# Pacific Decadal Variability and Central Pacific Warming El Niño in a Changing Climate

## Grant DE-SC0005111

## FINAL Report

## Period October 2010 to September 2015

**PIs:**

Niklas Schneider

Co-PIs: E. Di Lorenzo, K. Cobb, B. T. Anderson & D. J. Vimont

**NOAA Collaborator:**

M. A. Alexander

Funded by:

**Regional and Global Climate Modeling (RGCM) Program**

Climate and Environmental Sciences Division of the U.S. Department of Energy

Office of Science, Biological and Environmental Research (BER) program.

U.S. DEPARTMENT OF ENERGY

**Project PI D. Di Lorenzo prepared a final report for the entire collaborative project. This report augments in sections B (Summary, page 4), C (Report of Findings, page 5) and D (Publications, page 19) results specific to the University of Hawaii portion or not included in the Di Lorenzo compilation of the project.**

## (A) PROJECT OVERVIEW & GOALS

This project aimed at understanding how natural low-frequency modes of Pacific variability will respond to anthropogenic climate change. Recent work by the PIs has shown that decadal climate variability of the Pacific is only partially explained by the Pacific Decadal Oscillation (PDO). A better representation of the Pacific decadal climate dynamics must include the North Pacific Gyre Oscillation (NPGO), which is associated with basin- and regional-scale changes in ocean circulation, sea-surface temperatures, and ecosystem transitions. The El Niño Southern Oscillation (ENSO) drives an important fraction of both the PDO and NPGO variability. While the canonical eastern Pacific warming (EPW) El Niño drives a PDO response, new evidence suggests that the non-canonical central Pacific warming (CPW) El Niño (or 'Modoki') is dynamically linked to the NPGO. The IPCC AR4 climate model projections suggest that the frequency of CPW El Niño events will increase in response to climate change, suggesting that the NPGO variance will increase at the expense of the PDO. In the proposed research, we examine the dynamical relationship between these modes of low-frequency Pacific climate variability and anthropogenic climate change in both observations and climate models.

**The first research goal** of this proposal is to assess how the dynamics and statistics of the EPW/PDO and CPW/NPGO modes are represented in the IPCC AR4 and AR5 coupled climate models during the 20th century, and how these dynamics and statistics are projected to evolve under continued greenhouse forcing during the 21st century.

**The second research goal** of this proposal is to identify and quantify the statistical significance of any anthropogenic changes in CPW/NPGO variance with respect to natural variability, and identify the specific dynamics responsible for the CPW/NPGO's response to climate change.

This project brought together a diverse group of climate scientists that pursue these research goals using a wide range of methodologies designed to isolate, quantify and diagnose the effects of anthropogenic forcing on Pacific decadal climate variability. These methodologies include (a) linear inverse statistical techniques to examine the IPCC models (Di Lorenzo, Anderson, Schneider), (b) annually-resolved multi-proxy climate reconstructions over the last 300 years to examine the range of decadal and secular variations of the climate modes (Cobb, Di Lorenzo), and (c) targeted coupled climate model experiments to isolate specific mechanisms of the low-frequency modes' responses to climate change (Vimont, Alexander).

Overall, improved understanding of the historical, current, and future evolution of the NPGO and PDO will provide significantly enhanced predictability of decadal-scale variations that influence global weather and climate patterns, as well as marine ecosystems.

## (B) HYPOTHESES AND FRAMEWORK

In order to analyze the decadal climate variability in the IPCC models we developed a set of hypotheses or framework for diagnosing the climate variability of the models over the Pacific sector.

A synthesized understanding of the hypotheses underlying the mechanics of Pacific low-frequency variability and the links between the ocean/atmospheric modes of the Pacific are presented in the schematic of Figure 1. In this schematic there are two sets of dominant dynamics -- the EPW/PDO (red path) and CPW/NPGO (blue path), which are physically linked and connected through the ENSO system in the tropics. Both the PDO and NPGO are to first order the oceanic expressions of the atmospheric forcing associated with the AL and NPO variability, respectively, and therefore integrate the low-frequency variations of the EPW and CPW through atmospheric teleconnections from EPW→AL→PDO [Alexander, 1992; Alexander et al., 2002; Newman et al., 2003] and CPW→NPO→NPGO [Di Lorenzo et al., 2010]. A link also exists from the extra-tropics back to the tropics through the SFM by which NPO→CPW/EPW [Vimont et al., 2003; Anderson et al., 2003], giving rise to the potential for a feedback between tropics and extra-tropics along the path NPO→CPW→NPO. While the AL and NPO atmospheric forcings have maximum loading in the central and eastern North Pacific, their forcing also drives prominent decadal variations in the western North Pacific. Specifically, the oceanic adjustment to the SSHa anomalies of the AL/PDO and NPO/NPGO radiate Rossby waves that propagate into the western boundary. The arrival of the AL/PDO SSHa is associated with changes in the axis of the KOE [Miller and Schneider, 2000; Qiu et al., 2007], while the arrival of the NPO/NPGO SSHa modulates variations in the speed of the KOE [Ceballos et al., 2009]. These two modes of KOE variability – the KOE meridional mode (shift in axis) and the KOE Zonal mode (change in speed) – have been shown to capture the first two dominant modes of variability of SSHa in the KOE [Taguchi et al., 2007].

## (B) SUMMARY

The PODX project contributed to 21 peer-review publications. Below is an executive summary for the findings related to goals #1 and #2.

1) *Climate models used in the CMIP5 show important deficiencies in representing the dynamics of climate variability of the Pacific Ocean. Most notably the connection between the tropics (e.g. ENSO) and the extra-tropic (e.g. PDO, NPGO). In the extra-tropics the dynamics of the PDO are statistically consistent with observations and do not show any significant change in future climate. In contrast the dynamics of NPGO are not well reproduced. This miss-representation may be critical for accurate predictions of the Pacific Ocean response to climate change. The NPGO dynamics are linked to the central Pacific El Niño, and evidence suggest that the variance of the NPGO and the CPW are increasing with climate change. Future studies will have to (1) explore in further detail the dynamics that energize the CPW/NPGO system in the context of a varying mean state (e.g. climate change), and (2) better understand the*

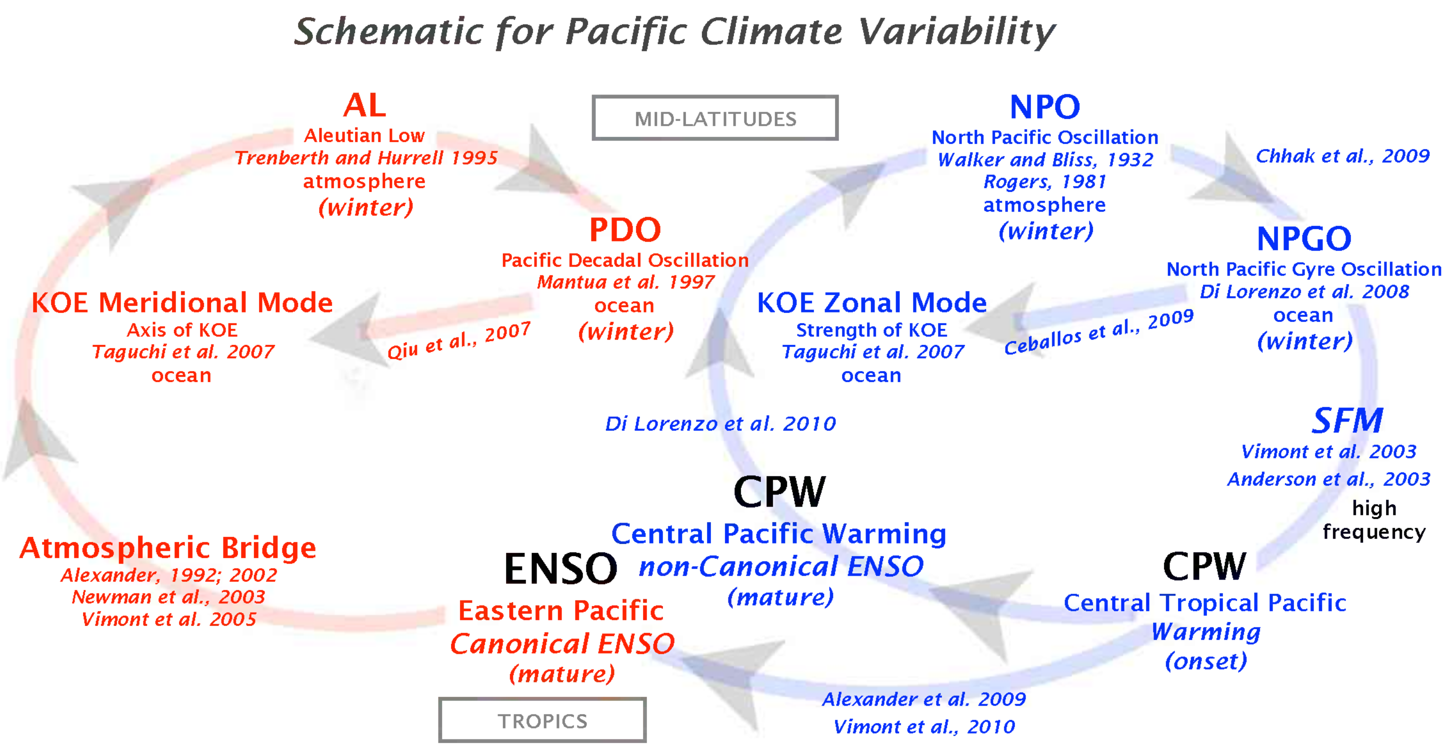


**Figure 1: Framework of Pacific Climate Variability.** This schematic shows the links between the ocean and atmospheric modes of low-frequency variability in the Pacific (see section *Framework of Pacific Climate Variability* for a detailed description).

*nature of the tropical/extra-tropical teleconnection dynamics in climate models.*

2) *Using simplified statistical models and proxy reconstruction of past climate variability we find evidence that the variance of El Niño in the 21st century is increasing. In particular, our findings suggest that the CPW/NPGO system will be energized as global surface temperature continue to rise. The dynamics underlying these changes are likely connected to the so called Meridional Modes (MM). These modes are characterized by positive thermodynamics feedback between the ocean and atmosphere in tropical basin that lead to amplification of sea surface temperature anomalies. These MM have been shown to be optimal excitation patterns for both the EP and CP ENSO. Future studies will have to explore climate model resolve the MM dynamics and understand their sensitivity to changes in mean state and changes in the statistics of atmospheric stochastic variability in the extra-tropics. Both of these two factors influence the MM and its impact on Pacific climate variability.*

***Further findings of University of Hawaii:*** *The team has contributed to two review articles on ENSO diversity (Capotondi et al. 2015) and on the PDO (Newman et al. 2015) that detail the state of the art on these important climate modes. We have explore impacts of changes in thermocline spiciness (density compensating temperature and salinity variations) on the evolution of ENSO (Grissom 2013). This line of inquiry is continuing with further results on the role of spiciness in decadal climate variability forthcoming. In the context of mid—latitude air-sea interaction, the atmospheric boundary layer response to SST* *fronts, such as found in the Kuroshio as part of the decadal North Pacific variability, was detailed in Schneider and Qiu (2015). The impact of the large scale atmospheric responses on decadal forecasts of the Kuroshio extension was explored in Qiu et al. (2014).*

## (C) REPORT of FINDINGS

We now report on individual scientific findings that form the basis for our summary statements.

*The PIs contributions are listed in each task and the year of publication is reported in parenthesis. The findings are listed in reverse chronological order.* ***Manuscript not reported in PI E. Di Lorenzo's final report are marked by *.***

### The Pacific Decadal Oscillation, revisited*

by M. Newman, M. A. Alexander, T. R. Ault, K. M. Cobb, C. Deser, E. Di Lorenzo, N. J. Mantua, A. J. Miller, S. Minobe, H. Nakamura, N. Schneider, D. J. Vimont, A. S. Phillips, J. D. Scott and C. A. Smith (2015, submitted)

The Pacific decadal oscillation (PDO), the dominant year-round pattern of monthly North Pacific sea surface temperature (SST) variability, is an important target of ongoing research within the meteorological and climate dynamics communities, and is central to the work of many geologists, ecologists, natural resource managers, and social scientists. Research over the last fifteen years has led to an emerging consensus: the PDO is not a single phenomenon, but is instead the result of a combination of different physical processes, including both remote tropical forcing and local North Pacific atmosphere/ocean interactions, which operate on different timescales to drive similar PDO-like SST anomaly patterns. How these processes combine to generate observed PDO evolution, including apparent regime shifts, is shown using simple autoregressive models of increasing spatial complexity. Simulations of recent climate in coupled GCMs are able to capture many aspects of the PDO, but do so based on a balance of processes often more independent of the Tropics than is observed. Finally, it is suggested that assessment of PDO-related regional climate impacts, reconstruction of PDO-related variability into the past with proxy records, and diagnosis of Pacific variability within coupled GCMs should all account for the effects of these different processes, which only partly represent direct forcing of the atmosphere by North Pacific Ocean SSTs.

### ENSO and Meridional Modes: A null hypothesis for Pacific climate variability*

Di Lorenzo, E., G. Liguori, N. Schneider, J. C. Furtado, B. T. Anderson and M. A. Alexander, (2015)

Pacific low-frequency variability (timescale > 8 year) exhibits a well-known El Niño-like pattern of basin-scale sea surface temperature, which is found in all the major modes of Pacific decadal climate. Using a set of climate model experiments and observations, we decompose the mechanisms contributing to the growth, peak and decay of the Pacific low-frequency spatial variance. We find that the El-Niño-like interdecadal pattern is established through the combined actions of Pacific Meridional Modes (MM) and the El Niño Southern Oscillation (ENSO). Specifically, in the growing phase of the pattern, sub-tropical stochastic excitation of the MM, and its ENSO-precursor dynamics, become an important source of tropical low-frequency variance (e.g. red noise). Once in the tropics, ENSO amplifies and distributes this low frequency energy in the extra-tropics through global teleconnections in the peak and decaying phases. In this stochastic red noise model of Pacific climate, the timescale of the MM/ENSO progression and extra-tropical decay (1-2 year) permits the stochastic excitation of the decadal and interdecadal variance.

## The atmospheric response to weak sea surface temperature fronts*

Schneider, N. and B. Qiu (2015)

The response of the atmospheric boundary layer to fronts of sea surface temperature (SST) is characterized by correlations betweenwind stress divergence and the downwind component of the SST gradient and between the wind stress curl and the crosswind component of the SST gradient. The associated regression (or coupling) coefficients for the wind stress divergence are consistently larger than those for the wind stress curl. To explore the underlying physics, the authors introduce a linearized model of the atmospheric boundary layer response to SST-induced modulations of boundary layer hydrostatic pressure and vertical mixing in the presence of advection by a background Ekman spiral. Model solutions are a strong function of the SST scale and background advection and recover observed characteristics. The coupling coefficients for wind stress divergence and curl are governed by distinct physics. Wind stress divergence results from either large-scale winds crossing the front or from a thermally direct, cross-frontal circulation. Wind stress curl, expected to be largest when winds are parallel to SST fronts, is reduced through geostrophic spin-down and thereby yields weaker coupling coefficients.

## Understanding ENSO Diversity*

Capotondi, A., A. T. Wittenberg, M. Newman, E. Di Lorenzo, J.-Y. Yu, P. Braconnot, J. Cole, B. Dewitte, B. Giese, E. Guilyardi, F.-F. Jin, K. Karnauskas, B. Kirtman, T. Lee, N. Schneider, Y. Xue, and S.-W. Yeh (2015)

The El Niño Southern Oscillation (ENSO) is a naturally occurring mode of tropical Pacific variability, with global impacts on society and natural ecosystems. While it has long been known that El Niño events display a diverse range of amplitudes, triggers, spatial patterns, and life cycles, the realization that ENSO's impacts can be highly sensitive to this event-to-event diversity is driving a renewed interest in the subject. This paper surveys our current state of knowledge of ENSO diversity, identifies key gaps in understanding, and outlines some promising future research directions.

## A coupled decadal prediction of the dynamic state of the Kuroshio Extension system*

Qiu, B., S. Chen, N. Schneider and B. Taguchi, (2014)

Being the extension of a wind-driven western boundary current, the Kuroshio Extension (KE) has long been recognized as a turbulent current system rich in large-amplitude meanders and energetic pinched-off eddies. An important feature emerging from recent satellite altimeter measurements and eddy-resolving ocean model simulations is that the KE system exhibits well-defined decadal modulations between a stable and an unstable dynamic state.Here the authors show that the decadally modulating KE dynamic state can be effectively defined by the sea surface height (SSH) anomalies in the 31–36N, 140-165E region. By utilizing the SSH-based KE index from 1977 to 2012, they demonstrate that the time-varying KE dynamic state can be predicted at lead times of up to ;6 yr. This long-term predictability rests on two dynamic processes: 1) the oceanic adjustment is via baroclinic Rossby waves that carry interior wind-forced anomalies westward into the KE region and 2) the low-frequency KE variability influences the extratropical storm tracks and surface wind stress curl field across the North Pacific basin. By shifting poleward (equator-ward) the storm tracks and the large-scale wind stress curl pattern during its stable (unstable) dynamic state, the KE variability induces a delayed negative feedback that can enhance the predictable SSH variance on the decadal time scales.

## Optimal growth of Central and East Pacific ENSO events

by Vimont, D. J., M. A. Alexander, and M. Newman (2014)

Central Pacific (CP)-type and Eastern Pacific (EP)-type El Nino and the Southern Oscillation (ENSO) events are investigated using linear inverse modeling. Optimal initial conditions and growth rates for CP or EP ENSO events are identified explicitly using a CP or EP ENSO norm. The dominant difference in initial conditions that lead to CP and EP ENSO events is the role of the second empirical orthogonal function of tropical sea surface temperature, which represents the Pacific Meridional Mode (PMM). Optimal initial conditions for CP-type ENSO events include warm SST anomalies in the central subtropical Pacific (a characteristic of the PMM) while optimal initial conditions for EP-type ENSO events are focused in the eastern equatorial Pacific and Southern Hemisphere subtropics along about 25 degrees S. Thermocline anomalies differ in initial structures and in their influence on SST for CP and EP events. Results point to different roles of the PMM and thermocline variations in the evolution of CP and EP ENSO events.

## Origin of Decadal-Scale, Eastward-Propagating Heat Content Anomalies in the North Pacific

by Taguchi, B., and N. Schneider (2014)

Upper ocean heat content (OHC) is at the heart of natural climate variability on interannual-to-decadal time scales, providing climate memory and the source of decadal prediction skill. In the midlatitude North Pacific Ocean, OHC signals are often found to propagate eastward as opposed to the frequently observed westward propagation of sea surface height, another variable that represents the ocean subsurface state. This dichotomy is investigated using a 150-yr coupled GCM integration. Simulated OHC signals are distinguished in terms of two processes that can support eastward propagation: higher baroclinic Rossby wave (RW) modes that are associated with density perturbation, and spiciness anomalies due to density-compensated temperature and salinity anomalies. The analysis herein suggests a unique role of the Kuroshio-Oyashio Extension (KOE) region as an origin of the spiciness and higher mode RW signals. Wind-forced, westward-propagating equivalent barotropic RWs cause meridional shifts of the subarctic front in the KOE region. The associated anomalous circulation crosses mean temperature and salinity gradients and thereby generates spiciness anomalies. These anomalies are advected eastward by the mean currents, while the associated surface temperature anomalies are damped by air-sea heat exchange. The accompanying surface buoyancy flux generates higher baroclinic, eastward-propagating RWs. The results suggest that the large OHC variability in the western boundary currents and their extensions is associated with the spiciness gradients and axial variability of oceanic fronts.

## The effect of low-frequency spiciness anomalies on the El Nino-Southern Oscillation*

By L. M. Grissom (2013) MS thesis

Low-frequency subsurface spiciness anomalies generated in the northern and southern subtropics of the Pacific Ocean advect geostrophically westward and equatorward where they often enter the equatorial undercurrent (EUC). Assuming the spiciness anomalies in each hemisphere are generated independently, the temperature gradient across the pycnocline, dT/dρ, may vary significantly on decadal time scales in the EUC as a result of convergent spiciness anomalies. Observations of dT/dρ from an eight-year time series of Argo float profile data show variability around the mean value of approximately 10% in the warm pool region where the EUC forms. Decadal variability may be significantly larger. As spiciness anomalies propagate east in the EUC, they may affect the sea surface temperature in the cold tongue region, which is sensitive to the subsurface temperature and vertical displacements of the pycnocline. Using a modified Zebiak-Cane ENSO model, the effect of dT/dρ variability on ENSO is studied. Results show that dT/dρ variability in the NINO3 region similar to that shown by Argo observations has a significant affect on ENSO variance; as dT/dρ increases (decreases), ENSO variance increases (decreases). This result is primarily due to an increase in the growth rate of ENSO resulting from an increase in the sensitivity of the thermocline feedback and the non-linearity of the system. These results indicate that for accurate forecasting of ENSO, low-frequency spiciness variability in the subtropical and western equatorial Pacific should be considered.

## Increasing variance in North Pacific climate relates to unprecedented ecosystem variability off California

by Sydeman, W. J., J. A. Santora, S. A. Thompson, B. Marinovic, and E. Di Lorenzo (2013)

Changes in variance are infrequently examined in climate change ecology. We tested the hypothesis that recent high variability in demographic attributes of salmon and seabirds off California is related to increasing variability in remote, large-scale forcing in the North Pacific operating through changes in local food webs. Linear, indirect numerical responses between krill (primarily Thysanoessa spinifera) and juvenile rockfish abundance (catch per unit effort (CPUE)) explained >80% of the recent variability in the demography of these pelagic predators. We found no relationships between krill and regional upwelling, though a strong connection to the North Pacific Gyre Oscillation (NPGO) index was established. Variance in NPGO and related central Pacific warming index increased after 1985, whereas variance in the canonical ENSO and Pacific Decadal Oscillation did not change. Anthropogenic global warming or natural climate variability may explain recent intensification of the NPGO and its increasing ecological significance. Assessing non-stationarity in atmospheric-environmental interactions and placing greater emphasis on documenting changes in variance of bio-physical systems will enable insight into complex climate-marine ecosystem dynamics.

## Decadal Response of the Kuroshio Extension Jet to Rossby Waves: Observation and Thin-Jet Theory

by Sasaki, Y. N., S. Minobe, and N. Schneider (2013)

This study examines interannual to decadal variability of the Kuroshio Extension (KE) jet using satellite altimeter observations from 1993 to 2010. The leading empirical orthogonal function (EOF) mode of sea level variability in the KE region represents the meridional shift of the KE jet, followed by its strength changes with a few month lag. This shift of the KE jet lags atmospheric fluctuations over the eastern North Pacific by about three years. Broad sea level anomalies (SLAs) emerge in the eastern North Pacific 3-4 years before the upstream KB jet shift, and propagate westward along the KE jet axis. In the course of the propagation, the meridional scale of the SLAs gradually narrows, and their amplitude increases. This westward propagation of SLAs with a speed of about 5 cm s(-1) is attributed to the westward propagation of the meridional shift of the jet, consistent with the thin-jet theory, whose importance has been suggested by previous numerical studies. In addition, the westward-propagating signals tend to conserve their quasigeostrophic potential vorticity anomaly, which may explain the characteristic changes of SLAs during the propagation. After the westward-propagating signals of positive (negative) SLAs reach at the east coast of Japan, the upstream KB jet strengthens (weakens) associated with the strength changes of the northern and southern recirculation gyres. Interestingly, this strength change of the KE jet propagates eastward with a speed of about 6 cm s(-1), suggesting an importance of advection by the current.

## Estimating Central Equatorial Pacific SST Variability over the Past Millennium. Part II: Reconstructions and Implications

by Emile-Geay, J., K. M. Cobb, M. E. Mann, and A. T. Wittenberg (2013)

Reducing the uncertainties surrounding the impacts of anthropogenic climate change requires vetting general circulation models (GCMs) against long records of past natural climate variability. This is particularly challenging in the tropical Pacific Ocean, where short, sparse instrumental data preclude GCM validation on multidecadal to centennial time scales. This two-part paper demonstrates the application of two statistical methodologies to a network of accurately dated tropical climate records to reconstruct sea surface temperature (SST) variability in the Nino-3.4 region over the past millennium. While Part I described the methods and established their validity and limitations, this paper presents several reconstructions of Nino-3.4, analyzes their sensitivity to procedural choices and input data, and compares them to climate forcing time series and previously published tropical Pacific SST reconstructions. The reconstructions herein show remarkably similar behavior at decadal to multidecadal scales, but diverge markedly on centennial scales. The amplitude of centennial variability in each reconstruction scales with the magnitude of the A. D. 1860-1995 trend in the target dataset's Nino-3.4 index, with Extended Reconstructed SST, version 3 (ERSSTv3) > the Second Hadley Centre SST dataset (HadSST2) > Kaplan SST; these discrepancies constitute a major source of uncertainty in reconstructing preinstrumental Nino-3.4 SST. Despite inevitable variance losses, the reconstructed multidecadal variability exceeds that simulated by a state-of-the-art GCM (forced and unforced) over the past millennium, while reconstructed centennial variability is incompatible with constant boundary conditions. Wavelet coherence analysis reveals a robust antiphasing between solar forcing and Nino-3.4 SST on bicentennial time scales, but not on shorter time scales. Implications for GCM representations of the tropical Pacific climate response to radiative forcing are then discussed.

## Estimating Central Equatorial Pacific SST Variability over the Past Millennium. Part I: Methodology and Validation

by Emile-Geay, J., K. M. Cobb, M. E. Mann, and A. T. Wittenberg (2013)

Constraining the low-frequency (LF) behavior of general circulation models (GCMs) requires reliable observational estimates of LF variability. This two-part paper presents multiproxy reconstructions of Nino-3.4 sea surface temperature over the last millennium, applying two techniques [ composite plus scale (CPS) and hybrid regularized expectation maximization (RegEM) truncated total least squares (TTLS)] to a network of tropical, high-resolution proxy records. This first part presents the data and methodology before evaluating their predictive skill using frozen network analysis (FNA) and pseudoproxy experiments. The FNA results suggest that about half of the Nino-3.4 variance can be reconstructed back to A. D. 1000, but they show little LF skill during certain intervals. More variance can be reconstructed in the interannual band where climate signals are strongest, but this band is affected by dating uncertainties (which are not formally addressed here). The CPS reliably estimates interannual variability, while LF fluctuations are more faithfully reconstructed with RegEM, albeit with inevitable variance loss. The RegEM approach is also tested on representative pseudoproxy networks derived from two millennium-long integrations of a coupled GCM. The pseudoproxy study confirms that reconstruction skill is significant in both the interannual and LF bands, provided that sufficient variance is exhibited in the target Nino-3.4 index. It also suggests that FNA severely underestimates LF skill, even when LF variability is strong, resulting in overly pessimistic performance assessments. The centennial-scale variance of the historical Nino-3.4 index falls somewhere between the two model simulations, suggesting that the network and methodology presented here would be able to capture the leading LF variations in Nino-3.4 for much of the past millennium, with the caveats noted above.

## Synthesis of Pacific Ocean Climate and Ecosystem Dynamics

by Di Lorenzo, E., et al. (2013)

The goal of the Pacific Ocean Boundary Ecosystem and Climate Study (POBEX) was to diagnose the large-scale climate controls on regional transport dynamics and lower trophic marine ecosystem variability in Pacific Ocean boundary systems. An international team of collaborators shared observational and eddy-resolving modeling data sets collected in the

Northeast Pacific, including the Gulf of Alaska (GOA) and the California Current System (CCS), the Humboldt or Peru-Chile Current System (PCCS), and the Kuroshio-Oyashio Extension (KOE) region. POBEX investigators found that a dominant fraction of decadal variability in basin- and regional-scale salinity, nutrients, chlorophyll, and zooplankton taxa is explained by a newly discovered pattern of ocean-climate variability dubbed the North Pacific Gyre Oscillation (NPGO) and the Pacific Decadal Oscillation (PDO). NPGO dynamics are driven by atmospheric variability in the North Pacific and capture the decadal expression of Central Pacific El Ninos in the extratropics, much as the PDO captures the low-frequency expression of eastern Pacific El Ninos. By combining hindcasts of eddy-resolving ocean models over the period 1950-2008 with model passive tracers and long-term observations (e.g., CalCOFI, Line-P, Newport Hydrographic Line, Odate Collection), POBEX showed that the PDO and the NPGO combine to control low-frequency upwelling and alongshore transport dynamics in the North Pacific sector, while the eastern Pacific El Nino dominates in the South Pacific. Although different climate modes have different regional expressions, changes in vertical transport (e.g., upwelling) were found to explain the dominant nutrient and phytoplankton variability in the CCS, GOA, and PCCS, while changes in alongshore transport forced much of the observed long-term change in zooplankton species composition in the KOE as well as in the northern and southern CCS. In contrast, cross-shelf transport dynamics were linked to mesoscale eddy activity, driven by regional-scale dynamics that are largely decoupled from variations associated with the large-scale climate modes. Preliminary findings suggest that mesoscale eddies play a key role in offshore transport of zooplankton and impact the life cycles of higher trophic levels (e.g., fish) in the CCS, PCCS, and GOA. Looking forward, POBEX results may guide the development of new modeling and observational strategies to establish mechanistic links among climate forcing, mesoscale circulation, and marine population dynamics.

## Highly Variable El Nino-Southern Oscillation Throughout the Holocene

by Cobb, K. M., N. Westphal, H. R. Sayani, J. T. Watson, E. Di Lorenzo, H. Cheng, R. L. Edwards, and C. D. Charles (2013)

The El Nino-Southern Oscillation (ENSO) drives large changes in global climate patterns from year to year, yet its sensitivity to continued anthropogenic greenhouse forcing is uncertain. We analyzed fossil coral reconstructions of ENSO spanning the past 7000 years from the Northern Line Islands, located in the center of action for ENSO. The corals document highly variable ENSO activity, with no evidence for a systematic trend in ENSO variance, which is contrary to some models that exhibit a response to insolation forcing over this same period. Twentieth-century ENSO variance is significantly higher than average fossil coral ENSO variance but is not unprecedented. Our results suggest that forced changes in ENSO, whether natural or anthropogenic, may be difficult to detect against a background of large internal variability.

## Triggering of El Nino onset through trade wind-induced charging of the equatorial Pacific

by Anderson, B. T., R. C. Perez, and A. Karspeck (2013)

Sea surface temperature variations over the equatorial Pacific associated with the El Nino/ Southern Oscillation (ENSO) produce changes in climates across the globe. Here we report evidence from observationally constrained ocean data for the initiation of warm ENSO events (El Ninos) resulting from subsurface equatorial Pacific heat content increases related to tropical/extratropical sea level pressure (SLP) changes over the North Pacific. We hypothesize that the increase in heat content is a response to SLP-generated variations in the North Pacific trade winds, which we term trade wind charging of the equatorial Pacific. Experiments using a high-resolution numerical ocean model verify that the charging of subsurface heat content along the equatorial Pacific can be induced by SLP-generated trade wind variations. Furthermore, analysis of the numerical model results and historical observations indicates that the trade wind-induced ocean heat content increases are sufficiently large to initiate the onset of El Nino events, which mature approximately 12 months after the trade wind forcing itself.

## Extratropical forcing of El Nino-Southern Oscillation asymmetry

by Anderson, B. T., J. C. Furtado, K. M. Cobb, and E. Di Lorenzo (2013)

Boreal winter near-surface atmospheric circulations over the Hawaiian region are known to influence the state of the tropical Pacific and initiate the development of El Nino-Southern Oscillation (ENSO) events. Here we show that these same preceding near-surface circulations have an additional influence on the longitudinal position of the resultant ENSO-related sea surface temperatures (SSTs) as well, with warm (cold) events systematically shifted to the east (west) of the typical SST anomalies. In influencing this positioning, these atmospheric circulations in turn modify the near- and far-field climate responses to these SSTs such that during warm events, the typical ENSO-related responses east (west) of the dateline are generally enhanced (reduced); conversely, during cold events, the typical ENSO-related responses are generally reduced (enhanced). The fact that the extratropical atmospheric circulations in question influence the asymmetry of ENSO extremes with a 12 month lead time carries important implications for predicting the socioeconomic impacts of these events.

## Analysis of the Atlantic Meridional Mode Using Linear Inverse Modeling: Seasonality and Regional Influences

by Vimont, D. J. (2012)

Predictability and variability of the tropical Atlantic Meridional Mode (AMM) is investigated using linear inverse modeling (LIM). Analysis of the LIM using an "energy" norm identifies two optimal structures that experience some transient growth, one related to El Nino-Southern Oscillation (ENSO) and the other to the Atlantic multidecadal oscillation(AMO)/ AMM patterns. Analysis of the LIM using an AMM-norm identifies an "AMM optimal" with similar structure to the second energy optima (OPT2). Both the AMM-optimal and OPT2 exhibit two bands of SST anomalies in the mid-to high-latitude Atlantic. The AMM-optimal also contains some elements of the first energy optimal (ENSO), indicating that the LIM captures the well-known relationship between ENSO and the AMM. Seasonal correlations of LIM predictions with the observed AMM show enhanced AMM predictability during boreal spring and for long-lead (around 11-15 months) forecasts initialized around September. Regional LIMs were constructed to determine the influence of tropical Pacific and mid-to high-latitude Atlantic SST on the AMM. Analysis of the regional LIMs indicates that the tropical Pacific is responsible for the AMM predictability during boreal spring. Mid-to high-latitude SST anomalies contribute to boreal summer and fall AMM predictability, and are responsible for the enhanced predictability from September initial conditions. Analysis of the empirical normal modes of the full LIM confirms these physical relationships. Results indicate a potentially important role for mid-to high-latitude Atlantic SST anomalies in generating AMM (and tropical Atlantic SST) variations, though it is not clear whether those anomalies provide any societally useful predictive skill.

## Linkages between the North Pacific Oscillation and central tropical Pacific SSTs at low frequencies

by Furtado, J. C., E. Di Lorenzo, B. T. Anderson, and N. Schneider (2012)

The North Pacific Oscillation (NPO) recently (re-)emerged in the literature as a key atmospheric mode in Northern Hemisphere climate variability, especially in the Pacific sector. Defined as a dipole of sea level pressure (SLP) between, roughly, Alaska and Hawaii, the NPO is connected with downstream weather conditions over North America, serves as the atmospheric forcing pattern of the North Pacific Gyre Oscillation (NPGO), and is a potential mechanism linking extratropical atmospheric variability to El Nio events in the tropical Pacific. This paper explores further the forcing dynamics of the NPO and, in particular, that of its individual poles. Using observational data and experiments with a simple atmospheric general circulation model (AGCM), we illustrate that the southern pole of the NPO (i.e., the one near Hawaii) contains significant power at low frequencies (7-10 years), while the northern pole (i.e., the one near Alaska) has no dominant frequencies. When examining the low-frequency content of the NPO and its poles separately, we discover that low-frequency variations (periods > 7 years) of the NPO (particularly its subtropical node) are intimately tied to variability in central equatorial Pacific sea surface temperatures (SSTs) associated with the El Nio-Modoki/Central Pacific Warming (CPW) phenomenon. This result suggests that fluctuations in subtropical North Pacific SLP are important to monitor for Pacific low-frequency climate change. Using the simple AGCM, we also illustrate that variability in central tropical Pacific SSTs drives a significant fraction of variability of the southern node of the NPO. Taken together, the results highlight important links between secondary modes (i.e., CPW-NPO-NPGO) in Pacific decadal variability, akin to already established relationships between the primary modes of Pacific climate variability (i.e., canonical El Nio, the Aleutian Low, and the Pacific Decadal Oscillation).

## Testing for the Possible Influence of Unknown Climate Forcings upon Global Temperature Increases from 1950 to 2000

by Anderson, B. T., J. R. Knight, M. A. Ringer, J.-H. Yoon, and A. Cherchi (2012)

Global-scale variations in the climate system over the last half of the twentieth century. including long-term increases in global-mean near-surface temperatures. are consistent with concurrent human-induced emissions of radiatively active gases and aerosols. However, such consistency does not preclude the possible influence of other forcing agents, including internal modes of climate variability or unaccounted for aerosol effects. To test whether other unknown forcing agents may have contributed to multidecadal increases in global-mean near-surface temperatures from 1950 to 2000. data pertaining to observed changes in global-scale sea surface temperatures and observed changes in radiatively active atmospheric constituents are incorporated into numerical global climate models. Results indicate that the radiative forcing needed to produce the observed long-term trends in sea surface temperatures-and global-mean near-surface temperatures-is provided predominantly by known changes in greenhouse gases and aerosols. Further, results indicate that less than 10% of the long-term historical increase in global-mean near-surface temperatures over the last half of the twentieth century could have been the result of internal climate variability. In addition. they indicate that less than 25% of the total radiative forcing needed to produce the observed long-term trend in global-mean near-surface temperatures could have been provided by changes in net radiative forcing from unknown sources (either positive or negative). These results, which are derived from simple energy balance requirements. emphasize the important role humans have played in modifying the global climate over the last half of the twentieth century.

## Intensification of seasonal extremes given a 2 degrees C global warming target

by Anderson, B. T. (2012)

Current international efforts to reduce greenhouse gas emissions and limit human-induced global-mean near-surface temperature increases to 2A degrees C, relative to the pre-industrial era, are intended to avoid possibly significant and dangerous impacts to physical, biological, and socio-economic systems. However, it is unknown how these various systems will respond to such a temperature increase because their relevant spatial scales are much different than those represented by numerical global climate models-the standard tool for climate change studies. This deficiency can be addressed by using higher-resolution regional climate models, but at great computational expense. The research presented here seeks to determine how a 2A degrees C global-mean temperature increase might change the frequency of seasonal temperature extremes, both in the United States and around the globe, without necessarily resorting to these computationally-intensive model experiments. Results indicate that in many locations the regional temperature increases that accompany a 2A degrees C increase in global mean temperatures are significantly larger than the interannual-to-decadal variations in seasonal-mean temperatures; in these locations a 2A degrees C global mean temperature increase results in seasonal-mean temperatures that consistently exceed the most extreme values experienced during the second half of the 20th Century. Further, results indicate that many tropical regions, despite having relatively modest overall temperature increases, will have the most substantial increase in number of hot extremes. These results highlight that extremes very well could become the norm, even given the 2A degrees C temperature increase target.

## Decadal Shifts of the Kuroshio Extension Jet: Application of Thin-Jet Theory

by Sasaki, Y. N., and N. Schneider (2011)

Meridional shifts of the Kuroshio Extension (KE) jet on decadal time scales are examined using a 1960 2004 hindcast simulation of an eddy-resolving ocean general circulation model for the Earth Simulator (OFES). The leading mode of the simulated KE represents the meridional shifts of the jet on decadal time scales with the largest southward shift in the early 1980s associated with the climate regime shift in 1976/77, a result confirmed with subsurface temperature observations. The meridional shifts originate east of the date line and propagate westward along the mean jet axis, a trajectory inconsistent with the traditionally used linear lone Rossby waves linearized in Cartesian coordinates, although the phase speed is comparable to that in the traditional framework. The zonal scale of these westward propagation signals is about 4000 km and much lamer than their meridional scale. To understand the mechanism for the westward propagation of the KE jet shifts, the authors consider the limit of a thin jet. This dynamic framework describes the temporal evolution of the location of a sharp potential vorticity front under the assumption that variations along the jet are small compared to variations normal to the jet in natural coordinates and is well suited to the strong jet and potential vorticity gradients of the K E. For scaling appropriate to the decadal adjustments in the KE, the thin-jet model successfully reproduces the westward propagations and decadal shifts of the jet latitude simulated in OFES. These results give a physical basis for the prediction of decadal variability in the K E.

## Decadal-Scale SST and Salinity Variations in the Central Tropical Pacific: Signatures of Natural and Anthropogenic Climate Change

by Nurhati, I. S., K. M. Cobb, and E. Di Lorenzo (2011)

Accurate projections of future temperature and precipitation patterns in many regions of the world depend on quantifying anthropogenic signatures in tropical Pacific climate against its rich background of natural variability. However, the detection of anthropogenic signatures in the region is hampered by the lack of continuous, century-long instrumental climate records. This study presents coral-based sea surface temperature (SST) and salinity proxy records from Palmyra Island in the central tropical Pacific over the twentieth century, based on coral strontium/calcium and the oxygen isotopic composition of seawater (delta(18)O(SW)), respectively. On interannual time scales, the Sr/Ca-based SST record captures both eastern and central Pacific warming "flavors" of El Nino-Southern Oscillation (ENSO) variability (R = 0.65 and 0.67, respectively). On decadal time scales, the SST proxy record is highly correlated to the North Pacific gyre oscillation (NPGO) (R = -0.85), reflecting strong dynamical links between the central Pacific warming mode and extratropical decadal climate variability. Decadal-scale salinity variations implied by the coral-based delta(18)O(SW) record are significantly correlated with the Pacific decadal oscillation (PDO) (R = 0.54). The salinity proxy record is dominated by an unprecedented trend toward lighter delta(18)O(SW) values since the mid-twentieth century, implying that a significant freshening has taken place in the region, in line with climate model projections showing enhanced hydrological patterns under greenhouse forcing. Taken together, the new coral records suggest that low-frequency SST and salinity variations in the central tropical Pacific are controlled by different sets of dynamics and that recent hydrological trends in this region may be related to anthropogenic climate change.

## Generation of Decadal Anomalies in the Thermocline

by Kilpatrick, T., N. Schneider, and E. Di Lorenzo (2011)

The generation of variance by anomalous advection of a passive tracer in the thermocline is investigated using the example of density-compensated temperature and salinity anomalies, or spiciness. A coupled Markov model is developed in which wind stress curl forces the large-scale baroclinic ocean pressure that in turn controls the anomalous geostrophic advection of spiciness. The "double integration" of white noise atmospheric forcing by this Markov model results in a frequency (omega) spectrum of large-scale spiciness proportional to omega(-4), so that spiciness variability is concentrated at low frequencies. An eddy-permitting regional model hindcast of the northeast Pacific (1950-2007) confirms that time series of large-scale spiciness variability are exceptionally smooth, with frequency spectra proportional to omega(-4) for frequencies greater than 0.2 cpy. At shorter spatial scales (wavelengths less than similar to 500 km), the spiciness frequency spectrum is whitened by mesoscale eddies, but this eddy-forced variability can be filtered out by spatially averaging. Large-scale and long-term measurements are needed to observe the variance of spiciness or any other passive tracer subject to anomalous advection in the thermocline.

## North Pacific Decadal Variability and Climate Change in the IPCC AR4 Models

by Furtado, J. C., E. Di Lorenzo, N. Schneider, and N. A. Bond (2011)

The two leading modes of North Pacific sea surface temperature (SST) and sea level pressure (SLP), as well as their connections to tropical variability, are explored in the 24 coupled climate models used in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) to evaluate North Pacific decadal variability (NPDV) in the past [twentieth century; climate of the twentieth century (20C3M) scenario] and future [twenty-first century; Special Report on Emissions Scenarios (SRES) A1B scenario] climate. Results indicate that the two dominant modes of North Pacific oceanic variability, the Pacific decadal oscillation (PDO) and the North Pacific Gyre Oscillation (NPGO), do not exhibit significant changes in their spatial and temporal characteristics under greenhouse warming. However, the ability of the models to capture the dynamics associated with the leading North Pacific oceanic modes, including their link to the corresponding atmospheric forcing patterns and to tropical variability, is questionable. The temporal and spatial statistics of the North Pacific Ocean modes exhibit significant discrepancies from observations in their twentieth-century climate, most visibly for the second mode, which has significantly more low-frequency power and higher variance than in observations. The dynamical coupling between the North Pacific Ocean and atmosphere modes evident in the observations is very strong in the models for the first atmosphere-ocean coupled mode, which represents covariability of the PDO pattern with the Aleutian low (AL). However, the link for the second atmosphere-ocean coupled mode, describing covariability of an NPGO-like SST pattern with the North Pacific Oscillation (NPO), is not as clearly reproduced, with some models showing no relationship between the two. Exploring the tropical Pacific-North Pacific teleconnections reveals more issues with the models. In contrast with observations, the atmospheric teleconnection excited by the El Nino-Southern Oscillation in the models does not project strongly on the AL-PDO coupled mode because of the displacement of the center of action of the AL in most models. Moreover, most models fail to show the observational connection between El Nino Modoki-central Pacific warming and NPO variability in the North Pacific. In fact, the atmospheric teleconnections associated with El Nino Modoki in some models have a significant projection on, and excite the AL-PDO coupled mode instead. Because of the known links between tropical Pacific variability and NPDV, these analyses demonstrate that focus on the North Pacific variability of climate models in isolation from tropical dynamics is likely to lead to an incomplete view, and inadequate prediction, of NPDV.

## Transient Growth of Thermodynamically Coupled Modes

by Vimont, D. J. (2010)

The dynamics of thermodynamically coupled disturbances in the tropics that bear a strong resemblance to observed meridional mode variations are investigated using two simple linear coupled models. Both models involve an ocean equation coupled to the atmosphere via the linearized effect of zonal wind variations on the surface bulk latent heat flux. The two models differ in their atmospheric components, which consist of (i) a Gill-Matsuno style model of the free troposphere in which atmospheric heating is parameterized to be linearly proportional to sea surface temperature and (ii) a reduced-gravity model of the tropical boundary layer in which SST anomalies are associated with hydrostatic pressure perturbations throughout the boundary layer. Both atmospheric models follow the standard shallow-water equations on an equatorial beta plane. Growth rates and propagation of coupled disturbances are calculated and diagnosed via eigenanalysis of the linear models and singular value decomposition of the Green's function for each model. It is found that the eigenvectors of either model are all damped, not orthogonal, and not particularly meaningful in understanding observed tropical coupled variability. The nonnormality of the system, however, leads to transient growth over a time period of about 100 days (based on the choice of parameters in this study). The idealized initial and final conditions that experience this transient growth resemble observed tropical meridional mode variations and tend to propagate equatorward and westward in accord with findings from previous theoretical and modeling studies. Instantaneous growth rates and propagation characteristics of idealized transient disturbances are diagnosed via the linearized atmospheric potential vorticity equation and via propagation characteristics of atmospheric equatorial Rossby waves. Constraints on the poleward extent of initial conditions or imposed steady forcing that can lead to tropical meridional mode variations are identified through analysis of the steady coupled equations. Three constraints limit the poleward extent of forcing that can generate tropical meridional mode variations: (i) a dynamical constraint imposed by the damping rate of the temperature equation as well as the propagation speed of the mode along its wave characteristic;

(ii) a constraint imposed by the effectiveness of zonal wind variations in generating surface latent heat flux anomalies; and (iii) the surface moisture convergence, which limits the poleward extent and strength of ocean to atmosphere coupling.

## Observational evidence for propagation of decadal anomalies in the North Pacific

by Sasaki, Y. N., N. Schneider, N. Maximenko, and K. Lebedev (2010)

The propagation of density-compensated (warm/salty or cool/fresh) spiciness anomalies in the North Pacific thermocline is investigated using Argo profiles for the period 2001-2008. A cool/fresh spiciness anomaly on 25 < sigma(theta) < 25.5 kg m(-3) isopycnals appears in the eastern subtropical North Pacific at 120 degrees W-150 degrees W in 2003-2004 with a salinity anomaly of about -0.15 PSS-78. This spiciness anomaly migrates southwestward, and arrives in the western tropical North Pacific at 145 degrees E-175 degrees W in 2008 with the salinity anomaly decreasing to about -0.043 PSS-78. Two warm/salty anomalies are observed to propagate along the same path from 2003 to 2005, and after 2005. The propagation path and speed of the anomalies are in good agreement with advection by the mean geostrophic current. In the course of propagation, the anomalies are diffused and are subject to high frequency injection of spiciness anomalies, especially in the eastern subtropical North Pacific. Citation: Sasaki, Y. N., N. Schneider, N. Maximenko, and K. Lebedev (2010), Observational evidence for propagation of decadal spiciness anomalies in the North Pacific, Geophys. Res. Lett., 37, L07708, doi:10.1029/2010GL042716.

## Central Pacific El Nino and decadal climate change in the North Pacific Ocean

by Di Lorenzo, E., K. M. Cobb, J. C. Furtado, N. Schneider, B. T. Anderson, A. Bracco, M. A. Alexander, and D. J. Vimont (2010)

Decadal fluctuations of the ocean and atmosphere over the North Pacific Ocean significantly affect the weather and climate of North America and Eurasia. They also cause transitions between different states of marine ecosystems across the Pacific Ocean(1-3). An important fraction of North Pacific low-frequency variability is linked to the North Pacific Gyre Oscillation(4), a climate pattern associated with decadal fluctuations of the ocean circulation. Decadal variations in the North Pacific Gyre Oscillation are characterized by a pattern of sea surface temperature anomalies that resemble the central Pacific El Nino, a dominant mode of interannual variability with far-reaching effects on global climate patterns(5-7). Here we use an ensemble of simulations with a coupled ocean-atmosphere model to show that the sea surface temperature anomalies associated with central Pacific El Nino force changes in the extra-tropical atmospheric circulation. These changes in turn drive the decadal fluctuations of the North Pacific Gyre Oscillation. Given that central Pacific El Nino events could become more frequent with increasing levels of greenhouse gases in the atmosphere(8), we infer that the North Pacific Gyre Oscillation may play an increasingly important role in shaping Pacific climate and marine ecosystems in the twenty-first century.

## (D) Publications

***Manuscript not reported in PI Di Lorenzo's report are marked by *.***


1. *M. Newman, M. A. Alexander, T. R. Ault, K. M. Cobb, C. Deser, E. Di Lorenzo, N. J. Mantua, A. J. Miller, S. Minobe, H. Nakamura, N. Schneider, D. J. Vimont, A. S. Phillips, J. D. Scott and C. A. Smith, 2015: The Pacic Decadal Oscillation, revisited. J. Climate , submitted.

2. *Capotondi, A., A. T. Wittenberg, M. Newman, E. Di Lorenzo, J.-Y. Yu, P. Braconnot, J. Cole, B. Dewitte, B. Giese, E. Guilyardi, F.-F. Jin, K. Karnauskas, B. Kirtman, T. Lee, N. Schneider, Y. Xue, and S.-W. Yeh, 2015: Understanding ENSO Diversity. Bull. Amer. Meteor. Soc. , 96, 921-938. doi: http://dx.doi.org/10.1175/BAMS-D-13-00117.1

3. *Di Lorenzo, E., G. Liguori, N. Schneider, J. C. Furtado, B. T. Anderson and M. A. Alexander, 2015: ENSO and Meridional Modes: A null hypothesis for Pacic climate variability. Geophys. Res. Lett. , 42 , doi: 10.1002/2015GL066281.

4. *Schneider, N. and B. Qiu, 2015: The atmospheric response to weak sea surface temperature fronts. J. Atmos. Sci. , 72 , 3356{3377, doi:10.1175/JAS D-14-0212.1.

5. *Qiu, B., S. Chen, N. Schneider and B. Taguchi, 2014: A coupled decadal prediction of the dynamic state of the Kuroshio Extension system. J. Climate , 27 , 1751-1764.

6. *Grissom, L. M. , 2013: The effect of low-frequency spiciness anomalies on the El Nino-Southern Oscillation. Master Thesis, University of Hawaii at Manoa, 43pp.

7. Vimont, D.J., M.A. Alexander, and M. Newman, Optimal growth of Central and East Pacific ENSO events. Geophysical Research Letters, 2014. 41(11): p. 4027-4034.

8. Taguchi, B. and N. Schneider, Origin of Decadal-Scale, Eastward-Propagating Heat Content Anomalies in the North Pacific. Journal of Climate, 2014. 27(20): p. 7568-7586.

9. Sydeman, W.J., et al., Increasing variance in North Pacific climate relates to unprecedented ecosystem variability off California. Global Change Biology, 2013. 19(6): p. 1662-1675.

10. Sasaki, Y.N., S. Minobe, and N. Schneider, Decadal Response of the Kuroshio Extension Jet to Rossby Waves: Observation and Thin-Jet Theory. Journal of Physical Oceanography, 2013. 43(2): p. 442-456.

11. Emile-Geay, J., et al., Estimating Central Equatorial Pacific SST Variability over the Past Millennium. Part II: Reconstructions and Implications. Journal of Climate, 2013. 26(7): p. 2329-2352.

12. Emile-Geay, J., et al., Estimating Central Equatorial Pacific SST Variability over the Past Millennium. Part I: Methodology and Validation. Journal of Climate, 2013. 26(7): p. 2302-2328.

13. Di Lorenzo, E., et al., Synthesis of Pacific Ocean Climate and Ecosystem Dynamics. Oceanography, 2013. 26(4): p. 68-81.

14. Cobb, K.M., et al., Highly Variable El Nino-Southern Oscillation Throughout the Holocene. Science, 2013. 339(6115): p. 67-70.

15. Anderson, B.T., R.C. Perez, and A. Karspeck, Triggering of El Nino onset through trade wind-induced charging of the equatorial Pacific. Geophysical Research Letters, 2013. 40(6): p. 1212-1216.

16. Anderson, B.T., et al., Extratropical forcing of El Nino-Southern Oscillation asymmetry. Geophysical Research Letters, 2013. 40(18): p. 4916-4921.

17. Vimont, D.J., Analysis of the Atlantic Meridional Mode Using Linear Inverse Modeling: Seasonality and Regional Influences. Journal of Climate, 2012. 25(4): p. 1194-1212.

18. Furtado, J.C., et al., Linkages between the North Pacific Oscillation and central tropical Pacific SSTs at low frequencies. Climate Dynamics, 2012. 39(12): p. 2833-2846.

19. Anderson, B.T., et al., Testing for the Possible Influence of Unknown Climate Forcings upon Global Temperature Increases from 1950 to 2000. Journal of Climate, 2012. 25(20): p. 7163-7172.

20. Anderson, B.T., Intensification of seasonal extremes given a 2 degrees C global warming target. Climatic Change, 2012. 112(2): p. 325-337.

21. Sasaki, Y.N. and N. Schneider, Decadal Shifts of the Kuroshio Extension Jet: Application of Thin-Jet Theory. Journal of Physical Oceanography, 2011. 41(5): p. 979-993.

22. Nurhati, I.S., K.M. Cobb, and E. Di Lorenzo, Decadal-Scale SST and Salinity Variations in the Central Tropical Pacific: Signatures of Natural and Anthropogenic Climate Change. Journal of Climate, 2011. 24(13): p. 3294-3308.

23. Kilpatrick, T., N. Schneider, and E. Di Lorenzo, Generation of Low-Frequency Spiciness Variability in the Thermocline. Journal of Physical Oceanography, 2011. 41(2): p. 365-377.

24. Furtado, J.C., et al., North Pacific Decadal Variability and Climate Change in the IPCC AR4 Models. Journal of Climate, 2011. 24(12): p. 3049-3067.

25. Vimont, D.J., Transient Growth of Thermodynamically Coupled Variations in the Tropics under an Equatorially Symmetric Mean. Journal of Climate, 2010. 23(21): p. 5771-5789.

26. Sasaki, Y.N., et al., Observational evidence for propagation of decadal spiciness anomalies in the North Pacific. Geophysical Research Letters, 2010. 37.

27. Di Lorenzo, E., et al., Central Pacific El Nino and decadal climate change in the North Pacific Ocean. Nature Geoscience, 2010. 3(11): p. 762-765.