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The response of pacific decadal variability to global warming

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Abstract. Pacific Decadal Variability (PDV) plays a pivotal role in understanding climate shifts. This study focuses on investigating the primary components of PDV, namely, the Pacific Decadal Oscillation (PDO) and the North Pacific Gyre Oscillation (NPGO). These components are defined as the first and second principal modes of the North Pacific sea surface temperature anomaly field. Our analysis indicates that under the influence of global warming, both PDO and NPGO exhibit a weakening of the amplitude and a shortening of the period. Furthermore, NPGO demonstrates a more pronounced response to a 2°C warming scenario compared to a 1.5°C increase. This heightened sensitivity is attributed to the accelerated propagation of Rossby waves, a consequence of enhanced ocean stratification. The findings of this research contribute to the establishment of a scientific foundation for informed environmental policy development, facilitating the promotion of environmental conservation and sustainable development.

Keywords: Global Warming, Pacific Decadal Oscillation (PDO), North Pacific Gyre Oscillation (NPGO).

1. Introduction

Global warming denotes the progressive increase in average temperatures within the Earth's climate system. The primary cause of this warming phenomenon can be attributed to the increase in greenhouse gases resulting from human activities, such as the emission of carbon dioxide, methane, and nitrous oxide. These greenhouse gases accumulate in the atmosphere, generating the so-called "greenhouse effect," which results in elevated Earth temperatures. The ramifications of global warming extend across Earth's ecosystems, including the thawing of glaciers, rising sea levels, and the deterioration of marine ecosystems. To address global warming, the international community has undertaken a series of measures, exemplified by the signing and enforcement of the Paris Agreement. This significant accord aims at limiting global warming to below 2°C and endeavors to achieve the more ambitious goal of 1.5°C. National contributions, determined on a country-by-country basis, collectively aim to reduce greenhouse gas emissions compared to existing policies. Nonetheless, substantial endeavors to curtail carbon emissions remain imperative for the attainability of the 2°C warming limit, as emphasized by Rogelj et al. [1]. Consequently, it is crucial to investigate the response of carbon dioxide under varying warming scenarios.

In pursuit of this objective, the Coupled Model Intercomparison Projects (CMIPs) have provided a framework for international collaboration, enabling research institutions worldwide to conduct climate system simulation experiments. These initiatives involve the comparison and evaluation of the

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performance of global climate models, ultimately contributing to the scientific foundation for comprehending global climate change [2]. Since its inception by the World Climate Research Programme (WCRP) in 1997, CMIPs have undergone several phases of comparative planning and currently operate in their sixth phase [3]. Each phase is characterized by specific objectives and research priorities. CMIPs, by integrating diverse climate models encompassing atmospheric, oceanic, terrestrial, and cryospheric components [4], undertake the critical task of studying and forecasting the climate system.

The global climate system exhibits not only a warming trend but also interdecadal oscillations. Distinct periods of global mean temperature align closely with variations in the Pacific Decadal Variability (PDV). Positive phases of PDV coincide with accelerated global warming periods, while negative phases correspond to stagnant warming periods. This observation suggests that PDV may exert regulatory influence over global mean temperature changes [5]. PDV represents a decadal-scale pattern manifesting in the Pacific Ocean and atmosphere over cycles of approximately 20 to 30 years. The discovery of PDV originated from fluctuations in salmon production in the Pacific Ocean [6], with its primary manifestation being the modulation of Pacific Ocean sea surface temperatures (SST). Analogous to the El Niño-Southern Oscillation (ENSO), PDV exhibits periodic oscillations in positive and negative phases. In the positive phase, the eastern Pacific Ocean SST is warmer, while the western Pacific Ocean SST is cooler. Conversely, during the negative phase, these patterns reverse. Unlike ENSO, PDV predominantly occurs in the North Pacific region and operates on an interdecadal time scale.

In light of these considerations, this study aims to explore how PDV responds to global warming. The response of PDV under varying warming conditions is investigated through the CMIPs initiative, offering valuable insights for addressing global warming and formulating effective climate policies.

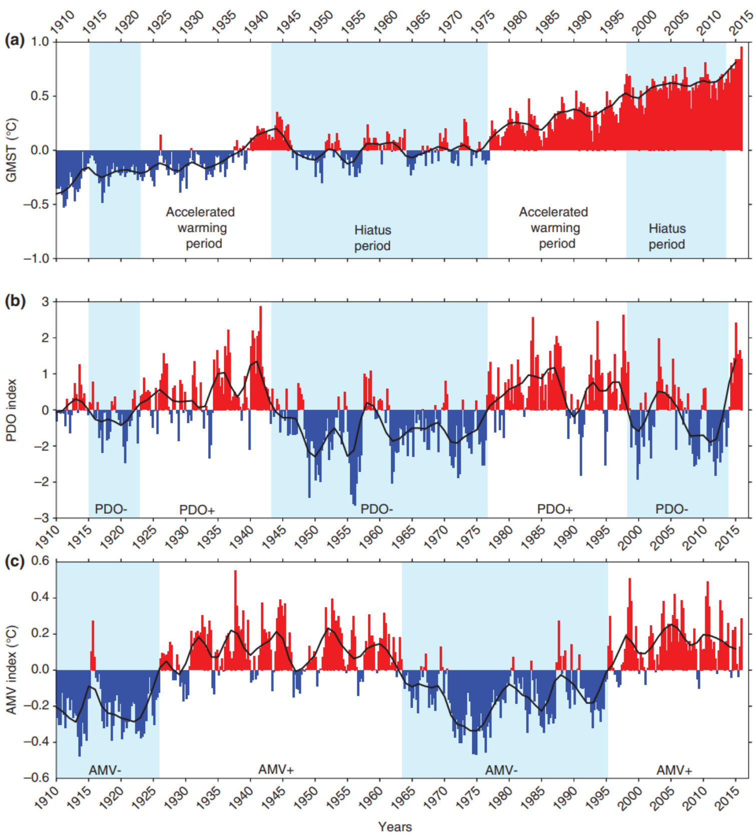

Figure 1. The anomalies of seasonal mean global mean surface temperature (GMST, in °C), relative to the 20th-century mean, were calculated for the period between 1910 and 2015 [7].

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2. Pacific Decadal Variability

2.1. Definitions

The Pacific Decadal Variability (PDV) phenomenon comprises two primary modes, namely, the Pacific Decadal Oscillation (PDO) and the North Pacific Gyre Oscillation (NPGO). These modes possess the capacity for transformation into one another. PDO is defined as the first mode resulting from the Empirical Orthogonal Function (EOF) analysis of the low-pass sea surface temperature (SST) anomaly field within the North Pacific region (20°N~60°N, 120°E~120°W). In contrast, NPGO is characterized as the second mode derived from the EOF analysis of either SST or sea level height data. While average annual SST data is generally employed for PDV analysis, it is noteworthy that some studies have highlighted the heightened prominence of PDV signals during the winter months [8]. Notably, PDO has an effect on interdecadal fluctuations in biological activity in the North Pacific, whereas NPGO plays a critical role in driving changes in salinity and nutrient content in the central and eastern North Pacific [9].

2.2. Pattern, Amplitude, and Period

PDO and NPGO, while both operating on decadal time scales, exhibit distinct spatial patterns. PDO is characterized by positive and negative centers of variation in its spatial pattern. Across the entire Pacific region, decadal SST anomalies are distributed with approximate equatorial symmetry, albeit with weaker variations in the central South Pacific. The SST anomaly in the central and western North Pacific exhibits a horseshoe-shaped structure, contrasting with the western coast of North America and the central and eastern equatorial Pacific. During the PDO's positive phase, the SST in the central and western North Pacific experiences abnormal cooling, while the West coast of North America, the equatorial Middle East Pacific, and the West coast of South America witness abnormal warming, with the opposite holding true during the PDO's cold phase. Notably, the amplitude is more pronounced in mid-latitudes and extends poleward. In contrast, NPGO exhibits a north-south dipole structure in SST anomalies [10].

2.3. Mechanism

PDO's origins may be traced to the tropical El Niño-Southern Oscillation (ENSO). During ENSO's positive phase, surface water temperatures in the equatorial Pacific rise, intensifying atmospheric convection and strengthening the Aleutian Low (AL). This, in turn, augments mid-latitude westerly winds, heightening sea surface evaporation and inducing cooling. Simultaneously, intensified westerly winds promote eastward surface water movement, replenishing colder waters from below, thus mitigating surface warming. Additionally, stochastic climate noise may contribute to PDO's dynamics. During PDO's positive phase, stochastic climate noise triggers high-pressure anomalies in the North Pacific Ocean, fortifying the AL, enhancing mid-latitude Pacific surface westerly winds, and amplifying turbulent heat flux loss, all contributing to North Pacific cooling. Weakened winds reduce subtropical vortex and Kuroshio strength, limiting northward transport of warm water and subsequently retarding cooling. Furthermore, reduced surface winds diminish turbulent heat flux loss [11].

PDO and NPGO may potentially represent two modes of PDV interconversion. Analogous to PDO, NPGO is influenced by atmospheric variations, particularly the North Pacific Oscillation (NPO). The decomposition of North Pacific Ocean sea level pressure anomaly through EOF analysis reveals NPO as the second mode [9]. Moreover, the westward propagation of Rossby waves in the subpolar Pacific and teleconnections with other ocean basins to the Pacific Ocean significantly impact the generation and propagation of PDV [9].

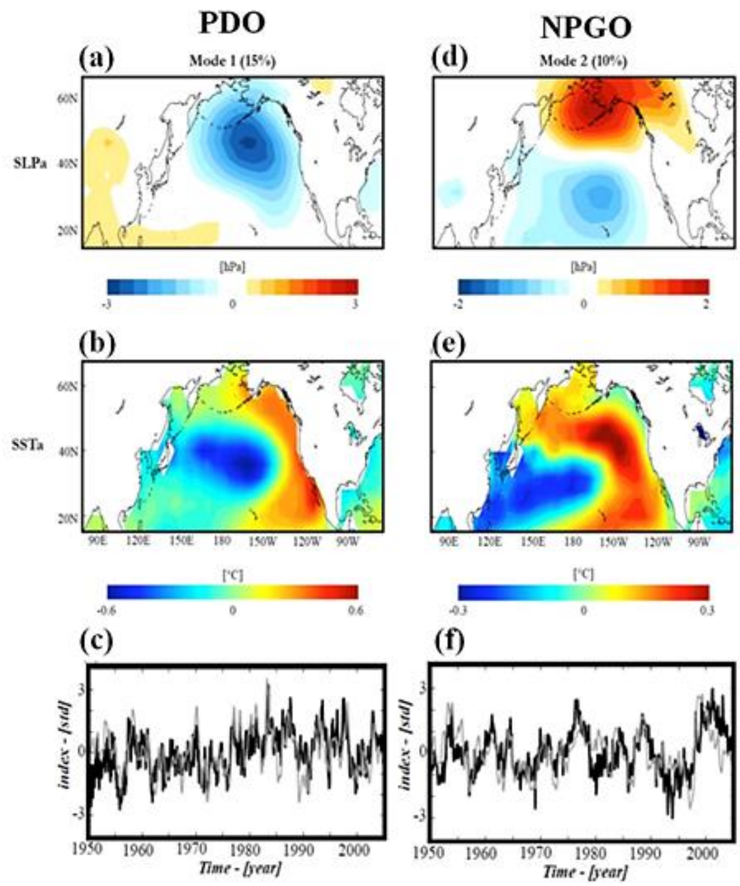

Figure 2. (a, b) PDO and (d, e) NPGO observed patterns derived from regression analysis of (a, d) sea level pressure anomalies (SLPa in hPa) and (b, e) sea surface temperature anomalies (SSTa) against the standard (c) PC1 (PDO index, black) and (f) PC2 (NPGO index, black). These patterns were derived from combined EOF analysis of North Pacific SLPa and SSTa data [9].

3. Response

To investigate the response of PDO and NPGO under the conditions of mild global warming (1.5°C and 2°C), Feng et al. [12] employed the CESM model. The observational data used in the study consisted of monthly mean sea surface temperature (HadISST) from the Hadley Center, covering the period from 1921 to 2005. The investigation compared the era of sustained global warming (LW, 2031-2100) with the pre-Industrial Revolution period (PI, 1850-1920) and the historical period (HIS, 1921-2005).

In summary, the intensities of both PDO and NPGO during the 1.5°C and 2°C global warming periods were found to be weaker than those during the historical periods, with shorter main periods. There were no significant differences observed in the intensity and duration of PDO under the two warming scenarios, whereas the intensity of NPGO was significantly reduced, and the period was shorter during the 2°C warming period compared to another scenario. This suggests that a 0.5°C increase in temperature had a more substantial impact on NPGO than on PDO. Furthermore, the next decadal standard deviation for both warming scenarios was essentially equal.

The predicted negative anomaly area of PDO was observed to be more southerly than expected, with the positive anomaly area extending westward, encompassing the entire Aleutian region and exhibiting a larger range. In terms of intensity, the simulated intensity was stronger than observed, and there were only minor differences in PDO intensity between different warming scenarios. Conversely, the intensity of NPGO decreased with increasing temperature, resulting in reduced amplitudes for both PDO and NPGO under the background of global warming. The primary cycle of PDO during the two stable

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warming periods exhibited minimal differences, shortening to 15 years and 45 years, respectively. In comparison, the primary cycle of NPGO experienced a smaller reduction, shortening to approximately 20 years.

This changing trend was also consistent with the scenario of more substantial warming. Among the 24 models in CMIP5, data from four models (E, I, U, X) with robust sea-air coupling simulations were selected to analyze PDO and NPGO under different temperature increase scenarios (RCP4.5, 8.5). The findings revealed that the spatial patterns of PDO and NPGO remained mostly consistent, with both modes experiencing shortened cycles. Specifically, under the RCP4.5 scenario, the PDO cycle was reduced to 10 years, while under the RCP8.5 scenario, the PDO cycle decreased to 8 years, and the NPGO cycle to 6 years [13].

In summary, the responses of PDO and NPGO under the backdrop of global warming consistently exhibit reduced intensity and shortened periods. This phenomenon can be attributed to global warming's impact on enhancing ocean stratification and accelerating Rossby waves, which collectively lead to the weakening of PDO and NPGO intensity, shorter periods, diminished amplitudes, and decreased predictability [14].

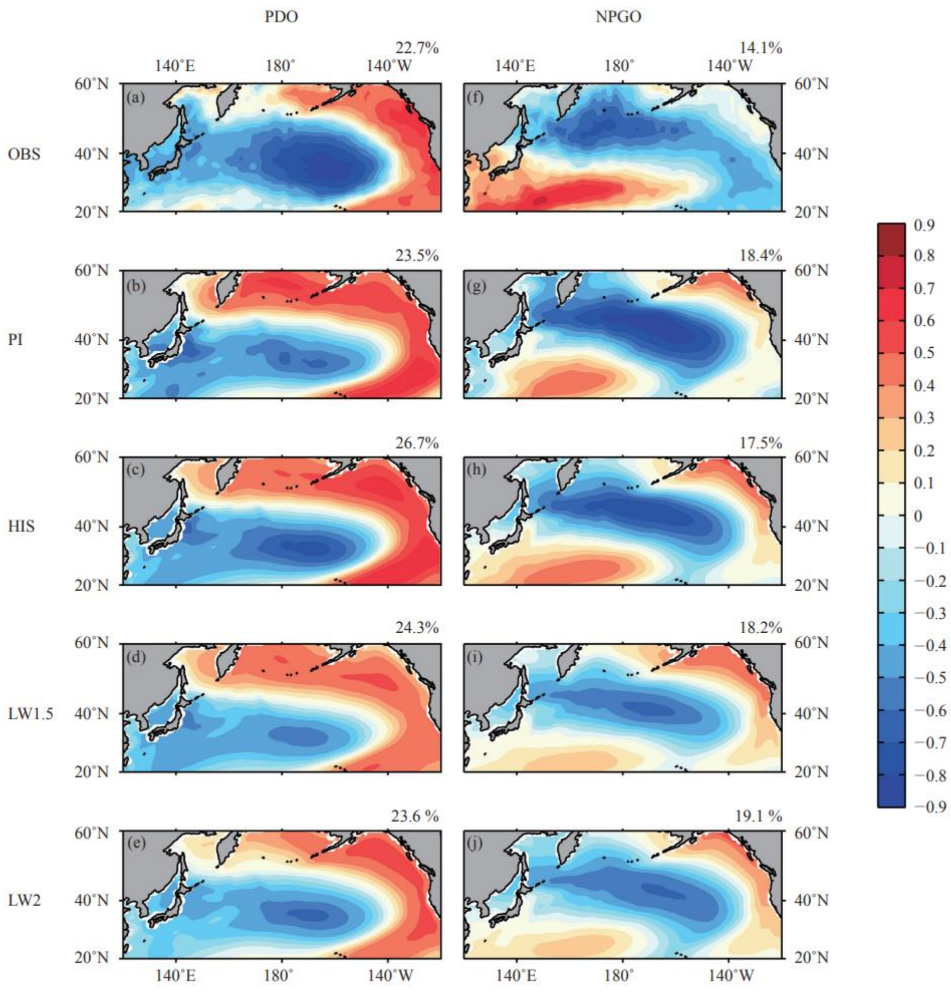

Figure 3. Spatial pattern of PDO and NPGO during different time stages [12].

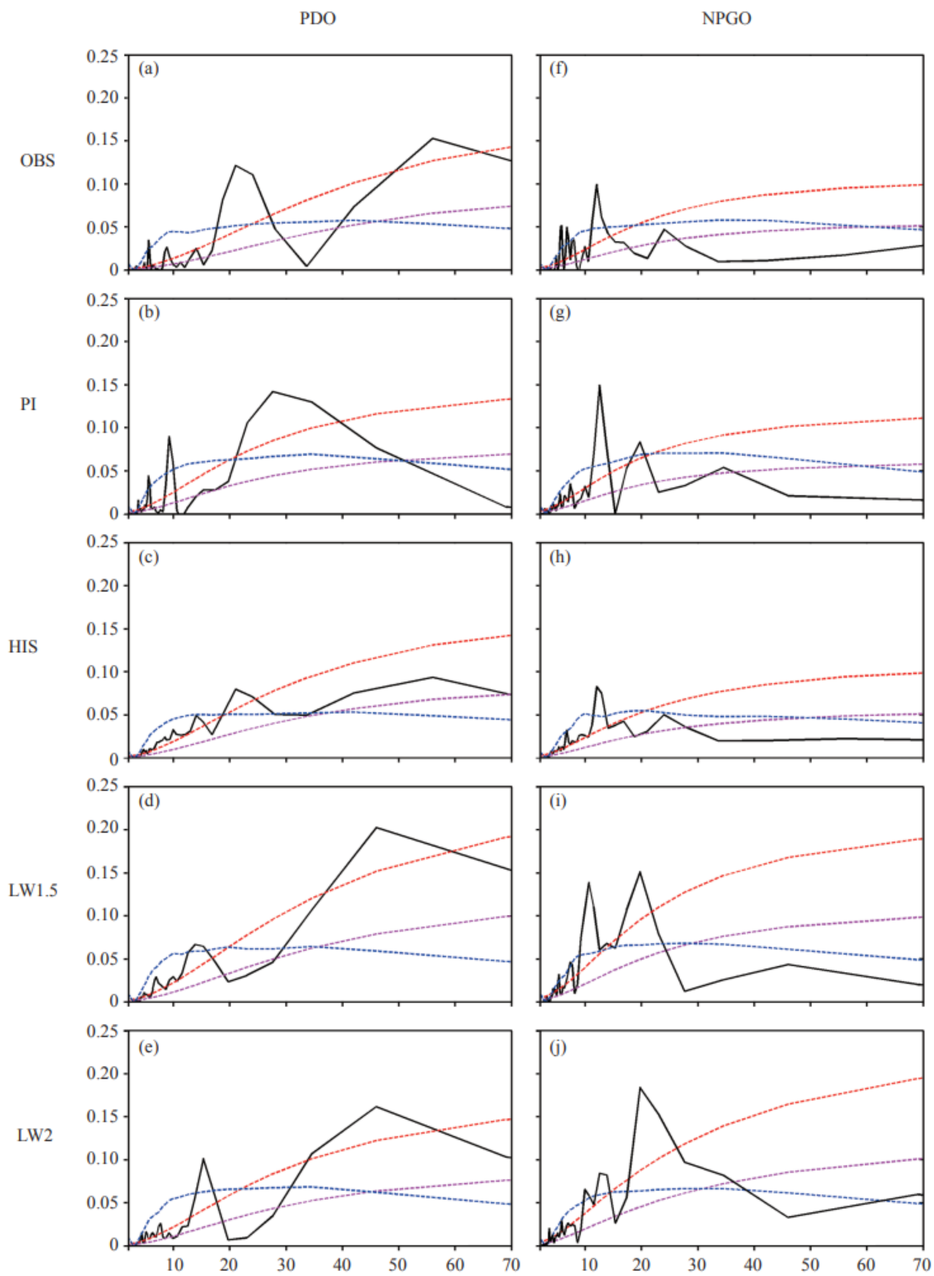

Figure 4. Power spectrum of PDO and NPGO during various time periods [12].

4. Conclusions and Discussion

PDV comprises two primary modes, namely the PDO and the NPGO. Both modes exhibit decadal time-scale characteristics but differ significantly in their spatial patterns. PDO manifests as a horseshoe-shaped pattern, marked by cold conditions in the central and western North Pacific during its positive phase, while NPGO presents an opposing north-south dipole structure. Atmospheric changes exert a notable influence on both PDO and NPGO, making them amenable to simulation and prediction through the Coupled Model Intercomparison Projects (CMIPs).

Under varying warming scenarios, encompassing both strong and weak warming, PDO and NPGO exhibit similar response patterns. Specifically, the spatial patterns of PDO and NPGO remain largely consistent, yet their intensities weaken, and their periods shorten. This response is closely tied to the acceleration of Rossby wave propagation induced by global warming, resulting in reduced predictability.

Nevertheless, the responses of PDO and NPGO differ under weak warming scenarios. In this context, PDO shows minimal variation between 1.5°C and 2°C warming, whereas NPGO experiences significant weakening and shorter periods during the 2°C warming scenario in comparison to the 1.5°C scenario, indicating a more pronounced response to a 0.5°C temperature increase.

Global warming exerts a profound impact on the environment and ecosystems, directly influencing the occurrence and evolution of natural disasters. An understanding of global warming is pivotal for predicting and mitigating the consequences of such disasters, thereby reducing associated losses. Against the backdrop of global warming, investigating the response of PDO and NPGO assumes paramount importance. PDV plays a pivotal role in regulating global average temperature fluctuations and offers insight into climate oscillations. Consequently, such research serves as a scientific foundation for anticipating and managing climate change. The fluctuations in PDO and NPGO further provide a valuable basis for the formulation of rational environmental policies, facilitating environmental conservation and fostering sustainable development.

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