal inertia of the upper layer. Most of the heat content in low-latitude oceans is situated in this layer, and thus is directly reflected in sea-level height. Hence, measurements of the upper ocean thermal field and sea level are also fundamental to ENSO. Upper-layer temperature is mostly controlled by a specific low-latitude dynamic (i.e., equatorial waves), and current measurements are needed, especially near the equator with the vanishing Coriolis force. In spite of less importance than in mid-latitudes, surface heat fluxes are also required.

The TOGA observing system was devoted to the large-scale monitoring of the upper tropical oceans. However, it was considerably questionable about the physics that maintains and perturbs the western Pacific warm pool, which is believed to be the center of action for ENSO. Hence, a multinational oceanography-meteorology experiment was conceived and carried out in 1992-93, with an intensive observation period (November 1992-February 1993) embedded into a yearlong period of enhanced monitoring. Twelve research vessels, seven research aircrafts, numerous ground-based stations, and additional moored and drifting buoys have collected a unique set of data. The plans for the TOGA Coupled Ocean-Atmosphere Coupled Experiment (COARE) is listed in *Webster and Lukas* [1992], and the results are summarized in *Godfrey et al*. [1998].

2.2. Some Use of the TOGA ENSO Observing System

It took the whole TOGA decade to install this system, and the 1997-98 El Niño was the first to be observed from start to finish from this comprehensive set of in situ and remotely sensed observations. In 1996, an accumulation of warm water in the warm pool appeared favorable for the development of El Niño. However, the succession of westerly wind bursts from December 1996 to June 1997, notably in March 1997, was instrumental in setting up this huge El Niño [*Lengaigne et al*., 2004, this volume]. Theses wind bursts advected the eastern edge of the warm pool eastward and excited equatorial downwelling Kelvin waves that depressed the thermocline in the east. This resulted in a distinct warming over the central and eastern parts of the equatorial basin (Fig. 2c). In August 1997 the surface warming joined, the unstable air-sea coupled system was fully effective and El Niño approached toward its mature phase. By that time, the accumulation of warm water in the warm pool was spread toward the eastern equatorial basin by eastward currents. During the end of the mature phase, the warm water in the equatorial band was slowly depleted by westward and meridionally divergent currents. The thermocline in the east slowly upwelled and this set up favorable condition for the shift into La Niña. With a drop of 8°C of SST in less than a month around 0°-130°W, the sudden turn from one of the strongest El Niño on record to La Niña was another surprise to the scientific community. Several interrelated and coincidental factors lead to this dramatic change. Easterly winds in the west generated equatorial upwelling Kelvin waves, while remaining westerly winds in the east generated equatorial upwelling Rossby waves. Opposite surface currents led to the breakup of the warm waters, the surfacing of the thermocline, and thus the drastic drop of SST around 0°-130°W. Several papers describe at length the 1997-98 El Niño-La Niña, with in particular *McPhaden* [1999] analyzing in situ observations and *Picaut et al*. [2002] space-based observations. Such descriptions enable the testing of El Niño theories (presented in Section 3).

The 2002-03 El Niño was also very well captured by the ENSO observing system. Despite an accumulation of warm waters in the western Pacific warm pool in 2001, a strong westerly winds in December 2001 resulted in a short-lived warming in the east. Only through a series of wind bursts in May and June 2002 that El Niño really developed in July 2002. Interestingly, this warm event was concentrated in the central part of the equatorial basin and did not affect much the eastern Pacific (Fig. 2d**)** even during its mature phase [*Lagerloef et al*., 2003; *McPhaden*, 2003].

2.3. Lessons from TOGA and Further Observational Needs

The biggest achievement of TOGA was the installation (for the first time in oceanography history) of an ocean observing system. It improved the understanding and modeling of ENSO, and proved its predictable capability. Besides, the observations clearly show that ENSO events originate differently in the last five decades. The El Niño events between 1950 and 1976 showed that the warm SST anomalies were first peaked along the South American coast in the boreal spring of the El Niño year and then propagated westward [*Rasmusson and Carpenter*, 1982]. The El Niños between 1976 and 1996 seems to originate from the equatorial western/central Pacific (Fig. 2), and the coastal warming occurs in the boreal spring subsequent to the El Niño year rather than in the boreal spring of the El Niño year. The 1997-98 El Niño develops in both the central Pacific and the South American coast during the spring of 1997 and the 2002-03 El Niño originates in the equatorial central Pacific. Why El

Niños originate differently in the last five decades is not understood yet, although high- and low-frequency variabilities are the most obvious candidates.

TOGA-COARE was not long enough to understand the link between the intraseasonal westerly winds, such as the Madden-Julian Oscillation (MJO) and Westerly Wind Bursts (WWBs), and El Niño [*Lengaigne et al*., 2004, this volume]. With the discovery of the salinity stratified barrier-layer in the western Pacific warm pool [*Lukas and Lindstrom*, 1991] and the possibility that it influences the development of El Niño [*Maes et al*., 2002], there is a strong need for more salinity measurements and in particular sea surface salinity (SSS). End of TOGA was marked by the progressive replacement of bottle samples by thermosalinograph onboard VOS. Together with satellite missions such as SMOS and Aquarius, these in situ SSS measurements will undeniably improve the ENSO observing system [*Lagerloef and Delcroix*, 2001].

The eastern tropical Pacific was somewhat forgotten during TOGA, and the 5-year experiment EPIC (Eastern Pacific Investigation Processes) was launched in 1999. This experiment was designed to improve the understanding of the ITCZ, its interaction with the cold water originating from the equatorial upwelling, and the physics of the stratus cloud deck that forms over the cold water off South America [*Cronin et al*., 2002].

As discussed in section 5, understanding of the low-frequency variations of ENSO requires an expansion of the present ENSO observing system and its extension toward the western boundary and beyond the tropics. A main goal of the Pacific Basin Extended Climate Study (PBECS) is to provide sufficient additional in situ and satellite observations to constrain data-assimilating models well enough that the processes affecting decadal modulation of ENSO can be studied in detail [*Kessler et al*., 2001]. This will require a whole set of additional measurements, such as repeated high-resolution expendable and hydrographic sections, several process experiments, and the integration with the Argo program of profiling floats [*Roemmich et al.*, 2001] and the Global Ocean Data Experiment (GODAE) [*Smith et al*., 2001]. All these efforts are part of the CLIVAR (Climate Variability and Predictability) program.

It will be long before these observing systems and experiments produce sufficient high-quality observations to explain the decadal modulation of ENSO. This strengthens the need for historical and paleoclimate records of ENSO, with coral, tree-ring, tropical ice core, sediment or other proxies [*Ortlieb*, 2000; *Mann*, 2000; *Markgraf and Diaz*, 2000] for observing and testing the evolution of ENSO in the past, present and future.

3. ENSO Mechanisms

The theoretical explanations of ENSO can be loosely summarized as two views. First, El Niño is one phase of a continual, self-sustaining, naturally oscillatory mode of the coupled ocean-atmosphere system. Second, El Niño is a stable (or damped) mode triggered by atmospheric random "noise" forcing. In an attempt to bridge the gap between these two views, *Philander and Fedorov* [2003] recently argued that ENSO is a weakly-damped or neutral mode. Whatever the case, ENSO involves the positive ocean-atmosphere feedback of *Bjerknes* [1969]. *Bjerknes* viewed that an initial positive SST anomaly in the equatorial eastern Pacific reduces the east-west SST gradient and hence the strength of the Walker circulation, resulting in weaker trade winds along the equator. The weaker trade winds in turn drive the ocean circulation changes that further reinforce SST anomaly.

The early idea of *Wyrtki's* [1975] sea level "buildup" in the western Pacific warm pool treats El Niño as an isolated event. *Wyrtki* suggested that prior to El Niño, the easterly trade winds strengthened, and there was a "buildup" in sea level in the western Pacific warm pool. A "trigger" is a rapid collapse of the easterly trade wind. When this happens, the accumulated warm water in the western Pacific would surge eastward in the form of equatorial Kelvin waves to initiate an El Niño event. The availability of more observed data since the 1980s has led the identification of atmospheric high-frequency variability (or "noise") as important "triggers" of El Niño. In this case, there is no necessary connection between one El Niño event and the next, i.e., El Niño is sporadic not cyclic [e.g., *Kessler*, 2002; *Philander and Fedorov*, 2003]. A random disturbance is needed to initiate an El Niño. On the other hand, numerical models suggest that ENSO is a self-sustaining and oscillatory mode of the coupled ocean-atmosphere system. The positive ocean-atmosphere feedback of *Bjerknes* [1969] leads the equatorial Pacific to a warm state. For both cases, a negative feedback is needed to turn the system around after it reaches its mature phase. Since the 1980s four major negative feedbacks have been proposed: wave reflection at the western boundary, discharge process, western Pacific wind-forced Kelvin wave, and anomalous zonal advection. These negative feedbacks may work together for terminating El Niño warming. Additionally, many studies have shown that the ocean-atmosphere coupling can produce unstable slow modes that can explain eastward and westward propagating property of interannual anomalies.

3.1. The Delayed Oscillator

A mechanism for the oscillatory nature of ENSO was originally proposed by *McCreary* [1983], based on the reflection of subtropical oceanic upwelling Rossby waves at the western boundary. *McCreary* [1983] and *McCreary and Anderson* [1984] explored shallow water ocean dynamics coupled to wind stress patterns that are changed by discontinuous switch depending on thermocline depth, and showed how oceanic Rossby waves might be involved in generating the interannual oscillations associated with ENSO. In spite of the use of a discontinuous switch in their atmosphere and of reflection of subtropical Rossby waves, ideas of their discussion of basin adjustment processes have been incorporated by later work. *Suarez and Schopf* [1988] introduced the conceptual delayed oscillator as a candidate mechanism for ENSO (Fig. 3), by considering the effects of equatorially trapped oceanic wave propagation. Based on the coupled ocean-atmosphere model of *Zebiak and Cane* [1987], *Battisti and Hirst* [1989] formulated and derived a version of the *Suarez and Schopf* [1988] conceptual delayed oscillator model and argued that this delayed oscillator model could account for important aspects of the numerical model of *Zebiak and Cane* [1987].

The conceptual delayed oscillator model is represented by a single ordinary differential delay equation:

$$\frac{dT}{dt} = AT - BT(t-\eta) - \varepsilon T^3, \tag{1}$$

where T is the SST anomaly in the equatorial eastern Pacific, A, B, η, and ε are constant model parameters. The first term of the right hand side (RHS) of Eq. (1) represents the positive feedback by ocean-atmosphere coupling in the equatorial eastern Pacific. The second term is the delayed negative feedback by free equatorial Rossby waves generated in the eastern Pacific coupling region that propagate to and reflect from the western boundary, returning as equatorial Kelvin waves to reverse the anomalies in the eastern Pacific coupling region. The last term is a cubic damping term. The delayed oscillator assumes that the western Pacific is an inactive region and eastern boundary wave reflection is unimportant, emphasizing the importance of wave reflection at the ocean western boundary. The delayed oscillator model of Eq. (1) can oscillate on interannual timescale over a broad range of model parameters [e.g., *McCreary and Anderson*, 1991; *Neelin et al*., 1998].

Graham and White [1988] presented sparse evidence of off-equatorial Rossby waves and their reflection at the western boundary and then empirically constructed a conceptual oscillator model for ENSO. As shown in *McCreary and Anderson* [1991], the conceptual equations of the *Graham and White* model can be reduced to a single equation that has similar form to Eq. (1) (also see the comments of *Neelin et al*. [1998]).

The work of *McCreary* [1983], *McCreary and Anderson* [1984], and *Graham and White* [1988] emphasized the reflection of off-equatorial Rossby waves at the western boundary whose importance in ENSO has been in debate. *Kessler* [1991] and *Battisti* [1989, 1991] argue that the equatorial Kelvin wave results primarily from the reflection of the gravest mode Rossby wave and that off-equator (poleward of ±8°) variations should not be a major factor in ENSO. In contrast, *Graham and White* [1991] contend that coupled model simulations of ENSO are greatly altered if effects from poleward of ±8° are neglected. However, all of these studies recognized wave reflection at the western boundary being important in terminating El Niño. *Li and Clarke* [1994] challenged validation of the delayed oscillator by noting a low lag correlation between the western Pacific equatorial Kelvin wave amplitude and zonal wind forcing that is inconsistent with the delayed oscillator theory. *Mantua and Battisti* [1994] showed that wave reflection at the western boundary did account for the termination of El Niño and that the low lag correlation is due to irregularity of ENSO.

3.2. The Recharge Oscillator

Wyrtki [1975] first suggested a buildup in the western Pacific warm water as a necessary precondition to the development of El Niño. This concept was later modified by covering the entire tropical Pacific Ocean between 15°S and 15°N [*Wyrtki*, 1985]. Prior to El Niño, upper ocean heat content or warm water volume over the entire tropical Pacific tends to build up (or charge) gradually, and during El Niño warm water is flushed toward (or discharged to) higher latitude. After the discharge, the eastern tropical Pacific becomes cold (La Niña) with the shallowing of the thermocline and then warm water slowly builds up again (recharge) before occurrence of next El Niño. The recharge and discharge processes have been also examined by *Zebiak* [1989a], *Miller and Cheney* [1990], and *Springer et al*. [1990] although the latitudinal bands of warm water are different from *Wyrtiki* [1985] (we will come back to this issue later).

The concept of the recharge and discharge processes is further emphasized by *Jin* [1997] (Fig. 4a). Based on the coupled model of *Zebiak and Cane* [1987], *Jin* [1997] formulated and derived the recharge oscillator model that can be represented by the following simple equations:

$$\left.\begin{aligned} \frac{dT}{dt} &= CT + Dh - \varepsilon T^3 \\ \frac{dh}{dt} &= -ET - R_h h \end{aligned}\right\}, \qquad (2)$$

where T is the SST anomaly in the equatorial eastern Pacific, and h is the thermocline depth anomaly in the equatorial western Pacific. C, D, ε, E, and R_h are the model parameters. For a certain set of model parameters, Eq. (2) can oscillate on interannual timescale.

Recently, many studies attempted to test the validity of this theoretical oscillator model by using observational data [e.g., *Meinen and McPhaden*, 2000, 2001; *Hasegawa and Hanawa*, 2003; *Holland and Mitchum*, 2003; *Sun*, 2003). These observational studies basically demonstrated the recharge and discharge of the equatorial Pacific warm water during the evolution of ENSO. However, the more appropriate variable in Eq. (2) may be one that represents the warm water over the entire equatorial Pacific rather than the one only in the equatorial western Pacific. These studies show that the warm water in the entire equatorial Pacific band (for example, from 5°S-5°N) highly correlates with the Nino3 SST anomalies, with the former leading the latter by about two seasons (Fig. 4b). The correlation between the equatorial western Pacific warm water and the Nino3 SST anomalies is relatively lower (but still significant), with the western Pacific warm water leading by five seasons. *Mechoso et al*. [2003] tested the validity of conceptual models by fitting their coupled GCM output (pre-filtered with singular spectrum analysis to extract the leading oscillatory mode) into the recharge oscillator model. They suggested that the recharge oscillator could provide a plausible representation of their modeling ENSO. Misfits between the recharge oscillator and the GCM oscillatory mode may be attributed to additional physics that are not included in the recharge oscillator model.

There is a debate on the latitudinal bands of the recharge and discharge of warm water. *Wyrtki* [1985] defined the warm water in the tropical Pacific between 15°S and 15°N. *Miller and Cheney* [1990] and *Springer et al*. [1990] showed that, during El Niño, the warm water volume is decreased near the equatorial band (8°S-8°N and 5°S-5°N, respectively), whereas the volume of the tropical Pacific is not affected by ENSO due to water recirculation in the tropical North Pacific. Recently, *Holland and Mitchum* [2003] seems to reconcile this conflict by demonstrating that warm water is indeed lost from the tropical Pacific as a whole over the course of an El Niño event, as suggested by *Wyrtki* [1985]. This loss, however, is relatively small compared to the redistribution within the tropics. *Kug et al*. [2003] showed that during El Niño meridional transport in the Northern Hemisphere is larger than that in the Southern Hemisphere, and that the asymmetric characteristics are mainly due to a southward shift of the maximum westerly wind anomalies during the mature phase of El Niño.

Sun [2003] presented a "heat pump" hypothesis for ENSO that can be summarized as follows. An increase in the warm pool SST increases the zonal SST contrast that strengthens the easterly trade wind and then helps the ocean to store more heat to the subsurface ocean. Because of the stronger wind and the resulting steeper tilt of the equatorial thermocline, the coupled system is potentially unstable and is poised to release its energy through an El Niño warming. The occurrence of El Niño pushes the accumulated heat poleward and prevents the further heat buildup in the western Pacific, and thereby stabilizes the coupled system. This ENSO "heat pump" hypothesis is conceptually similar to the recharge oscillator.

3.3. The Western Pacific Oscillator

Observations show that ENSO displays both eastern and western Pacific interannual anomaly patterns [*Rasmusson and Carpenter*, 1982; *Weisberg and Wang*, 1997a; *Mayer and Weisberg*, 1998; *Wang et al*., 1999b; *McPhaden*, 1999; *Wang and Weisberg*, 2000; *Vialard et al*., 2001]. During the warm phase of ENSO, warm SST anomalies in the equatorial eastern Pacific are accompanied in the off-equatorial western Pacific by shallow thermocline, relatively cold SST, and anomalous anticyclone. Also, while the zonal wind anomalies over the equatorial central Pacific are westerly, those over the equatorial western Pacific are easterly. Consistent with these observations, *Weisberg and Wang* [1997b] and *Wang et al.* [1999b] developed a conceptual western Pacific oscillator model for ENSO. To represent both eastern and western Pacific anomaly patterns, the model is constructed by the following four equations:

$$
\left.\begin{aligned}
\frac{dT}{dt} &= a\tau_1 + b_2\tau_2(t-\delta) - \varepsilon T^3 \\
\frac{dh}{dt} &= -c\tau_1(t-\lambda) - R_h h \\
\frac{d\tau_1}{dt} &= dT - R_{\tau 1}\tau_1 \\
\frac{d\tau_2}{dt} &= eh - R_{\tau 2}\tau_2
\end{aligned}\right\}, \qquad (3)
$$

where T is the SST anomaly in the equatorial eastern Pacific, h is the thermocline depth anomaly in the off-equatorial western Pacific, τ_1 and τ_2 are the equatorial zonal wind stress anomalies in the central Pacific and the western Pacific, respectively.

Arguing from the vantage point of a *Gill* [1980] atmosphere, condensation heating due to convection in the equatorial central Pacific [*Deser and Wallace*, 1990; *Zebiak*, 1990] induces a pair of off-equatorial cyclones with westerly wind anomalies on the equator (Fig. 5). These equatorial westerly wind anomalies act to deepen the thermocline and increase SST in the equatorial eastern Pacific, thereby providing a positive feedback for anomaly growth [represented by the first term of RHS of Eq. (3a)]. On the other hand, the off-equatorial cyclones raise the thermocline there via Ekman pumping. Thus, a shallow off-equatorial thermocline anomaly expands over the western Pacific [represented by Eq. (3b)] leading to a decrease in SST and an increase in sea level pressure in the off-equatorial western Pacific. During the mature phase of El Niño, the off-equatorial anomalous anticyclones initiate equatorial easterly wind anomalies in the western Pacific [*Wang*, 2000]. These equatorial easterly wind anomalies cause upwelling and cooling that proceed eastward as a forced ocean response providing a negative feedback [represented by the second term on RHS of Eq. (3a)]. Equations (3c) and (3d) relate the zonal wind stress anomalies in the equatorial central Pacific to the equatorial eastern Pacific SST anomalies, and the zonal wind stress anomalies in the equatorial western Pacific to the off-equatorial western Pacific thermocline anomalies, respectively. The model can oscillate on interannual timescale. Note that the western Pacific oscillator is also consistent with the onset of El Niño. During the onset and development phases of an El Niño, twin anomalous cyclones in the off-equatorial western Pacific initiate equatorial westerly wind anomalies [e.g., *Wang and Weisberg*, 2000] that produce downwelling Kelvin waves to warm the equatorial central and eastern Pacific.

Earlier studies have shown that the equatorial easterly wind anomalies in the western Pacific can force upwelling Kelvin waves that raise thermocline in the east [e.g., *Tang and Weisberg*, 1984; *Philander*, 1985]. Recently, *McPhaden and Yu* [1999], *Delcroix et al*. [2000], *Boulanger and Menkes* [2001], *Vialard et al*. [2001], *Picaut et al*. [2002], *Boulanger et al*. [2003], and *Hasegawa and Hanawa* [2003] have shown that the western Pacific oscillator is operated in nature. The western Pacific wind-forced Kelvin waves play an important role for terminating ENSO. For example, *Boulanger and Menkes* [2001] and *Boulanger et al*. [2003] demonstrated that, for the 1997-98 El Niño, about two-thirds of the Kelvin wave amplitude is actually forced by easterly wind in the western Pacific and the other one-third is due to wave reflection at the western boundary (the delayed oscillator). In nature, the equatorial easterly wind anomalies in the western Pacific are observed to become larger and larger (both amplitude and fetch) and move eastward after the mature phase of El Niño. The impact of the easterly wind-forced upwelling Kelvin waves is thus gradually strengthened by the increasing fetch and eastward migration of the easterly wind anomalies [e.g., *Picaut et al*., 2002].

3.4. The Advective-Reflective Oscillator

Picaut et al. [1996] found an oceanic convergence zone at the eastern edge of the warm pool, which is advected in phase with the Southern Oscillation Index over thousands of kilometers, eastward during El Niño, westward during La Niña. Based on this finding, the study of *Picaut and Delcroix* [1995] regarding zonal advection and wave reflection, and the fact that westerly (easterly) winds penetrate into the central (western) equatorial Pacific during El Niño (La Niña), *Picaut et al*. [1997] proposed a conceptual advective-reflective oscillator model for ENSO (Fig. 6). In this conceptual model, they emphasize a positive feedback of zonal currents that advect the western Pacific warm pool toward the east during El Niño. Three negative feedbacks tending to push the warm pool back to its original position and then into the western Pacific are: anomalous zonal current associated with wave reflection at the western boundary, anomalous zonal current associated with wave reflection at the eastern boundary, and mean zonal current converging at the eastern edge of the warm pool. During the warm phase of ENSO, equatorial westerly wind anomalies in the central Pacific produce equatorial upwelling Rossby and downwelling Kelvin waves that propagate westward and eastward, respectively. The westward propagating upwelling Rossby waves reflect to upwelling Kelvin waves after they reach the western boundary, whereas the eastward propagating downwelling Kelvin waves reflect to downwelling Rossby waves at the eastern boundary. Since both the upwelling Kelvin and downwelling Rossby waves have westward zonal currents in the equatorial band, they tend to push the warm pool back to its original position and then into the western Pacific. These negative feedbacks along with the negative feedback of the mean zonal current make the coupled ocean-atmosphere system to oscillate.

Unlike the delayed oscillator, the recharge oscillator, and the western Pacific oscillator, the advective-reflective oscillator does not have a set of simple and heuristic equations. Instead, using a linear wind-forced ocean numerical model that was restricted to the zonal current of the first baroclinic Kelvin and first meridional Rossby waves, *Picaut et al*. [1997] showed an interannual oscillation with specified model parameters. Based on the physics of the advective-reflective oscillator of *Picaut et al*. [1997], *Clarke et al*. [2000] presented a simple oscillatory model of the zonal displacement of the western Pacific warm pool that has a similar mathematical form to the delayed oscillator. Recent observational and modeling supports of the advective-reflective oscillator can be found in *Delcroix et al*. [2000], *An and Jin* [2001], *Picaut et al.* [2001, 2002], and *Dewitte et al*. [2003].

3.5. The Unified Oscillator

With the different conceptual oscillator models capable of producing ENSO-like oscillations, more than one may operate in nature. Motivated by existence of the above oscillator models, *Wang* [2001] formulated and derived a unified ENSO oscillator from the dynamics and thermodynamics of the coupled ocean-atmosphere system that is similar to the *Zebiak and Cane* [1987] coupled model. The unified oscillator includes the physics of all oscillator models discussed above. As suggested by the unified oscillator, ENSO may be a multi-mechanism phenomenon (see *Picaut et al*. [2002] for observational evidence) and the relative importance of different mechanisms may be time-dependent. Considering both eastern and western Pacific anomaly variations, the unified oscillator is represented by:

$$\left.\begin{aligned}\frac{dT}{dt}&=a\tau_1-b_1\tau_1(t-\eta)+b_2\tau_2(t-\delta)-\varepsilon T^3\\ \frac{dh}{dt}&=-c\tau_1(t-\lambda)-R_h h\\ \frac{d\tau_1}{dt}&=dT-R_{\tau 1}\tau_1\\ \frac{d\tau_2}{dt}&=eh-R_{\tau 2}\tau_2\end{aligned}\right\}, \tag{4}$$

where T is SST anomaly in the equatorial eastern Pacific, h is thermocline depth anomaly in the off-equatorial western Pacific, and τ_1 and τ_2 are zonal wind stress anomalies in the equatorial central Pacific and in the equatorial western Pacific, respectively. The parameters a, b_1, b_2, c, d, and e are constant. The parameters η, δ, and λ represent the delay times. The parameters ε, R_h, $R_{\tau 1}$, and $R_{\tau 2}$ are damping coefficients.

The first term on RHS of Eq. (4a) represents the positive feedback in the coupled system. The second term represents the negative feedback due to wave reflection at the western boundary. The third term represents the negative feedback due to the wind-forced wave contribution in the equatorial western Pacific. The last term is a cubic damping term that does not affect oscillatory behavior, but it limits anomaly growth [*Battisti and Hirst*, 1989; *Wang*, 2001]. Eq. (4b) states that the off-equatorial western Pacific thermocline anomaly is controlled by the wind stress in the equatorial central Pacific, with a damping rate of R_h^{-1}. Eq. (4c) shows that zonal wind stress anomaly in the equatorial central Pacific is related to the eastern Pacific SST anomaly, and Eq. (4d) states that the zonal wind stress anomaly in the equatorial western Pacific is related to the off-equatorial western Pacific thermocline anomaly. The unified oscillator of Eq. (4) can oscillate on interannual timescale.

By further simplifications and assumptions, the unified oscillator can reduce to the different ENSO oscillators. The delayed oscillator model does not consider the role of the western Pacific in ENSO. It is assumed that equatorial winds in the western Pacific do not affect the SST anomalies in the eastern Pacific. If we neglect the contribution of the wind-forced wave in the western Pacific, the unified oscillator of Eqs. (4a)-(4d) will exclude the role of the western Pacific in ENSO. By setting $b_2 = 0$ in Eq. (4a), the western Pacific variables τ_2 and h are decoupled from the coupled system. If we further drop the time derivative of Eq. (4c), the unified oscillator reduces to:

$$\frac{dT}{dt} = \frac{ad}{R_{\tau 1}} T - \frac{b_1 d}{R_{\tau 1}} T(t-\eta) - \varepsilon T^3 . \tag{5}$$

Equation (5) is the delayed oscillator of Eq. (1).

The recharge oscillator considers variations of eastern Pacific SST and western Pacific thermocline anomalies. As argued by *Jin* [1997], equatorial wave dynamics are important in adjustment of the equatorial ocean, but wave propagations are not explicitly in the recharge model. If the time derivatives in Eqs. (4c) and (4d) are dropped and all delay parameters are set to zero, i.e., $\eta = 0$, $\delta = 0$, and $\lambda = 0$, the unified oscillator reduces to:

$$\left.\begin{aligned} \frac{dT}{dt} &= \frac{ad - b_1 d}{R_{\tau 1}} T + \frac{b_2 e}{R_{\tau 2}} h - \varepsilon T^3 \\ \frac{dh}{dt} &= -\frac{cd}{R_{\tau 1}} T - R_h h \end{aligned}\right\}. \tag{6}$$

The mathematical form of Eq. (6) is the same as the recharge oscillator of Eq. (2).

The western Pacific oscillator emphasizes the role of the western Pacific anomaly patterns in ENSO. This oscillator model does not necessarily require wave reflection at the western boundary. Neglecting the feedback due to equatorial Rossby wave reflection at the western boundary of the unified oscillator by setting $b_1 = 0$, Eqs. (4a)-(4d) reduce to:

$$\left.\begin{aligned}\frac{dT}{dt} &= a\tau_1 + b_2\tau_2(t-\delta) - \varepsilon T^3 \\ \frac{dh}{dt} &= -c\tau_1(t-\lambda) - R_h h \\ \frac{d\tau_1}{dt} &= dT - R_{\tau 1}\tau_1 \\ \frac{d\tau_2}{dt} &= eh - R_{\tau 2}\tau_2\end{aligned}\right\}, \tag{7}$$

which is the western Pacific oscillator of Eq. (3).

The advective-reflective oscillator of *Picaut et al.* [1997] can also be represented by a set of simple and heuristic equations. During El Niño, it emphasizes a positive feedback of zonal currents that advect the western Pacific warm pool toward the east, extending thus the fetch of the westerly winds, and three negative advective feedbacks that tend to push the warm pool back to its original position and then into the western Pacific. In derivation and formulation of the unified oscillator model, it is shown that two advection terms of $u\partial\overline{T}/\partial x$ and $\overline{u}\partial T/\partial x$ are included in the first term of $a\tau_1$ in Eq. (4a) (also see *Battisti and Hirst* [1989]). Thus, the effects of zonal current are included in the term of $a\tau_1$. The effect of anomalous zonal current associated with wave reflection at the western boundary can be explained by the term of $-b_1\tau_1(t-\eta)$ in Eq. (4a) (also see *Clarke et al*. [2000]). The negative feedback of wave reflection at the eastern boundary is not considered by other oscillators. However, it can be added to Eq. (4a):

$$\frac{dT}{dt} = a\tau_1 - b_1\tau_1(t-\eta) + b_2\tau_2(t-\delta) - b_3\tau_1(t-\mu) - \varepsilon T^3, \tag{8}$$

where $b_3\tau_1(t-\mu)$ represents the effect of wave reflection at the eastern boundary. *Jin and An* [1999] also showed that the thermocline feedback (vertical advection of anomalous subsurface temperature by mean upwelling) and the zonal advective feedback of *Picaut et al*. [1997] are dynamically linked and can be added to the recharge oscillator model.

Harrison and Vecchi [1999] and *Vecchi and Harrison* [2003] emphasized the role of southward shift of westerly wind anomalies in the central and western Pacific for terminating El Niño. Their GCM (General Circulation Model) showed that a southward shift of westerly wind anomalies observed during the mature phase of El Niño can raise the thermocline in the equatorial cold tongue region and then affects El Niño. In fact, a shift of maximum westerly wind anomalies to the south of the equator causes a reduction of westerly wind anomalies on the equator. The reduction of equatorial westerly wind anomalies during mature phase of El Niño adjusts the already-deep thermocline and thus facilitates El Niño decay. This effect may be combined into above oscillator models by reducing strength of the positive feedback.

3.6. Coupled Slow Unstable Modes

Interaction between the tropical Pacific Ocean and atmosphere can produce unstable coupled modes. The simple coupled system (with constant mean states) displays a slow westward propagating unstable mode [*Gill*, 1985; *Hirst*, 1986] and a slow eastward propagating unstable mode [*Philander et al*., 1984; *Yamagata*, 1985; *Hirst*, 1986]. These two modes are further investigated numerically by *Hirst* [1988] and analytically by *Wang and Weisberg* [1996], showing that they can propagate and continuously regenerate on interannual timescales. The delayed oscillator is not relevant to these unstable modes. For example, *Wang and Weisberg* [1994] showed that the evolution of the eastward propagating mode is nearly identical for the closed and open ocean western boundary conditions (the open western boundary does not allow waves to be reflected). Energetics analyses show that a growth of the unstable modes requires the energy source term for the ocean exceeding the sum of the energy sink terms [*Yamagata et al*., 1985; *Hirst*, 1988; *Wang and Weisberg*, 1994].

Neelin [1991] introduced a slow SST mode theory, by emphasizing physical processes in the oceanic surface layer (not related to wave dynamics). A number of physical processes contribute to destabilization of SST modes and compete in terms of the direction of propagation. Whether the coupled system favors the SST modes or the ocean-dynamics modes (associated to the delayed oscillator) is determined by ocean adjustment process. For ENSO timescale, there are two key adjustments: one associated with the dynamical adjustment of the equatorial ocean, and the other associated with the thermodynamical changes in the SST due to air-sea coupling. When the dynamical adjustment of the ocean is fast compared with the changes in SST, the behavior of the coupled ocean-atmosphere system depends critically on the time evolution of the SST, but is less influenced by the ocean-wave dynamics. On the other hand, if the dynamical adjustment of the ocean is slow, the coupled ocean-atmosphere system is dominated by the equatorial wave dynamics that provide the "memory" for an interannual oscillation. *Jin and Neelin* [1993] and *Neelin and Jin* [1993] provided the complementarity between the SST mode and the ocean-dynamics modes, by arguing that in most of the parameter space the coupled modes will have a mixed nature, i.e., the mixed SST/ocean-dynamics modes. An advantage of the unstable slow modes is that they can explain the propagating property of interannual anomalies whereas the delayed oscillator mode produces a standing oscillation. *Wakata and Sarachik* [1991] showed that a transition from a propagating mode to a standing mode could occur by varying the latitudinal extent of mean equatorial upwelling.

3.7. A Stable Mode Triggered by Stochastic Forcing

Another view of ENSO is that El Niños are thought as a series of discrete warm events punctuating periods of neutral or cold conditions (La Niñas). That is, ENSO can be characterized as a stable (or damped) mode triggered by stochastic (random) atmospheric forcing or noise [e.g., *McWilliams and Gent*, 1978; *Lau*, 1985; *Pendland and Sardeshmukh*, 1995; *Moore and Kleeman*, 1999; *Thompson and Battisti*, 2001; *Dijkstra and Burgers*, 2002; *Zavala-Garay et al.*, 2003]. This hypothesis proposes that disturbances, external to the coupled system, are the source of random forcing that drives ENSO. Random forcing or noise can be referred to processes that evolve independently of ENSO and have a much smaller timescale. An attractive feature of this hypothesis is that it offers a natural explanation in terms of noise to the irregular behavior of ENSO variability. Since this view of ENSO requires the presence of atmospheric "noise", it easily explains why each El Niño is distinct and El Niño is so difficult to predict [e.g., *Landsea and Knaff*, 2000; *Fedorov et al.*, 2003; *Philander and Fedorov*, 2003]. However, it is difficult to explain why ENSO has a distinctive timescale of a few years.

No matter whether El Niño is a self-sustaining cyclic mode or a stable mode triggered by stochastic forcing, El Niño is growing up with warm SST anomalies in the equatorial central and eastern Pacific. After an El Niño reaches its mature phase, negative feedbacks are required to terminate growth of the mature El Niño anomalies in the central and eastern Pacific. In other words, the negative feedbacks associated with the delayed oscillator, the recharge oscillator, the western Pacific oscillator, and the advective-reflective oscillator may be still valid for demise of an El Nino even if El Niño is regarded as a stable mode triggered by stochastic forcing. The difference between a self-sustaining cyclic mode and a stable non-cyclic mode is that for a stable non-cyclic mode each El Niño is independent of the next but depends on noise for its initiation, whereas for a self-sustaining cyclic mode each El Niño is related to the next events of La Niña and El Niño. As an example, *Mantua and Battistti* [1994] discussed three simple ENSO scenarios: (1) periodic ENSO cycle, (2) non-periodic ENSO cycle, and (3) non-periodic, non-cyclic ENSO event. In the latter two cases, the warm SST anomalies in the eastern and central Pacific are initiated by something other than a reflected Kelvin wave issued by the preceding cold event. However, the reflected upwelling Kelvin waves can be always responsible for shutting down the growing instability in the equatorial central and eastern Pacific. A sequence of independent warm events can still be consistent with delayed oscillator physics since the termination of individual El Niño can occur as a result of wave reflection at the western boundary.

4. Effects of High-Frequency Variability on ENSO

Variability with frequency higher than ENSO timescale includes the seasonal cycle and the intraseasonal variability (ISV). Both the seasonal cycle and the ISV play roles in ENSO.

4.1. The Seasonal Cycle

The seasonal cycle can contribute to the irregularity of ENSO and the ENSO phase-locking [e.g., *Jin et al.*, 1994; *Tziperman et al*., 1995; *Chang et al*., 1995]. Using numerical models, these studies showed that interannual variability is periodic without seasonal cycle forcing, but as model parameters (related to the seasonal cycle and the ocean-atmosphere coupling) are increased the model interannual solution undergoes a transition from periodic to irregular (or chaotic) through a sequence of rational fractions of the seasonal cycle: ENSO remains phase-locked to the seasonal cycle. *Mantua and Battisti* [1995] found that interaction between the ENSO and the "mobile" mode (a near-annual timescale, westward propagating mode) is the cause for irregular variability in *Zebiak and Cane* [1987] model simulations. The transition to chaos of a model system can occur in any of three universally recognized standard scenarios: the period doubling route [*Chang et al,* 1995], the quasi-periodicity route [*Tziperman et al*., 1995], the intermittency route [*Wang et al.*, 1999a]. However, the study of *Jin et al.* [1996] indicates that at reasonable amplitude of ENSO, superstable frequency-locked regimes are more prevalent than chaotic regimes. Stochastic forcing appears thus necessary for the irregularity of ENSO [*Stone et al,* 1998].

4.2. The Intraseasonal Variability (ISV)

The prominent ISV in the western and central Pacific includes the westerly wind burst (WWB) and the Madden-Julian Oscillation (MJO). Although both the WWB and MJO show westerly winds over the western Pacific, they differ temporally and spatially. On average, the WWB has zonal width between 30° and 40° longitude, meridional width between 10° and 15° latitude, and duration between 7 and 10 days [e.g., *Harrison and Vecchi, 1997; Vecchi and Harrison*, 2000]. The MJO, a wave-like atmospheric phenomenon, has a timescale of between 30-90 days and has much larger structure than the WWB [*Madden and Julian,* 1994; *Slingo et al*., 1999]. The MJO propagates eastward and the WWB does not necessarily. The WWB tends to develop during active phases of the MJO (also tends to form from paired tropical cyclones and cold surges from mid-latitude), but the exact relationship between the WWB and MJO is not clear. They both have an influence on oceanic variability. However, the quantitative differences between the effects on the ocean by the WWB and MJO have not yet been determined. Therefore, we herein collectively review their roles in the ocean and ENSO (for a more detailed review see *Lengaigne et al.* [2004, this volume]).

The ISV, associated with the WWB and MJO in the western Pacific, has both a local effect and a remote effect on the eastern Pacific. The local effect includes a change in mixed layer depth, surface jets, and an oceanic cooling in the western Pacific that can be explained by varying both shortwave radiation and latent heat flux. Convective activity associated to the ISV increases atmospheric cloudiness that reduces shortwave radiation and then cools the western Pacific Ocean [e.g., *Weller and Anderson*, 1996]. Surface latent heat flux is also responsible for the SST cooling in the western Pacific Ocean. During the boreal winter and spring, the climatological zonal wind in the equatorial western Pacific varies from a weak westerly at 130°E-150°E to an easterly near the date line, with a reverse of direction around 150°E [e.g., *Wang*, 1995]. Superposition of an equatorial westerly anomaly in the above mean zonal wind in the western Pacific will have different effects on SST. In the region of a weak mean westerly at west of 150°E, a westerly wind anomaly increases the total wind speed, inducing the cooling of SST through enhanced evaporation. However, in the region of a weak mean easterly between 160E°-170°E, a westerly anomaly implies a reduction in the total wind speed, resulting in an increase in SST due to reduced evaporation. Therefore, an eastward SST gradient is produced, which in turn reinforces the equatorial westerly wind anomalies [*Lindzen and Nigam*, 1987]. A positive feedback is operating in the western Pacific westerly wind anomalies through thermodynamics.

The remote effect of the ISV on ENSO is via downwelling Kelvin waves generated by westerly wind anomalies in the western Pacific. Numerous studies have investigated the ocean responses to the ISV westerly wind anomalies [e.g., *Kessler et al*., 1995; *Hendon et al*., 1998; *Zhang*, 2001; *Zhang and Gottschalck*, 2002; *Kutsuwada and McPhaden,* 2002; *Cravatte et al*., 2003]. The westerly wind anomalies in the western Pacific generate downwelling Kelvin waves that propagate along the thermocline to the eastern Pacific. The Kelvin waves are also accompanied by anomalous surface currents that induce an eastward displacement of the eastern edge of the western Pacific warm pool [*Matsuura and Iizuka,* 2000; *Picaut et al*., 2002*; Lengaigne et al.,* 2002]. These two effects, zonal advection and thermocline increase the SST in the central and eastern Pacific and thus decrease the zonal temperature gradient. The resultant weakening of the trade winds will cause more warm water to flow eastward, causing even weaker winds. This positive feedback can result in the onset of an El Niño event. As an example, both observations and numerical models have shown the westerly wind anomalies in the western Pacific during the boreal winter and spring of 1996-97 play an important role in the onset of the 1997-98 El Niño [e.g., *McPhaden*, 1999; *Wang and Weisberg*, 2000; *McPhaden and Yu*, 1999; *Boulanger et al*., 2001; *Bergman et al*., 2001; *Picaut et al*., 2002]. *Cravatte et al;* [2003] recently noticed an oscillation in the surface winds over the warm pool around 120-day period. This oscillation, of unknown origin and distinct from MJO, generates equatorial Kelvin waves as strong as those excited by MJO. Both sets of Kelvin waves seem to be stronger during the onset of El Niño and may interfere for its development. Finally, the MJO activity associated with an easterly signature is one of the components that are responsible for the rapid SST shift from El Niño to La Niña in May 1998 [*Takayabu et al*., 1999].

As discussed in Section 3.7, the ISV has been treated as noise or disturbances that can drive or sustain ENSO. No matter whether ENSO is a self-sustaining mode or a stable mode triggered by stochastic forcing, the ISV plays a role on it. If the ISV is acting on a self-sustaining oscillatory system, then it is a source of the irregularity of ENSO. On the other hand, if the ISV is acting on a stable system, then it is the source of both its variability and irregularity. The impact of the ISV on ENSO may also depend on the timing of the ISV relative to the ENSO cycle and mean structures of the coupled ocean-atmosphere system [e.g., *Bergman et al*., 2001; *Fedorov*, 2002]. For example, strong MJO activity was also evident during the boreal winter of

1989-90 and early stage of development was similar to that of 1996-97. However, the development of El Niño was aborted in May 1990. The MJO was relatively quiescent during the boreal winter of 1981-82. A strong El Niño developed during 1982, but not as rapidly as it did during 1997. Using an idealized model, *Wang et al*. [1999] showed that the stochastic response of the ENSO system depends not only the dynamic regimes of the ENSO system but also on the properties of the stochastic forcing.

However, some studies showed that the ISV does not play a critical role to ENSO [e.g., *Zebiak*, 1989b; *Slingo et al*., 1999; *Syu and Neelin*, 2000; *Kessler and Kleeman*, 2000]. *Zebiak* [1989b] showed that, in his intermediate model, the atmospheric ISV does not seem to affect ENSO. *Syu and Neelin* [2000] demonstrated that a nosier signal with shorter timescales does not appear to have an obvious relation to the ENSO cycle in their model. *Kessler and Kleeman* [2000] concluded that the MJO can interact constructively with the onset of El Niño to amplify a developing warm event, however, the MJO on its own does not appear to be the cause of El Niño. *Slingo et al*. [1999] could not find an interannual relationship or linkage between the MJO and El Niño, while *Zhang and Gottschack* [2002] found a relation between Kelvin wave ISV forcing and SST anomalies in the eastern equatorial Pacific during El Niño, at least for the 1980-99 period. However, the detection and interpretation of ISV SST signals related to El Niño is complicated by the fact that zonal advection of the eastern edge of the warm pool is the process dominant in the central equatorial Pacific, while vertical advection is dominant in the east [*McPhaden*, 2002].

5. Low-Frequency Variability of ENSO

In this section, we first discuss observational evidence of decadal-multidecadal variability and warming trends in both the tropical and mid-latitude Pacific. Second, we summarize mechanisms proposed for tropical Pacific decadal-multidecadal variability. Third, we review interpretation of tropical Pacific warming trends, global warming, and ENSO. Finally, we discuss difficulties and uncertainties on studies of low-frequency variability.

5.1. Observational Evidence of Decadal-Multidecadal Variability and Warming Trends in the Tropical and Mid-latitude Pacific

Decadal and multidecadal variability has been observed in the North Pacific for more than a decade [e.g., *Nitta and Yamada*, 1989; *Trenberth*, 1990; *Minobe*, 2000]. It is thus relatively well documented but it is still unclear if a major or several decadal oscillations concern this region. For example, there is some evidence of four decadal ocean-atmosphere modes that occupy a thick layer of the North Pacific Ocean [*Luo and Yamagata*, 2002]. The most studied signal appears under the denomination of PDO for Pacific (inter) Decadal Oscillation [*Mantua et al*., 1997] or NPO for North Pacific decadal-multidecadal Oscillation [*Gershunov and Barnett*, 1998]. Both correspond to the leading EOF of SST North of 20°N. The PDO appears as a recurring pattern of ocean-atmosphere variability centered over the mid-latitudes of the North Pacific. Over the last century, the PDO is marked by the reversal of its prevailing polarity in 1925, 1947 and 1977. Cold PDO regimes prevailed in 1880-1924, and in 1947-1976, while warm regimes prevailed in 1925-1946 and from 1977 to the mid-1990s. Despite sparse data coverage, there are several evidences of decadal variability in the mid-latitudes or subtropics of the Southern Pacific [*Garreaud and Battisti*, 1999; *Linsley et al*., 2000; *Chang et al*., 2001]. In particular, the position of the South Pacific Convergence Zone (SPCZ) is subject to an interdecadal oscillation, in addition to an ENSO oscillation. Both oscillations have similar amplitudes, but they appear independent [*Folland et al*., 2002]. The interdecadal oscillation in the South Pacific can be regarded as the quasi-symmetric manifestation of the PDO.

The tropics and in particular the tropical Pacific are marked by several modes of decadal-multidecadal coupled modes [*Goswami and Thomas*, 2000; *White et al*., 2003]. However, their latitudinal extension is wider that those of ENSO (Fig. 7). Examination of the PDO over the entire Pacific basin reveals that its spatial signature in SST, SLP and wind stress is somewhat similar to the "horse shoe" signature of ENSO [*Mantua et al*., 1997; *Zhang et al*., 1997; *Garreaud and Battisti*, 1999; *Mestas-Nuñez and Enfield*, 2001; *Salinger et al*., 2001], and it is thus denominated as ENSO-like interdecadal oscillation by several authors. These ENSO and ENSO-like interdecadal oscillations deal obviously with different timescales and they are also different in their spatial structures. The decadal oscillation is marked by a SST anomaly in the eastern tropical less confined than those of ENSO, and by a relatively greater SST anomaly of opposite sign in the North Pacific (Fig. 7). In addition, their tropospheric signatures are quite different [*Mestas-Nuñez and Enfield*, 2001]. Besides, the PDO may also be distinct from the ENSO-like Pacific-wide decadal oscillation, as they appear dominated by 50 years and 20-30 years oscillations, respectively [*Minobe*, 2000; *Liu et al*., 2002]. On the other hand, *Tourre et al*. (2001) found two distinct decadal (9-12 years) and interdecadal (12-25 years) signals in the Pacific basin. In any case, the links between these tropical and/or Pacific-wide decadal-multidecadal oscillations and ENSO are crucial, either through the modulation of the basic ENSO oscillation in the tropical Pacific or through their teleconnections [*Gershunov and Barnett*, 1998; *Alexander et al.*, 2004, this volume].

Since study of decadal-multidecadal oscillations is difficult to apprehend from limited space-time data, several authors have focused on the recent 1976's global climate shift [*Guilderson and Schrag*, 1998; *Zhang et al*., 1998; *Karspec and Cane*, 2002; *Giese et al*., 2002]. Its signature in the tropical Pacific is particularly important with a rapid increase of SST (over a year). This warming is associated with an increase in the amplitude and period of ENSO, and an eastward displacement along the equator of the maximum anomalies of SST gradient, westerly wind, and thermocline slope [*Wang and An*, 2002]. The origin of this warming and climate shift is still unclear. *Zhang et al*. [1998] suggest that subducted warm-water issued from the North Pacific perturbed the tropical thermocline (a hypothesis refuted by *Guilderson and Schrag* [1998]), while *Giese et al*. [2002] consider also a subsurface bridge but originating from the subtropical South Pacific. Note that other shifts may have occurred around 1924-25, 1941-42 and 1957-58 in last century's SST [*Chao et al*., 2000], much probably as phase transitions of several decadal-multidecadal oscillations [*Minobe*, 2000]. The dominance of the 1976's shift may be related to the acceleration of the 20th century warming trend observed in the tropical Pacific. *Knutson and Manabe* [1998] noted that this warming trend in a broad triangular region of the eastern tropical and subtropical Pacific increases from 0.41°C (100 yr)$^{-1}$ since 1900 to 2.9°C (100 years)$^{-1}$ since 1971. Like the Pacific-wide decadal mode, this warming trend has an El Niño-like structure.

5.2. Mechanisms of Tropical Pacific Decadal-Multidecadal Variability

As discussed in the last section, both the tropical and mid-latitude Pacific show decadal-multidecadal variability. *Schneider and Latif* [2004, this volume] review mechanisms of North Pacific decadal-multidecadal variability (also see *Latif* [1998], *Miller and Schneider* [2000], and

Minobe [2000]). This subsection reviews mechanisms of tropical Pacific decadal-multidecadal variability. Many hypotheses have been proposed for tropical Pacific decadal-multidecadal variability and they can be divided into two categories: (1) tropical origins and (2) tropical-extratropical connections.

5.2.1. Tropical Origins

Tropical Pacific decadal-multidecadal variability can be generated in the tropics only without involving extratropical processes. This category includes many mechanisms. Stochastic atmospheric forcing can lead to decadal-multidecadal variability in the tropical Pacific [e.g., *Kirtman and Schoft*, 1998; *Latif et al*., 1998; *Burgers*, 1999; *Thompson and Battisti*, 2001]. Using a simple model, *Wang et al*. [1999a] showed that tropical Pacific decadal-multidecadal variability might result from the nonlinear interactions between the seasonal and interannual cycles. Recent papers [*Timmermann*, 2003; *Timmermann et al*., 2003] suggest an explanation for ENSO irregularity, ENSO amplitude modulation and tropical Pacific decadal variability, based on the idea of homoclinic/heteroclinic orbits. In this nonlinear concept, La Niña events appear to be unaffected by decadal variability. *Rodgers et al.* [2003] showed that nonlinear interaction between the asymmetry of El Niño and La Niña is another potential source of decadal variability.

Linear dynamics and local ocean-atmosphere interaction can be at the origin of decadal variability in the tropical Pacific Ocean. Tropical local wind may force the decadal variability in the tropical Pacific Ocean [*Schneider et al*., 1999a; *Karspeck and Cane*, 2002]. The decadal changes in the background wind, before and after the 1976's climate shift, qualitatively reproduce the observed changes in ENSO properties noted above [*Wang and An*, 2002]. The origin of the changes in the winds is unclear, with a mid-latitude SST influence suggested by *Pierce et al*. [2000] and local ocean-atmosphere coupling proposed by *Liu et al*. [2002]. *Liu et al.* [2002] found that decadal variability over the Pacific originates mainly from local coupled ocean-atmosphere systems within the tropical and North Pacific, respectively. They also suggest that decadal variability in the tropical Pacific can be enhanced by extratropical-tropical oceanic teleconnection. Using a coupled GCM, *Schneider* [2000] suggests an interesting coupled-atmosphere decadal mode effective within the tropical Pacific, in which advection of salinity compensated temperature along isopycnal (termed spiciness anomalies) sets the decadal timescale. Based on observations, *Luo and Yamagata* [2001] propose another mechanism for the tropical Pacific decadal variability with a key role of air-sea interaction in the SPCZ. These studies suggest that ENSO-like decadal variability is a self-sustained system central to the tropical Pacific.

5.2.2. Tropical-Extratropical Connections

Gu and Philander [1997] consider an oceanic bridge that subducts and advects in about 10 years midlatitude surface waters of anomalous temperature all the way to the Equatorial Undercurrent (EUC) via shallow subtropical cells (STCs) (see STCs' review by *Schott et al*. [2004, this volume]). The anomalous waters are subsequently brought to the surface by equatorial upwelling and finally moved poleward by Ekman divergence [*Johnson*, 2001]. The circuit can be closed through this poleward surface oceanic bridge. It can also be closed through the upwelling-induced changes in eastern equatorial SST that influence the tropical and extratropical winds, which in turn affect the initial midlatitude surface water anomalies. There is some evidence that North and South Pacific surface waters may subduct toward the equator, from observations [*Deser et al*., 1996; *Zhang et al*., 1998; *Johnson and McPhaden*, 1999], and from models [*McCreary and Lu*, 1994; *Liu*, 1994; *Rothstein et al*., 1998; *Harper*, 2000; *Solomon et al*., 2003]. However, the detailed data analysis of *Schneider et al*. [1999a] does not find any significant decadal link between the North Pacific and the equator through anomalous subduction. Besides, the temperature advected by the EUC is subject to strong seasonal and interannual variations that probably blur any remaining decadal signal [*Izumo et al*., 2002]. Finally, model studies [*Schneider et al*., 1999b; *Hazeleger et al*., 2001] indicate that decadal variability in the tropics is largely independent of the arrival of water anomalies subducted from the mid-latitudes. In parallel with the anomalous temperature transported by STCs of *Gu and Philander* [1997] as a mechanism of tropical decadal variability, *Kleeman et al*. [1999] proposed changes in STC strength that vary the amount of cold water transported into the equatorial thermocline. This mechanism is supported by the observation of a slowdown of STCs since the 1970s together with a decrease in equatorial upwelling [*McPhaden and Zhang*, 2002]. The results of an OGCM forced by observed winds are also consistent with the mechanism of STC strength [*Nonaka et al*., 2002]. They found that the STC-induced SSTs lag roughly two years behind those of local wind-forced equatorial SSTs, suggesting that the mechanism of STC strength is not dominant in generating tropical decadal oscillations and acts more to amplify than to initiate them.

A number of the previous studies have focused on adiabatic oceanic processes. For example, in *Gu and Philander* [1997] the ocean bridge is assured adiabatically through the subduction and advection of temperature anomalies. On the other hand, the surface forcing in the subduction region of the central North Pacific seems predominately diabatic in driving the heat equation, thus less adiabatic in affecting the vorticity equation [*Schneider et al*., 1999a].

Basin-wide diabatic processes may control the tropical thermocline on decadal timescale, without involving explicit connection between the tropics and mid-latitudes [*Boccaletti et al*., 2003]. These diabatic processes drive, on decadal timescale, the ocean-atmosphere system into a new balanced heat budget between the equatorial and mid-latitudes regions. The preliminary study of heat storage and heat budget of *Auad et al*. [1998], using a Pacific Ocean model and XBT data, suggests that the relative importance of diabatic and adiabatic processes differs if decadal or multidecadal variability is considered.

Another mechanism is wave signal transmitted in mid-latitude and back into the tropics. *Jacob et al*. [1994] suggested that the 1982-83 El Niño could have decadal effects on the northwestern Pacific circulation, through mid-latitude Rossby waves reflected from equatorial Kelvin waves on the American coasts. *Lysne et al*. [1997] found a weak decadal signal in their search for another oceanic bridge driven by wave dynamic: anomalous temperature propagated by mid-latitude Rossby waves into the western boundary, then by coastal Kelvin waves and finally by equatorial Kelvin waves. *Liu et al*. [2002] emphasized the importance of higher vertical modal structure for the decadal variability, as compared to ENSO. In fact, several authors have considered the inclusion of higher vertical and horizontal modes in the oceanic part of the ENSO delayed action oscillator to tentatively explain the decadal tropical variability, through wider ocean-atmosphere coupling, longer time in Rossby wave propagation and reflected slow equatorial coupled wave. Using coupled models, *Knutson and Manabe* [1998], *Yukimoto et al*. [2000], and *Jin et al*. [2001] note westward phase propagations of decadal upper ocean temperature or thermocline depth around 9-12°N, 20°N and 15-25°N, respectively. Similar decadal propagating signals appear in observations [*White et al*., 2003] and in a model forced over the 1958-97 period [*Capotondi and Alexander*, 2001]. Similarly, the ENSO recharge oscillator has been amended to include extra equatorial Rossby waves [*Jin*, 2001]. This amendment is supported by the observation of decadal variability in upper-heat content in the tropical Pacific [*Hasegawa and Hanawa*, 2003].

Since the PDO or NPO is one of the most important oscillations of decadal-multidecadal timescales on earth, it is an obvious candidate for forcing the tropical decadal variability through atmospheric bridge. Besides, on decadal timescale the largest SST anomalies and ocean heat content occur at mid-latitude not in the tropics [*Giese and Carton*, 1999]. The decadal change in the northern atmosphere is wide enough to alter the wind stress over the equatorial Pacific, hence the mean state of the equatorial thermocline and upwelling, and ultimately ENSO activity [*Barnett et al*., 1999; *Pierce et al*., 2000; *Wang and An*, 2002]. One cannot disregard the possibility that the atmospheric bridge may work the opposite way, with tropical Pacific decadal variability driving the North (and South) Pacific decadal oscillations [*Evans et al*., 2001]. Poleward propagation of atmospheric zonal wind anomalies from the equator to high-latitudes seems to be the robust decadal signal found simultaneously in SST and atmospheric angular momentum series [*Dickey et al*., 2003]. Finally, the atmospheric bridge between the decadal variability of the North Pacific and ENSO may well be the imprint of a common internal variability in the atmosphere [*Pierce*, 2002]. *Wang and Weisberg* [1998] found that the out-of-phase SST decadal signal in the mid-latitudes and the tropics is the result of tropical-extratropical interactions through changes in the atmospheric Hadley and Walker circulations.

5.3. Interpretation of Tropical Pacific Warming Trends, Global Warming, and ENSO

The reasons for the recent warming trend in the eastern tropical and subtropical Pacific [e.g., *Knutson and Manabe*, 1998] remain uncertain. Using SST and several atmospheric parameters, *Curtis and Hastenrath* [1999] find long-term trends in the tropical Pacific compatible with the radiative but not with the wind forcing. They also note the resemblance of these trends with El Niño patterns. *Liu and Huang* [2000] attribute the SST warming trend to the weakening trade wind, which reduces the advection of cold water. *Cane et al*. [1997] argue that the eastern equatorial Pacific has instead cooled since 1900, under increasing trade winds (difficulties in correcting wind products are briefly discussed in the next sub-section). In fact, *Lau and Weng* [1999] found a secondary cooling trend centered near the Niño-3 region, superimposed on a general warming trend.

Knutson and Manabe [1998] believe that the warming trend could not be solely due to natural climate variability, and that part of it may be attributed to sustained thermal forcing, such as greenhouse warming. Similarly, a statistical study by *Trenberth and Hoar* [1996] considers the probable role of greenhouse gases in the tendency for more frequent El Niño since the late 1970s. *Meehl and Washington* [1986] was one of the first modelers who looked at the changes within the tropics under an increase of atmospheric CO_2. Most coupled models in the late 1990s [e.g., *Meehl and Washington*, 1996; *Knutson and Manabe*, 1998; *Timmermann et al*., 1999] suggest that the eastern equatorial Pacific warms more rapidly than the west. The SST gradient along the equator slackened together with the easterlies, and this results in an El Niño-like pattern of changes. Another school of studies suggests that the CO_2 warming response should be La Niña-like, with an increase of the equatorial SST gradient [*Cane et al*., 1997; *Seager and Murtugudde*, 1997] and maximum warming in mid-latitudes. There are a number of arguments for an El Niño-like pattern in response to global warming. The cloud-shielding thermostat over the warm pool [*Ramanathan and Collins*, 1991; *Meehl and Washington*, 1996] or the evaporative surface cooling [*Knutson and Manabe*, 1995] will make the warming less efficient in the west than the east, and the SST equatorial gradient will decrease. The warm pool can also expand toward the east, increasing thus the overlying atmospheric convection and westerly winds [*Yu and Boer*, 2002]. In the absence of ocean dynamics, the atmospheric response to global warming over the equatorial Pacific is a decrease of easterlies [*Vavrus and Liu*, 2002]. On the contrary, the La Niña-like pattern is due to equatorial upwelling that reduces the surface warming in the east, leading to increased SST gradient along the equator and thus stronger easterlies. A coupled model forced by historical (1880-1990) and future greenhouse gaze concentrations result in a warming trend that initially has a La Niña-like pattern [*Cai and Whetton*, 2000]. The pattern shifts into El Niño-like after the 1960s and remains in this state during the 21st century. In this simulation, the shift (analogous to the observed 1976's shift) is explained by the delayed arrival of warm waters in the equatorial thermocline, transported by STCs from the extratropical La Niña-like pattern [*Cai and Whetton*, 2001b].

The plausible tendency for an El Niño-like pattern under global warming does not mean that the tropical Pacific will stay in a permanent El Niño. Superimposed on the new mean warm state, ENSO should remain but with probable changes in its behavior (possibly due to the change of the mean state). Using a low-resolution coupled model, *Knutson and Manabe* [1997] found a slight decrease in ENSO amplitude, no significant change in ENSO frequency and more pronounced multidecadal modulation of ENSO, in response to doubling or quadrupling of CO_2. With a finer model resolution, *Timmermann et al*. [1999] found more frequent El Niño and stronger La Niña. *Collins* [2000a] had to quadruple the concentration of greenhouse gazes in order to see ENSO changes. More frequent El Niño and La Niña occurs with 20% larger amplitude for both. Increases in meridional temperature gradients on either side of the equator and in vertical gradient of temperature in the thermocline are respectively responsible for the increases of ENSO frequency and amplitude. The recent experiment of *Hu et al*. [2001] also results in an El Niño-like mean pattern but with greater La Niña and weaker El Niño. These incoherent results underline the complexity of coupled model behavior under greenhouse warming.

5.4. Difficulties and Uncertainties on Studies of Low-Frequency Variability

A number of studies on low-frequency modulation of ENSO rely on the analyses of historical surface data (mostly SST, SLP, surface winds) that have been interpolated in time and space in a drastic way. It is recognized that global data coverage is adequate after 1950, if not after 1980 with the satellite era. Several research groups have built global products on a monthly basis and on a latitude-longitude grid that varies from 5° down to 1°. Most of all have extended the 1950's limit back to 100 years where volunteer observing ships were very rare, particularly in their journey through the Equatorial and Southern Pacific. For example, *Kaplan et al*. [1998] pointed out the discrepancies that arise from using several interpolated fields in the search of warming or cooling trends in the eastern tropical Pacific since 1900 (from – 0.3°C/100 years to + 0.3°C/100 years). A disputable assumption for building these products is the stability of their structural relations over the last one and a half century. If these research groups are very aware of the errors associated with these fields, other (internet) users may forget to consider such errors in their analyses. Other articles on the low-frequency modulation of ENSO have been written solely on the Southern Oscillation Index that is extended to 1866. However, it appears difficult to imagine that decadal or multidecadal oscillations have not put out of place the center of action of the Southern Oscillation from Tahiti and/or Darwin.

Similarly, several articles discussing decadal variations of ENSO during the last millennium rely on either a single set of proxy over an extended period of time [e.g., *Linsley et al*., 2000] or several sets of proxy in the same location over separate periods of time [e.g., *Cobb et al*., 2003]. The labor, time and cost involved in data collection and processing render multi-proxy analyses on ENSO decadal variability still uncommon [e.g., *Evans et al.,* 2001]. Such ENSO reconstruction suffers from technical and stability problems but also for the presupposition in climate influence. For example, ice core from tropical ice caps in Peru reflects much more the large-scale atmospheric variability over Amazonian and the western tropical Atlantic than over the eastern tropical Pacific [*Thompson et al*., 2000]. In any case, the potential of paleoclimate indicators is tremendous for understanding the decadal variability and long-term trend of ENSO and thus for separating the natural contribution from the anthropogenic contribution.

Statistical tools are sometime not adequate in extracting and explaining decadal and multidecadal ENSO signals, because of the shortness and uncertainty of the data and products or the difficulty in separating signals that have similar patterns (e.g., ENSO and ENSO-like). As noted by *Liu et al*. [2002], these tools are important for the diagnosis of decadal variability, but they may not be able to identify the true physical modes of variability (see also the various exchanges following the article "A cautionary note on the interpretation of EOFs" by *Dommenget and Latif* [2002]).

Other difficulties in the search of decadal mechanisms arise from the use of observations. Oceanic bridges between mid-latitudes and the equator are so far impossible to prove knowing the reduced number of hydrographical or CTDs observations in these regions over the last four decades. Delayed-type decadal oscillators cannot be truly established due to the complexity in extracting propagating signals from sparse data near the Swiss-cheese western boundary. As a consequence, many of the previous studies have used simplified or sophisticated models. Simplified models, such as those used by McCreary and collaborators (see *Schott et al*. [2004, this volume]) have the great advantage of pinpointing mechanisms. Sophisticated ocean models suffer less from insufficient physics, but they are still unable in reproducing subsurface equatorial countercurrents and thus complete STCs' patterns. In any case, the use of variable forcing instead of seasonal forcing in models that simulate STCs may result in an open circuit rather than a decadal close circuit [*Fukumori et al*., 2003]. Wind-forced model are also subject to spurious decadal variability and long-term trends due to the difficulty in correcting the gradual change since 1950 from Beaufort scale to anemometer on merchant ships [e.g., *Alory et al*., 2003].

Coupled models have also their own flaws. Many of them suffer from drifts that are often corrected in dubious ways. Most of coupled models are still far from reproducing realistic ENSO [*AchuaRao and Sperber*, 2002; *Davey et al*., 2002; *Latif et al.,* 2001]. Most of the simulated ENSO are too close to a biennial cycle, or have weak amplitudes, or cannot reproduce the well-known horseshoe pattern of SST anomalies over the tropical Pacific (Fig. 7). Hence, their ability in reproducing realistic decadal variability or warming trends in the tropical Pacific must be questioned. As a result, the projections of coupled models into the 21st century with and without CO_2 are yet hard to believe. As an example, using version 2 of the Hadley Centre coupled model, *Collins* [2000a] found that the amplitude and frequency of ENSO increase with a quadrupling of CO_2. In version 3, *Collin* [2000b] attributed the lack of significant modification in ENSO behavior to subtle non-linear changes in the physical parametrization schemes, rather than the main differences between the two versions of the model (horizontal resolution and flux adjustments). A promising way to infer ENSO response to global warming is through international multi-model intercomparison projects such as CMIP [*AchutaRao and Sperber*, 2002], which use a quantitative probabilistic approach that takes into account model errors.

6. Summary

The major components of the ENSO observing system consists of (1) a moored TAO/TRITON array for wind, ocean temperature, and ocean current measurements, (2) a Volunteer Observing Ship program for surface marine meteorological observations, (3) an island tide-gauge network for measuring sea level, (4) a system of surface drifters for SST and ocean currents, and (5) a suite of meteorological and oceanographic satellites. This system successfully monitored the 1997-97 and 2002-03 El Niños, and helped improve understanding and prediction of ENSO. However, it will be long before this observing system and ongoing or future additional measurements produce sufficient high-quality observations to explain the decadal modulation of ENSO. Thus, historical and paleoclimate records of ENSO are also needed for observing and testing the evolution of ENSO in the past, present and future.

Occurrence of ENSO has been explained as different views. The first view is that ENSO is regarded as a self-sustaining and oscillatory mode of the coupled ocean-atmosphere system. This view includes the delayed oscillator, the recharge oscillator, the western Pacific oscillator, and the advective-reflective oscillator. The oscillatory nature of ENSO requires both positive and negative ocean-atmosphere feedbacks. The positive ocean-atmosphere feedback is dated back to the Bjerknes' hypothesis in the 1960s. Four different negative feedbacks, required for terminating El Niño, have been proposed since the 1980s associated with the delayed oscillator, the recharge oscillator, the western Pacific oscillator, and the advective-reflective oscillator. The delayed oscillator assumes that wave reflection at the ocean western boundary provides a negative feedback for the coupled system to oscillate. The recharge oscillator argues that discharge and recharge of equatorial heat content cause the coupled system to oscillate. The western Pacific oscillator emphasizes equatorial wind in the western Pacific that provides a negative feedback for the coupled system. The advective-reflective oscillator emphasizes the importance of zonal advection associated with wave reflection at both the western and eastern boundaries and of the mean zonal current. These negative feedbacks may work together for terminating El Niño and their relative importance may be time-dependent. All of these ENSO oscillator models produce periodic solutions. Introduction of high-frequency variability to the periodic oscillatory models can lead to irregular or chaotic ENSO oscillations.

The self-sustaining ENSO view may also include the unstable slow (SST) modes. Interaction between the tropical Pacific Ocean and atmosphere can produce the unstable modes that propagate with a speed much slower than the conventional equatorially trapped waves. The slow modes can propagate either eastward or westward, depending upon the relative importance of zonal advection and vertical movements of the thermocline that determine SST variations. The slow SST modes, regenerated continuously on interannual timescale, can explain the propagating property of interannual anomalies, whereas the oscillator models (associated with ocean dynamics) produce a standing oscillation. Whether the coupled system favors a slowly propagating mode or a standing mode is determined by the ocean thermodynamical and dynamical adjustment processes.

Another view is that ENSO is a stable mode triggered by stochastic atmospheric forcing. This view receives renewed interest after the 1997-98 El Niño since it is characterized by strong activity of the WWB and MJO. The stable mode of ENSO view emphasizes that high-frequency disturbances are needed to initiate an El Niño. However, it is not necessarily in contradiction with the self-sustaining mode of ENSO view. The difference between a self-sustaining cyclic mode and a stable non-cyclic mode is that for a stable non-cyclic mode each El Niño is independent of the next but depends on high-frequency noise for its initiation, whereas for a self-sustaining cyclic mode each El Niño is related to the next events of La Niña and El Niño. For both cases, after an El Niño reaches its mature phase, negative feedbacks are still required to terminate growth of the mature El Niño anomalies. That is, the negative feedbacks associated with the delayed oscillator, the recharge oscillator, the western Pacific oscillator, and the advective-reflective oscillator may be still valid for demise of an El Nino even if El Niño is regarded as a stable mode triggered by stochastic forcing. The issue of ENSO as a self-sustaining oscillation mode or a stable mode triggered by random forcing is not settled down yet. It is possible that ENSO is a self-sustaining mode during some periods, a stable mode during others, or a mode between the former and the latter. The predictability of ENSO is more limited if ENSO is a stable mode triggered by stochastic forcing than if ENSO is a self-sustaining mode because its irregularity depends on random disturbances.

Variability with frequency higher and lower than ENSO timescale has been identified to play roles in ENSO. The seasonal cycle can contribute to the irregularity and the phase-locking of ENSO. The intraseasonal variability (ISV), associated with the WWB and MJO in the western Pacific, can be a source of both ENSO's variability and irregularity. Impact of the ISV on ENSO can be through downwelling Kelvin waves generated by equatorial westerly wind anomalies in the western Pacific that displace the warm pool eastward and propagate in the same direction affecting the SST in the central and eastern equatorial Pacific, respectively. The ISV is also hypothesized as noise or disturbances to initiate or drive El Niño.

Decadal-multidecadal variability and warming trends are observed in both the tropical and mid-latitude Pacific. The tropical Pacific decadal-multidecadal variability shows an ENSO-like oscillation, with a wider latitudinal extension than ENSO. This low-frequency variability appears to influence the global atmospheric circulation and climate and to alter the ocean productivity of the Pacific Ocean. Coupled ocean-atmosphere models show a decadal modulation of ENSO prediction skills. ENSO forecasts are skillful during decades when the amplitude of interannual variability is large, whereas forecast skill is relatively low when interannual variance is small. Many mechanisms have been proposed to explain tropical Pacific decadal-multidecadal variability. These mechanisms can be divided into two categories: (1) tropical origins and (2) tropical-extratropical connections. The tropical origins argue that tropical Pacific decadal-multidecadal variability originates from the tropics only without involving extratropical processes. This category includes mechanisms of atmospheric stochastic forcing, interactions between the seasonal and interannual cycles, internal nonlinear concept of homoclinic-heteroclinic orbits, nonlinearity between El Niño and La Niña, and local ocean-atmosphere interaction. The category of the tropical-extratropical connections emphasizes the linkage between the tropical and extratropical Pacific. The mechanisms of the tropical-extratropical connections include oceanic bridges, atmospheric bridges, and wave propagation. Despite recent progress in studies of decadal-multidecadal variability and warming trends, our understanding is very limited and uncertain due to the short and sparse observational data and imperfect climate models. We are not even sure if global warming will result in an El Niño-like or La Niña-like warming pattern in the tropical Pacific. Clearly, more studies for low-frequency variability are needed, including to improve compilation/reconstruction of various data and to improve climate models.

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References

AchutaRao, K., and K. R. Sperber, Simulation of the El Niño Southern Oscillation: results from the coupled model intercomparison project, *Clim. Dyn., 19,* 191-209, 2002.

Alory, G., S. Cravatte, T. Izumo, and K. B. Rodgers, Long-term trends and decadal variability in a forced OGCM in the tropical Pacific, *J. Phys. Oceanogr.,* 2003 (submitted).

An, S.-I., and F.-F. Jin, Collective role of thermocline and zonal advective feedbacks in the ENSO mode, *J. Climate*, 14, 3421-3432, 2001.

Auad, G., A. J. Miller, and W. B. White, Simulation of heat storages and associated heat budget in the Pacific Ocean 2. Interdecadal timescale, *J. Geophys. Res., 103*, 27,621-27,635, 1998.

Balmaseda, M. A., M. K. Davey, and D. L. T. Anderson, Decadal and seasonal dependence of ENSO prediction skill, *J. Climate, 8*, 2705-2715, 1995.

Barnett, T. P., D. W. Pierce, M. Latif, D. Dommenget, and R. Saravanan, Interdecadal interactions between the tropics and midlatitudes in the Pacific basin, *Geophys. Res. Lett., 26*, 615-618, 1999.

Barnston, A. G., Y. He, and M. H. Glantz, Predictive skill of statistical and dynamical climate models in SST forecasts during the 1997-98 El Niño episode and the 1998 La Niña onset, *Bull. Am. Meteorol. Soc., 80*, 217-244, 1999.

Battisti, D. S., and A. C. Hirst, Interannual variability in the tropical atmosphere-ocean model: influence of the basic state, ocean geometry and nonlineary, *J. Atmos. Sci.*, *45*, 1687-1712, 1989.

Battisti, D. S., On the role of off-equatorial oceanic Rossby waves during ENSO, *J. Phys. Oceanogr., 19*, 551-559, 1989.

Battisti, D. S., Reply, *J. Phys. Oceanogr., 21*, 461-465, 1991.

Battisti, D. S., and E. S. Sarachik, Understanding and predicting ENSO, *Rev. Geophys., Sup.*, *33*, 1367-1376, 1995.

Bergman, J. W., H. Hendon, and K. M. Weickmann, Intraseasonal air-sea interactions at the onset of El Niño, *J. Climate, 14*, 1702-1719, 2001.

Bjerknes, J., Atmospheric teleconnections from the equatorial Pacific, *Mon. Wea. Rev*., *97*, 163-172, 1969.

Boccaletti, G., R. C. Pacanowski, and S. G. H. Philander, A diabatic mechanism for decadal variability in the tropics, *J. Climate,* 2003 (submitted).

Boulanger, J.-P., and C. Menkes, The TRIDENT Pacific model. Part II : The thermodynamical model and the role of long equatorial wave reflection during the 1993-1998 TOPEX/POSEIDON period, *Clim. Dyn*., *17*, 175-186, 2001.

Boulanger, J.-P., S. Cravatte, and C. Menkes, Reflected and locally wind-forced interannual equatorial Kelvin waves in the western Pacific Ocean, *J. Geophys. Res*., 2003 (in press).

Burgers, G., The El Niño stochastic oscillator, *Clim. Dyn., 15*, 521-531, 1999.

Cai, W., and P. H. Whetton, Evidence for a time-varying pattern of greenhouse warming in the Pacific Ocean, *Geophys. Res. Lett*., 27, 2577-2580, 2000.

Cai, W., and P. H. Whetton, Modes of SST variability and the fluctuation of global mean temperature, *Clim. Dyn., 17,* 889-901, 2001a.

Cai, W., and P. H. Whetton, A time varying greenhouse warming pattern and the tropical-extratropical circulation linkage in the Pacific Ocean, *J. Climate, 14*, 3337-3355, 2001b.

Cane, M. A., A. M. Clement, A. Kaplan, Y. Kushnir, D. Pozdnyakov, R. Seager, S. E. Zebiak, and R. Murtugudde, Twentieth-century sea surface temperature trends, *Science, 275,* 957-960, 1997.

Capotondi, A., and M. A. Alexander, Rossby waves in the tropical North Pacific and their role in decadal thermocline variability, *J. Phys. Oceanogr., 31*, 3496-3515, 2001.

Chang, P., L. Ji, B. Wang, and T. Li, Interacions between the seasonal cycle and El Niño-Southern Oscillation in an intermediate coupled ocean-atmospher model, *J. Atmos. Sci*., *52*, 2353-2372, 1995.

Chang, P., B. S. Giese, L. Ji, and H. F. Seidel, Decadal change in the south tropical Pacific in a global assimilation analysis, *Geophys. Res. Lett., 28*, 3461-3464, 2001.

Chao, Yi, M. Ghil, and J. C. McWilliams, Pacific interdecadal variability in this century's sea surface temperatures, *Geophys. Res. Lett., 27,* 2261-2264, 2000.

Chavez, F. P., J. Ryan, S. E. Lluch-Cota, and M. Niquen, From Anchovies to sardines and back: multidecadal change in the Pacific Ocean, *Science, 299*, 217-221, 2003.

Clarke, A. J., J. Wang, and S. Van Gorder, A simple warm-pool displacement ENSO model, *J. Phys. Oceanogr., 30*, 1679-1691, 2000.

Cobb, K. M., C. D. Charles, H. Cheng, and R. L. Edwards, El Niño-Southern Oscillation and tropical Pacific climate during the last millennium, *Nature, 424*, 271-276, 2003.

Collins, M., The El Niño-Southern Oscillation in the second Hadley Centre coupled model and its response to greenhouse warming, *J. Climate, 13*, 1299-1312, 2000a.

Collins, M., Understanding uncertainties in the response of ENSO to greenhouse warming, *Geophys. Res. Lett., 27*, 3509-3512, 2000b.

Cravatte , S., J. Picaut, and G. Eldin, Second and first baroclinic Kelvin modes in the equatorial Pacific at intraseasonal timescales, *J. Geophys. Res., 108(C8),* 3266, doi:10.1029/2002JC001511, 2003.

Cronin, M. F., N. Bond, C. Fairall, J. Hare, M. J. McPhaden, and R. W. Weller, Enhanced oceanic and atmospheric monitoring underway in eastern Pacific, *Eos, 83,* 210-211, 2002.

Curtis, S., and S. Hastenrath, Long-term trends and forcing mechanisms of circulation and climate in the Equatorial Pacific, *J. Climate, 12*, 1134-1144, 1999.

Davey, M. K., and collaborators, STOIC: a study of coupled model climatology and variability in tropical ocean regions, *Clim. Dyn., 18*, 403-420, 2002.

Delcroix, T., B. Dewitte, Y. du Penhoat, F. Masia, and J. Picaut, Equatorial Kelvin and warm pool displacements during the 1992-1998 El Niño-Southern Oscillation events: observations and modeling, *J. Geophys. Res, 105*, 26045-26062, 2000.

Deser, C., and J. M. Wallace, Large-scale atmospheric circulation features of warm and cold episodes in the tropical Pacific, *J. Climate*, *3*, 1254-1281, 1990.

Deser, C., M. Alexander, and M. Timlin, Upper-ocean thermal variations in the North Pacific during 1970-1991, *J. Climate, 9,* 1840-1855, 1996.

Dewitte, B., S. Illig, L. Parent, Y. du Penhoat, L. Gourdeau, and J. Verron, Tropical Pacific baroclinic mode contribution and associated long waves for the 1994-999 period from an assimilation experiment with altimetric data, *J. Geophys. Res*, *108*, doi:10.1029/2002JC001362, 2003.

Diaz, H. F., M. P. Hoerling, and J. K. Eischeid, ENSO variability, teleconnections and climate change, *Inter. J Climate, 21,* 1845-1862, 2001.

Dickey, J. O., S. L. Marcus, and O. de Viron, Coherent interannual and decadal variations in the atmosphere-ocean system, *Geophys. Res. Lett., 30, 11, 1573, doi: 10.1029/2002GL016763,* 2003.

Dijkstra, H. A. and G. Burgers, Fluid dynamics of El Niño variability, *Annu. Rev. Fluid Mech., 34,* 531-558, 2002.

Dommenget, D. and M. Latif, A cautionary note on the interpretation of EOFs, *J. Climate, 15*, 216-225, 2002.

Evans, M. N., M. A. Cane, D. P. Schrag, A. Kaplan, B. K. Linsley, R. Villalba, and G. Wellington, Support for tropically-driven Pacific decadal variability based on paleoproxy evidence, *Geophys. Res. Lett., 28*, 3689-3692, 2001.

Fedorov, A. V., The response of the coupled tropical ocean-atmosphere to westerly wind bursts, *Q. J. R. Meteorol. Soc*., *128*, 1-23, 2002.

Fedorov, A. V., S. L. Harper, S. G. Philander, B. Winter, and A. Wittenberg, How predictable is El Niño? *Bull. Am. Meteorol. Soc*., *84*, 911-919, 2003.

Flügel, M., and P. Chang, Does the predictability of ENSO depend on the seasonal cycle? *J. Atmosph. Sci., 55,* 3230-3243, 1998.

Folland, C. K., J. A. Renwick, M. Salinger, and A. B. Mullan, Relative influence of the interdecadal Pacific oscillation and ENSO on the South Pacific Convergence Zone, *Geophys. Res. Lett., 29, 13, 10.1029/2001GL014201*, 2002.

Fukumori, I., T. Lee, B. Cheng, and D. Menemenlis, 2002. The origin, pathway, and destination of Niño3 water estimated by a simulated passive tracer and its adjoint, *J. Phys. Oceanogr*., 2003 (in press).

Garreaud, R. D., and D. S. Battisti, Interannual (ENSO) and interdecadal (ENSO-like) variability in the Southern tropospheric circulation, *J. Climate, 12*, 2113-2123, 1999.

Gershunov, A., and T. Barnett, Interdecadal modulation of ENSO teleconnection, *Bull. Am. Meteor. Soc., 79,* 2715-2725, 1998.

Giese B. S., J. A. Carton JA, Interannual and decadal variability in the tropical and midlatitude Pacific Ocean. *J. Climate, 12*, 3402-3418, 1999.

Giese, B. S., S. C. Urizar, and N. S. Fuckar, Southern hemisphere origins of the 1976 climate shift, *Geophys. Res. Lett., 29*, 10.1029/2001GL013268, 2002.

Gill, A. E., Some simple solutions for heat-induced tropical circulation, *Quart. J. Roy. Meteor. Soc.*, *106*, 447-462, 1980.

Gill, A. E., Elements of coupled ocean-atmosphere models for the tropics, in *Coupled Ocean-Atmosphere Models*, edited by J. C. Nihoul, pp303-327, Vol. 40, Elsevier Oceanography Series, Elsevier, 1995.

Godfrey, J. S., and Co-authors, Coupled Ocean-Atmosphere Response Experiment (COARE): an interim report, *J. Geophys. Res., 103,* 14,395-14,450, 1998.

Goswami, B. N., and M. A. Thomas, Coupled ocean-atmosphere inter-decadal modes in the tropics, *J. Meteor. Soc. Japan, 78*, 765-7775, 2000.

Graham, N. E., and W. B. White, The El Niño cycle: A natural oscillator of the Pacific Ocean-atmosphere system, *Science*, *24*, 1293-1302, 1988.

Graham, N. E., and W. B. White, Comments on "On the role of off-equatorial oceanic Rossby waves during ENSO*", J. Phys. Oceanogr., 21*, 453-460, 1991.

Gu, D., and S. G. H. Philander, Interdecadal climate fluctuations that depend on exchange between the tropics and extratropics, *Science, 275,* 805-807, 1997.

Guilderson, T. P., and D. P. Schrag, Abrupt shift in subsurface temperatures in the tropical Pacific associated with changes in El Niño, *Science, 281*, 240-243, 1998.

Gutzler, D. S., D. M. Kan, and C. Thornbrugh, Modulation of ENSO-based long-lead outlooks of Southwestern U.S. winter precipitation by the Pacific decadal oscillation, *Weath. Forecast., 17,* 1163-1172, 2002.

Harper, S., Thermocline ventilation and pathways of tropical-subtropical water mass exchange, *Tellus, 52A*, 330-345, 2000.

Harrison, D. E., and G. A. Vecchi, Westerly wind events in the tropical Pacific, 1986-95, *J. Climate*, *10*, 3131-3156, 1997.

Harrison, D. E., and G. A. Vecchi, On the termination of El Niño, *Geophys. Res. Lett., 26*, 1593-1596, 1999.

Hasegawa T., and K. Hanawa, Heat content variability related to ENSO events in the Pacific, *J. Phys. Oceanogr., 33*, 407-421, 2003.

Hasegawa T., and K. Hanawa, Decadal-scale variability of upper ocean heat content in the tropical Pacific, *Geophys. Res. Lett., 6,* doi:10.1029/2002GL016843, 2003.

Hayes, S. P., L. J. Mangum, J. Picaut, A. Sumi, and K. Takeuchi, TOGA-TAO: A moored arrayfor real-time measurements in the tropical Pacific Ocean, *Bull. Am. Meteorol. Soc.*, *72*, 339-347, 1991.

Hazeleger, W., P., M. Visbeck, M. Cane, A. Karspeck, and N. Naik, Decadal upper ocean temperature variability in the tropical Pacific, *J. Geophys. Res., 106*, 8971-8988, 2001.

Hendon, H. H., B. Liebmann, and J. D. Glick, Oceanic Kelvin waves and the Madden-Julian Oscillation, *J. Atmos. Sc., 55, 88-101*, 1998.

Hirst, A. C., Unstable and damped equatorial modes in simple coupled ocean-atmosphere models, *J. Atmos. Sci*., *43*, 606-630, 1986.

Hirst, A. C., Slow instabilities in tropical ocean basin-global atmosphere models, *J. Atmos. Sci*., *45*, 830-852, 1988.

Holland, C. L., and G. T. Mitchum, Interannual volume variability in the tropical Pacific, *J. Geophys. Res.*, 2003 (in press).

Hu, Z.-Z., L. Bengtsson, E. Roeckner, M. Cristoph, AQ. Bacher, and J. M. Oberhuber, Impact of global warming on the interannual and interdecadal climate modes in a coupled GCM, *Clim. Dyn., 17*, 361-374, 2001.

Izumo, T., J. Picaut, and B. Blanke, Tropical pathways, equatorial undercurrent variability and the 1998 La Niña, *Geophys. Res. Lett., 29*, doi:10.1029/2002GL015073, 2002.

Jacobs, G. A., H. E. Hurlburt, J. C. kindle, E. J. Metzger, J. L. Mitchell, W. J. Teague, and A. J. Wallcraft, Decade-scale trans-Pacific propagation and warming effects of an El Niño anomaly, *Nature, 370,* 360-363, 1994.

Janicot, S., S. Trzaska, and I. Poccard, Summer Sahel-ENSO teleconnection and decadal time scale SST variations, *Clim. Dyn., 18,* 303-320, 2001.

Jin, F. F., and J. D. Neelin, Modes of interannual tropical ocean-atmosphere interaction -- a unified view. Part I: Numerical Results. *J. Atmos. Sci*., *50*, 3477-3503, 1993.

Jin, F.-F., J. D. Neelin, and M. Ghil, El Niño on the Devil's Staircase: annual subharmonic steps to chaos, *Science*, *264*, 70-72, 1994.

Jin, F.-F., J. D. Neelin, and M. Ghil, El Niño/Southern Oscillation and the annual cycle: subharmonic frequency-locking and aperiodicity, *Physica D, 98,* 442-465, 1996.

Jin, F.-F., An equatorial ocean recharge paradigm for ENSO. Part I: Conceptual model, *J. Atmos. Sci.*, *54*, 811-829, 1997.

Jin, F.-F., and S.-I. An, Thermocline and zonal advective feedbacks within the equatorial ocean recharge oscillator model for ENSO, *Geophys. Res. Lett., 26*, 2989-2992, 1999.

Jin, F.-F., Low-frequency modes of tropical ocean dynamics, *J. Climate, 14,* 3874-3881, 2001.

Jin, F.-F., M. Kimoto, and X. Wang, A model of decadal ocean-atmosphere interaction in the North Pacific basin, *Geophys. Res. Lett., 28*, 1531-1534, 2001.

Johnson, G. C., and M. J. McPhaden, Interior pycnocline flow from the subtropical to the equatorial Pacific Ocean, *J. Phys. Oceanogr., 29*, 3073-3089, 1999.

Johnson, G. C., The Pacific Ocean subtropical cell surface limb, *Geophys. Res. Lett., 9*, 1771-1774, 2001.

Kaplan, A., M. A. Cane, Y. Kushnir, A. M. Clement, M. B. Blumenthal, and B. Rajagopalan, Analyses of global sea surface temperature 1856-1991, *J. Geophys. Res., 103*, 18,67-18,589, 1998.

Karspeck, and M. A. Cane, Tropical Pacific 1976-77 climate shift in a linear, wind-driven model, *J. Phys. Oceanogr., 32*, 2350-2360, 2002.

Kessler, W. S., Can reflected extra-equatorial Rossby waves drive ENSO? *J. Phys. Oceanogr.*, *21*, 444-452, 1991.

Kessler, W. S., M. J. McPhaden, and K. M. Weickmann, Forcing of intraseasonal Kelvin waves in the equatorial Pacific, *J. Geophys. Res., 100*, 10,613-10,631, 1995.

Kessler, W. S. and R. Kleeman, Rectification of the Madden-Julian Oscillation into the ENSO cycle, *J. Climate, 13,* 3560-3575, 2000.

Kessler, W. S., R. E. Davis, K. Takeuchi, and R. Lukas, The Pacific Basin Extended Climate Study, in *Observing the Ocean of the 21st Century*, edited by C. J. Koblinsky and N. R. Smith, pp. 473-484, Aust. Bur. Meteor. Melbourne, 2001.

Kessler, W. S., Is ENSO a cycle or a series of events? *Geophys. Res. Lett., 29(23)*, 2125, doi:10.1029/2002GL015924, 2002.

Kirtman B. P., P. S. Schopf, Decadal variability in ENSO predictability and prediction, *J. Climate, 11*, 2804-2822, 1998.

Kleeman, R., J. P. McCreary, and B. A. Klinger, A mechanism for generating ENSO decadal variability, *Geophys. Res. Lett., 26*, 1743-1746, 1999.

Knutson, T. R., and S. Manabe, Time-mean response over the tropical Pacific to increased CO_2 in a coupled ocean-atmosphere model, *J. Climate, 8,* 2181-2199, 1995.

Knutson, T. R., and S. Manabe, Simulated ENSO in a global coupled ocean-atmosphere model: multidecadal amplitude modulation and CO_2 sensitivity, *Bull. Am. Meteor. Soc., 10,* 138-161, 1997.

Knutson, T. R., and S. Manabe, Model assessment of decadal variability and trends in the tropical Pacific Ocean, *J. Climate, 11,* 2273-2294, 1998.

Kug, J.-S., and I.-S. Kang, Symmetric and antisymmetric mass exchanges between the equatorial and off-equatorial Pacific associated with ENSO, *J. Geophys. Res., 108(C8),* 3284, doi:10.1029/2002JC001671, 2003.

Kutsuwada, K., and M. J. McPhaden, Intraseasonal variations in the upper equatorial Pacific Ocean prior to and during the 1997-98 El Niño. *J. Phys. Oceanogr., 32,* 1133-1149, 2002.

Lagerloef, G. S., and T. Delcroix, Sea surface salinity: a regional case study for the tropical Pacific, in *Observing the Ocean of the 21st Century*, edited by C. J. Koblinsky and N. R. Smith, pp. 231-246, Aust. Bur. Meteor. Melbourne, 2001.

Lagerloef, G. S., and Co-authors, El Niño tropical Pacific Ocean surface current and temperature evolution in 2002 and outlook for early 2003, *Geophys. Res. Lett., 30(10),* 1514, doi:10.1029/2003GL017096, 2003.

Landsea, C. W., and J. A. Knaff, How much skill was there in forecasting the very strong 1997-98 El Niño, *Bull. Am. Meteorol. Soc., 81*, 2107-2120.

Latif, M., Dynamics of interdecadal variability in coupled ocean-atmosphere models, *J. Climate*, *11*, 602-624, 1998.

Latif, M., and Co-auhtors, A review of the predictability and prediction of ENSO, *J. Geophys. Res., 103*, 14375-14393, 1998.

Latif, M. and collaborators, ENSIP: the El Niño simulation intercomparison project, *Clim. Dyn., 18*, 255-276, 2001.

Lau, K. M., Elements of a stochastic-dynamical theory of long-term variability of the El Niño-Southern Oscillation, *J. Atmos. Sci., 42*, 1552-1558, 1985.

Lau, K.-M., and H. Weng, Interannual, decadal-interdecadal, and global warming signals in sea surface temperature during 1955-97, *J. Climate, 12*, 1257-1267, 1999.

Lengaine, M., J.-P. Boulanger, C. Menkes, S. Masson, G. Madec, and P. Delecluse, Ocean response to the March 1997 westerly wind event, *J. Geophys. Res., 107(C12),* 8015, doi:10.1029/2001JC000841, 2002.

Li, B., and A. J. Clarke, An examination of some ENSO mechanisms using interannual sea level at the eastern and western equatorial boundaries and the zonally averaged equatorial wind, *J. Phys. Oceanogr., 24*, 681-690, 1994.

Lindzen, R. S., and S. Nigam, On the role of sea surface temperature gradients in forcing low-level winds and convergence in the Tropics, *J. Atmos. Sci*., *44*, 2418-2436, 1987.

Linsley, B. K., G. M. Wellington, and D. P. Schrag, Decadal sea surface temperature variability in the subtropical South Pacific from 1726 to 1997 A.D., *Science, 290*, 1145-1148, 2000.

Liu, Z., A simple model of the mass exchange between the subtropical and tropical ocean, *J. Phys. Oceanogr., 24*, 1153-1165, 1994.

Liu, Z., and B. Huang, Cause of tropical Pacific warming trend, *Geophys. Res. Lett., 27,* 1935-1938, 2000.

Liu, Z., L. Wu, R. Gallimore, and R. Jacobs, Search for the origins of Pacific decadal climate variability, *Geophys. Res. Lett., 29, 10,* 10.1029/2001GL013735, 2002.

Lukas, R., and E. Lindstrom, The mixed layer of the western equatorial Pacific Ocean, *J. Geophys. Res., 96,* 3343-3357, 1991.

Luo, J.-J., and T. Yamagata, Long-term El Niño-Southern Oscillation (ENSO) like variation with special emphasis on the South Pacific, *J. Geophys. Res., 106*, 22,211-22,227, 2001.

Luo, J.-J., and T. Yamagata, Four decadal ocean-atmosphere modes in the North Pacific revealed by various analysis method, *J. Oceanogr., 58,* 861-876, 2002.

Lysne, J., P. Chang, and B. Giese, Impact of the extratropical Pacific on equatorial variability, *Geophys. Res. Lett., 24,* 2589-2592, 1997.

Madden, R. A., and P. R. Julian, Observations of the 40-50-day tropical oscillation – A review, Mon. Wea. Rev., 122, 814-837, 1994.

Maes, C., J. Picaut, and S. Belamari, Barrier layer and onset of El Niño in a Pacific coupled model, *Geophys. Res. Lett, 29, 24, 2206, doi:10.1029/2002GL016029*, 2002.

Mann, M. E., R. S. Bradley, and M. K. Hughes, Long-term variability in the El Niño/Southern Oscillation and associated teleconnections, in *El Niño and the Southern Oscillation,* *multiscale variability and regional impacts,* edited by H. Diaz and V. Markgraf, pp. 357-412, Cambridge University Press, 2000.

Mantua, N. J., and D. S. Battisti, Evidence of the delayed oscillator mechanism for ENSO: the "observed" oceanic Kelvin mode in the far western Pacific, *J. Phys. Oceanogr., 24*, 691-699, 1994.

Mantua, N. J., and D. S. Battisti, Aperiodic variability in the Zebiak-Cane coupled ocean-atmosphere model: Air-sea interactions in the western equatorial Pacific, *J. Climate, 8*, 2897-2927, 1995.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis, A Pacific interdecadal climate oscillation with impacts on salmon production, *Bull. Am. Meteor. Soc., 78*, 1069-1079, 1997.

Markgraf, V., and H. Diaz, The past ENSO record: a synthesis, in *El Niño and the Southern Oscillation, multiscale variability and regional impacts,* edited by H. Diaz and V. Markgraf, pp. 465-488, Cambridge University Press, 2000.

Matsuura, T., and S. Iizuka, Zonal migration of the Pacific warm pool tongue during El Niño events, *J. Phys. Oceanogr., 30*, 1582, 2000.

Mayer, D. A., and R. H. Weisberg, El Niño-Southern Oscillation-related ocean-atmosphere coupling in the western equatorial Pacific, *J. Geophys. Res.*, *103*, 18635-18648, 1998.

McCreary, J. P., A model of tropical ocean-atmosphere interaction, *Mon. Wea. Rev.*, *111*, 370-387, 1983.

McCreary, J. P., and D. L. T. Anderson, A simple model of El Niño and the Southern Oscillation, *Mon. Wea. Rev., 112*, 934-946, 1984.

McCreary, J. P., and D. L. T. Anderson, An overview of coupled ocean-atmosphere models of El

Niño and the Southern Oscillation, *J. Geophys. Res*., *96*, 3125-3150, 1991.

McCreary, J. P., and P. Lu, Interaction between the subtropical and equatorial ocean circulations: the subtropical cell, *J. Phys. Oceanogr., 24,* 466-497, 1994.

McPhaden, M. J., TOGA-TAO and the 1991-93 El Niño-Southern Oscillation event, *Oceanography, 6,* 36-44, 1993.

McPhaden, M. J., and Co-authors, The Tropical Ocean-Global Atmosphere observing system: A decade of progress, *J. Geophys. Res*., *103*, 14169-14240, 1998.

McPhaden, M. J., Genesis and evolution of the 1997-1998 El Niño, *Science, 283,* 950-954, 1999.

McPhaden, M. J. and X. Yu, Equatorial waves and the 1997-98 El Niño, *Geophys. Res. Lett, 26,* 2961-2964, 1999.

McPhaden, M. J., and D. Zhang, Slowdown of the meridional overturning circulation in the upper Pacific Ocean, *Nature, 415*, 603-608, 2002.

McPhaden, M. J., Mixed layer temperature balance on intraseasonal timescales in the equatorial Pacific, *J. Climate, 15*, 2632-2647, 2002.

McPhaden, M. J., Evolution of the 2002-2003 El Niño, *Bull. Am. Meteor. Soc.*, 2003 (in press).

McWilliams, J., and P. Gent, A coupled air-sea model for the tropical Pacific, *J. Atmos. Sci., 35*, 962-989, 1978.

Mechoso, C. R., J. D. Neelin, and J.-Y. Yu, Testing simple model of ENSO, *J. Atmos. Sci., 60*, 305-318, 2003.

Meehl, G. A., and W. M. Washington, Tropical response to increased CO_2 in a GCM with a simple mixed layer ocean: similarities to an observed Pacific warm event, *Mon. Wea. Rev., 114*, 667-674, 1986.

Meehl, G. A., and W. M. Washington, El Niño-like climate change in a model with increased atmospheric CO_2 concentrations, *Nature, 382*, 56-60, 1996.

Meinen, C. S., and M. J. McPhaden, Observations of warm water volume changes in the equatorial Pacific and their relationship to El Niño and La Niña, *J. Climate, 13*, 3551-3559, 2000.

Meinen, C. S., and M. J. McPhaden, Interannual variability in warm water volume transport in the equatorial Pacific during 1993-99, *J. Phys. Oceanogr., 31*, 1324-, 2001.

Mestas-Nuñez A. M., and D. B. Enfield, Eastern equatorial Pacific SST variability: ENSO and non-ENSO components and their climatic associations, *J. Climate, 14*, 391-402, 2001.

Miller, A. J., and N. Schneider, Interdecadal climate regime dynamics in the North Pacific Ocean: theories, observations and ecosystem impacts, *Prog. Oceanogr., 47*, 355-379, 2000.

Miller, G. T., and R. Cheney, Large-scale meridional transport in the tropical Pacific Ocean during the 1986-97 El Niño from Geosat, *J. Geophys. Res., 95,* 17905-17919, 1990.

Minobe, S., Interannual to interdecadal changes in the Bering Sea and concurrent 1998/99 changes over the North Pacific, *Prog. Oceanogr., 55*, 45-64 2000.

Mokhov, I. I., A. V. Eliseev, and D. K. Khvorost'yanov, Evolution of the characteristics of interannual climate variability associated with the El Niño and La Niña phenomenon, *Izv. Atmos. Ocean. Phys., 36*, 681-690, 2000.

Moore, A. M., and R. Kleeman, Stochastic forcing of ENSO by intraseasonal oscillations, *J. Climate, 12*, 1199-1220, 1999.

Neelin, J. D., The slow sea surface temperature mode and the fast-wave limit: analytic theory for tropical interannual oscillations and experiments in a hybrid coupled models, *J. Atmos. Sci.*, *48*, 584-606, 1991.

Neelin, J. D., and F. F. Jin, Modes of interannual tropical ocean-atmosphere interaction -- a unified view. Part II: Analytical results in the weak-coupling limit, *J. Atmos. Sci*., *50*, 3504-3522, 1993.

Neelin, J. D., and Co-authors, ENSO theory, *J. Geophys. Res*., *103*, 14,262-14,290, 1998.

Nitta, T., and S. Yamada, Recent warming of tropical sea surface temperature and its relationship to the northern hemisphere circulation, *J. Meteor. Soc. Japan, 67,* 375-383, 1989.

Nonaka, M., S.-P. Xie, and J. P. McCreary, Decadal variations in the subtropical cells and equatorial SST, *Geophys. Res. Lett., 29,* 10.1029/2001GL013717, 2002.

Ortlieb, L., The documented historical record of El Niño events in Peru: an update of the Quinn record (sixteen through nineteen centuries), in *El Niño and the Southern Oscillation, multiscale variability and regional impacts,* edited by H. Diaz and V. Markgraf, pp. 207-295, Cambridge University Press, 2000.

Penland, C., and P. Sardeshmuhk, The optimal growth of the tropical sea surface temperature anomalies, *J. Climate, 8*, 1999-2024, 1995.

Philander, S. G. H., T. Yamagata, and R. C. Pacanowski, Unstable air-sea interactions in the tropics, *J. Atmos. Sci*., *41*, 604-613, 1984.

Philander, S. G., *El Niño, La Niña, and the Southern Oscillation*, Academic Press, London, 289pp, 1990.

Philander, S. G., El Niño and La Niña, *J. Atmos. Sci*., *42*, 2652-2662, 1985.

Philander, S. G., and A. Fedorov, Is El Niño sporadic or cyclic? *Ann. Rev. Earth Planet. Sci., 31,* 579-594, 2003.

Picaut, J. and T. Delcroix, Equatorial wave sequence associated with the warm pool displacement during the 1986-1989 El Niño and La Niña, *J. Geophys. Res*., *100*, 18398-18408, 1995.

Picaut, J., M. Ioualalen, C. Menkes. T. Delcroix, and M. J. McPhaden, Mechanism of the zonal displacements of the Pacific warm pool: Implications for ENSO, *Science*, *274*, 1486-1489, 1996.

Picaut, J., F. Masia, and Y du Penhoat, An advective-reflective conceptual model for the oscillatory nature of the ENSO, *Science*, *277*, 663-666, 1997.

Picaut, J., and A. J. Busalacchi, Tropical ocean variability, *in Satellite Altimetry and Earth Sciences*, Academic Press, edited by L.-L. Fu and A. Cazenave, pp. 217-236, 2001.

Picaut, J., M. Ioualalen, T. Delcroix, F. Masia, R. Murtugudde, and J. Vialard, The oceanic zone of convergence on the eastern edge of the Pacific warm pool: a synthesis of results and implications for ENSO and biogeochemical phenomena*, J. Geophys. Res*., *106*, 2363-2386, 2001.

Picaut, J., E. Hackert, A. J. Busalacchi, R. Murtugudde, and G. S. E. Lagerloef, Mechanisms of the 1997-98 El Niño-La Niña as inferred from space-based observations, *J. Geophys. Res., 107*, doi:10.1029/2001JC000850, 2002.

Pierce, D. W., T. Barnett, and M. Latif, Connections between the Pacific Ocean tropics and midlatitudes on decadal timescales, *J. Climate*, *13*, 1173-1194, 2000.

Power, S., T. Casey, C. Folland, A. Colman, and V. Mehta, Inter-decadal modulation of the impact of ENSO on Australia, *Clim. Dyn., 15*, 319-324, 1999.

Ramanathan, V., and W. Collins, Thermodynamic regulation of ocean warming by cirrus clouds deduced from observations of the 1987 El Niño, *Nature, 351*, 27-32, 1991

Rasmusson, E. M., and T. H. Carpenter, Variations in tropical sea surface temperature and surface wind fields associated with the Southern Oscillation/El Niño, *Mon. Wea. Rev.*, *110*, 354-384, 1982.

Rodgers, K. B., P. Friederichs, and M. Latif, Decadal ENSO amplitude modulations and their effects on the mean state, *J. Climate*, 2003 (submitted).

Roemmich, D., and Co-authors, Argo: the global array of profiling floats, in *Observing the Ocean of the 21st Century*, edited by C. J. Koblinsky and N. R. Smith, pp. 248-257, Aust. Bur. Meteor. Melbourne, 2001.

Rothstein, L. M., R.-H. Zhang, A. J. Busalacchi, and D. Chen, A numerical simulation pf the mean water pathways in the subtropical and tropical Pacific Ocean, *J. Phys. Oceanogr., 28*, 322-342, 1998.

Salinger, M. J., J. A. Renwick, and A. B. Mullan, Interdecadal Pacific oscillation and South Pacific climate, *Int. J. Climate, 21,* 1705-1721, 2001.

Schneider, N. S., A. J. Miller, M. A. Alexander, and C. Deser, Subduction of decadal North Pacific temperature anomalies: Observations and dynamics. *J. Phys. Oceanogr., 29*, 1056-1070, 1999a.

Schneider, N., S. Vezke, A. J. Miller, D. W. Pierce, T. Barnett, C. Deser, and M. Latif, Pacific thermocline bridge revisited, *Geophys. Res. Lett., 26,* 1329-1332, 1999b.

Schneider, N., A decadal spiciness mode in the tropics, *Geophys. Res. Lett., 27*, 257-260, 2000.

Seager, R., and R. Murtugudde, Ocean dynamics, thermocline adjustment, and regulation of tropical SST, *J. Climate, 10*, 521-534, 1997.

Slingo, J. M., D. P. Rowell, K. R. Sperber and F. Nortley, On the predictability of the interannual behavior of the Madden-Julian Oscillation and its relationship with El Niño, *Quart. J. Roy. Met. Soc, 125,* 583-560, 1999.

Smith, N. R, and Co-authors, The upper ocean thermal network, in *Observing the Ocean of the 21st Century*, edited by C. J. Koblinsky and N. R. Smith, pp. 259-283, Aust. Bur. Meteor. Melbourne, 2001.

Solomon, A., J. P. McCreary, R. Kleeman, and B. A. Klinger, Interannual and decadal variability in an intermediate coupled model of the Pacific region, *J. Climate, 16*, 383-405, 2003.

Springer, S. R., M. J. McPhaden, and A. J. Busalacchi, Oceanic heat content variability in the tropical Pacific during the 1982/1983 El Niño, *J. Geophys. Res., 95*, 22089-22101, 1990.

Stone, L., P. I. Saparin, A. Huppert, and C. Price, El Niño chaos: the role of noise and stochastic resonance on ENSO cycle, *Geophys. Res. Lett., 25,* 175-178, 1998.

Suarez, M. J., and P. S. Schopf, A delayed action oscillator for ENSO, *J. Atmos. Sci*., *45*, 3283-3287, 1988.

Sun, D.-Z., A possible effect of an increase in the warm-pool SST on the magnitude of El Niño warming, *J. Climate, 16*, 185-205, 2003.

Syu, H.-H., and J. D. Neelin, ENSO in a hybrid coupled model. Part II: Prediction with piggyback data assimilation, *Climate Dyn., 16*, 35-48, 2000.

Takayabu, Y. N., T. Iguchi, M. Kachi, A. Shibata, and H. Kanzawa, Abrupt termination of the 1997-98 El Niño in response to a Madden-Julian-oscillation, *Nature*, *402*, 279-282, 1999.

Tang, T. Y., and R. H. Weisberg, On the equatorial Pacific response to the 1982/1983 El Niño-Southern Oscillation event, *J. Mar. Res.*, *42*, 809-829, 1984.

Thompson, C. J., D. S. Battisti, A linear stochastic dynamical model of ENSO. Part II: Analysis, *J Climate*, 14, 445-466, 2001.

Thompson, L. G., K. A. Henderson, E. Mosley-Thompson, and P.-N. Lin, The tropical ice record of ENSO, *El Niño and the Southern Oscillation, multiscale variability and global and* *regional impacts, Cambridge Univ. Press, H. F. Diaz and V. Markgraf editors,* pp. 325-356, 2000.

Timmermann, A., J. Oberhuber, A. Bacher, M. Esch, M. Latif, and E. Roeckner, Increased El Niño frequency in a climate model forced by future greenhouse warming, *Nature, 398,* 694-696, 1999.

Timmermann, A., Decadal ENSO amplitude modulation: a nonlinear paradigm, *Glob. Plan. Change, 37,* 135-156, 2003.

Timmermann, A., F.-F. Jin, and J. Abshagen, A nonlinear theory for El Nino bursting, *J. Atmos. Sci., 60,* 165, 2003.

Torrence, C., and P. J. Webster, Interdecadal changes in the ENSO-Monsoon system, *J. Climate, 12,* 2679-2690, 1999.

Tourre, Y., B. Rajagopalan, Y. Kushnir, M. Barlow, and W. B. White, Patterns of coherent decadal and interdecadal climate signals in the Pacific basin during the 20th century, *Geophys. Res. Lett, 28,* 2069-2072, 2001.

Trenberth, K. E., Recent observed interdecadal climate changes in the Northern Hemisphere, *Bull. Am. Meteor. Soc., 71*, 988-993, 1990.

Trenberth, K. E., and T. J. Hoar, The 1990-95 El Niño-Southern Oscillation event: longest on record, *Geophys. Res. Lett., 23,* 57-60, 1996.

Tziperman, E., M. Cane, and S. E. Zebiak, Irregularity and locking to the seasonal cycle in the ENSO-prediction model as explained by the quasi-periodicity route to chaos, *J. Atmos. Sci.*, *52*, 293-306, 1995.

Vecchi, G. A., and D. E. Harrison, Tropical Pacific sea surface temperature anomalies, El Niño, and equatorial westerly wind events, *J. Climate, 13,* 1814-1830, 2000.

Vecchi, G. A., and D. E. Harrison, On the termination of the 2002-03 El Niño, *Geophys. Res. Lett., 30,* 1964, doi:10.1029/2003GL017564, 2003.

Vialard, J., and Co-authors, A model study of oceanic mechanisms affecting equatorial Pacific sea surface temperature during the 1997-98 El Niño, *J. Phys. Oceanogr.*, *31*, 1649-1675, 2001.

Vavrus, S., and Z. Liu, Toward understanding the response of the tropical atmosphere-ocean system to increased CO_2 using equilibrium asynchronous coupling, *Clim. Dyn., 19*, 355-369, 2002.

Wakata, Y., and E. S. Sarachik, Unstable coupled atmosphere-ocean basin modes in the presence of a spatially varying basic state, *J. Atmos. Sci.*, *48*, 2060-2077, 1991.

Walker, G. T., Correlation in seasonal variations of weather VIII: A preliminary study of world weather, *Memoirs of the Indian Meteorological Department, 24*, 75-131, 1923.

Walker, G. T., Correlation in seasonal variations of weather IX: A further study of world weather, *Memoirs of the Indian Meteorological Department, 24*, 275-332, 1924.

Walker, G. T., and E. Bliss, World Weather V*, Memoirs of the Royal Meteorological Society*, *4*, 53-84,1932.

Wang, B., Transition from a cold to a warm state of the El Niño-Southern Oscillation cycle, *Meteorol. Atmos. Phys*., *56*, 17-32, 1995.

Wang, B., A. Barcilon, and Z. Fang, Stochastic dynamics of El Niño-Southern Oscillation, *J. Atmos. Sci., 56*, 5-23, 1999.

Wang, B., and S.-I. An, A mechanism for decadal changes of ENSO behavior: roles of background wind changes, *Clim. Dyn., 18,* 475-486, 2002.

Wang, C., and R. H. Weisberg, On the 'slow mode' mechanism in ENSO-related coupled ocean-atmosphere models, *J. Climate, 7*, 1657-1667, 1994.

Wang, C., and R. H. Weisberg, Stability of equatorial modes in a simplified coupled ocean-atmosphere model, *J Climate, 9*, 3132-3148, 1996.

Wang, C., and R. H. Weisberg, Climate variability of the coupled tropical-extratropical ocean-atmosphere system, *Geophys. Res;. Lett*., *25*, 3979-3982, 1998.

Wang, C., R. H. Weisberg, and H. Yang, Effects of the wind speed-evaporation-SST feedback on the El Niño-Southern Oscillation, *J. Atmos. Sci.*, *56*, 1391-1403.1999a

Wang, C., R. H. Weisberg, and J. I. Virmani, Western Pacific interannual variability associated with the El Niño-Southern Oscillation, *J. Geophys. Res.*, *104*, 5131-5149, 1999b.

Wang, C., and R. H. Weisberg, The 1997-98 El Niño evolution relative to previous El Niño events, *J. Climate*, *13*, 488-501, 2000.

Wang, C., On the atmospheric responses to tropical Pacific heating during the mature phase of El Niño, *J. Atmos. Sci*., *57*, 3767-3781, 2000.

Wang, C., A unified oscillator model for the El Niño-Southern Oscillation, *J. Climate*, *14*, 98-115, 2001.

Webster, P. J. and R. Lukas, TOGA-COARE: The Coupled Ocean-Atmosphere Response Experiment, *Bull. Am. Meteor. Soc.*, 73, 1377-1416, 1992.

Weisberg, R. H., and C. Wang, Slow variability in the equatorial west-central Pacific in relation to ENSO, *J. Climate*, *10*, 1998-2017, 1997a.

Weisberg, R. H., and C. Wang, A western Pacific oscillator paradigm for the El Niño-Southern Oscillation, *Geophys. Res. Lett*., *24*, 779-782, 1997b.

Weller, R. A., and S. P. Anderson, Surface meteorology and air-sea fluxes in the western equatorial Pacific warm pool during TOGA COARE, *J. Climate*, *9*, 1959-1990, 1996.

White, W. B., Y. M. Tourre, M. Barlow, and M. Dettinger, A delayed action oscillator shared by biennale, interannual, and decadal signals in the Pacific basin, *J. Geophys. Res., 108,* 3070, doi10.1029/2002JC001490, 2003.

Wyrtki, K., El Niño -- The dynamic response of the equatorial Pacific Ocean to atmospheric forcing, *J. Phys. Oceanogr*., *5*, 572-584, 1975.

Wyrtki, K., Water displacements in the Pacific and genesis of El Niño cycles, *J. Geophys. Res., 90*, 7129-7132, 1985.

Yamagata, T., Stability of a simple air-sea coupled model in the tropics, In *Coupled Ocean-Atmosphere Model*s, edited by J. C. J. Nihoul, pp637-657, Vol. **40**, Elsevier Oceanography Series, Elsevier, 1985.

Yu, B., G. J. Boer, The roles of radiation and dynamical processes in the El Niño-like response to global warming, *Clim. Dyn., 19*, 539-553, 2002.

Yukimoto, S., M. Endoh, Y. Kitamura, A. Kitoh, T. Motoi, and A. Noda, ENSO-like interdecadal variability in the Pacific Ocean as simulated in a coupled general circulation model, *J. Geophys. Res., 105*, 13,945, 13,963, 2000.

Zavala-Garay, J., A. M. Moore, C. L. Perez, and R. Kleeman, The response of a coupled mode of ENSO to observed estimates of stochastic forcing, *J. Climate, 16*, 2827-2842, 2003.

Zebiak, S. E., and M. A. Cane, A model El Niño-Southern Oscillation, *Mon. Wea. Rev*., *115*, 2262-2278, 1987.

Zebiak, S. E., Oceanic heat content variability and El Niño cycles, *J. Phys. Oceanogr., 19*, 475-486, 1989a.

Zebiak, S. E., On the 30-60 day oscillation and the prediction of El Niño, *J. Climate, 2*, 1381-

1387, 1989b.

Zebiak, S. E., Diagnostic studies of Pacific surface winds, *J. Climate*, *3*, 1016-1031, 1990.

Zhang, C., Intraseasonal perturbations in sea surface temperatures of the equatorial eastern Pacific and their association with the Madden-Julian Oscillation, *J. Climate, 14*, 1309-1322, 2001.

Zhang, C., and J. Gottschalck, SST anomalies of ENSO and the Madden-Julian Oscillation in the equatorial Pacific, *J. Climate, 15*, 2429-2445, 2002.

Zhang, R.-H., L. M. Rothstein, and A. J. Busalacchi, Origin of upper-ocean warming and El Niño change on decadal scales in the tropical Pacific Ocean, *Nature, 391*, 879-882, 1998.

Zhang, Y., J. M. Wallace, and D. S. Battisti, ENSO-like interdecadal variability: 1900-93, *J. Climate, 10*, 1004-10020, 1997.

Figure Captions

Figure 1. In situ components of the ENSO Observing System. The four major elements are (1) the TAO/TRITON array of moored buoys, (2) an island tide-gauge network, (3) surface drifters, (4) the Volunteer Observing Ship program. This ensemble of instruments deliver in near-real time via satellite data on surface and subsurface temperature and salinity, wind speed and direction, sea level, and current velocity. (Courtesy of the TAO Project Office).

Figure 2. SST anomaly composites showing different origin and development of El Niños in the last five decades. (a) El Niños between 1950 and 1976, (b) El Niños between 1977 and 1996, (c) the 1997-98 El Niño, and (d) the 2002-03 El Niño. The composites are calculated by averaging the SST anomalies during March-May of the El Niño year. Since the 2002-03 El Niño starts earlier, its composite used the SST anomalies of December 2001 to February 2002.

Figure 3. Schematic diagram of the delayed oscillator for ENSO.

Figure 4. Schematic diagram of the recharge oscillator for ENSO. (a) The four phases of the recharge oscillation: (I) the warm phase, (II) the warm to cold transition phase, (III) the cold phase, and (IV) the cold to warm transition phase. (b) The time series of the Nino3 SST anomalies (dashed) and the warm water volume anomalies (solid) over the entire equatorial tropical Pacific Ocean (5°S-5°N, 120°E-80°W) (Courtesy of Chris Meinen).

Figure 5. Schematic diagram of the western Pacific oscillator for ENSO.

Figure 6. Schematic diagram of the advective-reflective oscillator for ENSO.

Figure 7. The two leading modes of Niño-4 SST anomalies. The upper panel represents the reconstruction of Niño-4 SST with the ENSO and decadal modes (25% and 20% of variance, respectively). The lower panel represents the regression of SST anomalies upon each mode; note that the color scales are different (Courtesy of Mojib Latif).

ENSO Observing System

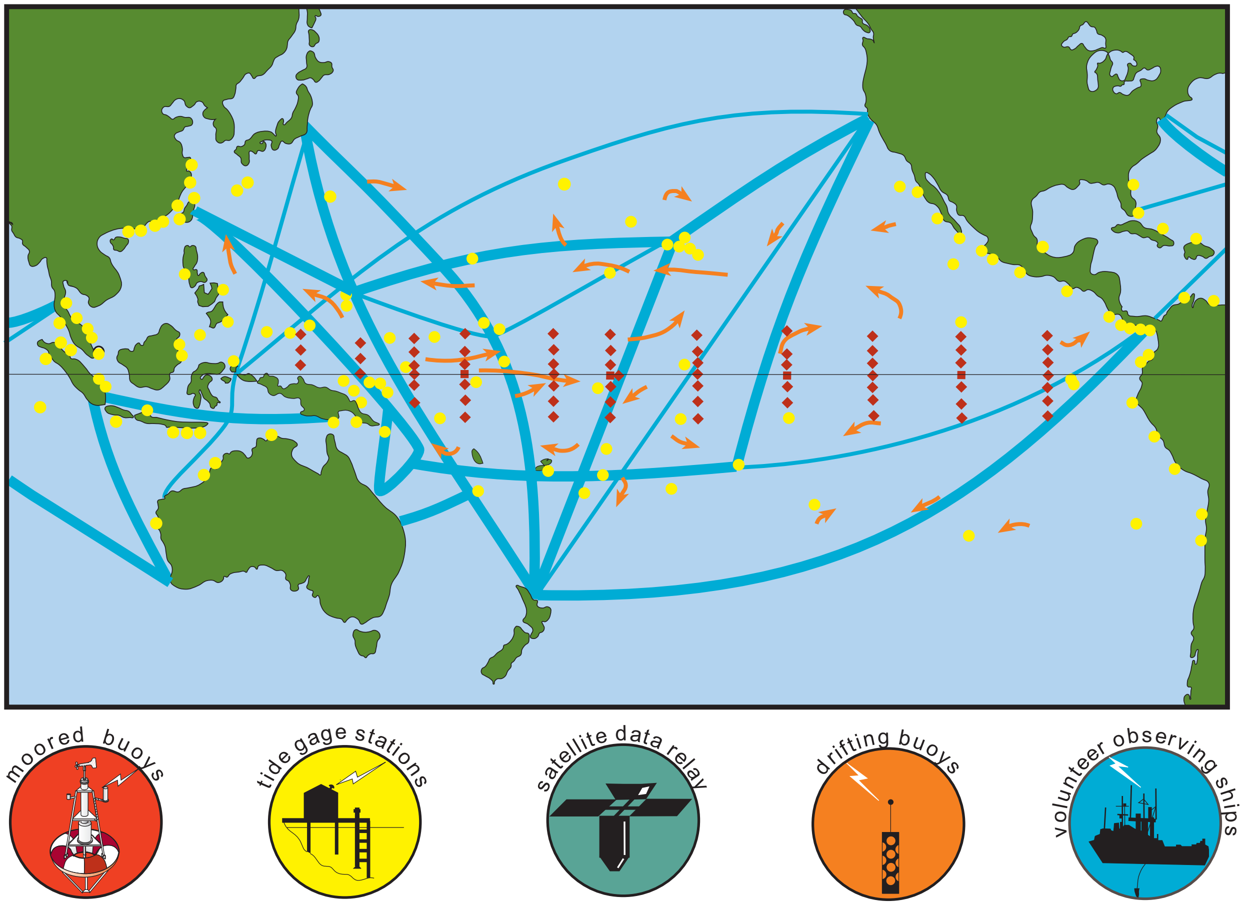


Figure 1

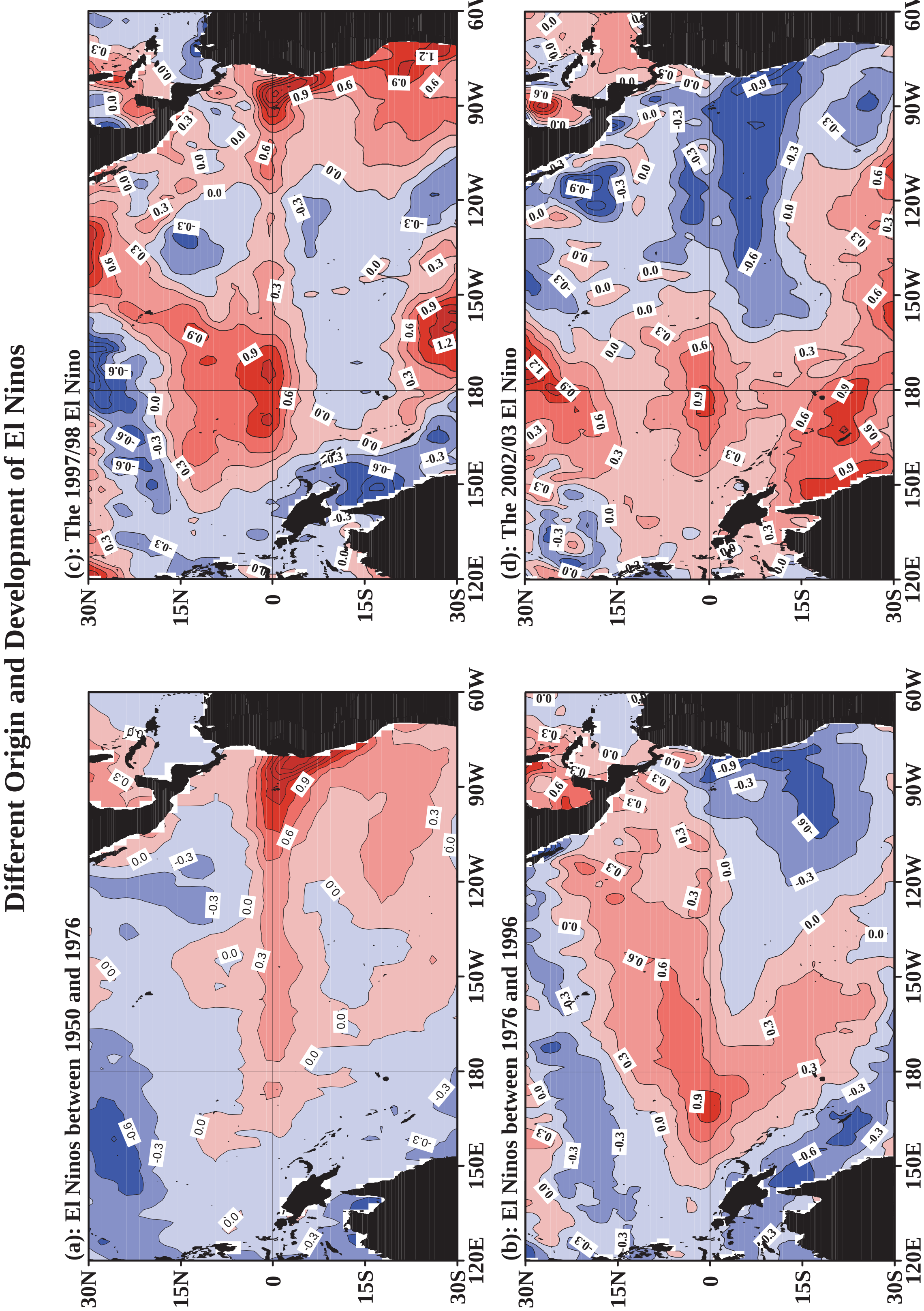

Different Origin and Development of El Ninos
(a): El Ninos between 1950 and 1976
(b): El Ninos between 1976 and 1996
(c): The 1997/98 El Nino
(d): The 2002/03 El Nino
30N
15N
0
15S
30S
120E
150E
180
150W
120W
90W
60W

Figure 2

The Delayed Oscillator

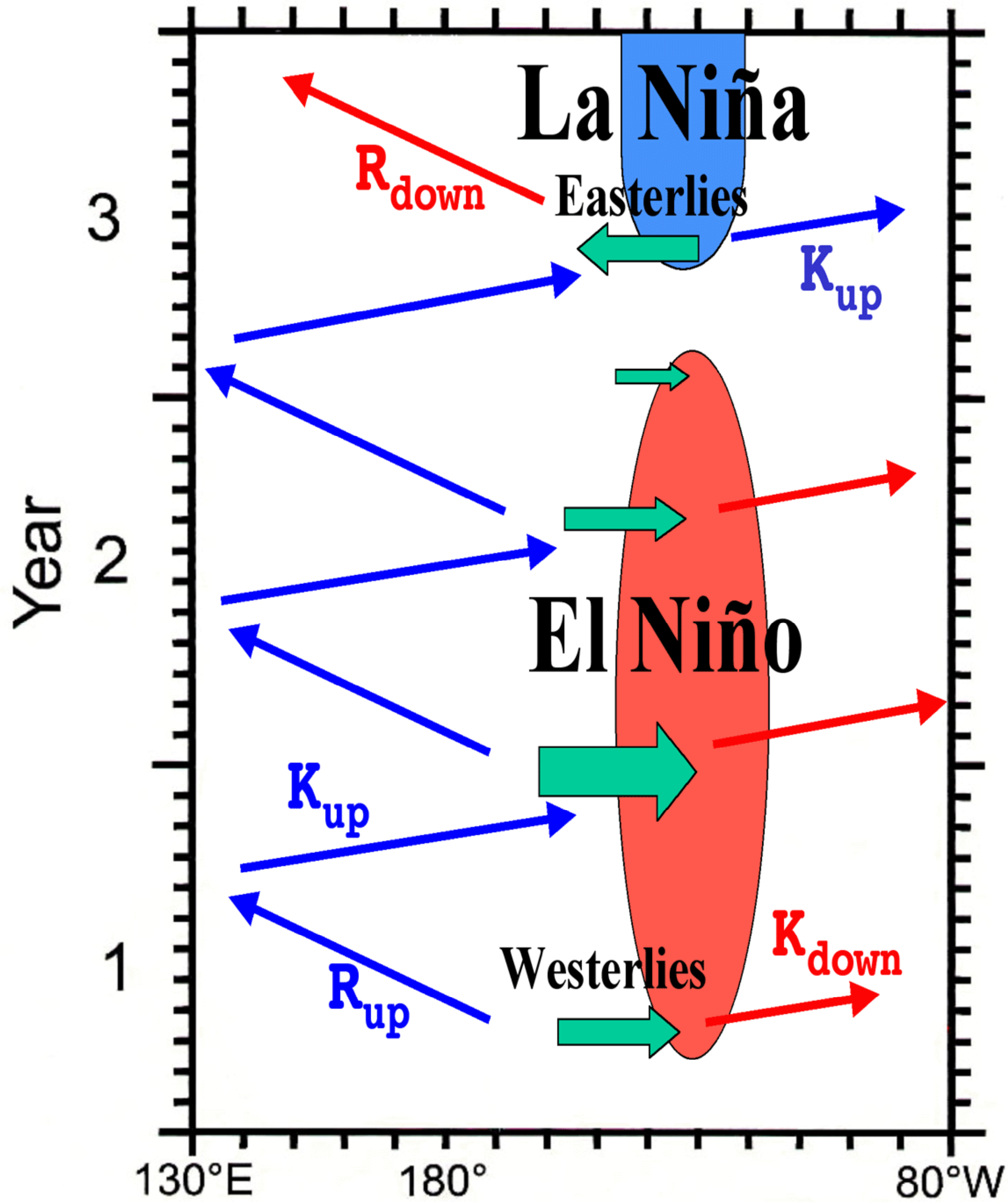


Figure 3

The Recharge Oscillator

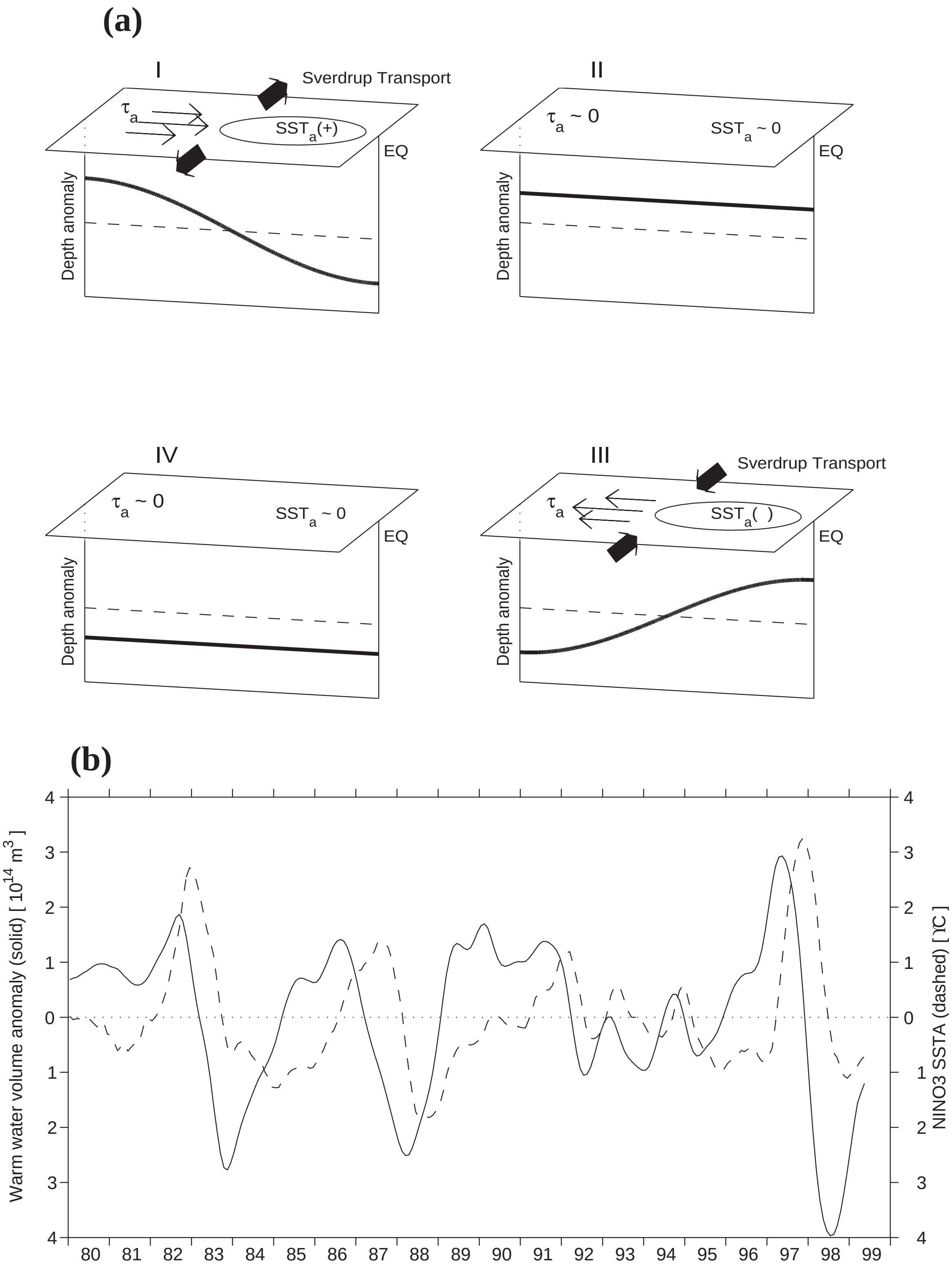
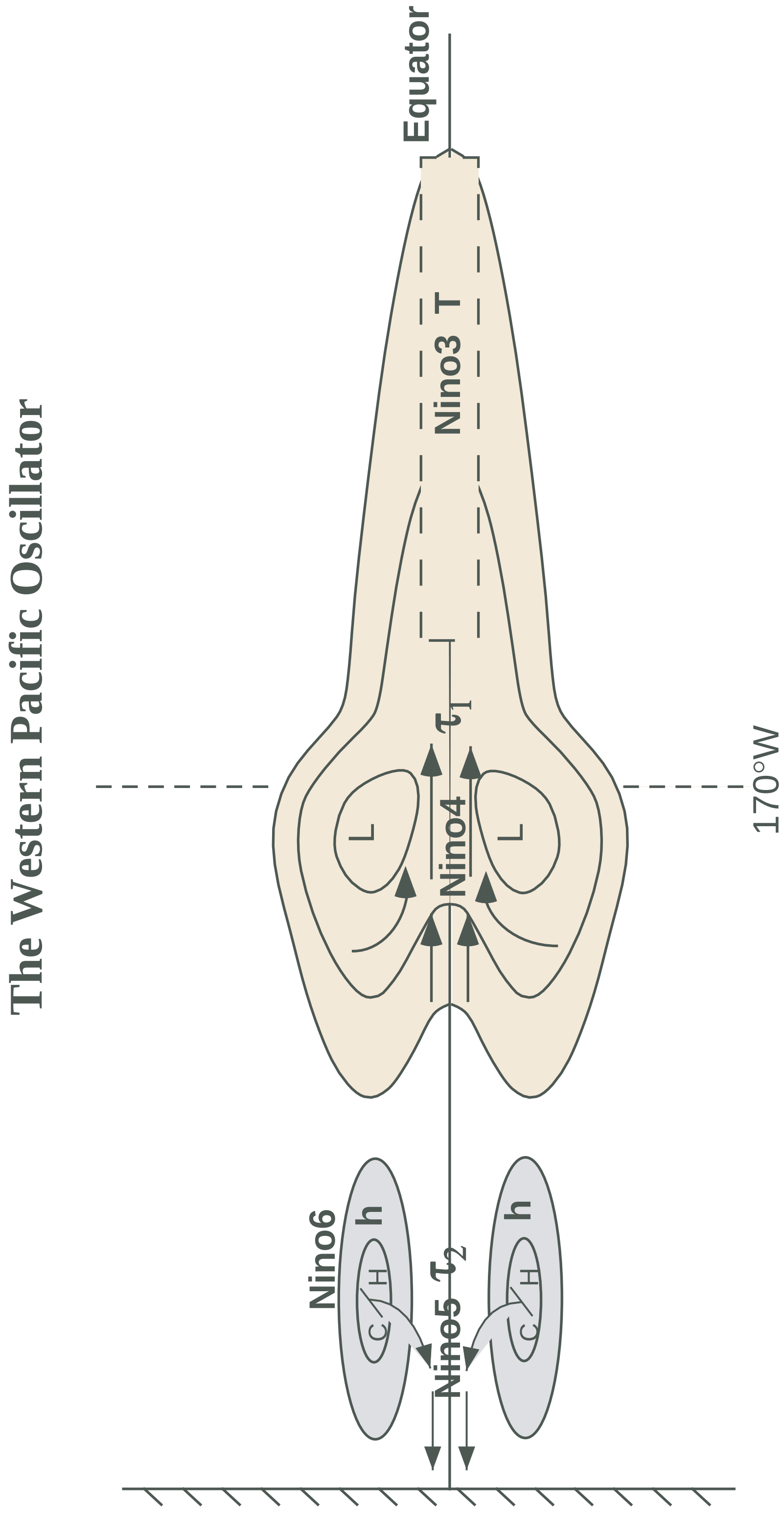


Figure 4



The Western Pacific Oscillator
Equator
Nino3 T
τ_1
Nino4
L
L
170°W
Nino6
h
h
Nino5 τ_2
C
H
C
H

Figure 5

The Advective-Reflective Oscillator

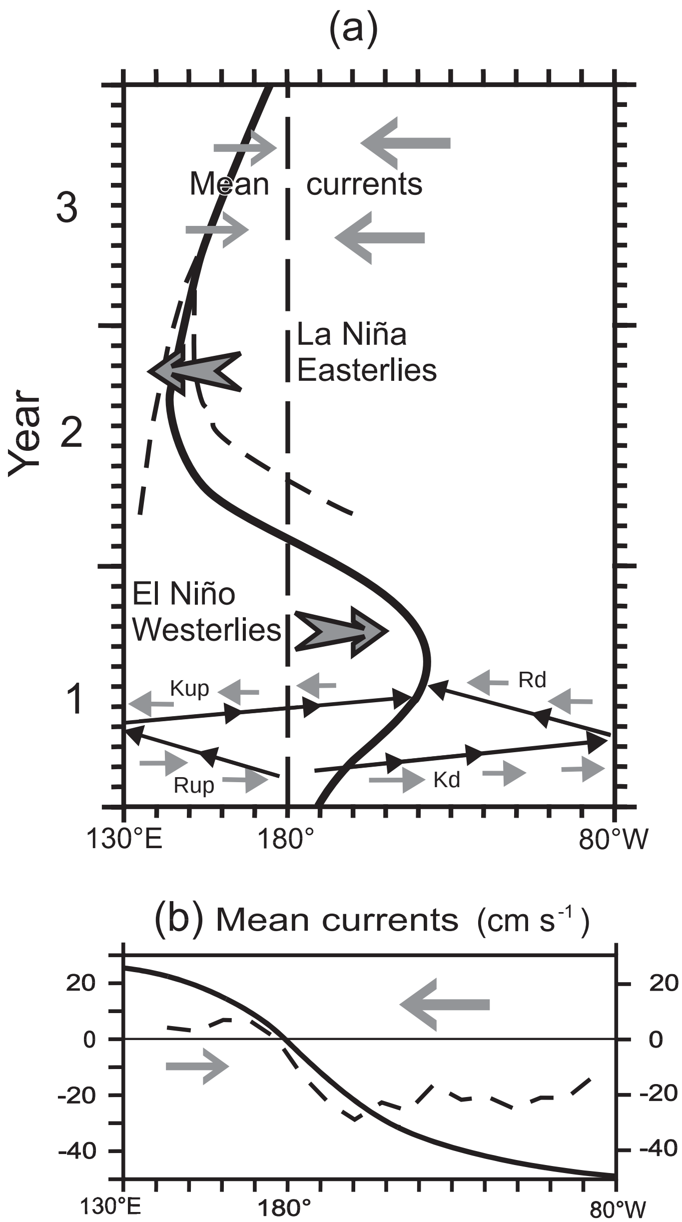


Figure 6

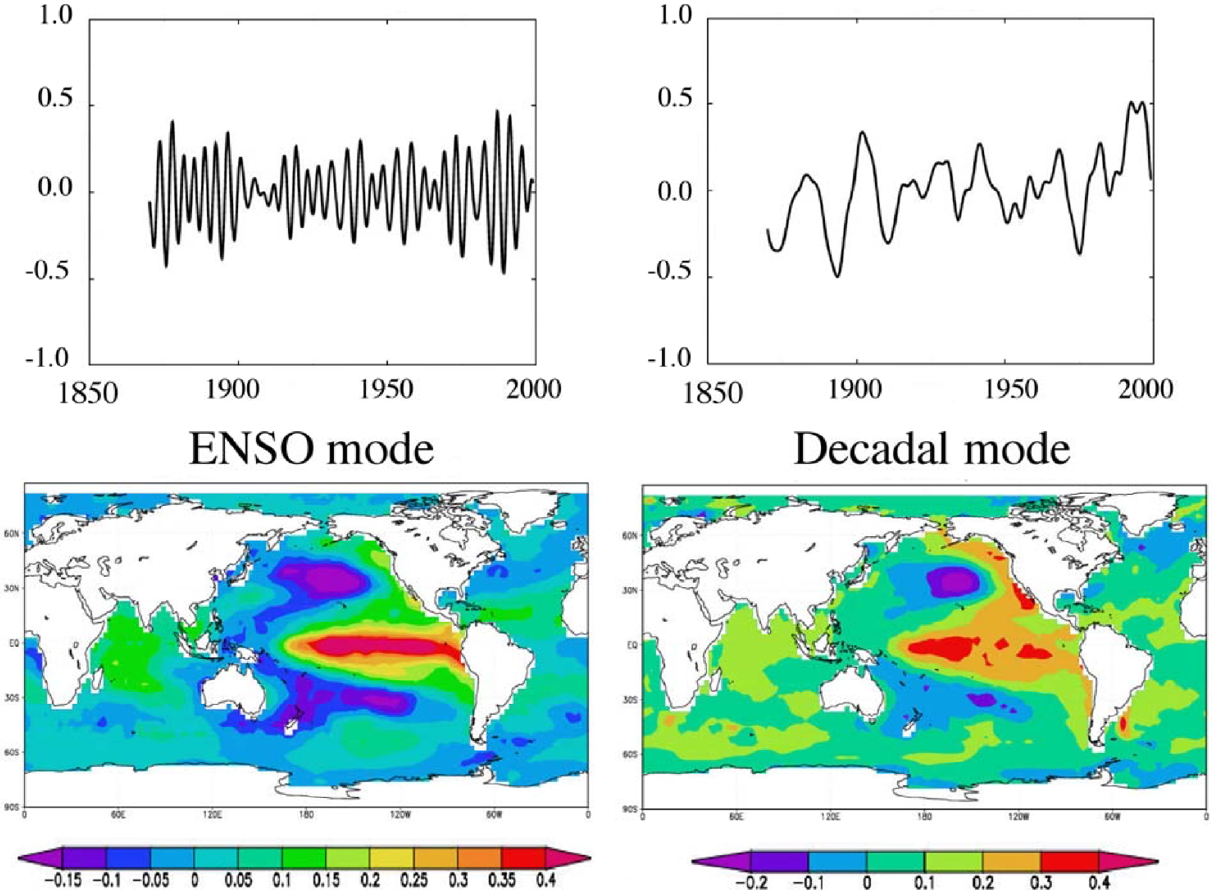

1.0
0.5
0.0
-0.5
-1.0
1850
1900
1950
2000
ENSO mode
Decadal mode
60N
30N
EQ
30S
60S
90S
0
60E
120E
180
120W
60W
−0.15 −0.1 −0.05 0 0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4
−0.2 −0.1 0 0.1 0.2 0.3 0.4

Figure 7