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## Short Communication

## Changing footprint of the Pacific Decadal Oscillation on global land surface air temperature

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Sea surface temperature modes have been found to modulate anthropogenic global warming rates on annual and decadal timescales, sometimes leading to periods of “slowdown” despite increasing greenhouse gas emissions [1]. Among well-known climate modes, including atmospheric patterns like North Atlantic Oscillation (NAO) and oceanic phenomena such as the Atlantic Multi-decadal Oscillation (AMO) and El Niño-Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO) emerges as a crucial factor modulating global temperature on a decadal scale, showing associations between its positive phases with rapid warming, and negative phases with reduced warming or even cooling (Fig. S1 and Table S1 online; [2]). Currently, despite that the PDO has entered its negative phase since the late 2010s, global temperatures have remained at historically high levels. Recent data from the US National Oceanic and Atmospheric Administration (NOAA) also indicate record-breaking global sea surface temperatures in past months (from April to September 2023). It is essential to explore the role of oceanic conditions and their potential implications for the trajectory of global warming.

Of prominent importance is that while the model projections of global temperature guide policy decisions, the simulations hardly reflect the influence of internal oceanic modes, especially the decadal influence from the PDO [2]. This gap has underscored the need for a comprehensive exploration of the historical relationship between the PDO and rates of warming or cooling, as well as the

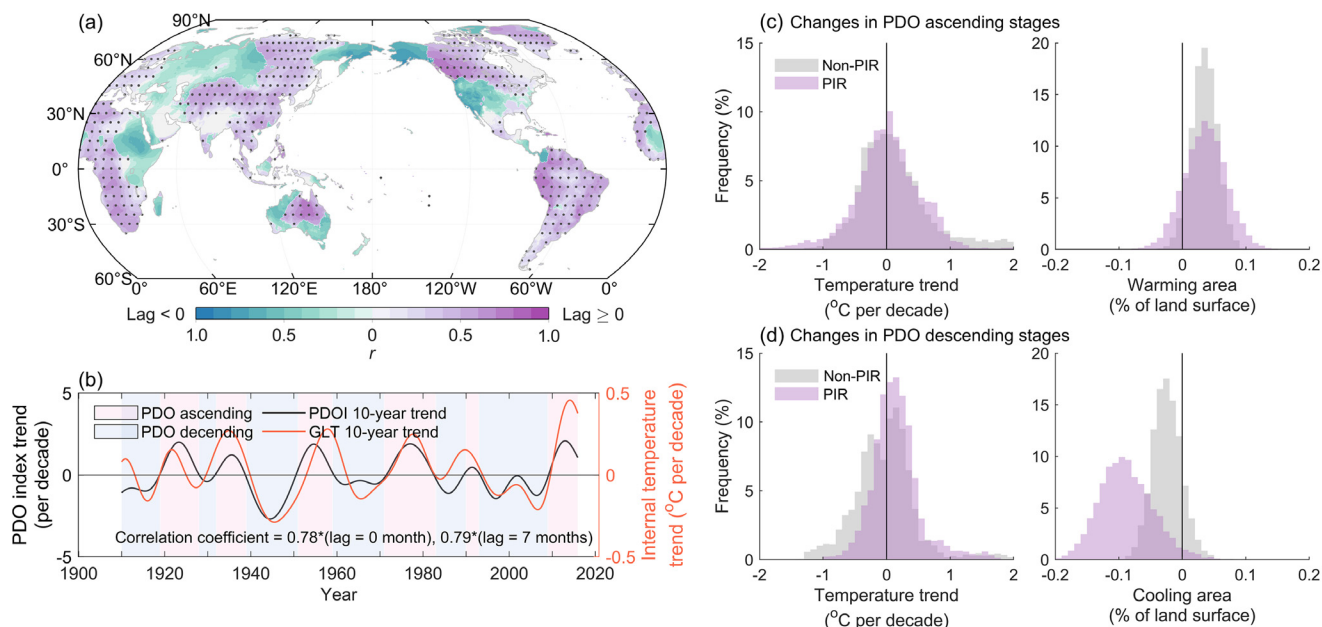
evolution of this relationship over time to provide a better understanding of the historical and ongoing warming.

To bridge the knowledge gap, we used a 120-year global land temperature (GLT) dataset (CRU TS v.4.06) as the dependent variable for PDO influence. To isolate the internal variation of temperature, we subtracted the ensemble mean of CMIP6 model-simulated land temperature (Table S2 online) from the observed GLT time series. This novel approach leverages the robust representation of forced changes in Earth system models [2], enabling us to examine the temperature variations that extend beyond the scope of Earth system models predictions. We then filtered high-frequency components from both the internal GLT and PDO index (PDOI) to reduce the influence of subseasonal, seasonal and inter-annual variability. We further calculated the 10-year running trends to see their connection. Our central hypothesis posits that oceanic heat absorption and release manifest as observable changes of PDOI (PDOI-trend), which can drive corresponding shifts in land temperature across the world [3].

To investigate the spatial patterns of the PDO influence on GLT, we defined the PDO footprint as the PDO-Influenced Region (PIR; Fig. 1a). These regions show a significant lagged correlation between the PDOI-trend and GLT-trend ( $P < 0.05$ ). With caution regarding cause-and-effect, we also used the Granger test and information flow to examine the statistical causal relationship between PDOI-trend and GLT-trend. In addition, we also analysed the internal temperature variation using observation-based external forcings as a supplementary approach (refer to Supplementary materials online for more details). Collectively this assessment is

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**Fig. 1.** PDO index and global land temperature relationships. (a) Spatial distribution of the maximal correlation coefficient between 10-year running trends in the PDO and internal temperature. The dot pattern indicates the PDO-Influenced Regions (PIR), i.e., PDO footprint, which have a significant  $r$  ( $P < 0.05$ ) and a positive lag. (b) 10-Year trends of smoothed PDO index and internal temperature variability. The background is shaded red for PDO ascending stages (PDO shifting from negative to positive phases), and blue for PDO descending stages (PDO shifting from positive to negative phases). Ascending (A) and descending (D) PDO stages are A1–A6 (1920–1928, 1933–1939, 1952–1959, 1972–1983, 1991–1993, 2010–2017) and D1–D6 (1911–1919, 1929–1932, 1940–1951, 1960–1971, 1984–1990, 1994–2009). The asterisk indicates a significant cross-correlation at a 95% confidence level. (c) Histograms of temperature trend and warming area changes in the recent three PDO ascending phases compared to first three ascending phases, derived using 10,000 bootstrapping repeats (Supplementary materials online). (d) As for (c), but the changes in PDO descending stages.

geared toward using past trends in the PDO-GLT interactions to explore potential changes in the acceleration of global warming in the future.

We find a significant correlation between the 10-year running trends of the filtered PDOI and the internal temperature time series across the period 1910–2016 ( $r = 0.79$ ,  $P < 0.05$ ; Fig. 1b). Furthermore, cross-correlation analyses reveal a lag of approximately 7 months between the two series, indicating that changes in the PDO generally precede changes in observed temperature. These results are robust regardless of using other observational datasets to obtain internal temperature including NOAA GlobalTemp, National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies, Berkeley Earth, and China LSAT2.0 (Fig. S2 online). However, the correlation differences resulting from the lag are relatively small at the global level, likely due to the averaging effect of global temperatures. When examined at regional scales, for example, in western Eurasia (Fig. S3 online), more pronounced correlation differences emerge. Yet, we observed a departure from synchronicity in the relationship between PDO and global mean temperature during certain periods, such as the early and late 1980s. This deviation could be attributed to factors like volcanic eruptions, ENSO events, and other climate variability modes that potentially influence the relationship regionally and globally (Fig. S1 online; [4]).

Considering the influence of other oceanic modes, such as the NAO, AMO, and ENSO, it is worth noting that while some of these patterns exhibit correlations with temperature variations, their correlation coefficients do not surpass that of the PDO (Table S1 online). For instance, the AMO, also recognized for impacting decadal temperature [2], displays a relatively modest cross-correlation between its 10-year running trend and internal temperature changes ( $r = 0.17$ , lag =  $-6$ ). Remarkably, the causal direction implied by the negative lag opposes that of the PDO with internal temperature changes. In contrast, our analysis underscores the robust correlation between the PDO and temperature changes

within the specific 10-year research scale, and the lagging allows a more thorough investigation of the PDO footprints.

The PDO-Influenced Region (PIR) that we defined as the PDO footprint, represents the primary region impacted by the PDO warming/cooling effect. The region has a maximum correlation ( $>0.85$ ) at a corresponding lag of 24 months globally (Fig. S4 online), spans across the tropics, eastern Asia, and parts of North America around the North Pacific, and covers 63% of the land surface (shaded red in Fig. 1a). The distribution of the PIR is possibly shaped by the mechanisms driving decadal and interannual variations of the PDO, involving North Pacific atmosphere–ocean interactions and tropical forcing [5]. Research by Kosaka and Xie [6] demonstrated that the tropical Pacific plays a significant role in driving global warming rates via model simulations. Considering that the North Pacific contributes to decadal variation, while the tropical Pacific and its teleconnections drive high-frequency PDO variability [7], we propose that the North Pacific, as a part of the broader IPO system, modulates the decadal variation of global land temperatures. Consequently, the PIR is broadly distributed throughout the tropics.

Regarding causation, we found that most of the PIR grids show significant information flow from the PDOI-trend to the internal GLT-trend ( $P > 0.05$ ) and pass Granger causality test (Fig. S5b online). The consistency of PIR patterns across different timescales (7 to 20 years), along with the similarity observed in the wavelet power spectrum between PDO-trend and GLT-trend within PIR, also support the robustness connection of PDO on decadal temperature changes in PIR (Figs. S5 and S6 online). It is important to note that this association represents a statistical correlation with a physically meaningful lag, not necessarily causality. And we note some coastal regions along the North Pacific rim, including coastal North America, are not classified within the PIR (Fig. 1a and Fig. S7 online). This could be attributed to the influence of the shared atmospheric system and the differing specific heat capacities of seawater and land, which together contribute to a limited causality

from the PDO to temperature, despite a high correlation coefficient in the region.

To examine the PDO contribution to temperature changes over time, we compared the internal temperature changes in ascending and descending PDO stages before and after ~1960 (Fig. 1c, d). We differentiated these stages by utilizing the 10-year running trend of the PDO as a criterion for classification (Fig. 1b). During PDO ascending stages, regions of warming have expanded in contemporary times, from 59% to 64% of the global land surface (Antarctic excluded; Fig. S8 online). Within the PIR, area fraction showing warming during PDO ascending phases increases from 38% to 40% worldwide, suggesting approximately 2% of previously cooling land surfaces have warmed since 1960.

Using bootstrapping, we confirmed the significance of the observed contraction in cooling areas and expansion in warming areas during PDO transitions pre- and post-1960, as well as the increased temperature trend (Supplementary materials online; Fig. 1c, d). Notably, the expansion of warming areas exhibits disparities between PIR and non-PIR regions, despite both being significant. Furthermore, the reduction in cooling areas is more pronounced in PIR than in non-PIR, suggesting a possible weakening of the PDO cooling effect. Consequently, we propose that these increases in the area and amplitude of the PIR warming area potentially drive an acceleration in the GLT warming unless counterbalanced by a sufficient rise in the cooling effect during the PDO's descending phase. Again, we emphasize that the internal temperature is the component derived from the difference between observation-based temperature and model simulations. So our findings highlight the inherent constraints of simulations, and refinement in our understanding of global warming, which connects to effective targeting of climate change mitigation.

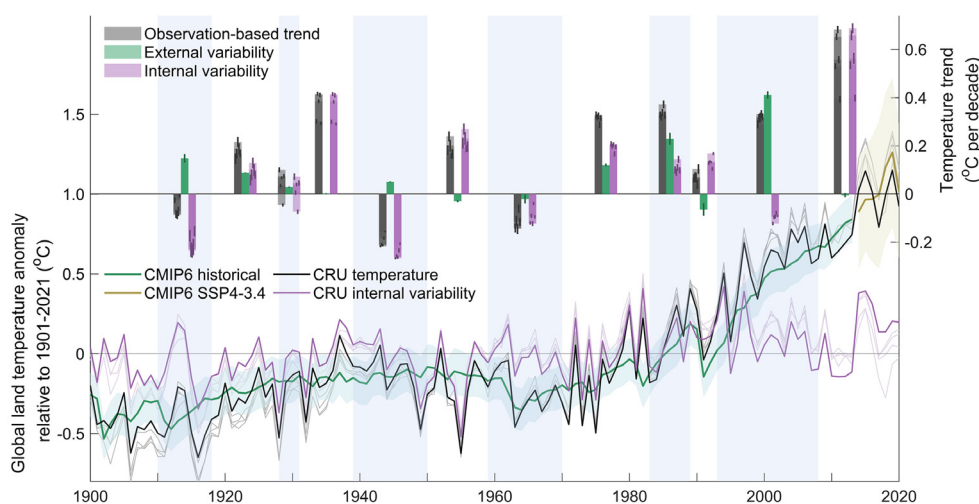
Comparing the warming rates attributed to anthropogenic forcings (external variability) and internal variability, Fig. 2 demonstrates that during PDO ascending stages, internal variability contributed more temperature increases than anthropogenic forcings. For example, in recent PDO Ascending Stage 6 (A6, 2010–2016), internal variability accounted for nearly all of the temperature increase, with accelerated rates primarily driven

by warming in PIR, contributing to record high global temperatures in 2016 (Figs. S9f and S10f online). During PDO descending stages, global land temperature warming from anthropogenic forcings would be more pronounced if not for the cooling effects of PDO-related internal variability. Yet due to the recent weakening of PDO cooling effect, the global temperature rise has been minimally offset, as evidenced by record high temperatures in 2022. Possibly for the reason that the cooling effect of the PDO is more concentrated in smaller areas than before, the cooling effect of the PDO seems to be less influential in the PIR during the ongoing PDO descending stage than in PDO Descending Stages 3 and 6 (Fig. 2).

As we inferred a causal relationship between the PDO and temperature variation statistically, prior studies on the PDO/IPO influence on temperature changes provide insights for interpreting the underlying physical mechanism. Observational and model data suggest that the cooling during negative PDO/IPO phases can play through two primary mechanisms [8,9]: (1) Strengthening of Pacific trade winds; and (2) greater heat uptake in the deeper ocean. Simulations by Douville et al. [10] revealed a positive feedback between the PDO and the Pacific trade winds, which in turn promotes updrafts in the central and eastern equatorial Pacific and cool the surrounding regions [8]. These winds may also alter ocean currents, increasing subsurface ocean heat absorption and slowing upper ocean warming [11–13].

Conversely, during shifts from negative to positive PDO phases, atmospheric circulations efficiently transfer oceanic heat to the atmosphere. Meanwhile, surface seawater increases density due to heat loss, promoting convection and continued upward transport of heat from the deeper ocean [3]. As such, we propose that PDO phase transitions, as reflected in PDO index changes, might be tied to ocean heat absorption and release; and through the interaction with the atmosphere, it takes time for an effective ocean–atmosphere positive feedback to develop and for the PDO to successively affect distant land temperatures.

Furthermore, our results point to an evolving, asymmetric effect of the PDO on warming and cooling. Specifically, we found that cooling area reduction is more pronounced in the PIR compared to non-PIR regions, while the expansion of warming areas exhibits



**Fig. 2.** Global land temperature (GLT) variations and temperature trends during PDO ascending/descending stages. The above shaded bars with error bars (gray, green and purple) represent overall temperature trends, external temperature trends (from CMIP6 simulations), and internal temperature trends, respectively (Supplementary materials online). The trends were calculated from decadal temperature anomalies (10-year cutoff lowpass filtered series) by linear regression. The error bars represent uncertainty at a 95% confidence level, and different temperature datasets, from left to right are CRU TS v.4.06, NOAA GlobalTemp, NASA GISS, Berkeley Earth, and China LSAT2.0. The time series below are the average of 38 CMIP6 model historical simulations (green) and 4 projections under scenario SSP4-3.4 (dark yellow; shaded: standard error). The black curve shows the observation-based estimate of global land temperature anomalies, and the purple curve is internal variability, equivalent to the difference between model simulations and observations-based estimate (CRU TS v.4.06; thin lines: NOAA GlobalTemp, NASA GISS, Berkeley Earth, and China LSAT2.0). The background is shaded light blue for PDO descending stages. Note that trends are derived from monthly records, and the displayed yearly temperature is for illustration purposes, and that the PDO ascending stage 6 (A6) extends until 2017.

relatively small disparity between the PIR and non-PIR. A possible explanation could be the potential uneven heat absorption and release during PDO phases fluctuations across past and more recent decades, leading disparate warming and cooling effects. This conjecture echoes with the IPCC's report [1] that the global ocean has absorbed 90% of the excess heat in the climate system in the past. However, we note that our analysis is based on the PDO index (Supplementary materials online), and the linkage between ocean oscillations and the Earth's energy imbalance remains complex and uncertain [4].

Another explanation for such asymmetry could be the possibility of a weakening PDO under global warming scenario, along with a shortening of phases [14]. A weakened PDO may have a less significant impact on warming or cooling, as it has reduced momentum and a shorter duration to exert a strong influence. This may partially explain the more significant reduction in cooling areas observed in the PIR since 1960 (Fig. 1d). We highlight the need to further investigate the evolving warming/cooling effect of the PDO, given its great capacity to modulate global temperature on a decadal scale that no other oceanic modes do, such as North Atlantic Oscillation and ENSO (Table S1 online).

According to the PDO fluctuation series from NOAA, the PDO appears to be at the almost bottom of its negative phase, while the expected cooling effect did not greatly abate the rise in global mean temperature with the past eight years reported as the warmest years (<https://climate.nasa.gov/news/3246/nasa-says-2022-fifth-warmest-year-on-record-warming-trend-continues/>). Given the confirmed El Niño event in 2023, marked by record-breaking sea surface temperatures, one concern is that the PDO ascending stage might be on the way. Such a stage could potentially accompany the release of stored excess heat, possibly accelerating global warming to higher levels regardless of the duration of the transition, as was the case in 2010–2016.

### Conflict of interest

The authors declare that they have no conflict of interest.

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### Author contributions

Zhenzhong Zeng provided the conception, funding acquisition, methodology and supervision. Lili Liang conducted the investigation, visualization and methodology, and wrote the original manuscript. Laurent Z.X. Li and Philippe Ciais helped develop the methodology. All authors contributed to the interpretation of the results and editing of the manuscript.

## Appendix A. Supplementary materials

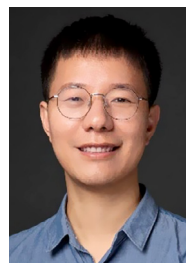
Supplementary materials to this short communication can be found online at <https://doi.org/10.1016/j.scib.2023.12.004>.

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