An overview of Pacific Climate Variability

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1. Background

Low-frequency fluctuations of the ocean and atmosphere over the North Pacific Ocean on interannual to decadal timescales significantly impact the weather and climate of North America and Eurasia [*see review by Alexander, 2010*], and drive important state transitions observed in marine ecosystems across the Pacific Ocean [*Roemmich and McGowan, 1995; Mantua et al., 1997; Hare et al., 1999; Martinez et al., 2009*]. Understanding how and if these natural climate cycles are altered by a changing climate is therefore of broad scientific and socioeconomic interest.

Low-frequency variability in the North Pacific

Previous studies document the wide-ranging impacts of North Pacific climate variability associated with the Pacific Decadal Oscillation (**PDO**) [*Mantua et al., 1997; Zhang et al., 1997; and others*]. The PDO emerges as the first mode of North Pacific sea surface temperature (SST) variability, and is highly correlated with the dominant mode of sea surface height anomalies (SSHa) [*Chhak et al., 2009*]. Its temporal modulations are linked to several important biological and ecosystem variables in the ocean [*Hare et al., 1999; Martinez et al., 2009; Hare and Mantua, 2000*]. To first order, the PDO is a forced response of the North Pacific ocean to atmospheric forcing by variability of the Aleutian Low (**AL**) – defined as the first mode of sea level pressure anomaly (SLPa) variations in the North Pacific (**Figure 1**) [*Newman et al, 2003*]. SSHa anomalies associated with the AL/PDO also excite westward propagating oceanic Rossby waves that drive dominant decadal scale variations in the North Pacific western boundary with a lag of ~3-4 years [*Qiu, 2007; and others*].

Recent work by the PIs has shown that low-frequency variability of the North Pacific is only partly explained by the PDO [*Di Lorenzo et al., 2008*]. A more complete representation of the decadal dynamics of the Pacific must include the North Pacific Gyre Oscillation (**NPGO**). Defined as the second dominant mode of SSHa variability in the Northeast Pacific [180°–110°W; 25°N–62°N], the NPGO captures the second mode of North Pacific SSTa (**Figure 1**) [*Di Lorenzo et al., 2008*] and drives prominent low-frequency changes in physical and biological variables across the Pacific (e.g. temperature, salinity, sea level, nutrients, chlorophyll-a, [*Di Lorenzo et al., 2008; 2009; and others*]), including strong state transitions in marine ecosystems (e.g. fish, *Sydeman and Thompson, 2010; Cloern et al., 2010*]). Like, the PDO, the NPGO is a basin-scale feature, capturing changes in the strength of both the North Pacific Current (NPC) [*Di Lorenzo et al., 2009*] and of the Kuroshio-Oyashio Extension (KOE) [*Ceballos et al., 2009*]; it also tracks significant SST anomalies in the tropical Pacific [*Di Lorenzo et al., 2008; Nurhati et al., in prep*].

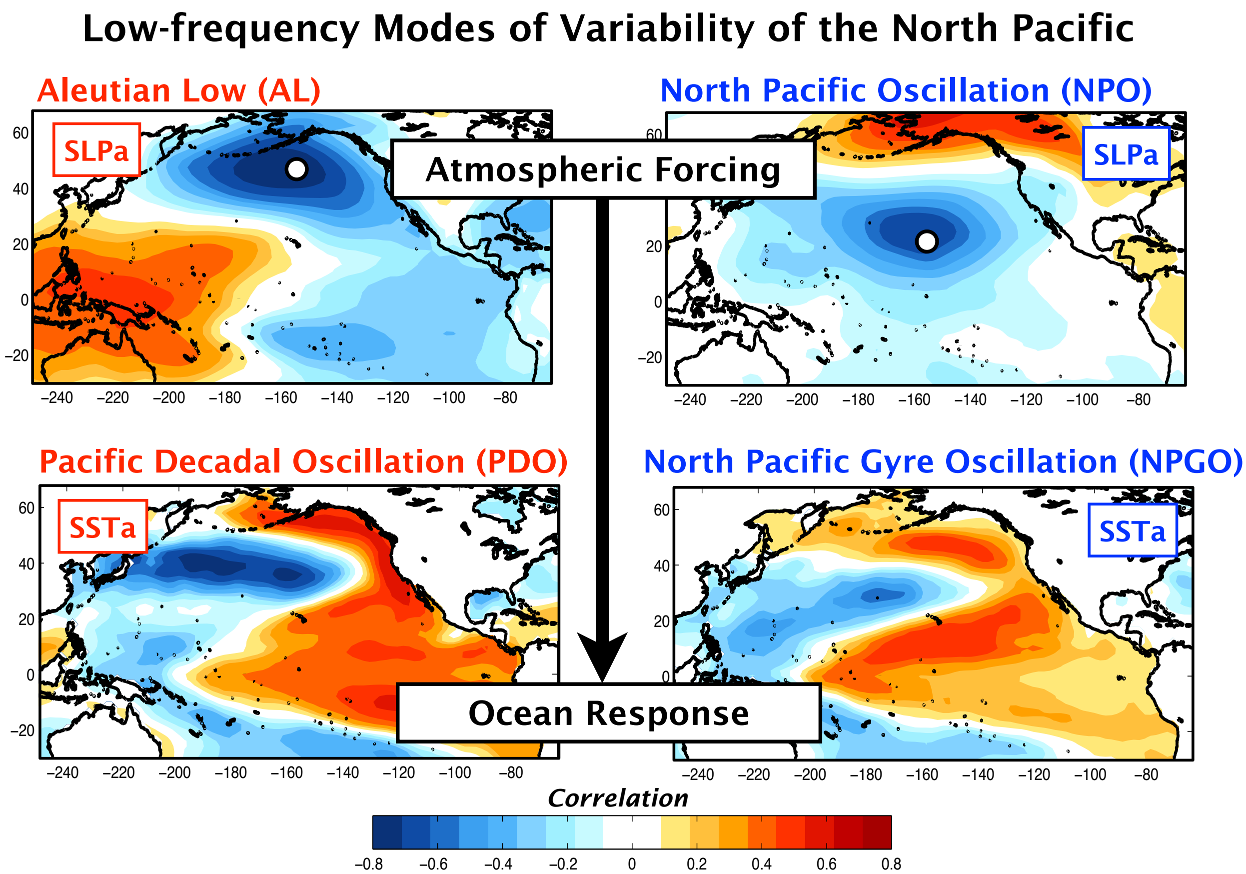

Figure 1: Correlation Maps of the two dominant modes of North Pacific variability. *Top row* shows the SLPa correlation maps of the first two modes of North Pacific atmospheric variability, referred to as AL and NPO. *Bottom row* shows the SSTa correlation maps of the two dominant modes of SSTa variability, referred to as PDO and NPGO.

More recent work by the PIs has shown that the NPGO is the oceanic response to atmospheric forcing associated with the North Pacific Oscillation (**NPO**) [*Di Lorenzo et. al., 2008; 2010 (see Appendix 7); Chaak et al., 2009*]. The NPO, defined as the second dominant mode of North Pacific SLPa (**Figure 1**) [*Walker and Bliss, 1932; Rogers et al., 1981*], is a well-known pattern of atmospheric variability that affects weather patterns over Eurasian and North America, particularly changes in storm tracks, temperatures, and precipitation [*Seager et al., 2005; Linkin and Nigam, 2008; and references therein*]. Therefore, both the PDO and the NPGO have their origins in distinct North Pacific atmospheric modes of variability, namely the AL and the NPO, respectively.

While the dynamics of the two North Pacific coupled ocean-atmosphere climate modes – the AL/PDO and NPO/NPGO – include elements independent of the tropics [*Latif and Barnett, 1994; Barnett et al., 1999; Pierce et al., 2001; Liu et al., 2002; Chaak et al.,* *2009, and others*], several studies have shown both statistically and dynamically [*Pierce et al., 2000; Deser et al., 2004; Alexander et al., 2002; 2008; Vimont, 2005; Newman et al. 2003; Di Lorenzo et al., 2010*] that a significant fraction of the interannual (2-7 year band, ~40%) and decadal (>7 year, ~40-75%) variability of both the AL/PDO and the NPO/NPGO is also driven by variations in the tropics.

Coupling and Feedbacks between the Tropics and Extratropics

Tropical Pacific climate variability is dominated by ocean/atmosphere coupled dynamics associated with the El Niño Southern Oscillation (**ENSO**). The traditional, or canonical, expression of ENSO is characterized by a pronounced eastern Pacific warming (**EPW**), a weakening of the trade winds, and positive (negative) SLPa anomalies over the western (eastern) tropical Pacific (**Figure 2**). These changes in the tropical atmospheric circulation modify the large-scale Hadley Cell and extratropical atmospheric circulation patterns via atmospheric teleconnections. Specifically, it has been shown that ENSO extremes excite variability in the AL through a well-known "atmospheric bridge" [*Alexander, 1992; Alexander et al., 2002*]. The ENSO-derived variability of the AL is integrated and low-passed by the ocean to yield the decadal PDO pattern in the North Pacific [*Newman et al., 2003*], providing a strong dynamical link between low-frequency climate variability in the tropics and extra-tropics.

In contrast to the canonical EPW-ENSO, recent studies isolate a new flavor of El Niño [*Ashok et al., 2007; 2009*] that has become more frequent than the canonical EPW El Niño in the late 20th century [*Yeh et al., 2009*]. This type of El Niño, (also referred to as the dateline El Niño [*Larkin et al., 2005*], El Niño Modoki [*Ashok et al., 2009*] or warm pool El Niño [*Kug et al., 2009*]) is characterized by a central Pacific warming (**CPW**) pattern [*Kao et al., 2009*]. The CPW has been linked to changes in tropical cyclone activity [*Kim et al., 2009*], storm tracks [*Ashok et al., 2009*], and shifts in global rainfall patterns [*Weng et al., 2009; Taschetto et al., 2009*]. SST anomalies associated with the CPW also modify the large-scale atmospheric circulation. However, its signature is different from the EPW (see SLPa patterns in **Figure 2**) in that the center of maximum convection is displaced westward with respect to the EPW. Consequently, the CPW is associated with a different pattern of atmospheric teleconnections to the extra-tropics [*Weng et al., 2009*].

Recent modeling work based on a collaboration between all the PIs [*Di Lorenzo et al., 2010*] suggests that CPW drives variability in the North Pacific atmosphere that is integrated to yield the oceanic NPGO pattern. Specifically, maximum CPW anomalies during boreal winter excite variability in the atmospheric NPO, which in turn drives the oceanic NPGO. This dynamical chain from CPW to NPO to NPGO explains over 75% of the low-frequency variability of the NPGO, highlighting the strong dynamical links that exist between tropical and extratropical climate variability in the Pacific basin.

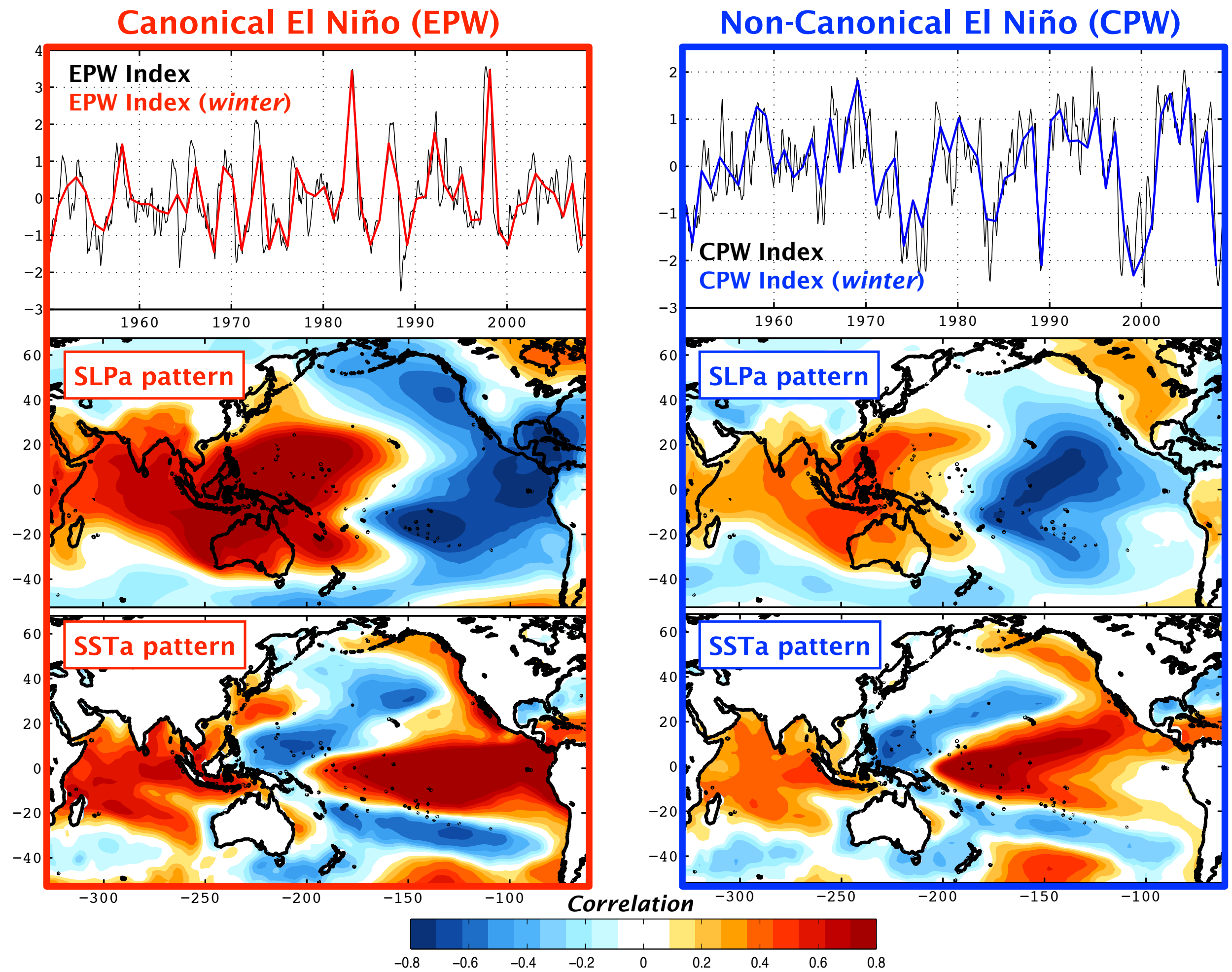

Figure 2: Canonical and *Non*-Canonical El Niño. *Top row* shows the timeseries of the canonical eastern Pacific warming (EPW) El Niño and non-canonical central Pacific warming (CPW) El Niño. The definitions of EPW and CPW follow Ashok et al., [*2007*]. *Bottom rows* show correlation maps of EPW and CPW winter (JFM averages) values with SLPa and SSTa.

The discovery of this new dynamical link between the CPW→NPO→NPGO reshapes our physical understanding of how tropical Pacific climate is coupled to the extra-tropics in that it provides the basis for a potential positive feedback between tropics and extra-tropics. Support for a dynamical feedback comes from past studies of the PIs on the *Seasonal Footprinting Mechanism* (**SFM**; [*Vimont et al., 2003; Anderson et al., 2003*]) whereby boreal winter-time variability in the NPO drives warm SST anomalies in the North Pacific that propagate into the central tropical Pacific by end of spring/summer through the wind/evaporation/SST (WES) feedback. This central Pacific warm anomaly weakens the Walker Cell and initiates an ENSO response in the tropics that peaks in the following winter [*Alexander et al., 2009*]. The ENSO response can be both of the EPW and CPW types. If the response is a CPW event this implies a positive feedback whereby NPO(winter)→CPW(next winter)→NPO(next winter). This feedback may provide a longer year-to-year persistence of the central Pacific warming in the tropics, which could explain why the CPW Index (Figure2) has a longer decorrelation timescale and predictability [*Kim et al., 2009*] than the EPW Index.

A proposed Framework of Pacific Climate Variability

Based on these results we propose a synthesized understanding of Pacific low-frequency variability and the links between the ocean/atmospheric modes of the Pacific via the schematic presented in **Figure 3.** 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.

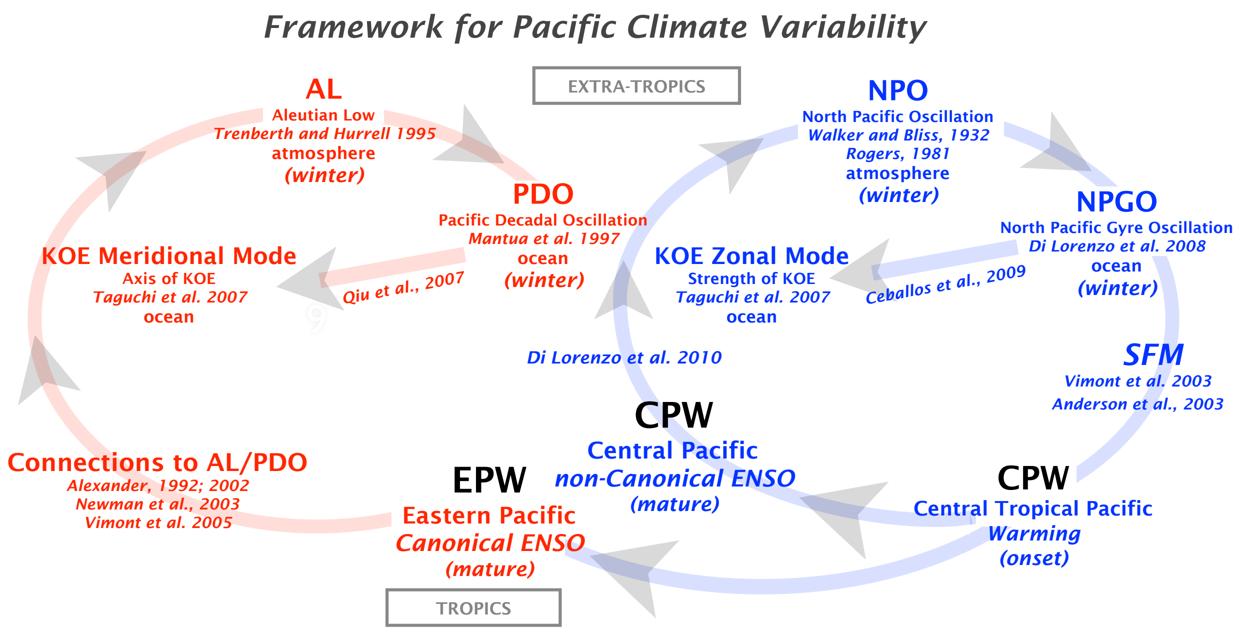

Figure 3: Framework of Pacific Climate Variability. This schematic shows the links between the ocean and atmospheric modes of low-frequency variability in the Pacific (see section *Framework of Pacific Climate Variability* for a detailed description).

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*].

Pacific climate variability and anthropogenic climate change

While no study has yet focused on the response of Pacific decadal-scale variability to anthropogenic forcing, many previous studies investigate the response of ENSO to anthropogenic climate change. Early work based on analyses of observational climate data and long model simulations highlights the difficulty of isolating statistically significant changes in ENSO amplitudes and/or frequencies from the relatively short instrumental record [*e.g. Trenberth and Hurrell, 1995; Rajagopalan et al., 1997; Wunsch, 1999, Wittenberg, 2009*]. Nonetheless, a recent study based on analysis of IPCC AR4 projections of 21^{st} century ENSO suggests that it is the flavor of ENSO that will change (towards more CPW and fewer EPW events) rather than the amplitude or frequency of ENSO variability (Yeh et al., 2009).

Given the links between CPW and the NPGO uncovered by the PIs, an anthropogenic shift towards CPW-ENSO at the expense of EPW-ENSO has profound implications for the evolution of Pacific decadal-scale variability under continued greenhouse forcing. If the IPCC model projections of CPW-ENSO are accurate, then our work suggests that NPGO variance will increase during the 21^{st} century, at the expense of PDO variance. This hypothesis finds preliminary support in recent studies showing that the NPGO explains a higher fraction of North Pacific low-frequency variance over the late 20th century than the PDO [*Di Lorenzo et al., 2008; Bond et al., 2003; Cummins and Freeland, 2007; Cloern et al., personal communication; and other authors*]. This shift in variance from PDO→NPGO is consistent with the shift in variance from EPW→CPW and may be an early sign of climate change impacts on Pacific decadal variability. Such a trend would likely shape weather, climate, and ecosystem responses to climate change throughout much of the Northern Hemisphere, particularly North America.

The preceding discussions and the conceptual framework of Pacific low-frequency of Figure 3 (see previous section) present an improved understanding of Pacific climate variability that expands beyond ENSO/PDO to include the PI's work on CPW/NPO/NPGO, and motivates an investigation into the evolution of Pacific low-frequency climate variability under continued anthropogenic forcing, using both observations and models.

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