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DECADAL PREDICTABILITY AND PREDICTION (T DELWORTH, SECTION EDITOR)

Mechanisms and Predictability of Pacific Decadal Variability

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Abstract

Purpose of Review This paper reviews recent progress in the understanding and prediction of pacific decadal variability (PDV). The PDV is now recognized to consist of multiple ocean-atmosphere modes and to be caused by multiple processes. At the leading order, PDV can be viewed as the reddening process of stochastic atmospheric variability on the extratropical ocean. However, PDV is also strongly tied to teleconnection dynamics interacting with the tropics, primarily the interactions between meridional modes in the extra-tropics and ENSO, and between the ENSO teleconnections and the dominant modes of atmospheric variability in the mid-latitude.

Recent Findings Extratropical oceanic Rossby waves are found to be crucial for determining the decadal time scales of the PDV and provide potentially an important source of predictability of PDV. Preliminary experiments with GCMs and empirical linear inverse models have shown some skill for the prediction of PDV in ocean surface temperatures. While the climate predictions in the first few years depend significantly on the oceanic initial condition, predictions of near decadal time scales are contributed mostly by the global warming trend. In addition, recent studies explored the role of ocean subsurface dynamics for multi-decadal predictability in the Pacific and suggest that subsurface dynamics may lead to important sources of decadal predictability in regional upwelling systems, namely the eastern boundary and polar gyre. Overall, the predictability of PDV and the related surface and subsurface signals remain to be much studied.

Summary Recent studies also start to explore the relation between PDV and global warming. It has been suggested that PDV can slow down or accelerate the global warming trend significantly. The influence of the anthropogenic climate change on PDV, however, has remained unclear.

Keywords Decadal variability modes · Stochastic driving · Oceanic Rossby wave · Climate prediction · Tropical-extratropical interaction · Modulation of global warming

Introduction

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 reviews by 3, 31, 88, 36, 92, 93, 18, 27], and drive important state transitions observed in marine ecosystems across the Pacific Ocean [123, 95, 55, 95]. Understanding how and if these natural climate fluctuations are predictable and altered by external forcing functions, such as anthropogenic forcing and influences from other oceanic basin, relies heavily on identifying the robust mechanisms that control the Pacific decadal variance.

Historically, climate variability of the Pacific Ocean on timescales longer than 10 year is described in terms of statistical modes of decadal variability such as the Interdecadal Pacific Oscillation (IPO; [116]), the Pacific Decadal

Key points

- Pacific decadal variability (PDV) emerges as a collection of multiple ocean and atmosphere mechanisms and modes
- Surface PDV is inherently dominated by the reddening of climate noise
- Key sources of decadal predictability emerge from mid-latitude surface Rossby waves and the upwelling of subsurface tracer anomalies
- Decadal variability may slow down or accelerate the global warming trend significantly

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Oscillation (PDO; [95]), the North Pacific Gyre Oscillation (NPGO; [33]) and the South Pacific Decadal Oscillation (SPDO, [104, 50, 59]). These climate modes, which are generally called the pacific decadal variability (here and after referred to as the PDV), are identified through principal component analysis of low-frequency sea surface temperature (SST) and sea surface height (SSH) variability of instrumental observations in different domains. The PDO and NPGO are the first and second empirical orthogonal function (EOF) of the SST variability in the North Pacific, the SPGO is the first EOF of SST variability in the South Pacific, while the IPO is the dominant EOF of low-frequency SST variability over the entire Pacific (detailed definition will be described later regarding Fig. 1). It should be pointed out that, although these modes are referred to as "oscillations," dominant periodicities in their temporal variability are hardly significant and difficult to identify as spectral peaks in instrumental observations. Rather, these modes exhibit broad spectral peak on the decadal to multi-decadal variability band, which is all that we can resolve with instrumental records that are limited to last ~100 years. To the first order, these modes capture the variance associated with the reddening of stochastic climate noises in the ocean (e.g., [57]) associated with a collection of processes involving ocean and atmosphere interactions in the mid-latitudes, subtropics and tropics (e.g., [37, 111]). The tropical Pacific plays a key role in Pacific decadal variability as evident by the tendency for all these modes to exhibit an inter-hemispheric symmetric pattern of decadal variability that resembles the El Niño Southern Oscillation (ENSO) in the low-frequency limit (e.g., 8-year lowpass data) (Fig. 1). This ENSO-like pattern [155], or more generally the dominant pattern of PDV, captures the largest fraction of low-frequency variability in the Pacific basin on timescales longer than 8 years (~42%).

Several studies have attempted to exploit the low-frequency timescale and persistence of the processes that contribute to the PDV ENSO-like pattern to make climate predictions of key surface climate variables like sea surface temperature (e.g., [78, 107, 108]). Over the last decade, the availability of fully coupled climate models has led to the emergence of decadal climate prediction as a new endeavor in climate research [68, 102, 99, 101]. The push toward decadal climate predictions also emerges from studies that link global warming hiatus (e.g., [71]) and the recent extremes in ocean and land sea surface temperatures and precipitation (e.g., drought, marine and land heatwaves) [12, 32, 38, 58, 145] to the dynamics or phase of different modes of PDV. Given the societal and ecological impact of PDV, our goal is to present an overview of the research progress on the PDV with the focus on the progresses made mainly in the last 5–10 years. More specifically, we will (1) review the different processes that energize the decadal variability of the Pacific basin (e.g., ENSO-like pattern), (2) discuss their decadal predictability potential, and (3) examine how these mechanisms may impact and may be altered by anthropogenic climate change.

The manuscript is organized as follows, "Mechanisms of Pacific Decadal Variability" reviews the different physical mechanisms underlying the surface and ocean subsurface PDV and their connection to the large-scale climate modes including ENSO, PDO, IPO, NPGO, and SPDO. These mechanisms provide the physical basis for predictability, which is discussed in "Predictability of Pacific Decadal Variability" along with the characteristic timescales. Finally, "Climate Change Projections and Pacific Decadal Variance" provides a review of projections on how anthropogenic climate change may impact or be impacted by key mechanisms that are important for the statistics of PDV.

Mechanisms of Pacific Decadal Variability

To understand the dynamics controlling the decadal variance of the Pacific, we decompose the Pacific basin domain in three latitudinal domains, an *extratropical* domain poleward of 20 N and 20 S, a *sub-tropical* domain between 5 and 20 degrees from the tropics, and the *tropical* domain within 5 S–5 N. In the mid-latitude domain, the ocean tends to respond passively to atmospheric forcing except in the western boundary current where the warm SSTs in the Kuroshio can impact the atmospheric circulation. In the sub-tropics, the coupling between ocean and atmosphere emerges from thermodynamic feedbacks. This can lead to the growth and propagation of coupled modes of variability such as the Meridional Modes (MM) (e.g., Chiang and [140, 141]) or to the excitation of wind induced off-equatorial Rossby waves and changes in the sub-tropical cells (e.g., [6, 70]), all of which have been shown to interact and trigger ENSO variability in the tropics. (Here, for convenience, ENSO refers generally to tropical climate variability of interannual to interdecadal time scales). Finally, in equatorial latitudes, the ocean and atmospheric coupling is the strongest and a wide range of positive coupled feedbacks (e.g., Bjerknes, zonal advection, thermocline) contribute to the growth of zonal modes that ultimately lead to the different expressions of ENSO (e.g., [15]). The teleconnections to the mid-latitude resulting from ENSO contribute to the atmospheric variability that drives the decadal climate modes in the extra-tropics (e.g., PDO, NPGO, and SPDO). As such, these modes integrate the combined action of remote ENSO forcing and local mid-latitude atmospheric noise, which leads to a spatial and temporal reddening of the ENSO spectrum (e.g., [20, 110, 125]).

Following the subdomain decomposition outlined above (e.g., mid-latitudes, sub-tropics, and tropics), we review

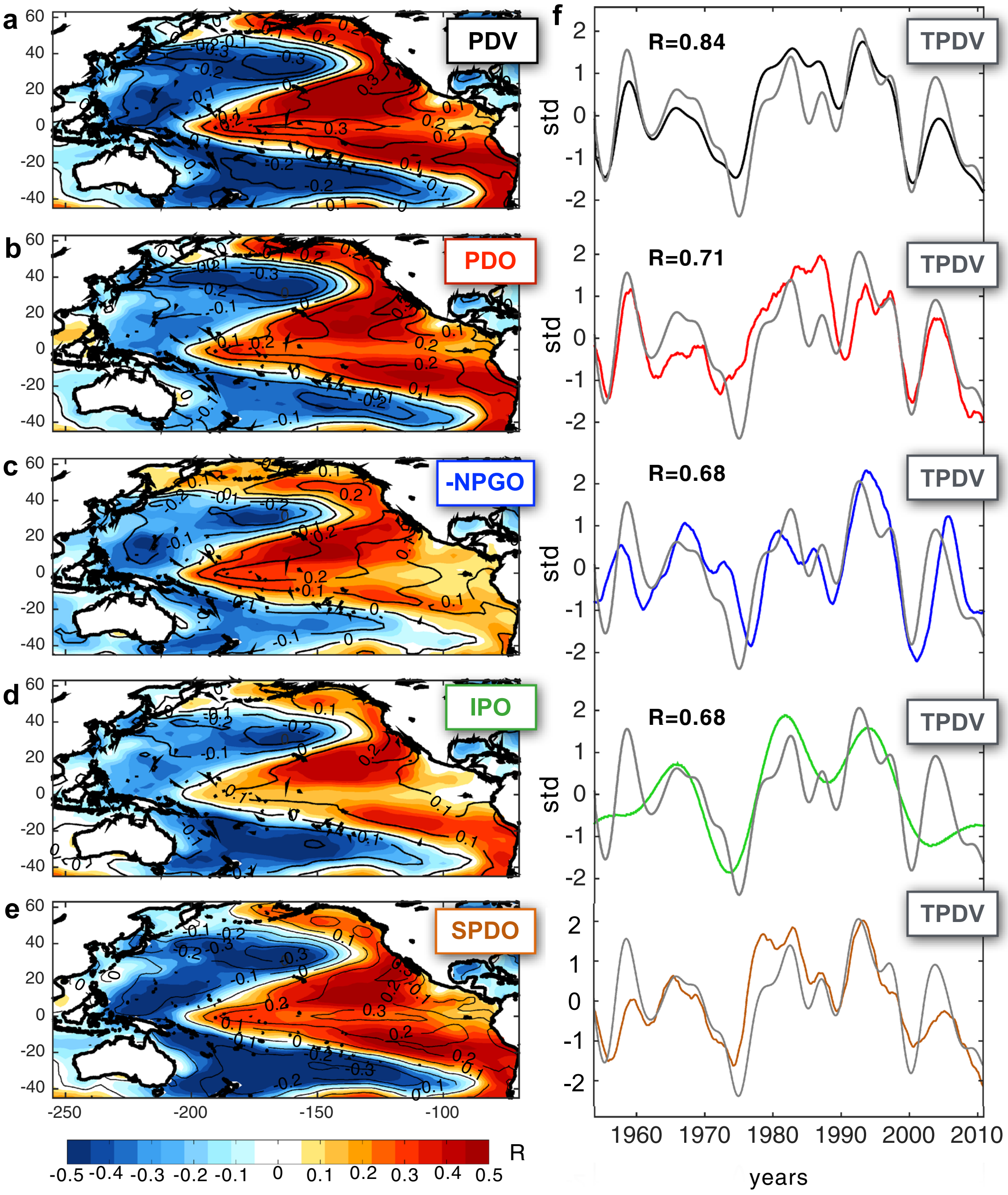

Fig. 1 ENSO-like pattern of Pacific low-frequency variability. Correlation maps between monthly NOAA ERSST.v3 SSTa and (**a**) Pacific Decadal Variability (PDV) index defined as the PC1 of 8-year low-pass SSTa over Pacific basin (45°S–65°N), (**b**) 8-year low-pass Pacific Decadal Oscillation (PDO) index, (**c**) 8-year low-pass negative North Pacific Gyre Oscillation (NPGO) index, (**d**) Interdecadal Pacific Oscillation (IPO) index, and (**e**) 8-year low-pass South Pacific Decadal Oscillation (SPDO) index. Regression coefficients are shown as black contours in units of °C. The time series of the indices are shown in **f** and compared against a Tropical Pacific Decadal Variability (TPDV) index defined as PC1 of 8 year low-pass SST over the equatorial Pacific (12°S–12°N)

the known forcing dynamics of the dominant climate modes ("Forcing Dynamics of Surface Modes of Pacific Low-Frequency Variability") in the mid-latitudes, the potential for ocean/atmosphere coupling in western boundaries with the emergence of preferred timescales of decadal variability ("Coupling Between Western and Eastern Boundary, and Atmospheric Feedback"), the role of subtropical dynamics in driving tropical ENSO-like variability ("Tropical-Extratropical Interactions"), and the role of tropical/extra-tropical coupling dynamics in synchronizing the interhemispheric symmetric pattern of decadal variability ("The Role of the Tropics in Pacific Decadal

Variability”). A summary and schematic of all the different mechanisms that lead to PDV are presented at the beginning of “Predictability of Pacific Decadal Variability,” where this PDV framework is used as a basis to discuss the predictability dynamics.

Forcing Dynamics of Surface Modes of Pacific Low-Frequency Variability

Previous studies document the wide-ranging impacts of North Pacific climate variability associated with the PDO ([95, 155]) defined as the first EOF of North Pacific SST variability (Fig. 1b). It has been recognized now that PDO is best characterized not as a single phenomenon but rather as a collection of different physical processes [111]. The PDO signature also emerges as the dominant mode of sea surface height anomalies (SSHa) [20] and of a variety of ecological indicators in the North Pacific ([55, 96, 56, 36]). Observations suggest that the PDO can be modeled to first order as the forced response of the ocean to the atmospheric forcing the Aleutian Low (AL) variability—defined as the first EOF mode of sea level pressure anomaly (SLPa) variations in the North Pacific between 20 N and 60 N [110, 125]. Although the PDO explains the largest fraction of low frequency variability in the North Pacific, a more complete representation of the decadal dynamics of the North Pacific includes the North Pacific Gyre Oscillation (NPGO) climate pattern. Defined as the second dominant EOF mode of SSHa variability in the Northeast Pacific [180°–110°W; 25°N–62°N], the NPGO tracks the second mode of North Pacific SSHa/SSTa (Fig. 1c) and drives prominent low-frequency changes in physical and biological variables across the Pacific (e.g., temperature, salinity, sea level, nutrients, chlorophyll-a, ([33, 34]; and others), including strong state transitions in marine ecosystems (e.g., fish, [134, 22, 65]). Similar to the PDO, the NPGO is also forced by atmospheric variability, specifically the North Pacific Oscillation (NPO) [20, 33, 35]. The NPO, defined as the second dominant mode of North Pacific SLPa [144, 124], is a well-known pattern of atmospheric variability that affects weather patterns over Eurasia and North America, particularly changes in storm tracks, temperatures, and precipitation ([129, 81]; 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 (see schematic summary of Fig. 2). Diagnostic relations such as these have the advantage of dealing with real-world observations of PDV, where the dynamics are implied from lead-lag relationships among climate variables. However, these statistical approaches are nevertheless constrained by the limited observations and the difficulty of testing the mechanisms explicitly.

Climate models provide a complementary approach to study the mechanism of PDV more explicitly. Using the “partial coupling” approach that activates ocean-atmosphere coupling in the tropical and extratropical regions separately, a recent study in a suite of GFDL climate models [152] demonstrates explicitly: the preferred multidecadal time scale of the model PDO is generated by the ocean-atmosphere coupling in the extratropical North Pacific, and is further enhanced by tropical climate variability. This confirms the findings in two previous models [84, 149, 158]. Therefore, in these models, even through the tropical Pacific is closely tied to the PDO in statistical analysis as in the observation (e.g., Deser et al. [30]), the tropical Pacific is not the origin of PDO. Instead, tropical Pacific acts as a relay to propagate and therefore synchronize the decadal variability signal from, say, the North Pacific, to both hemispheres. Furthermore, using the “partial blocking” approach that blocks the propagation of oceanic Rossby waves in different regions, these models found that multidecadal PDO is caused by the westward propagation of Rossby waves in the subpolar North Pacific ([159, 152]). The implication of the modeling studies on the real world PDO, however, may be limited by some model deficiencies, such as the weaker tropical impact on the North Pacific compared to observations ([108, 109]). Further studies with improved models and more advanced diagnostic analysis are needed to better understand the mechanism of PDO both statistically and dynamically.

While much attention has been given to the modes of North Pacific surface variability, the South Pacific also exhibit important decadal fluctuations that mirror the North Pacific counterpart. These dynamics are often described in the context of the dominant EOF of SST between 20 S and 60 S, also referred to as the SPDO (e.g., [82]; Kumar and Wen 2016) (Fig. 1e)—a basin scale low-frequency variation of SST that captures the ENSO-like pattern of decadal variability. Similar to the PDO, the SPDO integrates the multidecadal fluctuations of the atmospheric forcing with contributions from tropical teleconnections, internal variability of mid-latitude atmosphere and contributions from the annular modes. The PDO and the SPDO share a correlation of $R = 0.46$, and share correlation with ENSO (e.g., Niño34 index) with $R = 0.47$ and $R = 0.56$. Indeed, there is a coherence of decadal variability over the entire Pacific, as shown in the so called IPO mode [116], which is defined as the 1st EOF of the SST variability of the entire Pacific domain (Fig. 1d). One common feature of all these PDV modes, PDO, NPGO, SPDO and IPO, is a high correlation with a prominent activity center in the tropical Pacific (Fig. 1), which points to an important role of the tropical Pacific in synchronizing the decadal variability in both hemispheres. Finally, there are also studies suggesting a significant contribution to the PDO from the Atlantic decadal variability (Zhang et al. [156, 72]).

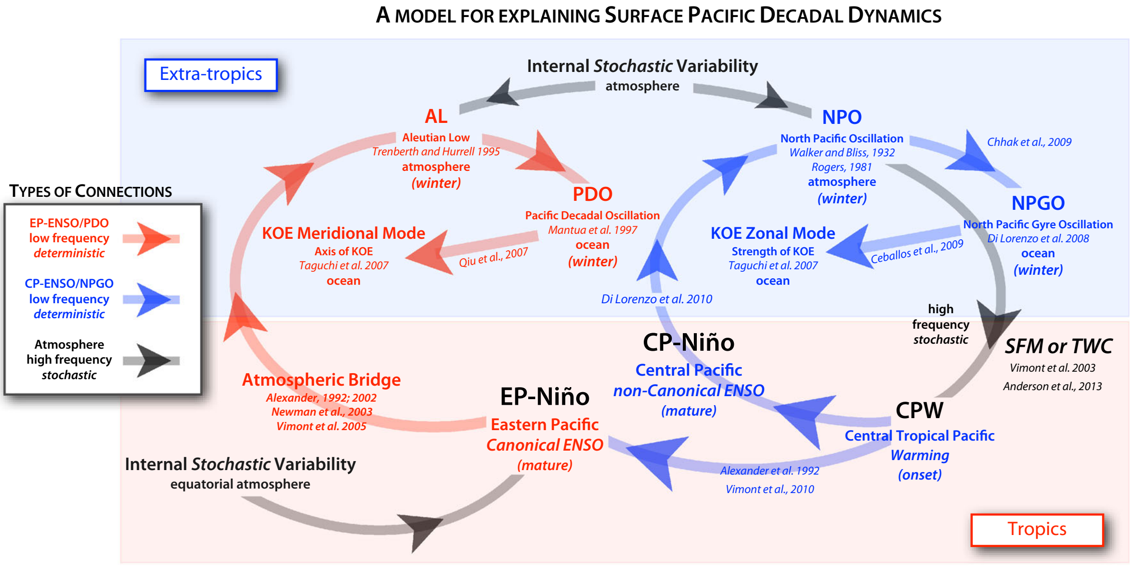

Fig. 2 Synthesis of Pacific climate dynamics and teleconnections. The Pacific Decadal Oscillation (PDO; red path) and North Pacific Gyre Oscillation (NPGO; blue path) outline teleconnections at low-frequency time scales. The gray path shows how sources of high-frequency stochastic variability in the atmosphere energize the Aleutian Low (AL), North Pacific Oscillation (NPO), and El Niño-Southern Oscillation (ENSO) systems. In the schematic, NPO low-frequency variability is linked to Central Pacific (CP)-El Niño; however, processes internal to the North Pacific atmosphere appear to drive its high-frequency variability (gray path). (Reproduced from [36])

Coupling Between Western and Eastern Boundary, and Atmospheric Feedback

The North and South Pacific western boundary currents are characterized by strong decadal variability. An important fraction of this variability is connected to large-scale atmospheric forcing in the central and eastern portions of the basins [46]. In the North Pacific, the Kuroshio-Oyashio Extension (KOE) region exhibits two dominant modes of SSHa decadal variability [136]. The first mode is associated with a shift in the axis of the KOE (KOE-meridional-mode), while the second mode corresponds to decadal modulation of the strength of the KOE (KOE-zonal-mode). Both of these modes are predominantly driven by the arrival of large-scale Rossby waves forced by atmospheric variability in the central and eastern North Pacific. Specifically, SSHa anomalies associated with the AL/PDO perturbations propagate westward and contribute to the meridional mode [75, 119, 121], while NPO/NPGO contribute to the zonal mode [16] (see schematic summary in Fig. 2). Although not all the low-frequency variability in the KOE is deterministically forced by atmospheric variations of the AL and NPO, the oceanic response and propagation of westward Rossby waves constitute an important basis for long-term predictions (e.g., [126]) as it takes about 2.5–4 years for the waves to propagate the information from the central North Pacific to the western boundary. A similar mechanism has also been identified in the South Pacific western boundary region [97], where simple linear vorticity models forced by observed large-scale winds can reproduce the low-frequency fluctuations of the western boundary [113]. Given that ENSO teleconnections have an important projection on the variations of the AL and of its South Pacific counterpart, some studies have suggested that these teleconnections of atmospheric Rossby waves can act as an important mechanism to synchronize the North and South Pacific western boundaries [1].

Although to first order the mid-latitude large-scale ocean variability is passively responding to atmospheric forcing, in the western boundary current systems, the SST seems to also be able to influence the large-scale atmosphere. The potential for atmospheric/ocean coupling and feedbacks in the western boundary has been explored in the KOE. Latif and Barnett [77] proposed a feedback whereby a wind-driven intensification of the sub-tropical gyre would enhance the transport of warm water along the western boundary, which in turn would feedback to the large-scale atmosphere and influence the gyre-scale circulation and western boundary transport again [77]. The timescale of this coupled ocean/atmosphere dynamics was estimated to be a few decades from climate model simulations. However, observational evidence for these mechanisms is weak. A faster feedback path has been proposed whereby the arrival of AL/PDO or NPO/NPGO long oceanic Rossby waves perturb the KOE SST frontal dynamics, which in turn feedback on the large-scale atmosphere (e.g., AL or NPO type pattern) that drive new oceanic Rossby waves directed to the KOE. This feedback loop would likely enhance the KOE ocean spectrum in the decadal band (e.g. [120, 121]).

A key question on the PDO dynamics is the atmospheric response to extratropical SST anomaly, notably in the KOE region. This response is critical for closing the potential feedback loop on the genesis of PDO and, more generally, for the global climate impact of PDO. However, due to the dominance and strongly nonlinear dynamical nature of atmospheric internal variability over the mid-latitude North Pacific, as well as the strong atmospheric teleconnection from the tropical Pacific, it has remained challenging to identify the atmospheric response to KOE SST in both observations and models [74]. The decadal atmospheric variability over the North Pacific is well correlated with the North Pacific SST variability with a warm SST corresponding to an equivalent barotropic high atmospheric anomaly in the Aleutian Low, consistent with the change of low level SST gradient and baroclinicity of the PDO, especially in winter [45]. It is however unclear how much this coherent atmospheric structure is caused by the internal atmospheric variability and how much is the response to North Pacific SST. Recent statistical analyses that make use of the lead-lag relationship between the atmosphere and ocean are able to extract the atmospheric response to KOE SST variability in the observations [48, 90, 92, 93]. For example, two independent methods identify a modest atmospheric response to North Pacific SST in winter, with an equivalent barotropic high response to a warm KOE SST anomaly [93]. Modeling studies with a high resolution atmospheric model simulate the atmospheric response to the shift of SST fronts in the Oyashio reasonably well [130]. It is suggested that the diabatic heating associated with the SST anomaly tends to be balanced by the transient eddy heat flux, generating a distinct atmospheric response that is different from the classical stationary linear response. These studies point to potentially modest nonlinear atmospheric response to mid-latitude SST anomaly. Further studies, especially with high resolution models, are, however, needed to confirm the robustness and elucidate the mechanism of the atmospheric response.

Other coupling dynamics between the eastern and western boundaries that can lead to multi-decadal predictability involve sub-surface oceanic dynamics. Recent observational studies suggest that tracer anomalies (e.g., temperature, oxygen, salinity) advected along subsurface isopycnals by the mean North Pacific Current can impact the surface decadal variability of the eastern boundary currents systems. Specifically, when the subsurface water mass anomalies reach the upwelling systems of the Gulf of Alaska sub-polar gyre and California Current coastal system [11, 117, 118]. It remains still unclear if these subsurface anomalies are primarily generated along the path of the North Pacific Current through anomalous advection acting on the mean tracer gradients (e.g., [66]) or if they are generated upstream in the KOE. Some modeling studies suggest that subsurface anomalies generated in the KOE can propagate along isopycnals all the way into the eastern North Pacific [135]. These subsurface dynamics have a predictability potential on timescale of 10–20 years, but remain largely unexplored in climate model predictability experiments.

Tropical-Extratropical Interactions

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 [77, 8, 114, 84, 20, 152], several studies have shown both statistically and dynamically [[4, 30, 114]; 2008; [35, 110, 140]] 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 driven by variations in the tropics. Similarly, in the South Pacific a large fraction of the SPDO variability (~32%) is connected to ENSO in the tropics.

Tropical pacific climate variability is dominated by ocean/atmosphere coupled dynamics associated with ENSO and its diverse expressions [15]. It is well known that tropical SST anomalies associated with eastern tropical warming (EPW) excite variability in the AL through the "atmospheric bridge" of teleconnection waves [2, 4]). The ENSO-derived variability of the AL is integrated and low-passed by the North Pacific ocean and contributes to the decadal PDO pattern there [108, 110, 125], providing a strong dynamical link between low-frequency climate variability in the tropics and extra-tropics. Similarly, in the South Pacific, the atmospheric teleconnection forced by tropical SST variability projects on the pattern of atmospheric forcing of the SPDO, leading to strong correlations between the Nino3.4. and SPDO index ($R = 0.57$) [44]. In the North Pacific, the correlation between PDO and Nino3.4 index is weaker ($R = 0.46$) and reflects the stronger role that internal atmospheric variability plays in driving the PDO.

In contrast to the canonical EPW-ENSO, recent studies isolate a new flavor of El Niño [7] that has become more frequent than the canonical EPW El Niño in the late twentieth century [151]. This type of El Niño, also referred to as the dateline El Niño [76], El Niño Modoki [7] or warm pool El Niño, is characterized by a central Pacific warming (CPW) pattern [62]. SST anomalies associated with the CPW, now in the central equatorial Pacific, modify the large-scale atmospheric circulation with a different pattern of atmospheric teleconnections to the extra-tropics from that of EPW [148]. The extra-tropical footprint of the CPW has been shown to impact the expression of the NPO [49] and drive a large fraction of the NPGO variance [35]. 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.

The dynamical link between the EPW➔AL➔PDO and CPW➔NPO➔NPGO (see summary schematic of Fig. 2) provides the basis for a potential positive feedback between tropics and extra-tropics. Support for a dynamical feedback comes from past studies on extra-tropical precursor of ENSO, specifically, the so called *Seasonal Footprinting Mechanism* (SFM [142, 143, 5]) and the off-equatorial *Trade Wind induced Charging* (TWC) of the equatorial Pacific [6]. In the SFM mechanism, boreal winter-time variability in the NPO (e.g., a weakening of the off equatorial trade winds) 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 [85]. This central Pacific warm anomaly weakens the Walker Cell and may initiate an ENSO response in the tropics that peaks in the following winter [2]. The ENSO response can be both of the EPW and CPW types. If the response is a CPW event, this may lead to 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 and of its extra-tropical expression [37], which could explain why the CPW temporal variability has a longer decorrelation timescale and predictability [67] than the EPW. In the TWC, the weakening of the off equatorial trade winds leads to a charging of the subsurface heat content along the central and western equatorial Pacific favoring ENSO conditions according to the recharge/discharge ENSO theory [60]. These mechanisms differ from earlier hypothesis of tropical-extratropical interaction that rely on the slow equatorward oceanic ventilation [83] for the extratropical climate system to impact the tropics [53].

Similar to the North Pacific SFM, off equatorial wind anomalies in the South Pacific have also been shown to contribute to ENSO variance [40, 157]. In fact, we anticipate that the schematic of Pacific decadal variability developed with a focus on the North Pacific (Fig. 2) is likely symmetric with respect to the equator with an important fraction of decadal variability originating from the South Pacific through a similar set of extra-tropical-tropical interaction dynamics. The growth and equatorward propagation of off equatorial coupled ocean/atmosphere modes (e.g., SST, winds) associated with the WES thermodynamic feedbacks are referred to as Meridional Modes (MM) [21, 141]. The cumulative contribution of MMs from the South and North still needs to be fully quantified. MM are not only important in the Pacific basin but have been shown to drive a dominant fraction of the tropical Atlantic multi-decadal SST variability (e.g., [150]).

The Role of the Tropics in Pacific Decadal Variability

It is clear that tropical atmospheric teleconnections play an important role in synchronizing decadal variability across the South and North Pacific, which is captured in dominant modes of SST and SSH such as the PDO, NPGO and SPDO. This "synchronization" process leads to the emergence of a basin-scale ENSO-like pattern as the first mode of lowpass (> 6 years) SST over the Pacific basin [60S 60N] [37, 155], also captured by the IPO. This connection of tropical to basin-scale low-frequency variability is evident by the high correlation that exist between the IPO and the dominant mode of tropical Pacific decadal variability (TPDV) (Fig. 1) defined as the dominant mode of lowpass SST in the tropical strip [5S 5N]. Although tropics plays a role in the "synchronization" of the Southern and Northern Hemisphere, it is still unclear if the TPDV emerges as the results of internal tropical dynamics (e.g., [149]), the residual of averaging limited number of interannual ENSO events [140], or of other dynamics that rely on off-equatorial wave dynamics [70, 69, 146] or extratropical-tropical interactions through surface ocean-atmosphere coupling discussed before [37]. Off-equatorial westward propagating Rossby wave can be excited over a broader range of latitudes, some extending further poleward to the subtropics. Since at a higher latitude, westward propagating Rossby waves take a longer time to cross the basin, this process can lead to a "decadal" ENSO-like variability in the tropics, which is then projected to the mid-latitudes via the classical atmospheric bridge [4]. Although this mechanism is plausible and reproduced in some model simulations, studies of off-equatorial ENSO precursors suggest that the internal noise of the atmosphere in the extra-tropics can override these westward propagating signals and play a more direct control on triggering ENSO (e.g., SFM, MM, TWC) (see [143, 6]). Evidence supporting the "stochastic" nature of off-equatorial forcing of ENSO comes from recent studies showing how the South and North Pacific ENSO precursors (e.g., MM) act independently in energizing ENSO-like variance in the tropics [40, 94]. While a large-fraction of basin-scale Pacific decadal variability is synchronized through the mediation of tropical variability, internal atmospheric noise in the extra-tropics and coupled ocean/atmosphere feedbacks in the western boundary drive an important fraction of the decadal variance that is not hemispherically symmetric, especially over the North Pacific (e.g., the 1st EOF of SSTs with the ENSO signal removed). It should be pointed out that the high correlation of all PDV modes with the tropics could be interpreted as a strong evidence of an active role of tropical Pacific in exciting and synchronizing all the PDV modes. This active role of tropics in PDV modes, however, has remained difficult to demonstrate explicitly, as discussed earlier in "partial coupling" experiments in climate models [149, 158, 152]. In those model experiments, the suppression of tropical climate variability does not suppress the decadal variability in the extratropics significantly, implying the origin of PDV in the extratropics. However, almost all current climate models suffer an underestimation of the correlation between the tropical Pacific and extratropical Pacific climate variability [109]. Therefore, these models, although still show significant tropical-extratropical correlation, could underestimate the active role of tropical Pacific.

Predictability of Pacific Decadal Variability

The dynamics discussed in the previous sections are summarized in a decadal variability framework that outlines deterministic lead/lag relationship in the Pacific climate system, which can be exploited for predictability on interannual to decadal scales ("A Framework for Understanding the Predictability of Pacific Decadal Variability"; Fig. 2). It is important to realize, however, that the existence of deterministic mechanisms does not always translate into skillful fully coupled climate predictions. The internal noise of the atmosphere can override deterministic lag responses in the Pacific climate and add significant noise to the regional footprint of the teleconnected responses (e.g., the impact of ENSO on rainfall over North America). It is therefore important to quantify in each system what fraction of the variability is explained by lead/lag dynamics vs. noise.

A Framework for Understanding the Predictability of Pacific Decadal Variability

The surface decadal variability of the North and South Pacific associated with the known modes of decadal variability can be viewed to the first order as a reddening of the local atmospheric forcing (e.g., the PDO as a reddening of the AL and the NPGO a reddening of the NPO, same for the SPDO) and tropical variability (Fig. 2). Although such a process can be described as an auto-regressive model, which is essentially unpredictable beyond the persistence time, there is some predictability that arises from two general sources: (1) a fraction of variability of the atmospheric forcing (e.g., AL, NPO, and SPO) is linked to tropical teleconnections and/or oceanic feedbacks (e.g. in the western boundaries), and (2) the decay dynamics of the PDO/NPGO modes carry a predictable response, most importantly the westward propagating Rossby waves that impact the western boundary with a delay of 2–4 years (Fig. 2). The preferred time scales of the PDO, as shown more clearly in some models, could contribute to the enhanced predictability relative to the linear damped persistence forecast [52]. There is also an important source of surface decadal predictability arising from the upwelling of subsurface water mass anomalies. These anomalies can contribute to decadal variations of SST and biogeochemical tracers, potentially impacting the climate and ecosystem in the key Pacific upwelling systems like the eastern tropical upwelling cold tongue region, the sub-polar gyre and eastern boundary upwelling systems. Several studies have documented the subsurface propagation of water mass anomalies along the path of the mean gyre circulation. Because of the slow propagation in the subsurface before reaching upwelling systems, these dynamics can lead to predictability on timescales of decades if the signal to noise ratio is strong. Examples of subsurface propagation have been discussed in the context of the westward branch of the sub-tropical gyre carrying signal into the sub-polar and eastern boundary upwelling systems for the mid-latitudes [117, 118], and of the south-eastward branch of the sub-tropical gyre carrying anomalies from the extratropics into the tropical Pacific [53].

In the next sections, we discuss some of the recent advances of decadal variability.

Advances in Predicting the Pacific Decadal Oscillation (PDO)

Historically, the PDO has been used as an analog to label and describe the Pacific decadal variance in climate models that are used for decadal predictions. While the dynamics that contribute to PDO-like variability in models and observations may differ in terms of how much of the variance is contributed by the individual mechanisms (e.g., ENSO teleconnections, local atmospheric noise, coupling via the western boundary, subsurface contributions, etc.), it is insightful to review and compare recent advances in predicting the PDO-like variability using climate model experiments.

In principle, the nonlinear and chaotic nature of the climate system imposes natural limits on the skillful predictions of any climate variability, including the PDO. It is nevertheless unclear what the predictability of different aspects of the PDO is, in different regions and for different climate variables. Preliminary model-based "predictability" studies, which probe these limits and investigate the physical mechanisms involved, support the potential for some skill in the prediction of annual to decadal average temperature associated with PDO-type variability. However, little predictability has been found in climate models for key societal variables like precipitation beyond annual time scales. The study of the predictability of PDO remains at its infancy. Current studies suggest several preliminary conclusions [41, 68]. First, the predictability of the PDO in state-of-the-art coupled climate models can be enhanced by proper initialization of the ocean in the first few years, but is dominated by the forced response to radiative forcing at longer time scales (e.g., greenhouse and aerosol forcing). Second, the predictability of the PDO, especially its signature over the North Pacific, is less than its counterpart over the North Atlantic. The cause of this difference in predictability, however, remains not fully understood. Recent studies also suggest that comparable decadal forecast for some climate variables, such as SST, can be made in linear statistical models as well as in state-of-the-art dynamic climate models [109, 111].

One diagnostic predictability for decadal variability is the variance ratio between the decadal variability σ_v^2 and the total variability σ_x^2: $p = \sigma_v^2/\sigma_x^2$. This variance ratio does not necessarily represent the true upper bound for prediction or potential predictability; nevertheless, it provides a simple and convenient measure of the relative importance of decadal variability and is therefore sometimes also referred to as potential predictability [9, 10]. A higher variance ratio indicates a large portion of decadal variability in the total variability and therefore maybe more predictable (but see discussion later). The map of decadal variance ratio for surface air temperature averaged for CMIP5 RCP4.5 scenario simulations shows that both the North and South Pacific have a substantial decadal variance ratio, comparable with the Atlantic. One notable feature in the Pacific is the minimum decadal variance ratio in the equatorial Pacific (see Fig. 11.1 of [68]). This region is dominated by the interannual variability of ENSO, and therefore the relative amount of decadal variability is small. The decadal variance ratio can be further decomposed into two parts, one contributed by the internal variability and one forced variability, the former being associated with the internal variability modes such as PDO and AMO while the latter with the responses to external radiative forcing such as greenhouse gases, solar variability and volcanic eruption. In climate models, the forced response can be obtained by the ensemble mean of the forced climate simulations, leaving the residual as the internal variability. This separation shows substantial decadal variance ratio for internal variability in the North Pacific and North Atlantic, as well as a dominance of the forced response over the global (see Fig. 11.1 of [68]; also see [9, 10] for more details). Therefore, from the variance perspective, for both the internal variability and forced response, the PDO in the Pacific is as important as AMO in the Atlantic. This conclusion, however, remains untested in the observations, partly because the separation of forced and internal variability is difficult using one realization of the observed climate state trajectory.

Early prognostic prediction studies of oceanic variability in the North Pacific focused on the prediction of some specific features. For example, Schneider and Miller [126] showed that the observed wintertime sea surface temperature anomalies in the confluence region of the Kuroshio–Oyashio Currents in the western North Pacific can be skillfully predicted at lead times of up to 3 years. The predictions are based on the history of the wind stress over the North Pacific and the lead time is assumed to be associated with the oceanic Rossby wave dynamics.

Full CGCMs have been used to study the predictability of PDO prognostically. In the initial stage, most prediction studies are carried out in the perfect model context. Power and Colman [115] find predictability on multi-year time scales in SST and on decadal time-scales in the sub-surface ocean temperature in the off-equatorial South Pacific in their model. Sun and Wang [133] suggest that some of the temperature variability linked to PDV can be predicted approximately 7 years in advance. Teng et al. [137] investigate the predictability of the first two EOFs of annual mean SST and upper ocean temperature identified with PDV and find predictability of the order of 6 to 10 years. Meehl et al. [100] consider the predictability of 19-year filtered Pacific SSTs in terms of low order EOFs using an analogue method and find some predictability on these long time scales Kirtman et al. [68]. The physical mechanism for the predictability in these experiments has not been studied in detail, but is likely related to oceanic Rossby waves.

Recently, prognostic predictability studies have been carried out for real world hindcasts as well as future predictions. With proper initialization of the ocean, these studies suggest enhanced predictability of the PDO in coupled climate models in the first few years. At longer time scales, however, the predictability is dominated by the forced response to radiative forcing. Furthermore, in contrast to the "potential predictability" inferred from the variance ratio, prognostic predictability studies suggest a substantially lower hindcast skill for PDO than AMO. Figure 3 shows the ensemble mean decadal hindcast of surface air temperature in CMIP5 models [41] for the prediction of year 2–5 and 6–9. It is seen that the RMSSS (one minus the RMSE of ensemble-mean prediction relative to the RMSE of the mean climate) skill is the lowest in the Pacific, especially in the central North and tropical Pacific. Unlike the traditional weather prediction and seasonal prediction, however, the skill of decadal prediction here is contributed significantly by the long term monotonic trend, which is forced by the external radiative forcing, rather than the internal variability itself. The contribution of internal variability and external forcing to the hindcast can be inferred from the role of initialization as seen in the ratio of RMSEs between the runs with initialization and those without initialization. A reduced RMSE ratio below 1 implies a contribution of the prediction of internal variability. Figure 3c, d shows that initialization can lead to some improvement of the decadal forecast skill (red shading of low RMSE with initialization, in the 2–5 year as well as 6–9 year predictions). However, over most of the globe, the RMSE reduction is not significant, implying a major contribution to the prediction skill by the external forcing or trend. In the North Pacific and North Atlantic, the reduction is more in the North Atlantic than in the North Pacific, implying a lower predictability of the internal variability mode of PDO than AMO. A further comparison of the hindcast

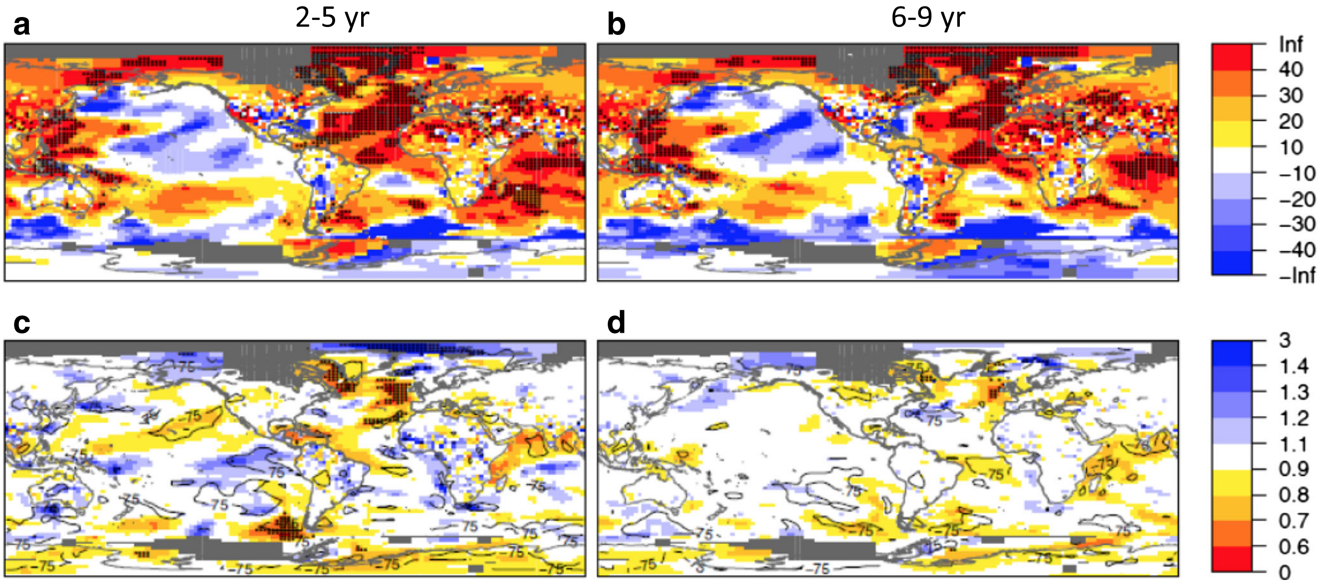

Fig. 3 Near-surface air-temperature forecast quality. **a**, **b** RMSSS (multiplied by 100) of the ensemble mean of the Init multi-model for predictions averaged over the forecast years 2–5 (**a**) and (6–9) (**b**). A combination of temperatures from the GHCN/CAMS air temperature over land, ERSST and GISTEMP1200 over the polar areas is used as a reference. Black dots correspond to the points where the skill score is statistically significant with 95% confidence using a one-sided F-test taking into account the autocorrelation of the observation minus prediction time series. **c**, **d** Ratio of RMSEs between the Init and NoInit multi-model experiments for predictions averaged over the forecast years 2–5 (**c**) and 6–9 (**d**). Contours are used for areas where the ratio of at least 75% of the individual forecast systems has a vale above or below 1 in agreement with the multi-model ensemble mean results. Dots are used for the points where the ratio is statistically significant above or below 1 with 90% confidence using a two-sided *F* test that takes into account the autocorrelation of the observation minus prediction time series. Poorly observationally sampled areas are masked in gray. (Adapted from [41])

skills, in both correlation skill and RMSE, for surface temperatures of the global mean, AMO and IPO, for both the initialized hindcast and historical run without initialization shows that global temperature has the highest prediction skill due entirely to the forced response. The IPO has the lowest hindcast skill with little improvement due to initialization, such that the prediction mainly captures the trend. The AMO, in contrast, has a higher skill than IPO, and the higher skill is contributed mainly by the initialization. Indeed, the initialization seems to allow the model to predict the transition of variability beyond the trend, such as the cooling in the 1960s as well as the warming after 1990s (see Fig. 1 and the discussion of [41] for more details). A similar conclusion can be drawn from statistical predictions after filtering the linear trend in LIM without trend, which show a higher prediction skill in the North Atlantic than in the North Pacific (Fig. 5 of [109]).

Given the comparable decadal variance ratio of the PDO and AMO, why does the PDO have a lower forecast skill in the North Pacific? One major reason is suggested to be the relatively weaker linear trend in the North Pacific [41]. Another reason could be the relatively higher importance of the ENSO impact, which is unpredictable beyond interannual time scale and therefore acts as a climate noise for decadal prediction. It is known that ENSO can impact the North and South Pacific significantly through the atmospheric teleconnections [89]. In the context of climate forecast, this remote ENSO impact may be inferred from simple statistical analysis. The local persistence and in turn the damped persistence forecast skill for surface temperature is comparable between the North Pacific and North Atlantic; the forecast skill in the North Pacific, however, becomes lower than in the Atlantic when the prediction is made using a multivariate Linear Inverse Model (LIM) that includes the remote SST impact, especially from the tropical Pacific ([110], 2013). This forecast skill distribution in the linear statistical model resembles closely that of the IPCC AR5 models, and therefore can be used as a benchmark [109]. There are also studies that attribute the lower skill in the North Pacific to the failure of predicting several largest warming events, notably the 1963 and 1968 events [54]. The different behavior of surface and subsurface temperatures of the PDO also contributes to the low forecast skill of PDO [105, 106, 132] and the intermittent processes associated with the interaction of different components of climate variability in the North Pacific [51]. In spite of these studies, it remains unclear what are the mechanisms leading to the low forecast skill in the North Pacific. Indeed, it is not even clear if the low predictability is truly low in the North Pacific or PDO in nature. Some climate models can predict important features of the PDO, such as the major transitions of the PDO. Many features associated with the 1976/77 and 1998/99 climate shifts can be predicted for up to a decade in the Kiel Climate Model [39] and CCSM4 [103]. Therefore, it remains an important question to understand if the lower skill in the current forecasts of the PDO represents the true bound of Pacific decadal predictability or if improved models and forecast schemes can lead to longer and more accurate forecasts. There are other questions related to the IPO predictability. Given that the ENSO teleconnections in current climate models tend to be weaker than in observations [109], would an improved model produce an even lower forecast skill in the North Pacific? Given that the IPO is largely symmetric in the North and South Pacific, why does the forecast skill tend to be high in the South Pacific, and indeed is comparable with that in the South Atlantic in dynamical (Fig. 3) and statistical predictions [109]? Even within the extratropical North Pacific, why does the predictability seem to exhibit a sharp dipole pattern with the low predictability concentrated in the north, separated from a high predictability to the south (Fig. 3a, b)? Much work is needed in understanding these issues.

Climate Change Projections and Pacific Decadal Variance

Recent studies suggest that PDO, and especially the ENSO-like Pacific basin-wide signature of the IPO, can play an important role in the modulation of global warming by absorbing the heat induced by the increase of greenhouse gases into the deep ocean. Observations of the last century shows that the positive phase of IPO (with a warm tropical Pacific) tends to coincide with an accelerated global warming while the negative phase of IPO tends to coincide with the slow down or even “hiatus” of global warming [43]. In particular, the most recent global warming hiatus after ~1998 has received great attention. This warming hiatus has been attributed to the change of IPO [98, 101, 147, 43], the Atlantic AMO [17] and the radiation forcing associated with aerosol and stratosphere water vapor [131, Kaufmann et al. 2011). More recently, a comprehensive analysis suggests that this hiatus is contributed predominantly by the IPO [25]. Dynamically, the IPO’s control of global mean temperature change is exerted by the eastern equatorial Pacific SST [71] through tropical atmospheric heating and then global atmospheric teleconnections [139]. Energy budget analysis further suggests that the missing heat associated with this hiatus is stored in the ocean [138], mostly in the upper Indo-Pacific Ocean between 100 to 300 m [112, 79], while the heat induced by anthropogenic forcing is transported to the deep ocean in the North Atlantic and Southern Ocean below 700 m [17, 94]. These studies highlight the role that the ENSO-like decadal pattern (e.g., IPO) plays in modulating global temperature trends, because of its large spatial footprint and, most importantly, its key center of action in the tropical Pacific, where it can efficiently transmit its influence globally. It is therefore reasonable to assume that this IPO modulation on globally rising temperatures will continue into the future, creating interdecadal periods of accelerated warming and hiatus (to the extent that warming trend will be comparable to the past).

It is also conceivable that the ENSO-like decadal variability is not independent of global warming. Nevertheless, it remains challenging to study the potential global warming impact on PDV. Although observations show a trend towards stronger PDV in a warmer climate, the observational records are too short to assess its significance. Some paleoclimate records suggest that ENSO variance is increasing under anthropogenic forcing [23]. Given that ENSO energizes the PDV, this may lend further support to the observational trend in PDV variance that emerges from a more energetic interaction between Meridional Modes and ENSO [80]. However, more long-term and high-resolution paleo-records and reconstructions [42] are required to establish how robust this trend is. As of now, impact of global warming on PDV heavily relies on climate modeling which have known challenges in capturing the dynamics of PDV (e.g., Furtado et al. [49]).

There are also recent modeling studies on the response of PDO to global warming (e.g., [26]). In contrast with some of the observational evidence of an increasing PDV under global warming, some climate modeling studies suggest that the North Pacific oceanic decadal variability in SST and atmospheric variability associated with the PDO become weaker and the time scale shorter [44, 153, 154]. It is suggested that global warming intensifies the upper ocean stratification [14, 15], accelerating baroclinic Rossby waves and leading to a faster decay of the PDO signature. A similar response has been found in the Atlantic for AMO. In response to global warming, the AMO becomes shorter and weaker, which is likely caused by the speed up of baroclinic Rossby waves associated with the intensified stratification in response to global warming; faster Rossby waves reduce the delay time of the negative feedback in the delayed oscillation analogue and tends to suppress the amplitude of the AMO [19]. It may be possible that internal dynamics of the PDO in the higher latitudes (e.g., Rossby waves) tends to counteract the increase in decadal variability that results from the interactions between Meridional Modes and ENSO in the tropics and subtropics [80]. These preliminary results, however, remain highly uncertain and require much further studies. If confirmed, they suggest that both the North Atlantic and North Pacific share similar responses, even though the mechanism for PDO and AMO may differ significantly, the former being suggested to be associated with the change of the variability of the Atlantic Meridional Overturning Circulation (AMOC) [29], while the latter associated with the change in the wind-driven circulation (“Mechanisms of Pacific Decadal

Variability”). It is possible that the Rossby wave adjustment plays a role in both the AMOC [64, 61] and Pacific gyre circulation (see “Mechanisms of Pacific Decadal Variability”), leading to similar responses in both modes.

Summary

The last decade has seen the simultaneous development of the understanding and prediction of Pacific Decadal Variability. These studies have offered new insights as well as new challenges to our understanding of PDV. The PDV is now recognized to consist of multiple ocean-atmosphere modes and to be caused by multiple processes. To the first order, the PDV can be viewed as the reddening process of stochastic atmospheric variability on the extratropical ocean. However, in the Pacific, PDV is also strongly tied to teleconnections dynamics to and from the tropics, primarily the interactions between Meridional Modes and other ENSO precursor dynamics in the extra-tropics and ENSO, and between the ENSO teleconnections and the dominant modes of atmospheric variability in the mid-latitudes (see Fig. 2 schematic). In the mid-latitudes, oceanic Rossby waves are found to be crucial for determining the decadal time scales of the PDV and are an important source of predictability of PDV.

While much of the ongoing research has focused on the predictability of PDV that emerges from surface and upper ocean processes, fewer studies explore the role of ocean subsurface dynamics for multi-decadal predictability in the Pacific. In the mid- and high latitude, most studies that rely on oceanic wave propagation have focused on the 1st mode of baroclinic Rossby wave, which is the non-Doppler shift mode and therefore propagates westward regardless of the mean flow [86, 87]. However, there is evidence that the heat content anomalies during the PDO cycle propagates tilted from the zonal direction and is affected by the mean advection. These could be related to the second baroclinic mode, or the advective mode [86, 87] or even unstable planetary modes [24, 25]. Towards the subtropics, some studies have explored the role of subsurface equatorward oceanic ventilation as mean for the extra-tropics to impact the decadal variability in the tropics. However, observational evidence for a strong and predictable contribution via this subsurface pathway is yet to be found. In contrast, in the mid-latitudes, recent observational analyses suggest that subsurface dynamics may lead to important sources of decadal predictability in regional upwelling systems, namely the eastern boundary and polar gyre. Unfortunately, this source of subsurface predictability remains largely unexplored in climate models, which do not adequately resolve the upwelling dynamics of these regional circulation systems.

Preliminary experiments with GCMs and empirical linear inverse models have been carried out for realistic prediction of upper ocean PDV. These prognostic studies show some skill for the prediction of PDV in ocean temperatures. While the climate predictions in the first few years depend significantly on the oceanic initial condition, predictions of near decadal time scales are contributed mostly by the global warming trend (see “Predictability of Pacific Decadal Variability”). So far, the prediction skills from dynamic models are comparable with that from linear statistical models, indicating the potential effectiveness of correlations among the observed modes in determining decadal climate prediction.

In spite of this progress, much work is needed to improve our understanding and prediction of PDV. Coupled model predictions of PDV remain at its infancy. The nature and limit of the predictability of PDV is far from understood. Current prediction studies have not focused on the links between the predictability and physical mechanism of the PDV. Indeed, it remains unclear what mechanisms determine the time scales of the different modes of PDV not only in the observation but also in CGCMs. The different PDV modes have been identified statistically and therefore are statistical modes. The mechanisms proposed so far are determined mainly using statistical methods and therefore the corresponding dynamics remain speculative in nature. Explicit dynamic experiments are needed to better understand these modes; however, climate models have challenges in reproducing the observed features of the PDV, especially its temporal statistics and the teleconnections among modes.

Although it is clear that the tropics play a key role in PDV, there are still uncertainties in the processes linking tropics and extra-tropics on decadal timescales. It is well known that tropical climate variability can impact extratropical PDV modes significantly. Recent studies suggest possible impacts of extratropical climate variability on the tropics through coupled climate teleconnections (e.g., Meridional Modes, SFM, TWC) (see “Tropical-Extratropical Interactions” and “The Role of the Tropics in Pacific Decadal Variability”). It still remains speculative if these interactions constitute significant feedbacks that maintain, or even enhance the persistence of, different variability modes. This uncertainty leaves it unclear if the tropical climate variability acts as a signal or noise to the decadal predictability of PDV.

Furthermore, previous studies on PDV predictability have focused mostly on the surface climate variability (see section 3), while much less attention has been paid to the decadal prediction of subsurface variability. Given the importance that subsurface decadal variability of upwelling water mass anomalies (e.g. oxygen, nutrients) play on marine ecosystems, one future direction is to enhance our understanding and prediction capability of the subsurface signatures of the PDV by enhancing both observational and modeling efforts.

Finally, the role of PDV on future global climate change and its potential modulation by climate changes remain to be better understood. It has been recognized recently that natural multidecadal variability modes, notably the IPO, can slow down or accelerate the global warming trend significantly (see "Climate Change Projections and Pacific Decadal Variance"). However, there as still discrepancy among models on how these modes and the mechanisms of PDV are influenced by anthropogenic forcing. Future research will necessarily combine improving climate models that more adequately resolve basin and regional-scale decadal dynamics with long-term and diverse observational and paleoclimate records (e.g., physical, chemical and biological). The ability for ecological systems to integrate the low-frequency climate variability may be exploited to further fingerprint the key processes that regulate PDV and in turn improve the physical basis for decadal and climate change predictions of Pacific climate.

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Compliance with Ethical Standards

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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