



March 19, 2026

Delta Independent Science Board
c/o Delta Stewardship Council
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Via email: disb@deltacouncil.ca.gov

Dear Delta Independent Science Board Members (Chair Dr. Inge Werner, Chair-Elect Dr. Diane McKnight, Past Chair Dr. Lisa Wainger, and Colleagues),

Thank you for the opportunity to speak today at the Delta ISB meeting about the role of AI in advancing Delta science. AI is transforming scientific research, and it was encouraging to see members sharing thoughts on the AI-focused sessions at the 2026 Interagency Ecological Program (IEP) Annual Workshop this week (March 16–18). The plenaries and talks highlighted potentially transformational ways these tools can accelerate synthesis, integration, and real-time insights across Delta research.

As a follow-up to my remarks, I am attaching a draft literature synthesis that was developed with the help of AI, "Accelerated North Pacific Warming and the Kuroshio-Oyashio Extension: A Literature Synthesis" (March 2026). This review integrates recent research (primarily 2022–2026) on:

- Sea surface and subsurface temperature increases in western boundary current extensions at 2–3 times the global mean rate,
- Dramatic acceleration in mode- and intermediate-water heat uptake (nearly doubling between 2000–2010 and 2010–2020),
- Mixed-layer shoaling amplifying SST seasonality and marine heatwave intensity,
- Shifts in marine heatwave drivers from primarily atmospheric to oceanic preconditioning,

- Emerging evidence that a substantial fraction (~53%) of PDO variance since 1950 is externally forced, with structural changes to North Pacific SST EOF patterns (e.g., the rise of a pan-basin warming mode), and
- Implications for non-stationary climate indices and ecosystem responses.

As my talk at the IEP workshop highlighted (see attached slides), these dynamics are resulting in temperature and precipitation shifts in California hydroclimate. We are seeing enhanced upper-ocean heat content, altered mixing, more frequent extremes, and the need for robust trend attribution in long-term monitoring and adaptive management. The synthesis also flags model limitations (e.g., resolution dependencies and CMIP6 pattern biases) relevant to improving projections for climate adaptation in the Delta.

This work was co-developed in collaboration with large language models, specifically Claude Opus 4.6 (Anthropic) for literature search, structural organization, and iterative synthesis, and ChatGPT 4.6 (OpenAI) for draft review.

In practice, the AI collaboration went substantially beyond formatting or editorial assistance. The final synthesis integrates 56 references across five subdisciplines — physical oceanography, climate dynamics, mode water thermodynamics, fisheries ecology, and statistical climate analysis. I think this is a breadth that no single researcher could hold in working memory simultaneously. (Although I have been trying since 2022 with OneNote.)

Claude performed targeted searches of the scientific literature, retrieving and cross-referencing papers in real time as the synthesis developed. For example, when I identified a gap in the paper's coverage of the 1988/89 North Pacific regime shift, Claude searched the literature, surfaced key mechanistic studies (including coral proxy evidence of changing Kuroshio heat transfer), and helped me trace the implications across regime shift dynamics, fisheries decorrelation evidence, and theoretical frameworks for PDO variability.

A search for western boundary current heat budgets surfaced a 2025 paper (Sun et al., *Geophysical Research Letters*), which proved critical: it demonstrates that ocean heat transport anomalies in the Kuroshio-Oyashio Extension produce deep atmospheric circulation responses, establishing a causal pathway from ocean to atmosphere that had not previously been connected to the Pacific decadal variability literature. This finding, combined with existing work on the Atlantic Multidecadal Oscillation (Zhang et al., 2016), allowed us to identify a significant gap in the current literature, whether time-varying ocean heat transport convergence has become an active driver of Pacific decadal variability, rather than a passive response to atmospheric forcing. The synthesis now explicitly flags this gap.

All scientific interpretations, cross-disciplinary connections, editorial decisions, and final content remain fully my responsibility, with AI serving as a collaborative partner to manage complexity across a literature too large and multidisciplinary for any individual to synthesize unaided. The approach is described in detail in the document's Methods section. This methodology aligns closely with the practical, human-led AI integrations discussed at the IEP Workshop and in today's meeting: the human researcher directs the inquiry, evaluates physical plausibility, and makes all scientific judgments, while AI provides the working memory and search capacity to hold dozens of papers in simultaneous context.

I offer this synthesis as a resource for the Board's ongoing work, particularly in light of the emerging climate science discussions. I hope to continue following up with the Delta Science Program and researchers in California.

Thank you again for your essential independent oversight of Delta science, and focus on bringing clarity to key questions.

Sincerely,

A handwritten signature in black ink, appearing to read 'D. Des Jardins', with a stylized flourish at the end.

Deirdre Des Jardins

California Water Research

Attachments:

KOE synthesis draft

IEP workshop talk slides (pdf): Anthropogenically driven Pacific climate shifts and California hydroclimate

Accelerated North Pacific Warming and the Kuroshio-Oyashio Extension: A Literature Synthesis

Deirdre Des Jardins

DRAFT

March 2026

Abstract

The Kuroshio-Oyashio Extension (KOE) region in the northwestern Pacific Ocean is one of the fastest-warming areas in the global ocean. This literature review synthesizes recent research documenting temperature increases in the KOE, examining sea surface temperature (SST) trends, subsurface heat accumulation, marine heatwave dynamics, and the role of mode waters in heat storage and redistribution. The evidence consistently demonstrates that warming in western boundary current extension regions outpaces global mean rates by a factor of two to three, with subsurface heat uptake in mode and intermediate water layers nearly doubling between 2000–2010 and 2010–2020. This differential warming has implications for the interpretation of traditional North Pacific climate indices: recent work indicates that a substantial fraction of Pacific Decadal Oscillation (PDO) variance since 1950 is externally forced, and that the spatial patterns extracted by empirical orthogonal function analysis have shifted as the climate has warmed. These findings have significant implications for regional climate, global heat budgets, and the analytical frameworks used to characterize North Pacific decadal variability.

1. Introduction

The Kuroshio-Oyashio Extension (KOE), located between approximately 35–44°N and 140–180°E in the northwestern Pacific, represents one of the most dynamically active ocean regions on Earth. Here, the warm, northward-flowing Kuroshio Current meets the cold, southward-flowing Oyashio Current, creating intense thermal fronts, vigorous mesoscale eddy activity, and substantial air-sea heat exchange. The KOE plays a fundamental role in global climate through its influence on atmospheric circulation patterns, storm tracks, and carbon uptake (Wu et al. 2012; Kelly et al. 2010).

Although the Pacific Decadal Oscillation (PDO) is commonly defined as the leading pattern of North Pacific sea-surface temperature variability (Mantua et al., 1997), it is increasingly understood not as a single physical mode but as a collection of interacting dynamical processes (Newman et al., 2016). Within this framework, the KOE is not merely a regional response to the PDO; it is one of the dynamical constituents through which PDO-like variability is organized. The canonical PDO pattern includes a strong western North Pacific expression in the KOE region, and Wills et al. (2019) showed that ocean circulation signatures in the KOE, particularly subpolar gyre variability and zonal advection, constitute a dynamically independent component of the PDO not captured by atmospheric teleconnections from the tropics alone. Linear inverse model analyses identify a distinct KOE mode with a strong regional projection and basin-scale footprint (Wu, Di Lorenzo, et al., 2026). Changes in the Kuroshio Extension are therefore directly relevant to the structure and interpretation of PDO variability.

A landmark study by Wu et al. (2012) established that post-1900 surface ocean warming over subtropical western boundary current paths, including the KOE, has proceeded two to three times faster than the global mean surface ocean warming rate. This accelerated warming was associated with poleward shifts and intensification of the boundary currents in conjunction with systematic wind changes. More recently, Li, England, and Groeskamp (2023) demonstrated that global ocean heat uptake has accelerated substantially, with mode and intermediate water layers carrying the vast majority of the Argo-era ocean heat content increase. This warming has been accompanied by increasing upper-ocean stratification over the past half-century (Li, Cheng, et al., 2023), which reduces mixed layer depths and amplifies the surface expression of temperature anomalies. The tropical source region for much of this heat has itself undergone dramatic change: Roxy et al. (2019) showed that tropical SST warming has led to an almost twofold expansion of the Indo-Pacific warm pool, from an area of 2.2×10^7 km² during 1900–1980 to 4×10^7 km² during 1981–2018, with the expansion non-uniform and more pronounced over the western Pacific. A breakpoint analysis confirmed that the shift to higher warm pool values occurred during 1979–1980, coinciding with the shift in global mean SSTs and followed by accelerated surface warming in response to anthropogenic emissions. These findings have spurred intensive investigation into the mechanisms driving KOE warming and its broader implications.

The differential warming of the KOE also has implications for interpreting the PDO itself. The IPCC Sixth Assessment Report (IPCC, 2021) recognized that the standard methodology for isolating internal variability from external forcing at decadal timescales carries inherent ambiguity, and subsequent research (discussed in Section 7) has quantified the extent to which PDO variability includes an externally forced component. More broadly, the progression across three North Pacific regime shifts (1976–77, 1988/89, 1998–99) documented in Section 6 suggests a transition from an atmospheric-integrator framework (Schneider and Cornuelle, 2005) toward one in which oceanic heat transport plays an increasingly active role. Zhang et al. (2016) demonstrated that time-varying ocean heat transport convergence is a leading cause of multidecadal variability in the Atlantic, and Roberts et al. (2017) showed that ocean dynamics dominate full-depth heat budgets in all western boundary current regions. Whether an equivalent mechanism operates in the Pacific, with the KOE serving as the critical relay between tropical heat sources and extratropical climate variability, remains a significant gap in the current literature.

This review synthesizes the current literature on temperature increases in the KOE region, organized around six major themes: (1) accelerated sea surface temperature warming, (2) subsurface heat accumulation and ocean heat content changes, (3) marine heatwave occurrence and drivers, (4) mode water warming and dynamics, (5) decadal variability and regime shifts, and (6) implications for the Pacific Decadal Oscillation and Victoria Mode. We conclude with a discussion of remaining uncertainties and future research directions.

2. Accelerated Sea Surface Temperature Warming

Multiple studies have confirmed that the KOE exhibits the fastest long-term SST warming rate in the North Pacific Ocean. Du et al. (2022), analyzing satellite-derived SST data from 1982 to 2021, identified the KOE (141–175°E, 35–44°N) as having both the largest SST variability and the most rapid warming trend in the basin. This enhanced warming reflects the confluence of several factors, including changes in wind-driven ocean circulation, poleward migration of subtropical gyres, and positive feedbacks between SST anomalies and atmospheric circulation.

The mechanisms underlying accelerated KOE warming involve both dynamic and thermodynamic processes. Tomita and Kubota (2005) documented a remarkable increase in

latent and sensible heat flux over the KOE during the 1990s, with the trend reaching approximately $5.8 \text{ W m}^{-2} \text{ yr}^{-1}$. This increase was driven primarily by rising SST, which reached its maximum value in a 50-year record during 1998–1999, coinciding with a documented regime shift in the Pacific climate system.

Wu et al. (2012) attributed the enhanced warming to synchronous poleward shifts and/or intensification of global subtropical western boundary currents, driven by systematic changes in atmospheric winds over both hemispheres. The study emphasized that these circulation changes amplify the thermodynamic warming signal, making western boundary current regions particularly sensitive to climate change. However, the authors noted substantial uncertainties in detection and attribution, calling for long-term monitoring networks to better constrain these trends. This accelerated surface warming is accompanied by intensifying subsurface heat accumulation: Li, England, et al. (2023) demonstrated that global ocean heat uptake nearly doubled between 2000–2010 and 2010–2020, with mode and intermediate water layers accounting for approximately 89% of the Argo-era ocean heat content increase. The ocean heat content trend in subtropical mode water is concentrated overwhelmingly in the KOE region, linking the surface warming documented here to the subsurface changes discussed in Section 3.

The most recent decade has seen a further acceleration. Hu et al. (2024) documented that SST anomalies averaged over the North Pacific (20°N – 60°N , 120°E – 110°W) during 2013–2023, relative to a 1981–2010 baseline, were the highest of any ocean basin. During the preceding period of 2000–2012, North Pacific warming tracked the global ocean average and remained relatively modest, consistent with the hiatus in global warming. Since 2013, however, positive anomalies in the North Pacific have substantially exceeded global ocean values. The spatial pattern of this accelerated warming, characterized by basin-wide positive anomalies between 20°N and 60°N , does not correspond to the PDO, which flips sign between the eastern and western North Pacific. The pattern correlation between the PDO SST anomaly and observed SST anomaly over 2013–2023 is only 0.30, indicating that the PDO cannot be the major factor accounting for the domain-averaged warming during this period.

In summary, the KOE is warming at the surface two to three times faster than the global mean, driven by the combined effects of thermodynamic warming and dynamical changes in the Kuroshio system, with the post-2013 period showing further acceleration that exceeds what

traditional climate indices can explain. This accelerated surface warming sets the stage for the subsurface changes discussed in the following section.

3. Subsurface Heat Accumulation and Ocean Heat Content

While SST warming provides the most visible signature of KOE heating, the subsurface changes introduced in Section 2 deserve detailed examination. The acceleration in ocean heat uptake documented by Li, England, et al. (2023) is disproportionately concentrated in mode and intermediate water layers: after volumetric correction, combined warming in these layers accounts for approximately 76% of global ocean warming during the Argo era (2005–2020), underscoring the importance of mode water formation regions like the KOE.

Sugimoto et al. (2017) provided direct evidence of enhanced warming in North Pacific Subtropical Mode Water (NPSTMW), formed through deep winter mixing in the KOE region. This warming signal is subsequently advected into the subtropical gyre interior, where it influences stratification, nutrient supply, and ecosystem dynamics. Lee (2009), in a technical note for U.S. CLIVAR, projected that under CO₂ doubling scenarios, NPSTMW volume would increase by approximately 40% due to warming, with the core layer becoming warmer and fresher.

Model studies have revealed important resolution dependencies in projecting subsurface warming. In preliminary results presented at the 2025 EGU General Assembly, An et al. (2025) compared high-resolution and low-resolution coupled climate models and found that only high-resolution simulations captured future deep warming reaching 600 m depth in the KOE. Low-resolution models confined warming to the upper 300 m, suggesting that coarse-resolution projections may substantially underestimate subsurface heat accumulation in energetic western boundary current regions. These findings await full peer-reviewed publication but are consistent with known resolution sensitivities in western boundary current modeling.

3.1 Upper-Ocean Heat Budget Dynamics

Understanding the relative contributions of surface heat fluxes and oceanic advection to KOE warming requires detailed heat budget analyses. Pak et al. (2017), using a 1/12° ocean general circulation model from 1981 to 2013, demonstrated that winter heat storage rate on interannual-

to-decadal timescales is determined primarily by oceanic heat advection rather than air-sea heat flux. The role of advection became particularly prominent after the 1990 regime shift, with meridional shifting of the Oyashio Extension front identified as the principal driver.

Hu et al. (2020) examined heat budgets for decadal variability in Pacific Ocean heat content and found that in the KOE region, a dipole pattern of zonal heat advection anomaly amplifies ocean heat content anomalies as they move eastward. Strong turbulent heat fluxes damp these anomalies, while both advection and surface flux contribute during Interdecadal Pacific Oscillation (IPO) phase transitions. Cronin et al. (2013), using Kuroshio Extension Observatory mooring data, showed that horizontal heat advection replenishes heat lost during winter mixing, with diffusivity at the mixed layer base up to two orders of magnitude larger in winter than summer due to inertial shear from storms and tropical cyclones.

3.2 Mixed Layer Shallowing and Seasonal Cycle Intensification

The subsurface heat accumulation documented in Sections 3 and 3.1 has a direct consequence for the upper ocean's thermal response to forcing: anthropogenic warming is systematically reducing mixed layer depths, with implications for SST variability in the KOE and the interpretation of climate indices derived from it.

Liu et al. (2024) demonstrated that the global SST seasonal cycle has intensified by $3.9 \pm 1.6\%$ over the period 1983–2022, with hotspot regions including the northern subpolar gyres experiencing intensification of up to 10%. The primary driver is increased greenhouse gas concentrations, with decreased anthropogenic aerosols also contributing. These changes in anthropogenic emissions lead to shallower mixed layer depths, reducing the thermal inertia of the upper ocean and enhancing the seasonality of SST. In addition, the direct impacts of increased ocean heat uptake and suppressed seasonal amplitude of surface heat flux contribute in the North Pacific and North Atlantic.

The spatial pattern of seasonal cycle intensification is concentrated in the KOE and North Pacific subpolar gyre, precisely the regions where mode water formation occurs and where Li, England, et al. (2023) documented the most intense acceleration in ocean heat content. Mixed layer heat budget decomposition reveals that the annual mean mixed layer depth contribution dominates the intensification, accounting for approximately 30% of the amplitude change over 40 years, while

the reduction in seasonal amplitude of mixed layer depth partially offsets this at approximately –20% (Liu et al., 2024). The net effect is strongly positive: the shallower mixed layer allows the same surface heat flux to produce a larger SST response, amplifying the expression of both internal variability and forced trends at the ocean surface.

Hu et al. (2024) provided direct quantitative support for the importance of mixed layer shallowing in recent North Pacific warming. Decomposing the accelerated warming observed since 2013, they found that ocean mixed layer shoaling, most notable between 40°N and 60°N, was the largest single contributor to SST anomalies, exceeding the contribution from net downward heat flux changes. A shallower mixed layer has lower heat capacity, so the same downward heat flux produces a larger near-surface warming response. The authors noted that global warming may be driving the shoaling through increased upper-ocean stability, making this a potentially self-reinforcing mechanism: anthropogenic warming shoals the mixed layer, which amplifies the SST expression of further warming.

Critically, climate models substantially underestimate the observed seasonal cycle intensification in the North Pacific. While observations show 3.5–5% global intensification across multiple SST datasets, individual large ensemble simulations from CMIP6 models produce values ranging from 1.6% to 5.4%, with several models capturing barely half the observed signal (Liu et al., 2024). The spatial pattern of the model-observation discrepancy is most pronounced in the KOE region, where models show diffuse, weak intensification while observations show a concentrated maximum. This underestimation is consistent with the broader pattern of model biases in representing forced changes in the North Pacific documented by Wills et al. (2022).

The intensification of the SST seasonal cycle has implications that extend beyond the ocean surface. Liu et al. (2024) demonstrated that the intensified SST seasonal cycle leads to an intensification in the seasonal cycle of dissolved oxygen, a critical factor for marine ecosystems, particularly in the North Pacific where oxygen minimum zones are already extensive. The temperature seasonal cycle is intensified not only at the ocean surface but throughout the mixed layer, indicating that the thermal impacts of mixed layer shallowing propagate through the upper water column.

Taken together, these studies indicate that KOE warming is not confined to the surface. It involves accelerating heat storage in mode and intermediate waters, changes in mixed-layer structure, altered upper-ocean heat budgets, and intensification of the SST seasonal cycle. These changes matter because they affect not only regional SST trends, but also the persistence, seasonal expression, and re-emergence behavior of North Pacific temperature anomalies, all of which are central to the decadal variability discussed in later sections.

4. Marine Heatwaves in the KOE

Marine heatwaves (MHWs) have become increasingly frequent and intense in the KOE region, with significant ecological and economic consequences. Du et al. (2022) catalogued major summer MHW events in 1999, 2008, 2012, and 2016, finding that these were driven primarily by air-sea heat flux anomalies with shortwave radiation as the dominant component. In contrast, MHWs in 2018, 2020, and 2021 were driven by ocean memory of winter warming, with northward Kuroshio Extension axis shifts and anticyclonic eddies preconditioning summer events.

The record-breaking 2024 warm-season MHW in the Kuroshio Extension region provides a compelling case study of compound drivers. Qiao and Tang (2025) found that the event peaked in mid-August 2024, with onset driven by anticyclonic eddies, northward Kuroshio Extension displacement, atmospheric blocking, and Eurasian teleconnection patterns linked to North Atlantic SST anomalies. Attribution analysis indicated that approximately 65% of the magnitude was attributable to thermodynamic warming and oceanic internal dynamics, while approximately 35% reflected atmospheric circulation changes. Critically, the authors concluded that anthropogenic forcing was necessary for such an extreme event to occur.

Pak et al. (2026) examined the role of mixed layer depth (MLD) in extensive summer MHWs, analyzing seven major events between 2001 and 2024. They found that surface heat flux terms explain approximately 65% of warming during MHW development, with MLD-related contributions (approximately 47%) comparable in magnitude to surface heat flux anomaly effects (approximately 36%). Reduced low cloud cover and intensified wind speed were identified as key drivers, highlighting the importance of coupled ocean-atmosphere feedbacks in MHW dynamics.

The growing frequency and intensity of KOE marine heatwaves reflects the compound influence of long-term warming, mixed layer shallowing, and oceanic preconditioning. The shift from primarily atmosphere-driven events (pre-2018) toward events with strong oceanic memory components suggests that the background state changes documented in Sections 2 and 3 are altering the character of extreme events in this region.

5. Mode Water Warming and Re-emergence

Mode waters, the thick and nearly homogeneous subsurface layers formed by deep winter convection, serve as critical heat reservoirs in the North Pacific. The KOE region is the primary formation site for both Subtropical Mode Water (STMW) and Central Mode Water (CMW), making mode water dynamics central to understanding regional and global heat budgets.

In a recent perspective, Xie (2025) described the "mode-water-go-round" re-emergence mechanism, wherein temperature anomalies in subtropical mode water are advected by gyre circulation on an approximately 12-year cycle before re-emerging in the Kuroshio Extension region. This mechanism explains delayed SST responses to remote forcing, including connections to the Atlantic Multidecadal Oscillation, and suggests that current SST anomalies carry information about forcing from over a decade prior.

Hosoda et al. (2004) examined interdecadal temperature variations in North Pacific Central Mode Water using an ocean general circulation model, finding that after the mid-1970s climate shift, the CMW path shifted eastward, producing subsurface warming through a dynamic mechanism. The study emphasized that coarse-resolution models fail to reproduce this signal and that lateral induction across the sloping mixed layer base is critical to CMW formation and variability.

The re-emergence mechanism that underpins PDO persistence depends critically on the depth of the mixed layer. Shi et al. (2022) demonstrated a global decline in ocean memory, measured by year-to-year autocorrelation of SST anomalies, over the 21st century, driven primarily by mixed layer depth shallowing under anthropogenic warming. As mixed layers shallow, the subsurface thermal reservoir that stores winter anomalies for re-emergence the following year becomes thinner, potentially altering the timescale and amplitude of the PDO's memory of past forcing. In

the North Pacific, this decline in ocean memory has implications for the persistence of decadal variability, suggesting that the statistical properties of the PDO, including regime duration and transition amplitude, may themselves be evolving with the forcing.

Mode waters thus serve a dual role in KOE climate dynamics: they store heat anomalies on decadal timescales and redistribute them through gyre circulation, while the re-emergence mechanism provides a physical basis for the persistence of North Pacific decadal variability. The observed warming of mode waters and the concurrent decline in ocean memory suggest that this persistence mechanism is itself changing under anthropogenic forcing.

6. Decadal Variability and Regime Shifts

The KOE exhibits pronounced decadal variability that modulates the long-term warming trend. Nonaka et al. (2006) used an eddy-resolving ocean model to simulate decadal-scale frontal migration, documenting a warm-to-cool transition from 1970 to the mid-1980s. They identified the Kuroshio Extension front as deep with a sharp sea surface height gradient, while the subarctic front was shallow with a tight SST gradient. Rossby wave propagation was identified as the primary mechanism explaining frontal variability.

The following subsections assess how the literature on KOE warming bears on the interpretation of major North Pacific regime shifts.

6.1 The 1976–77 Regime Shift and KOE Heat Flux

The 1976–77 North Pacific regime shift appears to have been mediated in part through the Kuroshio Extension region. Giamalaki et al. (2018) provided statistical evidence that an extreme atmospheric event, a persistent Aleutian Low during winter 1976–77 that was the strongest and most persistent such event throughout the entire study period (1948 to present), was associated with the shift. The Aleutian Low was present for more than double the average number of days during that winter, indicating a particularly intense and sustained event with the potential to alter oceanic physical parameters dramatically.

The first EOF of net heat flux revealed a pattern centered on the Kuroshio Extension region, explaining 22% of the variance. Change-point analysis detected a pronounced shift from negative to positive net heat flux in 1979, specifically a shift from heat flux out of the ocean to

heat flux into the ocean. Pixel-wise change-point analysis confirmed that changes around 1976–1978 were concentrated mainly in the western Pacific, particularly in the Kuroshio Extension region and part of the tropical Pacific. This spatial pattern is consistent with the hypothesis that maintenance of the oceanic conditions associated with the regime shift involved deviations in heat budget terms, specifically increased heat flux into the ocean concentrated in the Kuroshio Extension region.

The mechanism operates through basin-scale teleconnections. An extreme deepening of the Aleutian Low increases westerly winds and causes anomalous positive wind stress curl in the central North Pacific, which enhances southward Ekman drift and produces negative sea surface height anomalies that propagate into the Kuroshio Extension region through Rossby waves with a lag of 3–4 years. This process destabilizes the dynamical state of the Kuroshio Extension system, and the resulting SST variability generates anomalous heat fluxes that affect conditions across the entire North Pacific. The finding that the 1976–77 shift shows a strong KOE-centered heat-flux signature takes on additional significance in light of evidence that a substantial fraction of PDO variance is externally forced (Section 7.1), suggesting that even this iconic regime shift may have included an anthropogenic component.

6.2 The 1988/89 Shift: From PDO to NPGO Dominance

A distinct shift occurred in the North Pacific in the winter of 1988/89 that differed fundamentally from the 1976–77 transition. Overland et al. (2008), reviewing North Pacific regime shifts, found a clear 1989 shift in the winter PDO but not in the summer PDO, suggesting a seasonally dependent mechanism. Yeh et al. (2011) provided the most comprehensive analysis, demonstrating that while the 1976/77 shift was driven by tropical forcing through the Aleutian Low, the 1988/89 transition was not tropically forced. Tropical Ocean Global Atmosphere (TOGA) experiments, in which observed tropical SSTs were inserted into the model, reproduced the 1976/77 atmospheric changes but failed to reproduce the 1988/89 changes. Instead, the 1988/89 shift projected primarily onto the North Pacific Oscillation, linked to remote changes in the Arctic Oscillation. As a result, the leading mode of North Pacific SST variability changed from PDO-like during 1956–1988 to NPGO-like during 1977–2009.

The 1988/89 shift is characterized by basin-scale warming in the North Pacific centered along 45°N (Jo et al., 2013), and the SST trend since 1976/77 reflects the combined effects of both the 1988/89 and 1998/99 shifts. Tsunoda et al. (2008), using coral proxy records near Ishigaki Island in the Kuroshio region, found that winter SSTs shifted from being driven by the East Asian Winter Monsoon to being dependent on ENSO in response to the 1988/89 shift, and suggested that a change in heat transfer in the Kuroshio Current in 1988 may have contributed to the distinct character of this transition relative to 1976/77. The emergence of the NPGO as the dominant mode after 1988/89, the concurrent decline in Aleutian Low variance, and the evidence of changing Kuroshio heat transfer all point to a reorganization of North Pacific dynamics in which oceanic processes in the KOE region began playing a larger role relative to atmospheric forcing from the Aleutian Low.

6.3 The 1998–99 PDO Shift

Pak et al. (2017) documented that the role of oceanic advection in controlling heat storage rate became prominent after the 1990 regime shift, suggesting a fundamental change in the mechanisms governing interannual-to-decadal variability. Tomita and Kubota (2005) connected the 1998–1999 SST maximum to this regime shift, emphasizing that regime transitions can produce step-like changes in mean state superimposed on gradual warming trends. The turbulent heat flux over the KOE during the 1990s increased at approximately $5.8 \text{ W m}^{-2} \text{ yr}^{-1}$, reaching a maximum value in a 50-year record during 1998–1999.

Jo et al. (2013), examining the origin of the 1998/99 PDO shift, found that it was characterized by a dipole-like SST structure along 40°N, with significant warming in the southwestern and central North Pacific, precisely the KOE region. They noted that oceanic teleconnection from the tropics to the midlatitudes may have contributed to this transition, though the full mechanism remained incompletely understood. Nagano et al. (2022) provided further evidence for this tropical connection, showing that heat accumulated in the western tropical North Pacific is advected northward by the Kuroshio, with quasi-decadal temperature variations in this source region affecting PDO phase reversals through this western boundary current heat transport pathway.

Mesoscale eddies introduce additional complexity to KOE thermal variability. Shan et al. (2020) showed that eddy-induced heat flux anomalies can weaken thermal stratification and cause SST cooling despite no net change in air-sea heat exchange, through what they termed the OME-A EPE feedback mechanism. This finding has implications for understanding upper-ocean ecosystem dynamics and carbon storage in eddy-rich western boundary current extensions.

The regime shift literature underscores three points relevant to the broader themes of this review. First, the KOE serves as a critical node where atmospheric forcing, oceanic advection, and air-sea heat exchange converge during major North Pacific climate transitions. Second, the three shifts show a progression: the 1976–77 shift was driven by tropical forcing through the Aleutian Low, the 1988/89 shift was driven by extratropical atmospheric reorganization (North Pacific Oscillation/Arctic Oscillation) with evidence of changing Kuroshio heat transfer, and the 1998–99 shift involved direct oceanic teleconnection from the tropics via the western boundary current. This progression is significant in the context of the theoretical framework for PDO variability. Schneider and Cornuelle (2005) showed that ocean decadal variability can be modeled to first order as an oceanic integrator of atmospheric forcing, with the ocean boosting the low-frequency signal of the atmosphere; at decadal timescales, zonal advection in the KOE accounts for a share of PDO variance comparable to ENSO and the Aleutian Low. However, as Zhang et al. (2016) demonstrated for the Atlantic Multidecadal Oscillation, time-varying ocean heat transport convergence can be a leading cause of multidecadal variability in coupled models, rather than a passive oceanic response to atmospheric forcing. The progression across the three North Pacific regime shifts is consistent with the KOE transitioning from the atmospheric-integrator regime described by Schneider and Cornuelle to one increasingly shaped by active oceanic heat transport. Third, the step-like changes in mean state associated with regime shifts are superimposed on the accelerating warming trend documented in earlier sections, complicating the separation of forced trends from internal variability.

7. Implications for the Pacific Decadal Oscillation and Victoria Mode

The accelerated warming of the KOE relative to the broader North Pacific has implications for traditional climate indices, particularly the Pacific Decadal Oscillation (PDO). The PDO, defined as the leading empirical orthogonal function (EOF) of North Pacific SST variability, has long

been treated as a primary index of internal climate variability. However, recent research challenges this interpretation, suggesting that much of what has been characterized as PDO variability is in fact externally forced.

7.1 Anthropogenic Forcing of the PDO

Earlier work established the importance of external forcing for global decadal variability. Liguori et al. (2020), using 30-member large initial-condition ensembles with five Earth System Models, demonstrated that approximately 29–53% of decadal-scale variance in global mean SST over 1950–2010 was externally forced, with volcanic aerosol representation identified as the primary driver of this forced component. This finding suggested that given the unpredictable nature of future volcanic forcing, a substantial portion of decadal variability might not be predictable, raising the question of whether regional indices like the PDO showed similar forced fractions.

Smith et al. (2016) extended this framework to explain the early 21st-century warming slowdown, demonstrating that CMIP5 models robustly simulate a negative PDO phase in response to anthropogenic aerosols, implying that what had been attributed to internal variability was partly externally forced. They further showed that recovery from the 1991 Mount Pinatubo eruption contributed to the slowdown, reinforcing the role of volcanic forcing in PDO phase transitions. These findings challenged the prevailing view that the negative PDO during the slowdown period arose purely through internal variability.

Complementary studies have examined specific forcing pathways. Boo et al. (2015) demonstrated that direct sulfate aerosol forcing from China significantly influences multidecadal SST variability in the North Pacific, with the aerosol effect explaining a non-negligible fraction of the PDO-like signal in coupled simulations. Dittus et al. (2021) found that aerosol forcing is a key driver of recent North Pacific decadal variability, while Diao et al. (2021) showed that the zonally asymmetric component of anthropogenic aerosol forcing produces distinct SST and circulation responses in the North Pacific. Yeh et al. (2013) found that Chinese sulfate aerosol emissions alter the variability of North Pacific SST in ways that project onto the PDO pattern.

Klavans et al. (2025), using a 572-member multimodel ensemble from CMIP6, demonstrated that external forcing explains 53% of observed multidecadal PDO index variance between 1950 and 2014. Critically, this forced component reproduces the major PDO transitions in the 1970s

and 1990s to within a few years, even without accounting for tropical Pacific variability. The forced signal also explains 48% of the detrended, decadal SST variance in the Kuroshio-Oyashio Extension region specifically, demonstrating that these results are not an artifact of the traditional EOF-based approach to isolating PDO variability.

The IPCC Sixth Assessment Report (IPCC, 2021), published before the Klavans et al. study, had already signaled the methodological challenge underlying these findings. The AR6 Annex IV on Modes of Variability acknowledged that "there is no unique way to remove the impact of the external forcing in the observations at decadal to multidecadal timescales, and the chosen method may have significant implications for the interpretation of the PDV expression during the instrumental era." The report recognized the PDO as "a collection of multiple processes" (citing Newman et al., 2016) and identified zonal advection of temperature anomalies in the Kuroshio-Oyashio Extension as a key mechanism for decadal-to-interdecadal variability. This IPCC assessment, combined with the subsequent quantification by Klavans et al. (2025), indicates that the traditional treatment of PDV as purely internal variability requires revision.

These findings build on a body of work that has progressively refined understanding of the PDO's dynamical origins beyond the stochastic atmospheric forcing framework of Newman et al. (2003, 2016). Wills et al. (2018), using low-frequency component analysis, a form of linear discriminant analysis optimized for isolating slow variations in spatiotemporal data, demonstrated that global warming, multidecadal variability, and El Niño can be disentangled in Pacific SST observations, and that the PDO's decadal component is more distinct from ENSO than the Newman et al. AR1 model implies. Wills et al. (2019) further showed that ocean circulation signatures of North Pacific decadal variability, particularly subpolar gyre variability and zonal advection in the KOE, constitute a dynamically independent component of the PDO that is not captured by atmospheric bridge teleconnections from the tropics alone. These results indicate that the oceanic dynamics of the KOE play a more fundamental role in the PDO than the stochastic forcing paradigm acknowledges, which in turn makes the region's sensitivity to forced warming more consequential for the PDO's future evolution.

Wills et al. (2020) developed pattern recognition methods, including both low-frequency component analysis and signal-to-noise maximizing pattern analysis, to separate forced responses from internal variability in climate model ensembles and observations, demonstrating

that these methods can achieve reliable separation with up to ten times fewer ensemble members than traditional approaches. The application of these methods to observations revealed that temperatures in the eastern tropical Pacific have increased less than in other parts of the tropics, a result that most climate models fail to reproduce. Wills et al. (2022) extended this analysis to show that climate models exhibit systematic biases in the large-scale patterns of recent sea surface temperature and sea-level pressure change, with models producing too much warming in the eastern Pacific and too little in the western Pacific relative to observations. This model-observation discrepancy in the SST trend pattern is directly relevant to the PDO, as it implies that models underestimate the differential warming between the KOE and the eastern Pacific that drives the forced negative PDO trend identified by Klavans et al. (2025).

These findings collectively indicate that the 1976–77 and 1998–99 shifts, traditionally viewed as expressions of internal multidecadal oscillation, likely included externally forced components.

7.2 Structural Changes in North Pacific SST Modes

Werb and Rudnick (2023) revisited the calculation of EOFs and principal components of North Pacific SST from 1950 to 2021, finding that the period of persistent marine heatwaves beginning in 2014 caused a fundamental change to the spatial pattern of the first EOF compared to the established PDO pattern (calculated using 1950–1993 data). The second EOF, corresponding to the Victoria Mode, has also changed during this period, both in spatial pattern and in the amount of variance explained. The authors concluded that the PDO and other EOF-based metrics may not be as useful in the future as climate continues to change.

Cluett et al. (2025) provided a systematic analysis of this structural shift using sliding 30-year windows. When the global mean SST signal is not removed prior to EOF calculation (as is standard in PDO construction), the leading EOF for windows extending beyond 2013 is replaced by a unidirectional, basin-wide pattern with all loadings of the same sign, which the authors term the Pan-Basin Pattern (PBP). By the 1994–2023 window, this pattern explains 51% of variance, exceeding any historical 30-year interval of the PDO. The PBP index is strongly correlated with global mean SST ($r = 0.80$). When the global mean SST is removed, however, the canonical PDO spatial pattern remains stable, explaining 20–26% of variance across sliding windows, and the NPGO/Victoria Mode pattern similarly persists. The PDO appears as the second EOF of total

(non-detrended) SST anomalies, orthogonal to the PBP, with eigenvalues within the historical range. The authors interpret these results as indicating that the dominant mode of total North Pacific SST change is now secular warming, while the PDO and NPGO/Victoria Mode remain the leading internal climate modes.

This interpretation warrants careful consideration alongside the findings of Klavans et al. (2025). The Cluett et al. framework assumes that removing the global mean SST effectively isolates internal variability from external forcing. However, Klavans et al. demonstrated that a majority of PDO variance since 1950 is externally forced even after standard detrending procedures, and that this forced component operates primarily through spatially non-uniform warming concentrated in the KOE, precisely the kind of differential warming that would survive global mean SST removal. The pattern biases documented by Wills et al. (2022), in which models underestimate western Pacific warming relative to eastern Pacific warming, further suggest that the forced signal in the North Pacific is not well captured by a spatially uniform global mean. To the extent that global mean SST removal leaves regionally structured forced warming in the residual, the "internal" PDO isolated by Cluett et al. may itself contain a forced component. Whether the forced fraction of what remains after global mean removal is large enough to materially affect the interpretation is an open question that methods such as those being evaluated by ForceSMIP (Wills et al., 2026) are designed to address.

The Victoria Mode (VM), defined as the second EOF of North Pacific SST, exhibits a distinctive northeast-to-southwest tilted dipole pattern. Ji et al. (2024) found that low-frequency VM variability (periods greater than 8 years) has shown a significant increasing trend over the past century, and this enhanced VM variability now surpasses the PDO's variability in recent decades. They attributed this intensification to amplified atmospheric variability in the Hawaiian region, stemming from reinforced variability in tropical central Pacific SST. The study noted that changes in the Kuroshio-Oyashio Extension could also be contributing to the increased VM variability.

Xiao and Ren (2023) identified a further regime shift in North Pacific annual mean SST in 2013/14, characterized by a horseshoe warming pattern along the North American western coast extending toward the central Pacific, consistent with a phase reversal of the Victoria Mode. This shift appears unrelated to the PDO or Interdecadal Pacific Oscillation, as there were no

concurrent regime shifts in equatorial central-eastern Pacific SST or in Aleutian Low intensity. Notably, the warming in the northeastern Pacific horseshoe involves mechanisms distinct from the KOE warming documented in earlier sections: reduced wind stress and suppressed upwelling in the Gulf of Alaska and California Current system, amplified by the mixed layer shoaling discussed in Section 3.2, rather than the oceanic heat transport and mode water accumulation that dominate in the western Pacific. The timing coincides with the post-2013 acceleration documented by Hu et al. (2024) and the onset of the Pan-Basin Pattern identified by Cluett et al. (2025), suggesting that the mid-2010s marked a convergence of structurally different warming processes across the North Pacific basin.

8. Broader Western Boundary Current Context

The accelerated warming observed in the KOE is not unique but rather characteristic of western boundary current extension regions globally. Kelly et al. (2010) provided a comprehensive comparison of the Gulf Stream and Kuroshio Extension systems, documenting differences in mode water properties, recirculation gyre structure, and current variability while emphasizing shared sensitivity to climate forcing.

Studies of other western boundary current systems provide context for interpreting KOE trends. Malan et al. (2021), examining the East Australian Current, found that shelf waters poleward of 32°S are warming more than twice as fast as equatorward waters, driven by increased lateral heat advection poleward of the western boundary current separation. This process is applicable to western boundary currents broadly, including the Kuroshio, suggesting common mechanisms for enhanced coastal warming in these regions.

Goyal et al. (2021) examined Southern Hemisphere western boundary current responses to future atmospheric changes and found that extension regions warm three to four times the global mean. Zonally asymmetric atmospheric forcing explained more than 30% (equivalent to more than 2°C) of SST warming in the Tasman Sea and southern Australia regions, driven by increased advection of warm tropical water due to subtropical gyre changes. These findings suggest that atmospheric circulation changes will continue to amplify western boundary current warming throughout the 21st century.

Roberts et al. (2017), using observation-based heat budget analysis, showed that interannual variations in full-depth ocean heat content are dominated by ocean heat transport convergence rather than surface flux addition in all western boundary current regions, including the KOE. In these regions, surface temperature anomalies generated by ocean dynamics result in turbulent flux anomalies that drive the overlying atmosphere, rather than the reverse. Sun et al. (2025) confirmed the atmospheric side of this relationship, demonstrating that ocean heat transport anomalies in western boundary currents produce robust atmospheric circulation responses. The response is deepest over the Northern Hemisphere WBCs (Gulf Stream and KOE), where it extends into the upper troposphere through changes in vertical motion, condensational heating, and geopotential heights. These findings establish that the ocean-to-atmosphere causal pathway documented by Zhang et al. (2016) for the Atlantic Multidecadal Oscillation operates in western boundary current regions generally, though the equivalent role of time-varying ocean heat transport convergence as a driver of Pacific decadal variability has not yet been directly demonstrated.

9. Discussion and Future Directions

The literature reviewed here demonstrates that the KOE region is warming at rates substantially exceeding global means, with consequences extending from local marine ecosystems to global climate patterns and the interpretation of traditional climate indices. Several key findings emerge from this synthesis.

First, SST warming in the KOE has proceeded two to three times faster than global mean rates since 1900, driven by the combination of thermodynamic warming and dynamic changes including poleward shifts and intensification of the Kuroshio Current. Second, subsurface heat accumulation in mode and intermediate waters has accelerated dramatically, with heat uptake nearly doubling between 2000–2010 and 2010–2020. Third, marine heatwaves have become more frequent and intense, with compound drivers involving oceanic preconditioning, atmospheric blocking, and anthropogenic forcing. Fourth, mode water dynamics provide memory of past forcing while redistributing heat content within the subtropical gyre, though this memory mechanism itself appears to be weakening as mixed layers shallow. Fifth, a substantial fraction of PDO variance is externally forced (Klavans et al., 2025), and the spatial patterns

extracted by EOF analysis have shifted as the climate has warmed, with pan-basin warming now dominating the leading mode of total North Pacific SST variability (Cluett et al., 2025). Sixth, the twofold expansion of the Indo-Pacific warm pool (Roxy et al., 2019) has expanded the tropical heat reservoir that influences North Pacific variability through western boundary current transport.

Several important uncertainties remain. The relative contributions of dynamic versus thermodynamic drivers to enhanced warming are not fully quantified, particularly for subsurface layers. Model resolution dependencies suggest that current climate projections may underestimate future warming in western boundary current regions. The pattern biases documented by Wills et al. (2022) suggest that model deficiencies extend beyond resolution to fundamental aspects of how coupled models represent the spatial structure of forced warming: models produce too much warming in the eastern Pacific and too little in the western Pacific relative to observations, directly affecting their representation of the forced PDO signal. The mechanisms linking KOE variability to remote forcing, including connections to the Atlantic Multidecadal Oscillation through mode water pathways, require further investigation.

The forced component estimation problem has motivated a major community effort: the Forced Component Estimation Statistical Method Intercomparison Project (ForceSMIP; Wills et al., 2026), which evaluates diverse methods, including novel machine learning approaches and simple linear methods, for estimating the forced climate response from individual realizations, using large ensembles of climate models as test beds. The results of ForceSMIP will be directly relevant to assessing how reliably the forced and internal components of PDO variability can be separated as the forced fraction continues to grow.

The question of how to separate forced and internal components is illustrated by recent work using linear inverse models (LIMs). Wu, Di Lorenzo, et al. (2026) decomposed the PDO into three dynamical constituents: a KOE mode with a basin-scale footprint, a North Pacific-Central Tropical Pacific (NP-CP) teleconnection mode, and an ENSO mode. This decomposition provides genuine insight into the PDO's dynamical structure. Before constructing the LIM, the authors removed the forced warming trend by projecting onto the least-damped stationary eigenmode, which features a global La Niña-like warming pattern. The resulting KOE mode trends strongly negative over the observational period, while the NP-CP mode, which features a

warm horseshoe pattern in the northeastern Pacific, trends strongly positive. Read in light of the evidence reviewed here, these trends may reflect the spatial fingerprint of forced warming rather than purely internal dynamics. The KOE mode trends negative precisely because the KOE is warming two to three times faster than the global mean (Wu et al., 2012; Hu et al., 2024), and a global detrending pattern does not fully remove this regionally concentrated forced signal. The NP-CP mode's positive trend is consistent with warming in the northeastern Pacific, where the mixed layer shoaling documented in Section 3.2 (Liu et al., 2024; Hu et al., 2024) amplifies SST anomalies by reducing the thermal inertia of the upper ocean. To the extent that both LIM modes are capturing spatial expressions of forced warming that survive the global detrending step, the decomposition may be describing how forced warming is distributed across the PDO's dynamical constituents rather than isolating purely internal variability. This concern parallels the issue raised in Section 7.2 regarding the Cluett et al. (2025) analysis: the adequacy of any forced/internal separation depends on assumptions about the spatial structure of the forced response, and these assumptions remain under active investigation through efforts such as ForceSMIP (Wills et al., 2026).

The findings reviewed here also raise a broader conceptual question about the analytical frameworks used to characterize North Pacific climate variability. Empirical orthogonal function analysis, the mathematical foundation of the PDO index, extracts the eigenvectors of the covariance matrix of the observed SST field, providing a global linear approximation to the dominant patterns of variability over a given time window. This approach is valid when the statistical properties of the system are approximately stationary. However, the evidence reviewed here suggests that the covariance structure of North Pacific SSTs may no longer be stationary: Werb and Rudnick (2023) documented progressive rotation of the leading EOF as the analysis window extends toward the present, the forced fraction of PDO variance documented by Klavans et al. (2025) implies that the patterns themselves are not purely internal, and Liu et al. (2024) demonstrated that mixed layer shallowing is altering the thermal responsiveness of the upper ocean in precisely the regions where the PDO's oceanic component operates. If the forcing is not merely perturbing the system's state but is modifying the physical parameters that shape its variability (mixed layer depth, stratification, ocean-atmosphere coupling strength), then the interaction between forced changes and internal variability may become increasingly nonlinear, and the decomposition into cleanly separable "forced" and "internal" components may become

more difficult. This possibility warrants careful investigation, as it would have practical consequences for how PDO-related variability is used in climate projections and resource management.

The practical consequences of non-stationary PDO relationships are already apparent in the fisheries literature. Litzow et al. (2018), using EOF analysis of North Pacific SST anomalies and correlations with Gulf of Alaska salmon production, documented that around 1988/1989 the relative importance of the PDO and North Pacific Gyre Oscillation (NPGO) reversed: the NPGO became significantly correlated with the first principal component of North Pacific SST anomalies, while the PDO shifted to the second. Their EOF analysis of SST anomalies for 1989–2012, compared with the earlier 1950–1988 period, shows a warm anomaly emerging in the KOE region within the second eigenvector. Concurrently, interannual variance in the Aleutian Low declined abruptly, and correlations between regional SST, the PDO, and salmon production decayed toward zero. Litzow et al. attributed the breakdown to declining Aleutian Low variance, possibly linked to increased Central Pacific El Niño events. The subsurface oceanographic literature reviewed here suggests a complementary interpretation: the timing of the PDO-salmon decorrelation coincides with the shift in KOE dynamics documented in Sections 6.2 and 6.3: Yeh et al. (2011) showed that the 1988/89 shift was driven by the North Pacific Oscillation rather than tropical forcing, while Pak et al. (2017) showed that oceanic advection became the dominant driver of KOE heat storage after approximately 1990, and Tomita and Kubota (2005) documented rapidly increasing turbulent heat flux over the KOE through the 1990s. If the KOE was transitioning from being driven primarily by atmospheric forcing (Aleutian Low variability) to being driven increasingly by oceanic advection and forced warming, the PDO index would have progressively lost its connection to the physical processes that had historically governed ocean conditions for salmon, regardless of what was happening in the atmosphere. This interpretation is consistent with the temporal scope of Johnstone and Mantua (2014), who showed that regional atmospheric circulation changes could explain more than 80% of coastal northeast Pacific warming from 1900 to 2012, with climate models failing to reproduce the observed circulation trends. Their analysis ended precisely at the onset of the post-2013 acceleration documented by Hu et al. (2024), raising the question of whether the atmospheric-forcing framework that successfully explained a century of northeast Pacific variability may be

giving way to a regime in which oceanic heat transport and forced warming play a larger role. The fish, in effect, may have detected the non-stationarity before the climate indices did.

Future research priorities should include sustained observational networks such as the Kuroshio Extension Observatory to monitor long-term trends; high-resolution coupled modeling to capture mesoscale and frontal dynamics; improved process understanding of mode water formation, subduction, and re-emergence; development of climate indices that appropriately separate forced and internal components of variability, potentially including methods that account for time-varying covariance structure such as the low-frequency component analysis developed by Wills et al. (2018); and integrated assessments of warming impacts on marine ecosystems and fisheries. Given the KOE's role in global heat budgets and climate teleconnections, advances in understanding this region will have implications extending well beyond the northwestern Pacific.

10. Conclusions

The Kuroshio-Oyashio Extension region represents a critical hotspot for accelerated ocean warming, with SST increasing two to three times faster than global means and subsurface heat accumulation intensifying dramatically in recent decades. Marine heatwaves are becoming more frequent and severe, with anthropogenic forcing playing a necessary role in recent extreme events. Mode water dynamics serve as conduits for heat storage and redistribution, while decadal variability and regime shifts modulate long-term trends.

The differential warming of the KOE has implications for the interpretation of North Pacific climate indices. The evidence that a substantial fraction of PDO variance is externally forced, combined with structural changes to EOF patterns since 2014 and the emergence of pan-basin warming as the dominant mode of North Pacific SST variability, indicates that the traditional treatment of the PDO as purely internal variability requires revision. The Victoria Mode has strengthened as the KOE warming signal has intensified, emerging as an increasingly important component of North Pacific climate variability. These findings underscore the need for sustained observation, improved modeling, and new analytical frameworks to understand western boundary current systems and their role in a changing climate.

11. Methods

This synthesis draws on the author's extensive reading of the climate research literature from 2022 to the present. Because the relevant evidence spans physical oceanography, climate dynamics, statistical methodology, and fisheries ecology, assembling a coherent picture required reading across disciplinary boundaries and recognizing connections that individual studies, each working within the assumptions of their analytical tools, did not draw.

Large language models played a substantive role in this process. Claude Opus (Anthropic) served as a collaborative partner in literature searches, analysis, and synthesis, with the ability to hold the full text of the evolving manuscript, source material, and revision history in working memory simultaneously while the author directed the intellectual assembly. This capacity to maintain the complete structure of a complex argument across many iterations proved essential for a synthesis that required integrating findings from dozens of studies using different methodologies.

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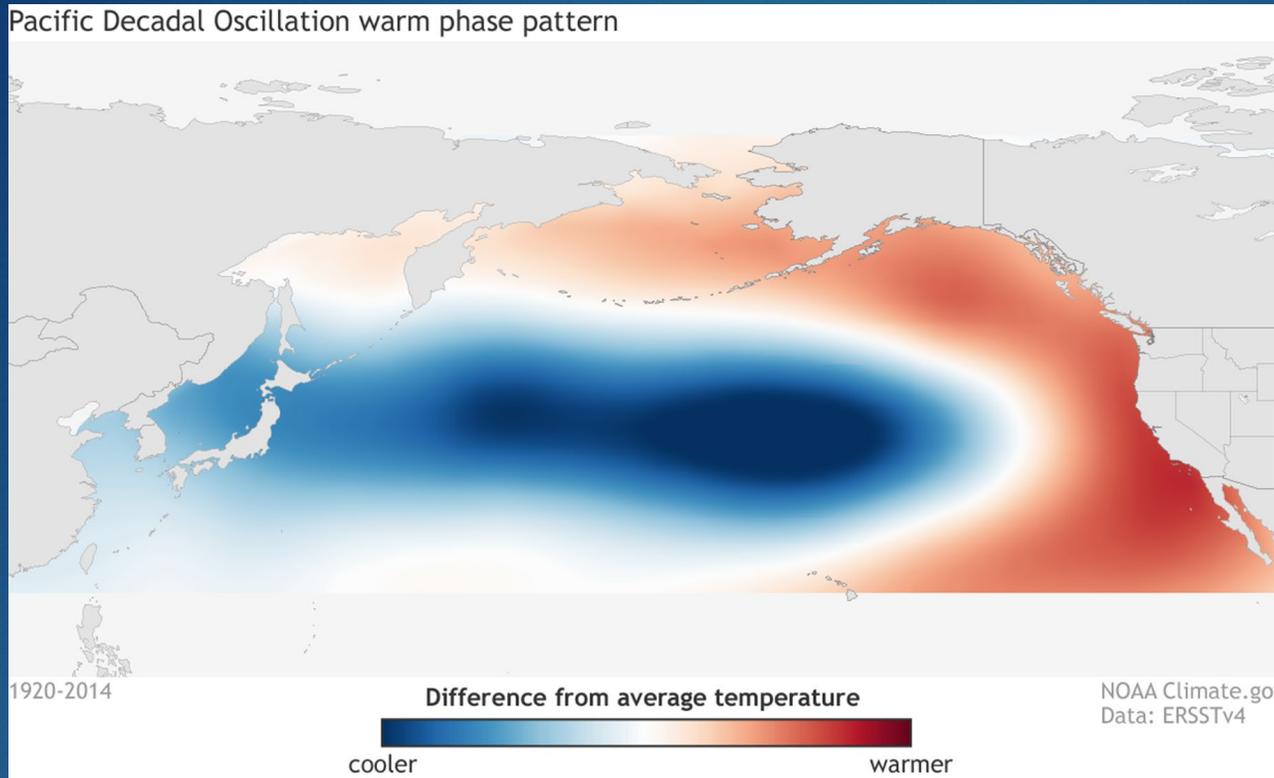
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IN HOT WATER

Anthropogenically driven
Pacific climate shifts and
California hydroclimate

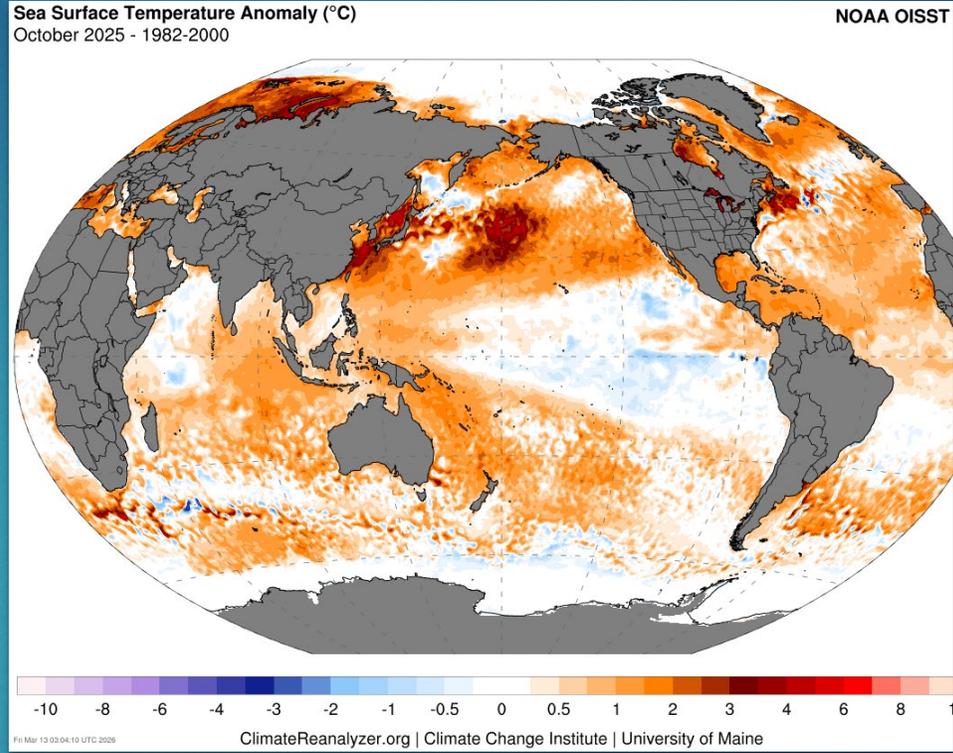
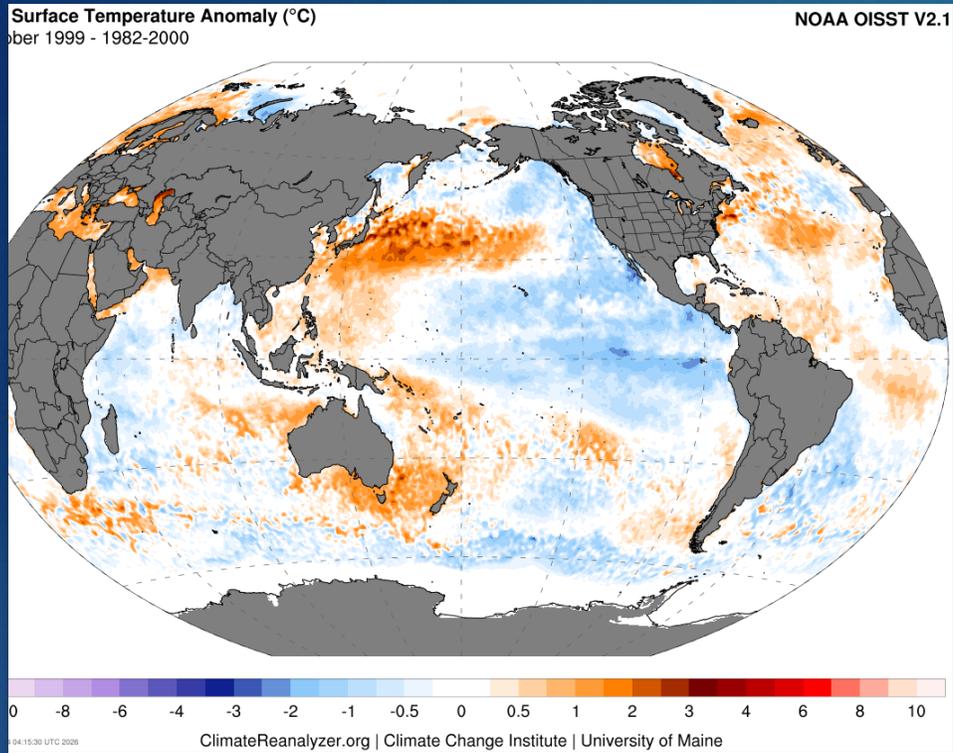
DEIRDRE DES JARDINS / CALIFORNIA WATER RESEARCH



Pacific Decadal Oscillation

Dominant pattern of sea surface temperature variability in the Pacific, north of 20°N.

Defined as leading EOF (statistical pattern) of monthly SST anomalies after removing warming signal



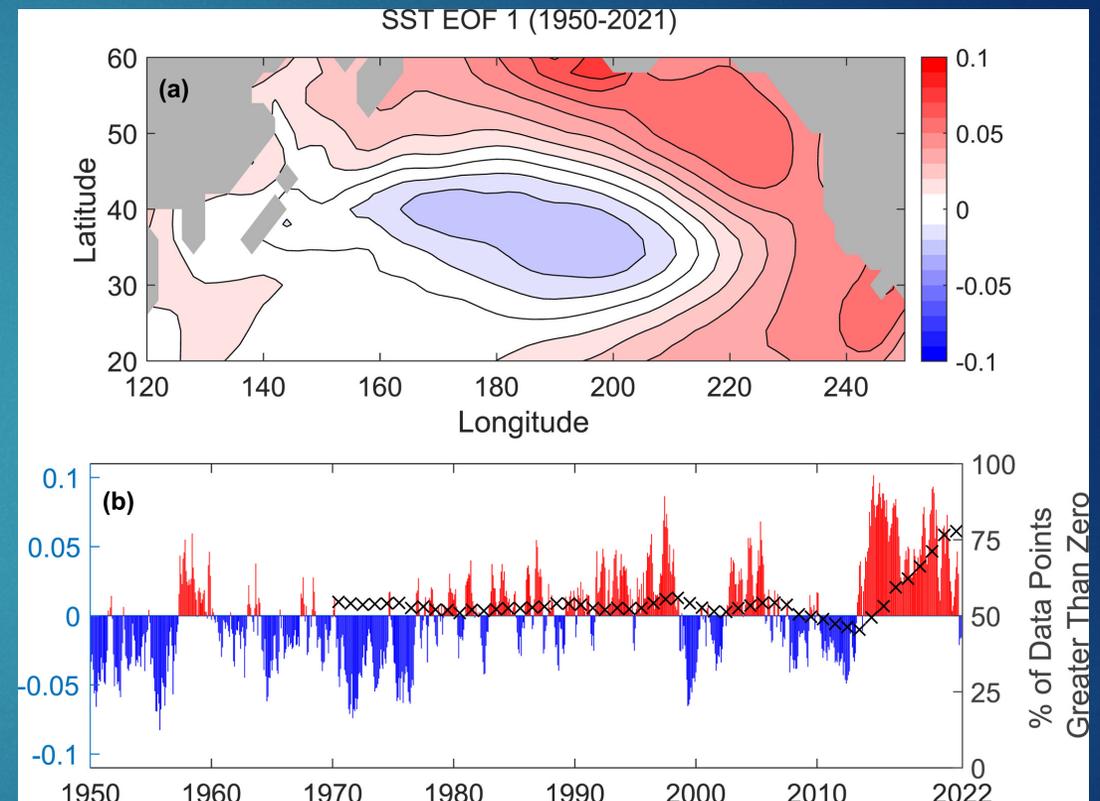
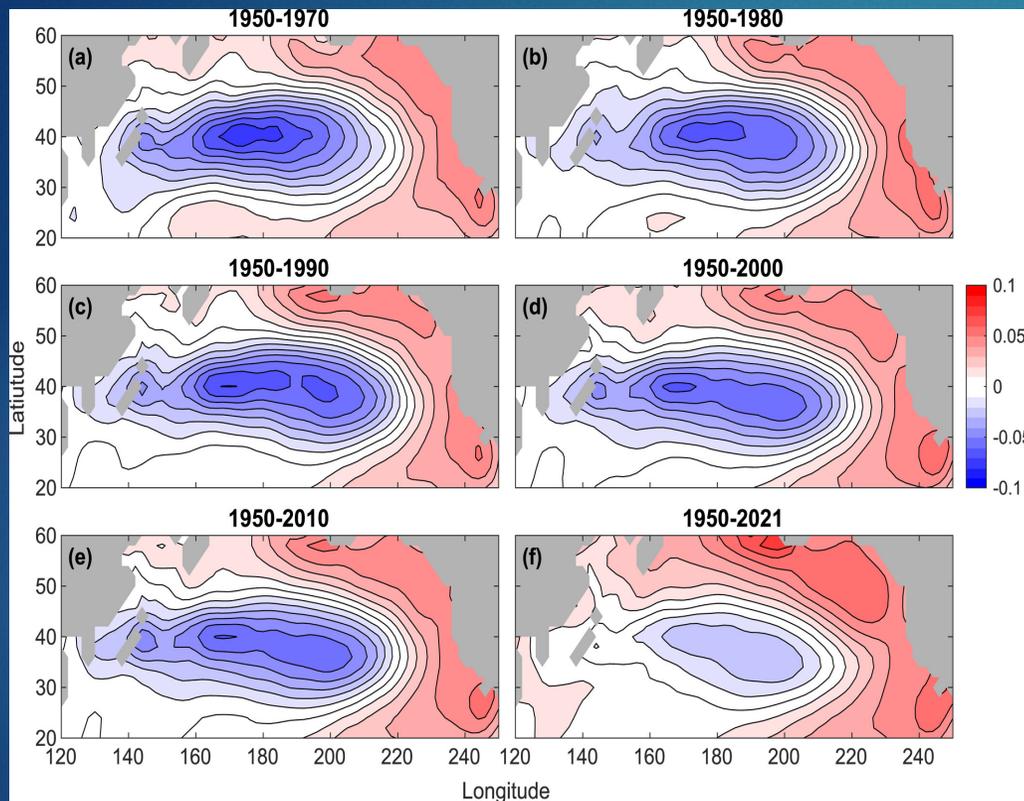
Change in cool Pacific Decadal Oscillation

Left (October 1999): Classic cool phase pattern

Right (October 2025): Still negative PDO, but with dramatic warming in the North Pacific

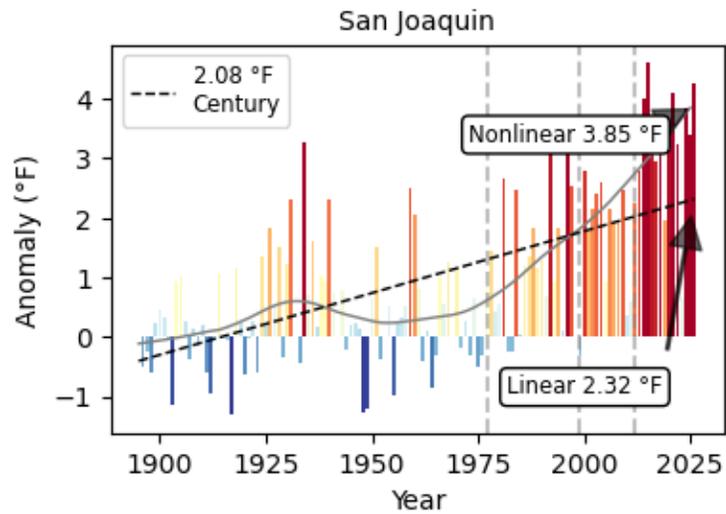
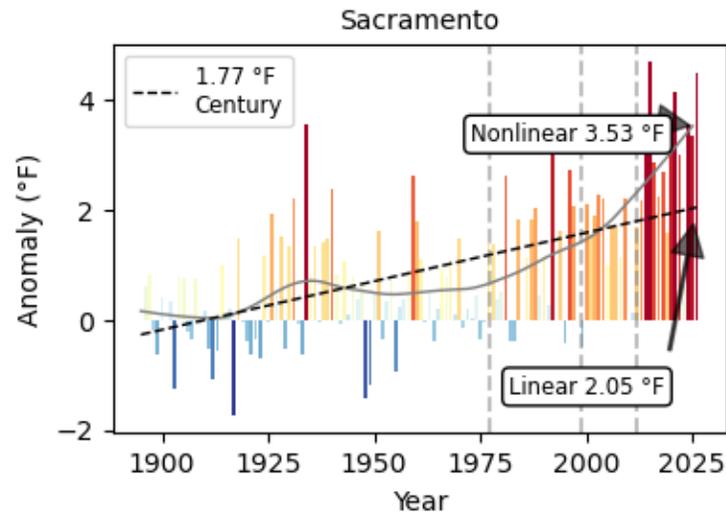
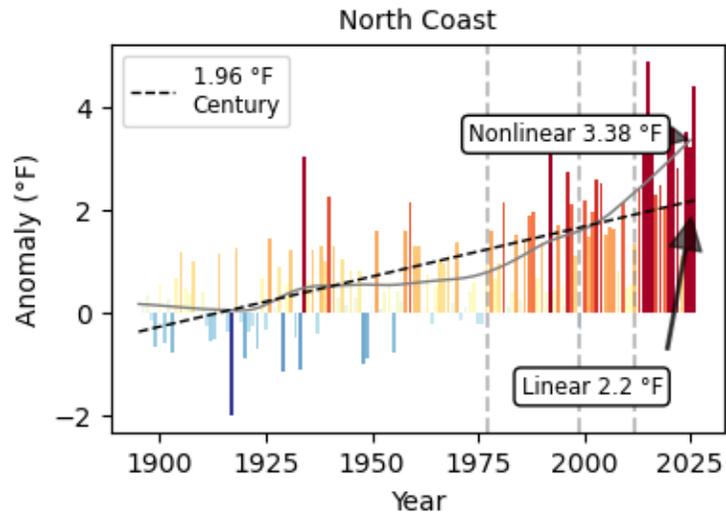
NOAA Optimum Interpolation Sea Surface Temperature (OISST) / Climate Reanalyzer

How PDO changes -- if you don't remove the warming trend first



Werb, B. and Rudnick, D., Remarkable Changes in the Dominant Modes of North Pacific Sea Surface Temperature Geophysical Research Letters, (2023). (cc 4.0)

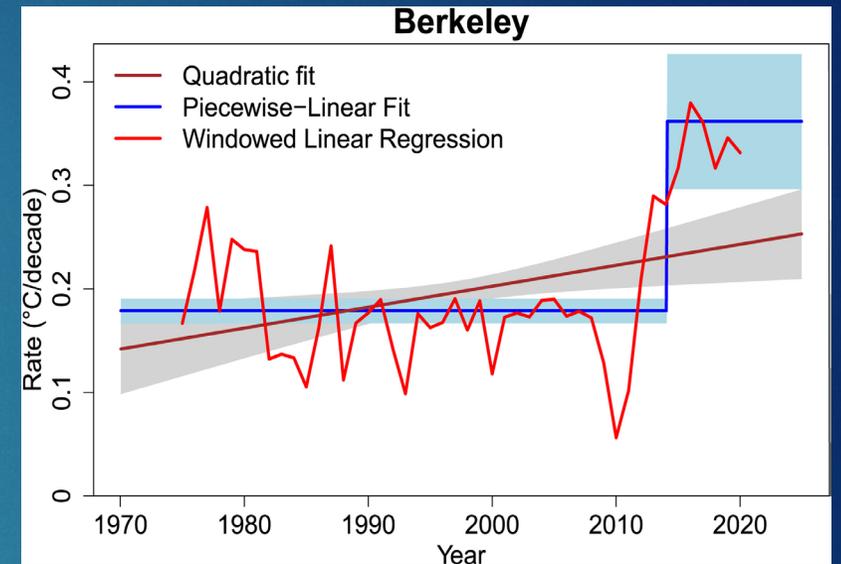
Nonlinear increase in temperatures



Nonlinear trend: Loess (40 year)
 Linear trend: Theil-Sen

Data: NOAA NCEI Divisional Timeseries
 Years: 1895 - 2025

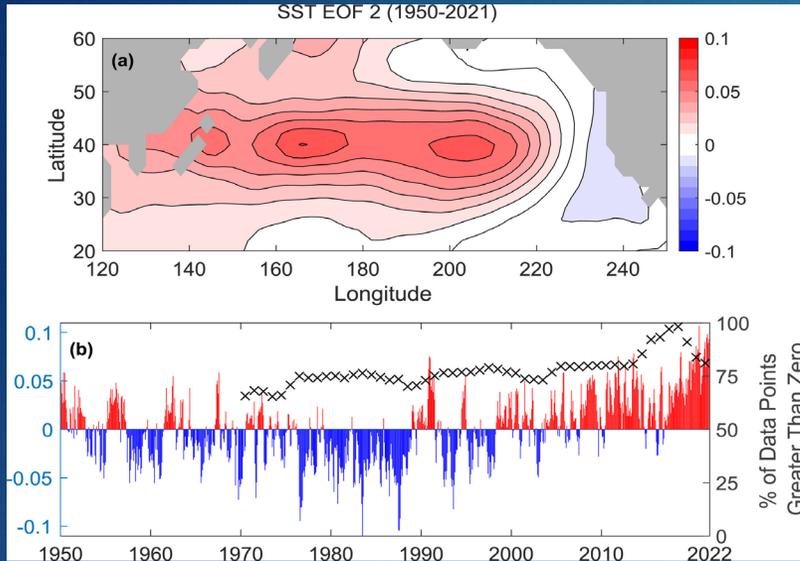
Pacific Climate Shift: 1977, 1999
 Temperature shift: 2012
 Baseline: 1895 - 1925



Global acceleration in warming around 2013-2014

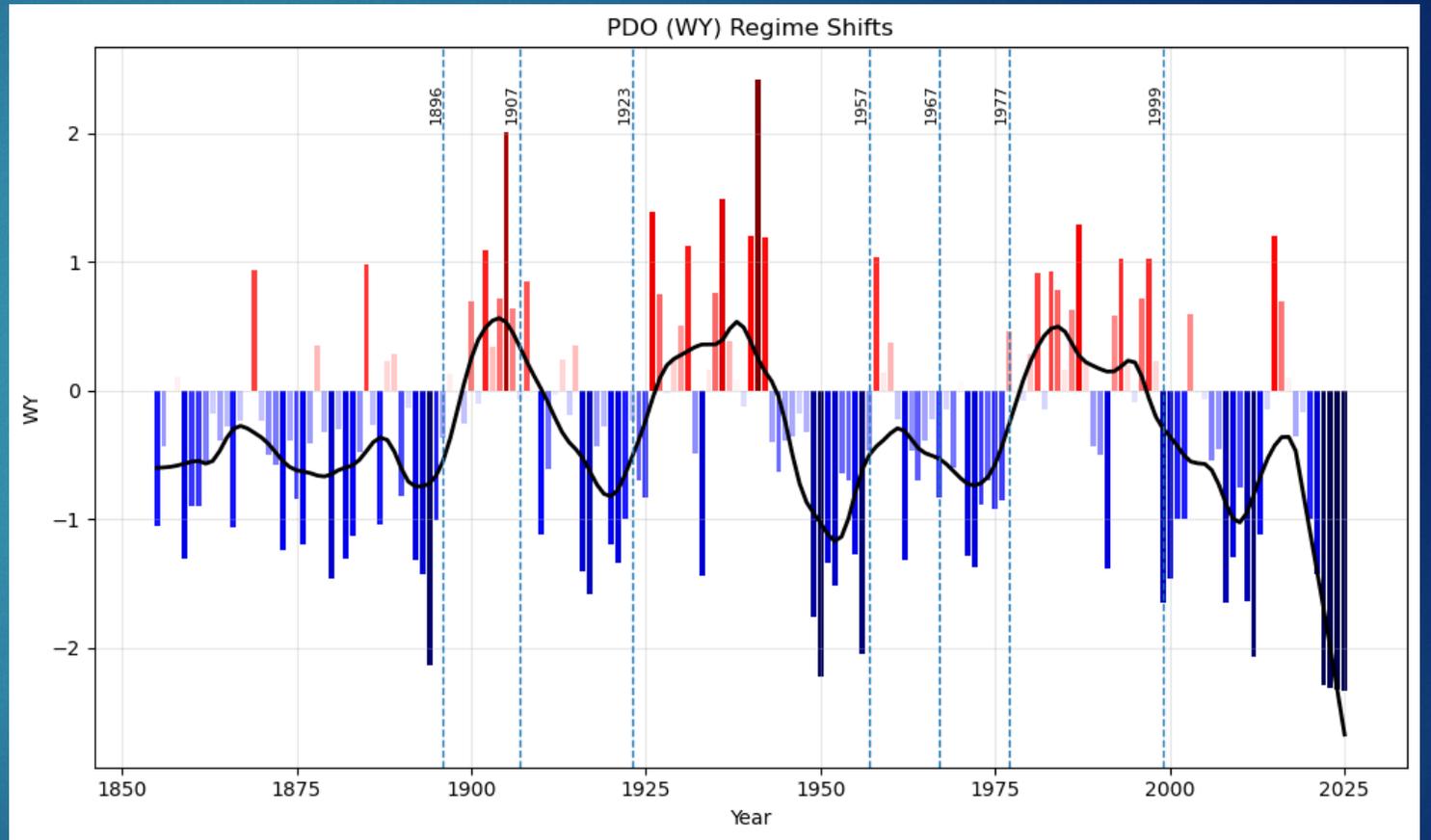
Foster, G., and Rahmstorf, S.: Global Warming Has Accelerated Significantly
 Geophysical Research Letters, (2026)
 (cc 4.0)

The big red blob



Second leading pattern (EOF) without removing warming trend

Webb, B. and Rudnick, D., Remarkable Changes in the Dominant Modes of North Pacific Sea Surface Temperature Geophysical Research Letters, (2023). (cc 4.0)



NOAA NCEI PDO (WY)
Pacific climate shifts – 1977, 1999 (STARS)

Northwest Pacific (Kuroshio extension) warming fastest

→ subtracting the global mean leaves a residual that resembles negative PDO

→ the standard PDO index trends negative

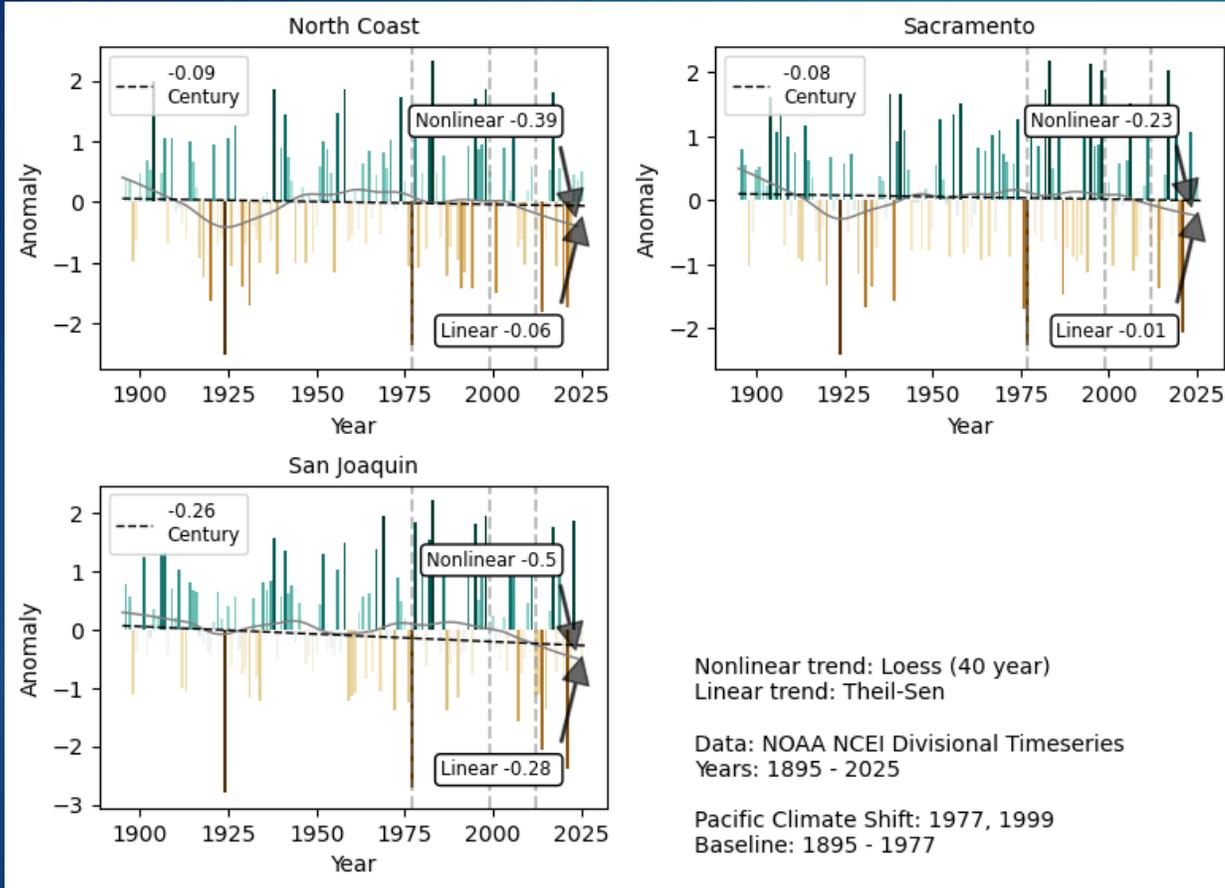
→ the NCEI PDO regression template (Mantua, 1900-93) amplifies this because it loads most heavily right on the Kuroshio extension where the differential is largest.

Increasingly extreme negative PDO values due to the *spatial pattern of forced warming* load onto the negative PDO pattern

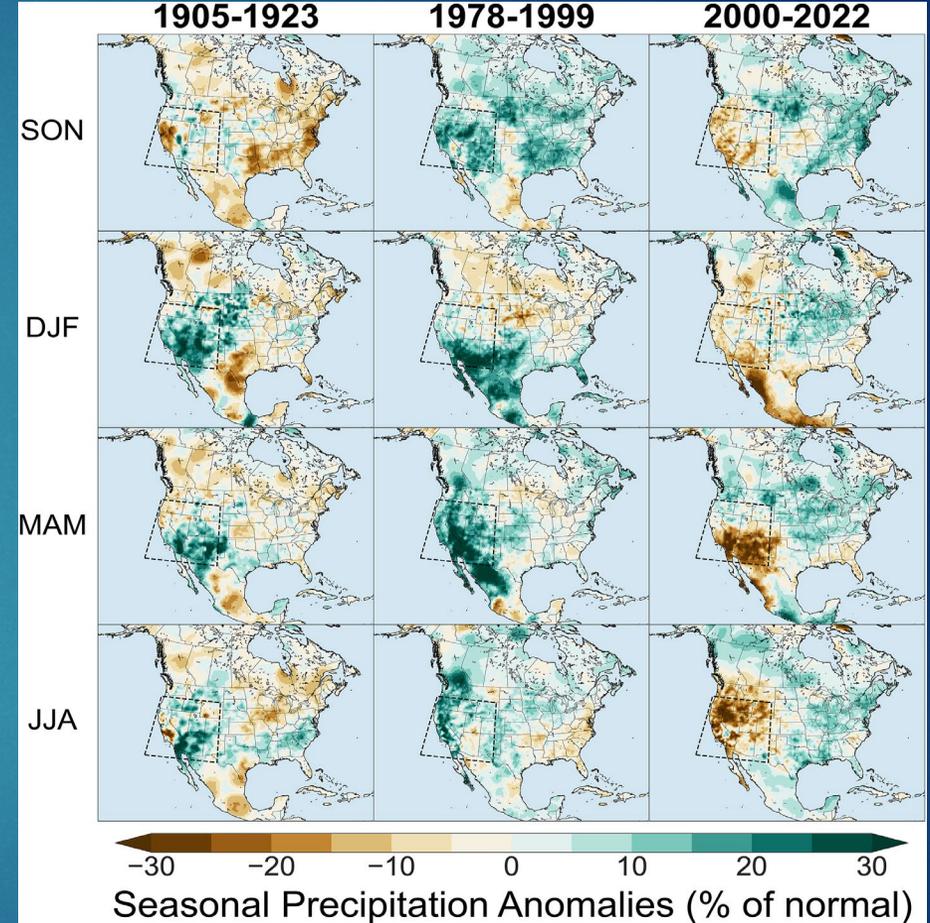
“A new, forced component of the PDO”

- ▶ Klavans, J.M., DiNezio, P.N., Clement, A.C. *et al.* Human emissions drive recent trends in North Pacific climate variations. *Nature* (2025).
- ▶ Bias-correction of outputs of ensemble of 70 climate models. External forcing of PDO index was 53% in observations versus 7% in climate models between 1950 and 2014.
- ▶ “We find that changes in external forcing explain key recent multidecadal shifts in observed North Pacific climate... and reproduces major PDO transitions in the 1970s and 1990s to within a few years, even without accounting for tropical Pacific variability...”

Megapluvial (+PDO) to megadrought (-PDO)



Nonlinear trends in precipitation (Sp01, WY)



Cook, B. et. al. Megapluvials in Southwestern North America AGU Advances, (2025) (cc 4.0)
 Megapluvials: 1905-1923, 1978-1999



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