

Interdecadal variability and climate change in the eastern tropical Pacific: A review

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Abstract

In this paper, we review interdecadal climatic variability in the eastern tropical Pacific Ocean. This variability dominates the climatic fluctuations in the North Pacific on scales between ENSO and the centennial trend and is commonly referred to as the Pacific Decadal Oscillation or PDO. We include a historical overview and a summary of observational work that describes the surface, tropospheric and subsurface signatures of this variability. Descriptions of interdecadal variability are incomplete at best, mostly due to limitations in the observational record. We emphasize that the well-known “ENSO-like” sea surface temperature (SST) pattern describing the PDO may not be an accurate representation. In the eastern tropical Pacific, the SST maxima are displaced north and south of the equator with larger amplitudes in the northern branch near the coast of North America, which has significant implications for the troposphere-driven circulations.

Several mechanisms have been proposed to explain the PDO. We review these mechanisms and models, which capture our present level of understanding of the problem. We conclude by reporting there is little evidence of both multidecadal variability and the centennial trend in the eastern tropical Pacific. This paper is part of a comprehensive review of the oceanography of the eastern tropical Pacific.

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1. Introduction

Since Wyrтки’s (1966, 1967) reviews of eastern tropical Pacific oceanography, there have been major advances in how we look at the oceans both spatially and temporally. Oceanography has matured from regional steady state mapping of properties and flow patterns to descriptions of oceanic and air–sea interaction processes and their variabilities at all time and space scales. In addition, there has been a growing awareness of the

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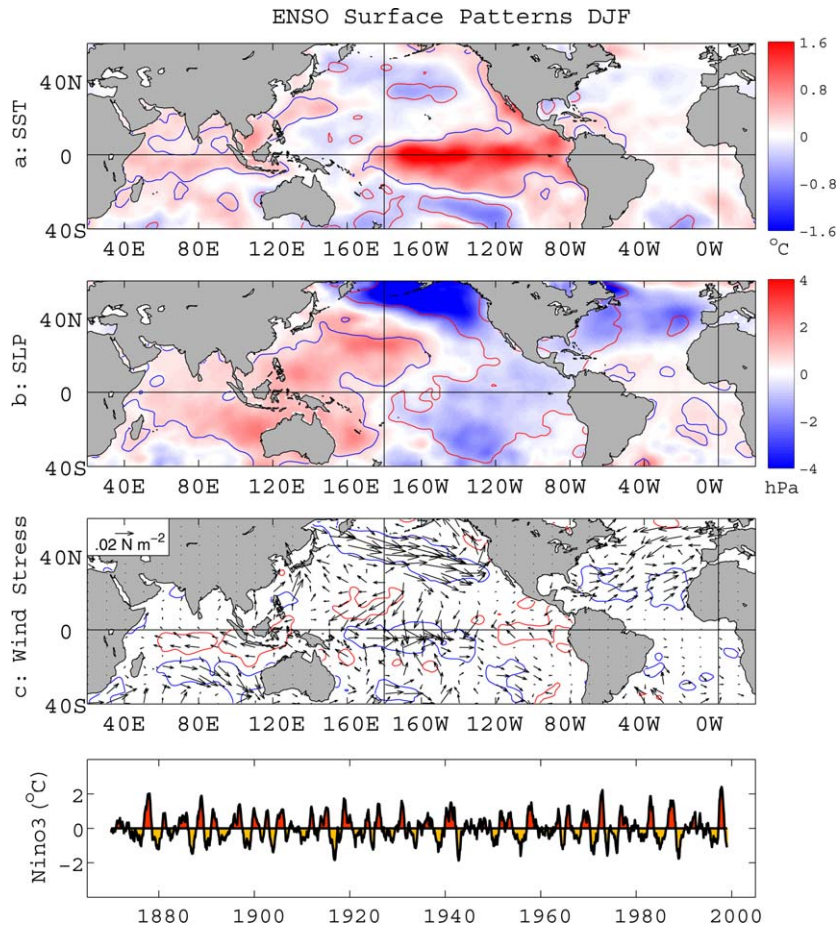


Fig. 1. Boreal winter (DJF) differences between composite averages with respect to the positive and negative values of the Niño-3 time series (bottom panel) reconstructed from the ENSO mode as explained in the text for: (a) SST, (b) SLP, and (c) surface wind stress. Significant positive (negative) differences in SST, SLP, and zonal wind stress are indicated with blue (red) contours.

fundamental role of the oceans in the global air–sea–land climate system. Key factors behind these advances have been the advent of satellite remote sensing (e.g., Fu, 2001), improved compilations of historical in situ surface marine observations (e.g., Woodruff et al., 1998), and the development of sophisticated ocean general circulation models that accompanied the rapid increase in computer power of the last decades (e.g., Böning and Semtner, 2001).

One of the areas where great progress has been made is in the study of the El Niño/Southern Oscillation (ENSO), a global air–sea interaction phenomenon with interannual time scales (typically in the 1.5–8 yr band) that is the largest source of variability in the historical record (Fig. 1, see also Wang and Fiedler, 2004, this volume). While interest in ENSO has remained high during the last decades, the realization that ENSO variability is modulated by longer-scale interdecadal and multidecadal¹ climate variability has received much attention in recent years. The development of long records of reconstructed instrumental and proxy data (Cook et al., 2000; Mann et al., 2000; Cobb et al., 2001; Evans et al., 2001) has allowed investigating these climatic processes with greater statistical confidence than is possible from the instrumental record alone. Because present climate forecast systems are based on ENSO, the motivation is that the lower frequency background variability can add predictability to these systems. It is also clear that a good understanding of inter-

¹ By “interdecadal” we refer to timescales longer than interannual and shorter than about 2–3 decades, and by “multidecadal” to timescales longer than interdecadal and shorter than the long-term centennial trend.

decadal/multidecadal variability is required to address the question of long-term changes associated with global warming.

Evidence of interdecadal fluctuations in the Pacific is found in oceanic, atmospheric, and land variables in and around the basin. Although the existence of Pacific interdecadal variability is not in question, details of its signature and the driving mechanisms are not well understood. Several hypotheses have been proposed to explain some of the observed features. Simplified and sophisticated ocean and atmosphere–ocean coupled simulations have been developed to test some of these hypotheses. Models seem to explain some of the observational results but are far from providing an adequate description.

The goal of this paper is to describe the present knowledge regarding climatic variability on interdecadal to centennial timescales in the Pacific sector, focusing in the eastern tropical Pacific region. However, because the effects of climatic fluctuations involve basin-to-global spatial scales and teleconnections (e.g., Timmerman et al., 1998) we include discussions of larger-scale patterns. We synthesize present knowledge by combining work by others with our own analyses. The oceanic variability is characterized from analyses of sea surface and subsurface water temperatures. The associated climatic effects are characterized from analyses of surface and tropospheric atmospheric variables. The paper is organized as follows. In Section 2 we present a historic overview of studies of Pacific interdecadal variability, in Section 3 the observational evidence for interdecadal variability, in Section 4 the theories and models for interdecadal variability, in Section 5 multidecadal variability and climate change. We conclude with a summary and discussion in Section 6.

2. History

The first studies of interdecadal climatic variability in the Pacific Ocean are Namias's (1972) early attempts to identify patterns of large-scale ocean–atmosphere interaction in the modern instrumental record. Using only a 20-year dataset he composited January–March sea surface temperature (SST) anomalies for the 10-year periods before and after the 1957 El Niño that strongly influenced the fisheries off the coast of California. He characterized that event as “the transition period . . . between two roughly decadal climatic regimes”. The patterns of mid-latitude SST that he found are remarkably similar to the dominant interdecadal “canonical pattern” of mid-latitude SST (the out-of-phase east–west SST structure seen in Fig. 2) that arises ubiquitously in modern statistical pattern analysis. He pointed out that these decadal regimes appear in other meteorological data through atmospheric teleconnections. He noted that the Aleutian Low was considerably south of normal during the 1960s when the SST pattern was in the cold central, warm eastern Pacific phase (Fig. 2, right panel). He anticipated that many other signatures of this phenomenon would be found in chemical and biological variables. He lastly emphasized that understanding “the stability of the decadal regimes . . . and the abrupt transition between regimes” is an important problem and cast the theoretical framework in terms of recurrent SST patterns that influence the formation of fronts, cyclones and anticyclones due to changes in stability of the underlying frictional boundary layer. Namias's (1972) descriptions are an uncanny synopsis of our current understanding of interdecadal variability.

During the 1970s and early 1980s, most work diagnosing interdecadal Pacific climate variability was geared toward developing an understanding of its potential in long-range (seasonal to interannual) atmospheric forecasting over North America (Cayan, 1980) and in documenting its origin as natural variability in contrast to global warming from increasing greenhouse gases in the atmosphere (Douglas et al., 1982). Isaacs (1976)

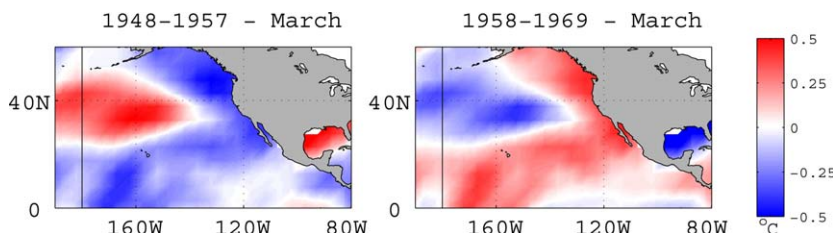


Fig. 2. Mean March SST anomalies for 1948–1957 (left) and 1958–1969 (right) relative to the 1947–1966 reference period showing the patterns in Namias (1972) (his Figs. 14 and 15) but reproduced using the Kaplan et al. (1998) dataset.

appears to be the first to suggest a strong influence of Pacific interdecadal climate variability on modern fisheries and other oceanic ecosystem variations.

It was not until the late 1980s and early 1990s that considerable attention turned to explaining the physical mechanisms and ocean-atmosphere linkages of interdecadal climate regimes dynamics (Graham, 1994; Miller et al., 1994a,b; Trenberth and Hurrell, 1994) and their influence on oceanic ecosystem regime changes (Venrick et al., 1987; Ebbesmeyer et al., 1991; Baumgartner et al., 1992; Beamish and Bouillon, 1993; Francis and Hare, 1994; Polovina et al., 1994; McGowan et al., 2003). This was due to the recognition that a major physical–biological climate shift had occurred in the winter of 1976–1977. The 1990s and 2000s have seen a large body of work emerge in this field, particularly after it was demonstrated rigorously that there was a specific spatial pattern associated with Pacific interdecadal variability, which is somewhat similar to ENSO, but different (Zhang et al., 1997). This rejuvenated interest in Pacific decadal variability has been summarized and discussed in a number of review articles (e.g., Latif, 1998; Miller and Schneider, 2000; Fiedler, 2002; Mantua and Hare, 2002; Miller et al., 2003).

3. Observations

Climatic variability in oceanic and atmospheric variables is characterized by spatial and temporal structures that depict larger amplitudes in preferred locations. To extract these spatial patterns researchers most commonly use two techniques: the index approach and Empirical Orthogonal Functions (EOF) analysis².

The index approach is based on using a climatic index, which is a time series of a variable or of an average of the variable at or around a given location. A spatial pattern is then estimated by temporal correlations, regressions or composites based on the climatic index and the full fields of the original variable. An example of a climatic index used in ENSO studies is Niño-3, which is the average of sea surface temperature (SST) anomalies over a rectangular region bounded by 90°W–150°W and 5°S–5°N in the eastern tropical Pacific. Some indices are defined by combining time series of the climatic variables over more than one location or region, such as the Southern Oscillation Index, which is based on sea level pressure differences at two locations across the south tropical Pacific (e.g., Peixoto and Oort, 1992). The climatic index from one variable can also be related to full fields of other variables to estimate patterns of co-variability.

EOF analysis (sometimes referred to as principal component analysis) is one of several eigenvalue techniques used in climate studies (e.g., Emery and Thomson, 1997; von Storch and Zwiers, 1999). It allows us to represent the spatial and temporal variability of climate variables as a number of “empirical modes”, with most of the variability explained by a small number of modes. Each empirical mode is formed by a space pattern and a time series, which are derived from the eigenvalues and eigenvectors of the covariance (or correlation) matrix. These functions are defined to be orthogonal in space and time. Sometimes the EOFs are linearly transformed or “rotated” to simplify or regionalize the spatial patterns (e.g., Richman, 1986), with the orthogonality properties of the rotated modes depending on how the unrotated modes are constructed and normalized (e.g., Mestas-Nuñez, 2000). Rotated EOFs are generally less sensitive to sampling errors than conventional EOFs (Cheng et al., 1995). Useful variations of conventional EOFs for studying propagating signals are complex (or Hilbert) EOFs, because they allow capture of phase propagation in a single mode (Rasmusson et al., 1981; Barnett, 1983; Horel, 1984). The EOF methods can also be extended to more than one variable to estimate modes of co-variability (e.g., canonical correlation analysis and singular value decomposition or SVD, von Storch and Zwiers, 1999).

Most theories proposed to explain Pacific interdecadal variability predict oscillatory behavior that is regarded as being superimposed on random noise. Miller and Schneider (2000) pointed out that the temporally and spatially limited observations preclude definitive characterizations of the Pacific interdecadal variability as oscillatory, step-like or random. Nevertheless, some observational studies, particularly in the biological sciences, are based on detecting whether a “regime shift” similar to the one that occurred in the mid 1970s has taken place. For example, a similar regime shift has been suggested for 1999 (Hare and Mantua, 2000;

² Note that although discussed here in the context of observations, these statistical techniques are also used to extract climatic signals from numerical model output.

Schwing and Moore, 2000). By “regime shift” they indicate a step-like change from a persistent and relatively stable period in the climatic variables to another distinctive and likely persistent period. Miller and Schneider (2000) classify the techniques used to detect step-like behavior as intervention analysis (Hare and Francis, 1995), interfering patterns of two or more decadal-scale periodicities (Minobe, 1999), and compositing techniques that posit step functions (Ebbesmeyer et al., 1991; Hare and Mantua, 2000). Among these, the compositing techniques have recently been called into question by Rudnick and Davis (2003) who showed that they are likely to find step-like shifts in Gaussian, red noise time series with stationary statistics. The problem may be unique to the compositing techniques of Ebbesmeyer et al. (1991) and Hare and Mantua (2000) but the study of Rudnick and Davis does raise questions about the applicability of the step-like concept for studying interdecadal variability.

In the remainder of this section, we review some applications of the index approach and EOF analysis to describe the surface and tropospheric signatures of Pacific interdecadal variability that affect the eastern tropical Pacific. We also describe the subsurface signature associated with this variability.

3.1. Sea surface

The observational record of SST is about 150 years long, with reasonable data density in the last 50 years and much sparser data in the first 100 years. Errors in these observations include changes in measurement methodology over time as well as sparse sampling frequency and coverage during the early part of the record (particularly before the beginning of the satellite era in the early 1980s). The problems of methodology changes over time have been partially corrected in datasets like the Comprehensive Ocean–Atmosphere Data Set (COADS, Woodruff et al., 1987, 1998) and from the United Kingdom Meteorological Office (UKMO, Parker et al., 1995; Rayner et al., 2003).

The issue of increased observations over time has been addressed by estimating statistical properties of the fields over the recent two decades or so, when the data are more abundant and using these properties to reconstruct the fields in the earlier period of sparse observations (Rayner et al., 1996; Smith et al., 1996; Kaplan et al., 1998). In this manner, statistical consistency over a century-long record on global scales is achieved at the cost of smoothing out some of the variability at the shorter spatial and temporal scales.

When EOF analysis is performed on the century-long global SST anomalies of Kaplan et al. (1998) the dominant modes of variability are the interannual ENSO and the global warming signal (e.g., Enfield and Mestas-Nuñez, 2000). In the intermediate band between interannual changes and global warming, there occur interdecadal and multidecadal modes with spatial patterns showing scales from basin to global. To extract this interdecadal/multidecadal variability from the Kaplan et al. (1998) dataset, it is convenient to estimate first the global ENSO mode using complex EOFs to account for phase propagation (Enfield and Mestas-Nuñez, 1999; Mestas-Nuñez and Enfield, 2001). Once the ENSO mode and a linear trend are removed from the data, EOF analysis can be used to describe the interdecadal and multidecadal variability. These modes tend to be centered on a given basin with the Pacific dominated by interdecadal variability and the Atlantic by multidecadal variability, but interaction between basins is also evident (Mestas-Nuñez and Enfield, 1999).

Mestas-Nuñez and Enfield (1999) found four rotated EOF modes with significant loadings in the Pacific in the interdecadal/multidecadal band and named them accordingly to where they had larger amplitudes and their temporal scales: Eastern North Pacific interdecadal (see also, Wu and Liu, 2003), eastern tropical Pacific interdecadal, central tropical Pacific interdecadal, and North Pacific multidecadal (see also, Wu et al., 2003). All of them show some similarity to the canonical cold central, warm eastern Pacific structure of Namias (1972). However, Mestas-Nuñez and Enfield (1999) attributed the Eastern North Pacific interdecadal mode as the one that captured the core essence of the Pacific interdecadal variability described in many papers (e.g., Miller et al., 1994b; Trenberth and Hurrell, 1994; Deser et al., 1996; Latif and Barnett, 1996; Mantua et al., 1997; Nakamura et al., 1997; Zhang et al., 1997; Giese and Carton, 1999) and which is commonly referred to as Pacific Decadal Oscillation (PDO) after Mantua et al. (1997) who coined the name. Other names that are used in the literature are “ENSO-like” (Zhang et al., 1997) and Interdecadal Pacific Oscillation or IPO (Power et al., 1999).

To focus on the eastern tropical Pacific and on the contrast between ENSO and interdecadal variability, Mestas-Nuñez and Enfield (2001) use the index approach with different versions of the Niño-3 index. The

ENSO patterns were constructed by composites of global SST, sea level pressure (SLP), and surface wind vector anomalies on a Niño-3 time series reconstructed from the leading global complex EOF of interannual SST anomalies (Fig. 1). For the composite surface patterns they use the University of Wisconsin–Milwaukee version of COADS that covers the 1945–1993 period (da Silva et al., 1994). The spatial patterns associated with the interdecadal component were obtained in the same way but using the decadal component of the Niño-3 index (Fig. 3). These ENSO and interdecadal patterns of SST, SLP and surface winds agree well with interannual and interdecadal surface regression patterns estimated by Zhang et al. (1997, see their Figs. 12 and 11, respectively). Interdecadal patterns of SST and SLP like those of Fig. 3 also emerge as one of the leading SVD modes of the covariance of these variables after they have been smoothed with a 5-yr running mean (Kaplan et al., 2000).

The ENSO SST pattern (Fig. 1a) has larger amplitudes in the Equatorial Pacific and out-of-phase variability in the central North and South Pacific. The interdecadal SST pattern in Fig. 3a has similarities as well as differences with the ENSO pattern in Fig. 1a. The main similarity is the large-scale structure with opposite phases in the tropical/eastern Pacific and the extratropical regions of the central Pacific in both hemispheres. The main difference is in the equatorial region of the eastern tropical Pacific, where the ENSO pattern has a maximum (Fig. 1a), but the decadal pattern has a relative minimum (Fig. 3a). This has important climatic implications, as we will discuss in Section 3.2. The interdecadal pattern in Fig. 3a, however, shows significant amplitudes in a latitudinal band that extends westward from the Peru–Chile upwelling area to the interior of the eastern tropical Pacific and a significant localized maximum near the Costa Rica Dome.

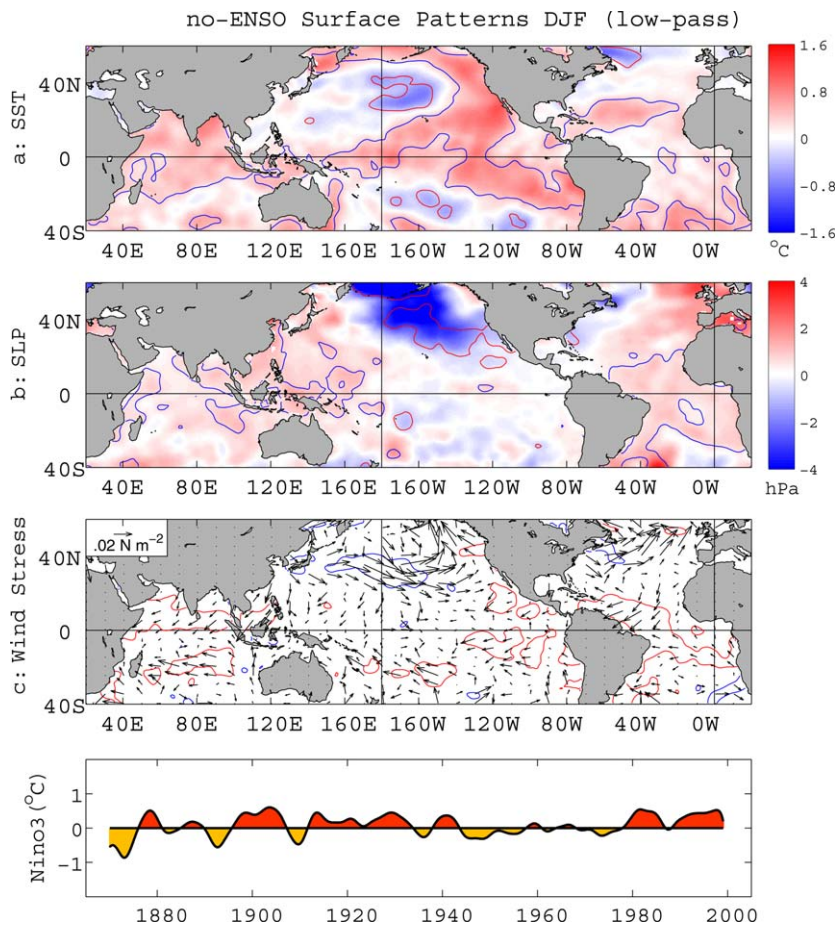


Fig. 3. As in Fig. 1, but for the DJF averages of the low-pass component of the non-ENSO Niño-3 time series (bottom panel).

It is worth noting that the interdecadal SST pattern in Fig. 3a differs somewhat from the PDO pattern shown in Mantua et al. (1997), but some of the differences may come from the different time periods and SST datasets used. For better comparison, we have correlated both Mantua et al. (1997) and Mestas-Nuñez and Enfield (2001) indices with the Kaplan et al. (1998) SSTs for the same (1945–1993) period in Fig. 4a and b, respectively. The relative minimum in the eastern tropical Pacific is not so evident in Fig. 4a as it is in Figs. 3a and 4b. In fact, Fig. 4a shows larger correlation values overall in the Pacific, particularly in the northern latitudes. Despite the differences with Mantua et al. (1997), the Mestas-Nuñez and Enfield (2001) interdecadal SST pattern agrees better with many other representations of Pacific interdecadal variability found in the literature (Latif and Barnett, 1996; Zhang et al., 1997; Garreaud and Battisti, 1999; Mestas-Nuñez and Enfield, 1999; Tourre et al., 2001). We believe that the differences in the patterns have to do with the way in which Mantua et al. define the PDO (i.e. the leading EOF of North Pacific SST anomalies north of 20°N). Because their definition is based on unrotated modes of unfiltered SST anomalies, their pattern is likely to be contaminated by modes other than the interdecadal, including ENSO that has larger amplitudes along the equatorial Pacific and the North Pacific multidecadal mode that has larger amplitudes in the extratropical North Pacific. Indeed the interannual and multidecadal nature of the Mantua et al. PDO index time series is evident in Fig. 4 (bottom panel).

Regarding the surface atmospheric associations with the Pacific interdecadal variability and ENSO, the Pacific interdecadal variability also has a SLP (Fig. 3b) and a surface wind pattern (Fig. 3c) that are broadly similar to the corresponding ENSO patterns (Fig. 1b and c) on the large scale. In the eastern tropical Pacific, however, there are mostly insignificant pressure anomalies and even a weak local high-pressure anomaly,

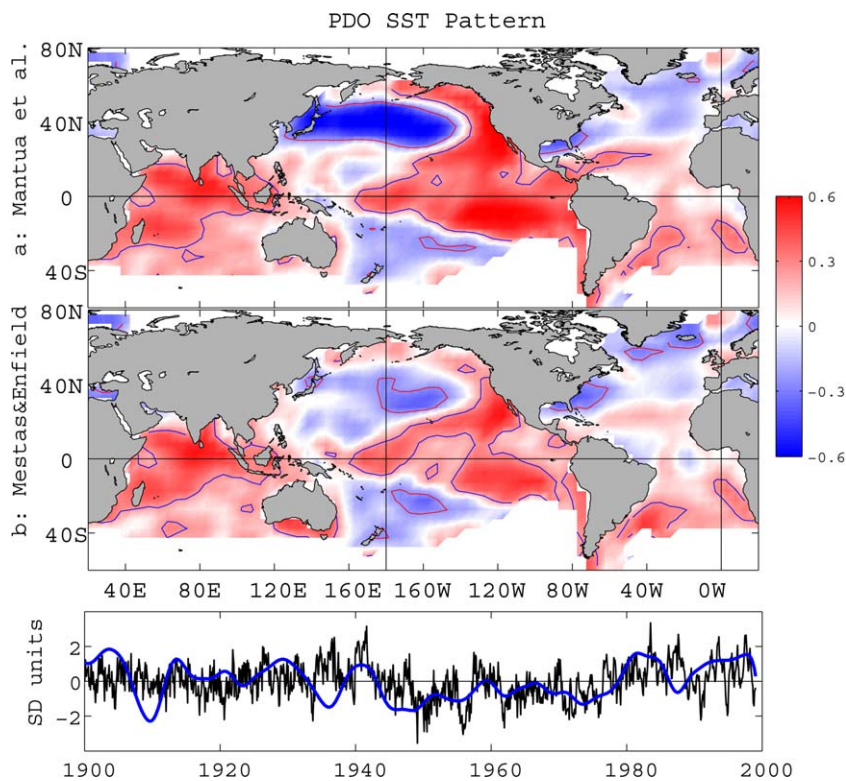


Fig. 4. The bottom panel shows the Mantua et al. (1997) (thin black) and the Mestas-Nuñez and Enfield (2001) (thick blue, same as in bottom of Fig. 3 but normalized) monthly indices of Pacific interdecadal variability in standard deviation units for the period January 1900–January 1999. The top (a) and (b) panels show the correlation patterns constructed using these respective indices and the Kaplan et al. (1998) SST dataset for the shorter 1945–1993 period of the COADS observations used in Figs. 1 and 3. The blue (red) contour indicates the + (–) 0.25 correlation. The Mantua et al. index was obtained from the web-site <http://jisao.washington.edu/pdo/PDO.latest> maintained by the Joint Institute for the Study of the Atmosphere and Oceans at the University of Washington.

rather than the equatorial low-pressure anomalies associated with ENSO. The zonal easterly wind anomaly band that is typically at the equator for ENSO is split in two easterly bands just north and south of the equator for the interdecadal zonal wind anomalies (Fig. 3c).

3.2. Tropospheric

Study of the tropospheric signature of the interdecadal variability and how it compares to ENSO can be done using the 50-year record (1949–1950 to 1998–1999) of the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) atmospheric reanalyses and the same SST Niño-3 indices of ENSO and interdecadal variability used in Section 3.1 (Mestas-Nuñez and Enfield, 2001). The reanalyses are constructed by assimilating surface and tropospheric observations into an atmospheric numerical model (Kalnay et al., 1996). In Fig. 5 we show the tropospheric ENSO patterns of Mestas-Nuñez and Enfield (2001) at the lower (850 hPa, Fig. 5a), upper (200 hPa, Fig. 5b) and mid (500 hPa, Fig. 5c) tropo-

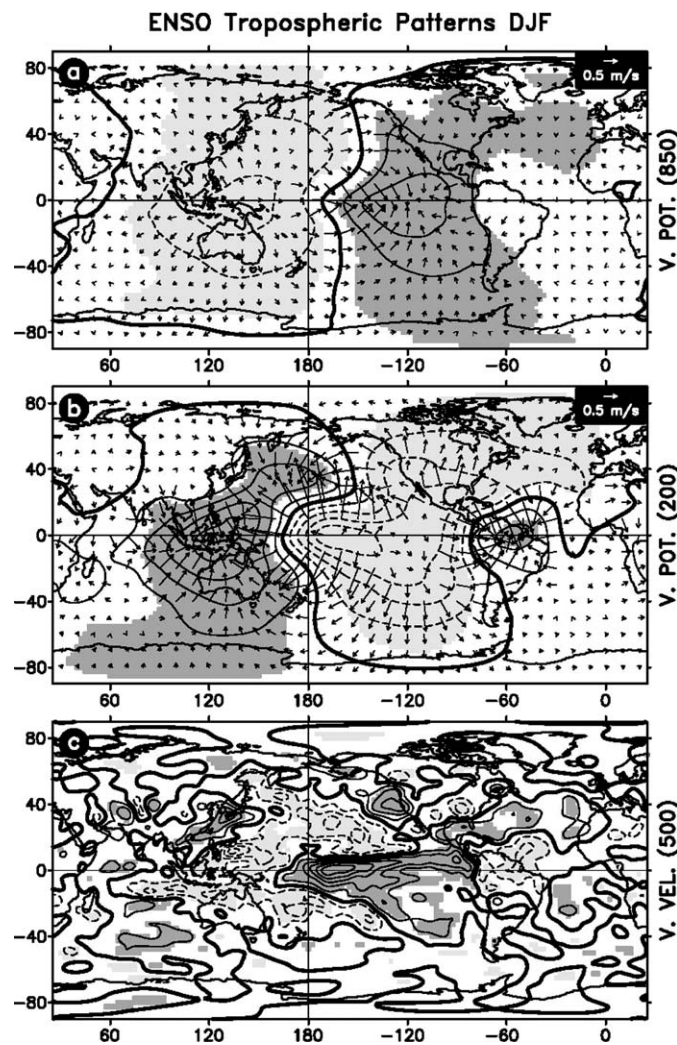


Fig. 5. Differences between composite averages with respect to the time series in the bottom panel of Fig. 1 for velocity potential and divergent components of the wind at: (a) 850 hPa and (b) 200 hPa and (c) pressure vertical velocity scaled by (-1) so that positive velocities (solid contours) indicate upward motions. The contour intervals for velocity potential and pressure vertical velocity are $8 \times 10^5 \text{ m}^2 \text{ s}^{-1}$ and $8 \times 10^{-3} \text{ Pa s}^{-1}$, respectively. Significant positive (negative) differences in velocity potential and vertical velocity are heavily (lightly) shaded.

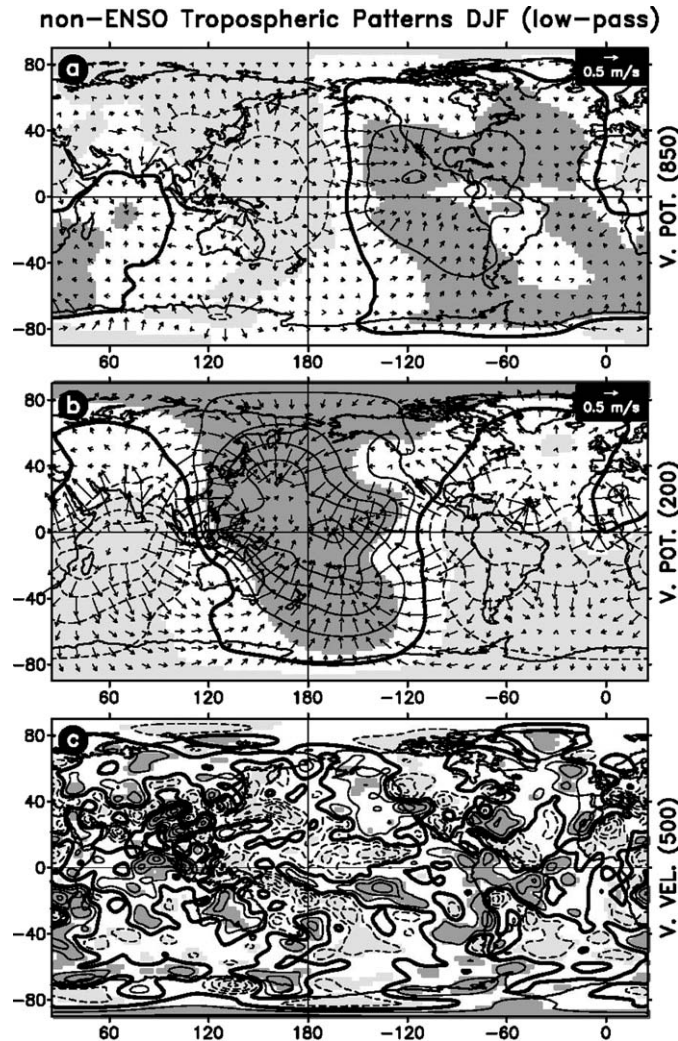


Fig. 6. Same as Fig. 5 but for the non-ENSO low-passed component of the Niño-3 time series (bottom panel of Fig. 3).

sphere. The velocity potential³ is used as a measure of the large-scale circulation because it is the only part of the wind that contributes to vertical motions and thus may help identify tropospheric teleconnections. The arrows in Fig. 5a and b indicate the divergent component of the wind at 850 and 200 hPa, calculated as the gradient of the respective velocity potential fields. The three contour patterns in Fig. 5 are obtained by the difference of composites (warm minus cold) of the corresponding reanalysis fields on the interannual Niño-3 time series shown in the bottom panel of Fig. 1.

The tropospheric interdecadal patterns of Mestas-Nuñez and Enfield (2001) are shown in Fig. 6 which are constructed as in Fig. 5, but using the Pacific interdecadal index shown in the bottom panel of Fig. 3. At the lower level (Fig. 6a) the interdecadal pattern is similar to the ENSO pattern (Fig. 5a). However the convergence center over the eastern tropical Pacific is now split into two off-equatorial convergence regions with a stronger northern branch off the North American coast. This is consistent with the structure of the SST pattern in Fig. 3a because the warmer interdecadal SST anomalies and the associated regions of surface convergence and mid-troposphere upward motion are located off the equator in that region with warmer anomalies

³ The velocity potential is a scalar function with its gradient equal to the divergent component of the wind. The divergent wind vectors are everywhere normal to the lines of constant velocity potential.

in the northern hemisphere. The 200-hPa pattern (Fig. 6b) is very different from the corresponding ENSO pattern (Fig. 5b); being shifted about 90° to the east relative to the ENSO signal. The 200-hPa pattern is also very strongly divergent over northern South America, which is opposite to ENSO. The 500 hPa vertical velocity (Fig. 6c) does not show the strong upward motion seen with ENSO on the equator east of the dateline. Alternatively, areas of strong uplift are seen just east and south of the equator and over the Amazonian region. Note that for ENSO the Amazonian region corresponds to an area of subsidence. Altogether, the Walker and Hadley circulations of the interdecadal and ENSO components are quite different in terms of the zonal flows and the polarities of the divergence centers. The implication is that ENSO and interdecadal variabilities in the eastern tropical Pacific may have nearly opposite impacts on far field regional climates based on their respective phases within the Niño-3 region.

3.3. Subsurface

Describing the subsurface structure of the interdecadal variability is problematic because there are fewer observations available there than at the sea surface. Satellites cannot “see” beyond the ocean surface and the researcher must rely on in situ observations. In the tropical Pacific, the Tropical Atmosphere Ocean (TAO) mooring array provides in situ subsurface and surface observations since about 1984, but similar arrays are not available poleward of about 10° latitude. Most of the available data are temperature-depth profiles from ships of opportunity (e.g., Levitus and Boyer, 1994). A new global program (Argo, www-argo.ucsd.edu) using subsurface drifters is underway that may provide valuable observations of temperature and salinity for future studies.

The available subsurface observations reveal decadal signals in the upper 400 m that subduct in the North Pacific and propagate southward in the thermocline (Deser et al., 1996). Furthermore Zhang et al. (1998, 1999) suggested that a subsurface warm anomaly generated in the regime shift of the mid 1970s in the North Pacific Ocean might have influence of El Niño in the 1980s. They proposed that a warm anomaly penetrated as subducted subtropical waters and was advected into the tropics, affecting the tropical thermocline and driving the formation of a warm surface anomaly. However, Schneider et al. (1999) analyzed the subsurface data and found that mid-latitude warm anomalies do not appear to reach the equator with sufficient strength to affect the tropical circulation.

A recent study of decadal changes in ocean circulation in the tropical and subtropical Pacific by McPhaden and Zhang (2002) has found a slowdown in the wind-driven meridional overturning cells in the upper North and South Pacific Oceans. They observed a 25% decrease in the transport convergences and a commensurate 0.8°C increase in the temperature of tropical surface waters over the past 25 years that corresponded with the 1976–1977 climate shift (Miller et al., 1994a). This finding supports an alternative hypothesis that has been proposed to explain decadal modulations of ENSO (Kleeman et al., 1999) and which is discussed in Section 4.

4. Models and mechanisms

There are several mechanisms that have been proposed to explain the observed interdecadal variability in the Pacific sector. We will summarize them here as those of tropical origin, those that involve tropical–extratropical interaction, and those of extratropical origin.

4.1. Tropical origin

Interdecadal climate variability in the Pacific sector is often linked to source mechanisms contained within the tropics. If tropical interdecadal variability is indeed present, the tropics can then impose its own long-term variability on extratropical regions via atmospheric and oceanic teleconnections (see Section 4.2). A tropical origin for interdecadal variability also has the benefit of explaining the equatorially symmetric components of the observed interdecadal variations because atmospheric and oceanic teleconnections have many equatorially symmetric characteristics.

Numerous mechanisms have been proposed as models for tropical Pacific interdecadal variability. In principle, this variability can be explained simply by the tropical Pacific wind variability using a linear model that

simulates only baroclinic waves (Karspeck and Cane, 2002). Interdecadal variations also occur in the same type of model that is often invoked to explain ENSO variations (Karspeck et al., 2004). This is the so-called delayed oscillator model that suggests that baroclinic Rossby waves propagate westward to the western boundary (with a delay of years) and reflect as equatorial Kelvin waves that switch the phase of ENSO. Generating interdecadal variations requires Rossby waves to propagate at higher latitudes than those associated with ENSO (Lysne et al., 1997; White et al., 2003) or with higher vertical baroclinic mode structures, such as a three layer, rather than two layer, model ocean (Liu et al., 2002; Moon et al., 2004).

Interdecadal equatorial thermocline oscillations are also possible in linear shallow-water or quasi-geostrophic ocean models when thermocline adjustments at middle latitudes are included in the so-called basin mode theories (Cessi and Louazel, 2001; Cessi and Primeau, 2001; Jin, 2001; Liu, 2003; Spydell and Cessi, 2003; Yang and Liu, 2003). Westward propagating long Rossby waves forced by interdecadal wind-stress curl anomalies transit the basin slowly and enter the western boundary region where gravity or Kelvin-like waves rapidly send the pressure signal around the basin and back to the eastern boundary. There, long Rossby waves are radiated, completing the resonance loop. These basin-mode theories, however, require very weak dissipative effects in both the ocean interior and in the coastal boundary layers, which seems unlikely in nature. Fundamentally non-linear theories can also produce decadal timescales in simple models (Tziperman et al., 1995; Chang et al., 1996; Timmerman and Jin, 2002; Timmerman, 2003). It is, however, unclear if any of these equatorially based models are relevant in explaining observed interdecadal variations or even those that occur in full-physics global coupled models.

4.2. Tropical–extratropical interactions

Deterministic forcing from the tropics clearly has an effect in establishing decadal SST variability in the middle latitudes. The forcing of the dominant mid-latitude SST pattern in the central North Pacific (around the subtropical front) and the eastern North Pacific (along the North American West Coast) has long been linked to atmospheric teleconnections from the tropics associated with ENSO events on interannual timescales (Alexander et al., 2002). Miller and Schneider (2000) termed this characteristic structure the “canonical SST pattern” because of its historical importance and because it can be concisely explained as direct, surface-forced response to Aleutian Low variations. The forcing of the second mid-latitude SST pattern in the Kuroshio/Oyashio Extension region (around the subarctic front) is only weakly linked to tropical teleconnections. The independent behavior of the Kuroshio/Oyashio Extension SST has been clarified through its enhanced decadal variance relative to the canonical SST pattern (Deser and Blackmon, 1995; Nakamura et al., 1997) and through its links to decadal wind-stress curl forcing (Deser et al., 1996; Miller et al., 1998; Deser et al., 1999). Both of these SST patterns project onto the PDO pattern, which should be considered as an amalgam of the canonical SST and Kuroshio/Oyashio SST patterns that are forced by different physical processes.

Recent studies (Newman et al., 2003) with a simple first-order Markov model reveal that a large part of the PDO index is explicable in terms of atmospheric forcing from tropical teleconnections. They use a Hasselmann (1976) type simple model with forcing specified by the tropical SST index, a damping rate specified by SST persistence (with re-emergence as in Deser et al., 2003) and stochastic atmospheric forcing (simulating mid-latitude weather). The forcing with tropical origins (Deser et al., 2004) clearly drives a large part of the canonical SST pattern portion of the PDO, in the sense of a reddened ENSO spectrum. However, the simple model result is somewhat deficient in decadal timescale energy. This suggests that the Kuroshio/Oyashio Extension SST pattern portion of the PDO is not simply driven by (or at least is not in phase with) this tropical forcing. Adding a lagged Kuroshio/Oyashio Extension response pattern, mimicking the gyre-scale spin-up delay, may improve the fit of the Newman et al. (2003) simple model. Alternatively, ocean-atmosphere feedbacks or other remote forcing may be the reason for extra energy at interdecadal timescales. Nonetheless, the simple model of Newman et al. (2003) is a reasonable null hypothesis of mid-latitude decadal variability against which other more sophisticated models must be compared.

Associated with atmospheric teleconnections are oceanic teleconnections via Kelvin wave-like disturbances emanating from the tropics, moving northwards along the North American coast and radiating Rossby waves into the interior North Pacific (Jacobs et al., 1994; Meyers et al., 1996; Clarke and Lebedev, 1999). These oceanic teleconnections mainly affect the thermocline and coastal sea level (Chelton and Davis, 1982) but appear

to have little influence on interdecadal SST, except very close to the eastern boundary. Along the eastern boundary, this physical linkage between the tropics and extratropics can exert a strong effect on the oceanic ecosystem through changes in coastal upwelling and in the thermocline depth distribution and subsurface temperature (Bograd and Lynn, 2001; Chavez et al., 2002). In the interior, the local and remote atmospheric forcing overwhelms the interdecadal SST signal from the oceanic planetary waves (Wu and Liu, 2003).

In contrast to tropical processes forcing mid-latitude interdecadal variability, mid-latitude processes may as well drive tropical interdecadal variability. Changes in the temperature of water subducted north of Hawaii and advected into the thermocline may influence the temperature of water upwelled along the equator (Gu and Philander, 1997). Variations in spiciness⁴ along tropical-subtropical subduction paths can occur in a full-physics coupled model in what appears to be a coupled mode involving subtropical wind stress curl driving spiciness changes in the thermocline (Schneider, 2000). The spiciness changes in water upwelled along the equator can alter both the mean state of the tropical coupled ocean-atmosphere system as well as the magnitude and frequency of ENSO variations (Schneider, 2004). This type of tropical-subtropical interaction is a modified version of the Gu and Philander (1997) hypothesis that was originally proposed to link surface-forced SST of the mid-latitude North or South Pacific to the tropical thermocline via equatorward subduction along isopycnal surfaces. While neither observations (Schneider et al., 1999) nor full-physics coupled models seem to contain oscillations explicable in terms of the original Gu-Philander theoretical framework, various other related pathways are still under investigation. A related hypothesis links the strength of the wind-driven overturning circulation with tropical warming (cooling) caused by decrease (increase) of equatorial upwelling (Kleeman et al., 1999) and this hypothesis seems to be consistent with observations (McPhaden and Zhang, 2002), as noted in Section 3.3.

4.3. Extratropical origin

Early simple climate models treated SST as a response to stochastic forcing by the atmosphere, which represent high-frequency daily weather fluctuations (Hasselmann, 1976; Frankignoul and Hasselmann, 1977). The spectral response of SST exhibited a general enhancement of energy at interdecadal frequencies due to an assumed linear damping term, which mimicked a thermal feedback to the atmosphere. These simple models provide a remarkably good explanation of the spectra of observed oceanic variables in middle latitudes. Because these models are so simple, they are often referred to as zero-order models of decadal variability. More sophisticated versions of these stochastic models allow for ocean current response (Frankignoul et al., 1997), atmospheric response to the SST feedback (Barsugli and Battisti, 1998) and advective ocean-atmosphere interaction (Saravanan and McWilliams, 1998). Major deviations from these simple spectral models that allow significant ocean-atmosphere feedbacks are the subject of an increasing number of theoretical investigations.

The mid-latitude ocean may generate feedbacks to the overlying atmosphere resulting in increased stochastic oceanic variance at decadal timescales or possibly resulting in coupled ocean-atmosphere decadal modes. These mid-latitude modes may consequently influence the tropical Pacific SST and ocean circulation through forcing by atmospheric and oceanic teleconnections (Barnett et al., 1999; Pierce et al., 2000; Vimont et al., 2001; Solomon et al., 2003). Latif and Barnett (1994) proposed the original mid-latitude mode hypothesis based on their analysis of a coupled model. They suggested that an enhancement of variance at 20-year timescales was due to a lagged response of the mid-latitude gyre to forcing by the atmosphere and subsequent ocean-to-atmosphere feedback. Hints of mid-latitude feedback processes have also been noted in several more recent modeling studies (e.g., Solomon et al., 2003; Wu and Liu, 2003).

Schneider et al. (2002) showed that the Kuroshio/Oyashio Extension SST field in the coupled model originally studied by Latif and Barnett (1994) does drive a local atmospheric response through surface heat fluxes. The atmospheric response was clearly seen in model rainfall fields over the ocean. But there was no evidence that this atmospheric response was part of a coupled mode as Latif and Barnett (1994) originally suggested.

⁴ Spiciness is the coordinate orthogonal to density on a T-S diagram, such that high spiciness indicates hot and salty water relative to water of the same density that is cooler and fresher.

Rossby waves, which adjust the gyre circulation, did allow the Kuroshio/Oyashio Extension region to respond with a several-year lag to wind-stress curl changes (Schneider and Miller, 2001; Qiu, 2003). It is important to note that the atmosphere is sensitive to changes in the Kuroshio/Oyashio Extension SST because the atmospheric storm tracks of the westerlies pass over this region (Peng et al., 1997). In contrast, the atmosphere is not very sensitive to the canonical SST pattern in Fig. 3a, which may simply represent a passive ocean response to the atmosphere.

5. Multidecadal variability and climate change

There is little evidence for multidecadal variability in the eastern tropical Pacific. From the rotated EOF analysis of the Kaplan et al. (1998) SST (Mestas-Nuñez and Enfield, 2001) multidecadal fluctuations were found mostly in the extratropical North Pacific through two modes: The North Pacific multidecadal mode and the Atlantic multidecadal mode. The North Pacific multidecadal mode has large loadings over the western North Pacific, very small out-of-phase loadings in the central tropical Pacific, and almost no signal in the eastern tropical Pacific. The Atlantic multidecadal mode has large amplitudes in the North Atlantic but it also shows large amplitudes in the Gulf of Alaska, suggesting the idea of a tropospheric bridge between the eastern North Pacific and the North Atlantic (Enfield and Mestas-Nuñez, 1999). This mode shows secondary in-phase variations in the South Pacific at about 20°S and very small loadings in the eastern tropical Pacific. The link between the North Atlantic and the South Pacific may take place through the troposphere as in the case of ENSO.

The small contribution of multidecadal timescales to the eastern tropical Pacific SST variability is evident in time series of the Niño-3 index from the Kaplan et al. (1998) data after removing ENSO. The non-ENSO Niño-3 is dominated by interdecadal variability (Fig. 3d) and there is little evidence of the long-term trend associated with global warming. However, when estimating the trend the uncertainties are large and depend on the dataset used (Hurrell and Trenberth, 1999). For example, estimates based on Kaplan et al. (1998) show negative and positive trends in the eastern tropical Pacific (Cane et al., 1997; Enfield and Mestas-Nuñez, 1999) and in contrast estimates from the United Kingdom Meteorological Office (UKMO) dataset (version GISST 2.3b) show only positive values (about 0.3–0.45 °C per century) in that region (Hurrell and Trenberth, 1999).

Hurrell and Trenberth (1999) point out that the analysis method of the Kaplan et al. (1998) SST reconstruction may not be suitable for studying the long-term trend. A more recent UKMO SST analysis combines Kaplan et al. (1998) and UKMO EOF reconstruction methods with an improved treatment of the long-term trend and give results more similar to the Kaplan et al. (1998) analysis than older UKMO versions (Rayner et al., 2003). This analysis further attempts to recover the smaller temporal and spatial scales lost by the EOF reconstruction by merging the reconstructed with the original data. Analysis of this and other improved SST datasets may bring new insights into the multidecadal and longer variability.

6. Summary and discussion

We have presented a review of climatic variability in the eastern tropical Pacific on timescales between interannual (ENSO) and the centennial trend that is associated with global warming. We focused on the interdecadal component of the variability but included a description of the longer multidecadal variability and of the centennial trend. A historical overview shows how the ideas about interdecadal fluctuations evolved from Namias's (1972) description of "regime" changes around the 1957 El Niño.

We summarized results from observational work that describes the space and time structure of the variability. The spatial patterns at the surface (Fig. 3) and in the troposphere (Fig. 6) have similarities to, as well as differences from, the corresponding ENSO patterns (Figs. 1 and 5). The large-scale structure is similar to ENSO with larger amplitudes in the tropical Pacific and out-of-phase variations in the central mid-latitude Pacific. The main differences between the ENSO and interdecadal patterns are over the eastern tropical Pacific. There the interdecadal variability in SST has larger amplitudes off the equator, shifting the centers of convergence and altering the middle and upper tropospheric circulation. Over most of the US the interdecadal and ENSO mid-tropospheric vertical velocity anomalies have the same sign, suggesting that decadal warm anomalies over the eastern tropical Pacific can reinforce ENSO impacts over the US (e.g., Gershunov and Barnett, 1998).

Additional research is needed to more fully understand the source and impacts of interdecadal climate variability in the Pacific. This can only be achieved through gathering extensive long-term observations in the key source and impact regions, including especially the tropical Pacific and the Kuroshio/Oyashio Extension region, and interpreting these observations with simple and complex modeling studies. This research must also include both physical and biological components, particularly since the oceanic ecosystem is so sensitive to these changes and can serve as an indicator of important climate changes.

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