

Central Pacific El Niño and decadal climate change in the North Pacific Ocean

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Decadal fluctuations of the ocean and atmosphere over the North Pacific Ocean significantly affect the weather and climate of North America and Eurasia. They also cause transitions between different states of marine ecosystems across the Pacific Ocean^{1–3}. An important fraction of North Pacific low-frequency variability is linked to the North Pacific Gyre Oscillation⁴, a climate pattern associated with decadal fluctuations of the ocean circulation. Decadal variations in the North Pacific Gyre Oscillation are characterized by a pattern of sea surface temperature anomalies that resemble the central Pacific El Niño, a dominant mode of interannual variability with far-reaching effects on global climate patterns^{5–7}. Here we use an ensemble of simulations with a coupled ocean-atmosphere model to show that the sea surface temperature anomalies associated with central Pacific El Niño force changes in the extra-tropical atmospheric circulation. These changes in turn drive the decadal fluctuations of the North Pacific Gyre Oscillation. Given that central Pacific El Niño events could become more frequent with increasing levels of greenhouse gases in the atmosphere⁸, we infer that the North Pacific Gyre Oscillation may play an increasingly important role in shaping Pacific climate and marine ecosystems in the twenty-first century.

Previous studies document the wide-ranging impacts of North Pacific decadal-scale climate variability associated with the Pacific Decadal Oscillation¹² (PDO) and the North Pacific Gyre Oscillation^{4,9–11} (NPGO). The PDO closely tracks the first mode of North Pacific sea surface temperature (SST) variability, and is connected to atmospheric circulation anomalies associated with the El Niño Southern Oscillation^{12–14} (ENSO). The NPGO, defined as the second dominant mode of sea surface height anomalies in the central and eastern North Pacific⁴ (see the Methods section), closely tracks the second dominant mode of North Pacific SST anomalies, and is associated with decadal-scale variations in the ocean gyres circulation^{4,11}. The NPGO explains prominent low-frequency fluctuations of upper ocean salinity and nutrients observed in long-term records in the central and eastern North Pacific⁹, as well as a variety of other ecosystem indicators¹⁵. However, the origin of the NPGO low-frequency variability remains unknown, as does its sensitivity to greenhouse climate forcing.

Analysis of Pacific basin SST fields show that the SST signature of the decadal-scale NPGO shares important common features with the Central Pacific warming (CPW) El Niño pattern (Fig. 1; see the Methods section). The CPW, also referred to as the Date Line El Niño⁵, El Niño Modoki⁶ or warm-pool El Niño⁷, emerges as

the second mode of tropical Pacific SSTs, and has been linked to changes in tropical global cyclone activity¹⁶, storm tracks⁶ and shifts in global rainfall patterns¹⁷. Both the CPW and NPGO patterns are characterized by strong central tropical Pacific warming that extends northeastwards to the west coast of North America, and by central North Pacific cooling. Defined in the tropics, the CPW's SST anomalies are largest in the tropical Pacific, whereas the NPGO, as a North Pacific index, has greater amplitude in the extratropics. Given that the regions used to define the NPGO and CPW do not overlap, the overall similarities between the NPGO and the CPW spatial patterns (Fig. 1) suggest that a dynamical link exists between the NPGO and CPW.

In this study we show that central tropical Pacific SST variability associated with the CPW El Niño drives the decadal-scale NPGO pattern through an atmospheric teleconnection involving large-scale sea-level pressure (SLP) anomalies in the central North Pacific. It is well known that tropical Pacific warming reshapes large-scale atmospheric circulation in the North Pacific¹⁸. Given that the ocean acts as an integrator and low-frequency filter of the atmospheric variability¹⁹, tropically forced atmospheric circulation anomalies in the North Pacific can generate low-frequency climate variability.

A significant fraction of the NPGO ocean variability is driven by atmospheric variability in the North Pacific¹⁰ (see also the Methods section). The low-frequency atmospheric forcing of the NPGO, extracted by correlating the NPGO index with Pacific-wide SLP anomalies (Fig. 2; see the Methods section), is characterized by a dipole structure with low SLP over the Hawaiian region and high SLP over Alaska. If we compare this structure with the atmospheric expression of the CPW (Fig. 2), we find that both patterns share variance and a significant SLP loading in the proximity of Hawaii. The Hawaiian SLP variability explains an important fraction of the NPGO low-frequency variability. We show this using a statistical hindcast model (see the Methods section), where the rate of change of the NPGO index is driven by the atmospheric variability associated with the southern pole of the NPGO's SLP forcing pattern, here defined as the time series of SLP anomalies averaged over the Hawaiian region (SLP_{HI}; 158° W–135° W; 13° N–24° N; Fig. 2a, white rectangle). The time series that results from the statistical model hindcast explains a significant fraction of the NPGO variance (Fig. 2c; $R = 0.65$; >99% significance, see the Methods section), especially on low-frequency timescales. Formally this model is a first-order autoregressive process (AR1) in which the ocean NPGO is considered a slave to the atmosphere and integrates the variability of the SLP_{HI}.

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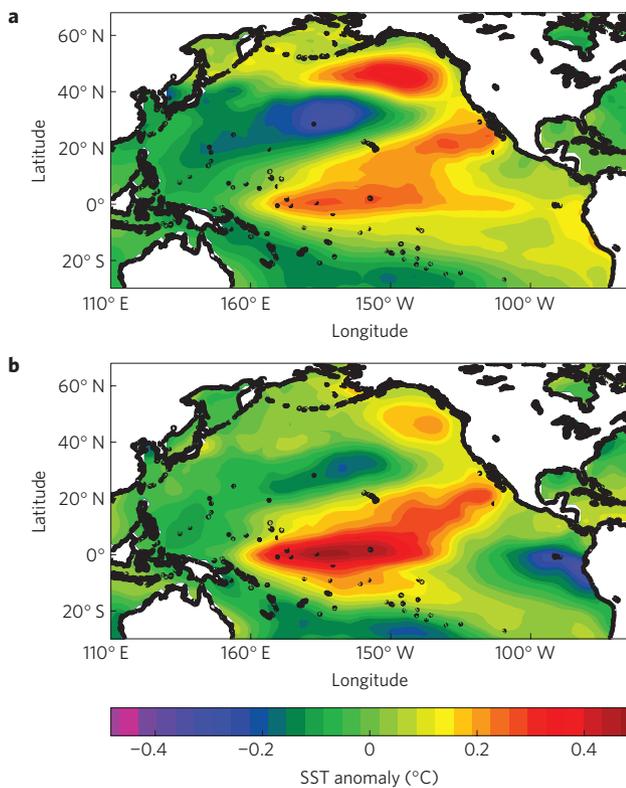


Figure 1 | Spatial structure of SST anomalies of the CPW El Niño and the NPGO. a, b. The NPGO (a) and the CPW (b) patterns are obtained by regressing the monthly NOAA SST anomaly reanalysis with the CPW and NPGO indices, respectively.

Previous studies have linked the NPGO's atmospheric forcing pattern (Fig. 2a) to intrinsic variability associated with the North Pacific Oscillation¹⁰ (NPO; Supplementary Fig. S1). The NPO, defined as the second dominant mode of SLP variability in the North Pacific²⁰, is also characterized by two centres of action, one over Alaska and another north of Hawaii, and is widely regarded as a purely stochastically driven phenomenon intrinsic to the North Pacific atmosphere²⁰. However, analyses of Pacific SLP fields indicate that the low-frequency (>8 yr) variability of the NPO (Supplementary Fig. S1) also bears a strong resemblance to the CPW SLP pattern, including strong low-frequency variance in the Hawaiian region (158° W–135° W; 13° N–24° N). This comparison is consistent with the hypothesis that low-frequency variations of SLP in the Hawaii region, which are an important contributor to the NPGO's low-frequency variability, are linked to SST anomalies in the central tropical Pacific associated with CPW.

Results from atmospheric general circulation model (AGCM) simulations coupled to a mixed-layer ocean model (ML) lend further support to the idea that the low-frequency variations of the atmospheric SLP over the Hawaiian region, here measured with the SLP_{HI} index, are driven by changes in central tropical Pacific SSTs. We use a 45-member ensemble of the AGCM–ML (ref. 21; see the Methods section), wherein each ensemble member is forced with prescribed SST anomalies from 1950 to 2008 in a narrow region in the equatorial Pacific (12° S–12° N), and interactive fluxes between the AGCM and the ML elsewhere. We isolate the specific tropical SST pattern that drives the deterministic component of the model's resulting SLP_{HI} variability by correlating, for each AGCM–ML ensemble member, the model's SLP_{HI} values during boreal winter (January–February–March, JFM)—the period in which the SLP_{HI} variance is maximum—with the corresponding JFM tropical Pacific SST anomalies that force each simulation. The average correlation

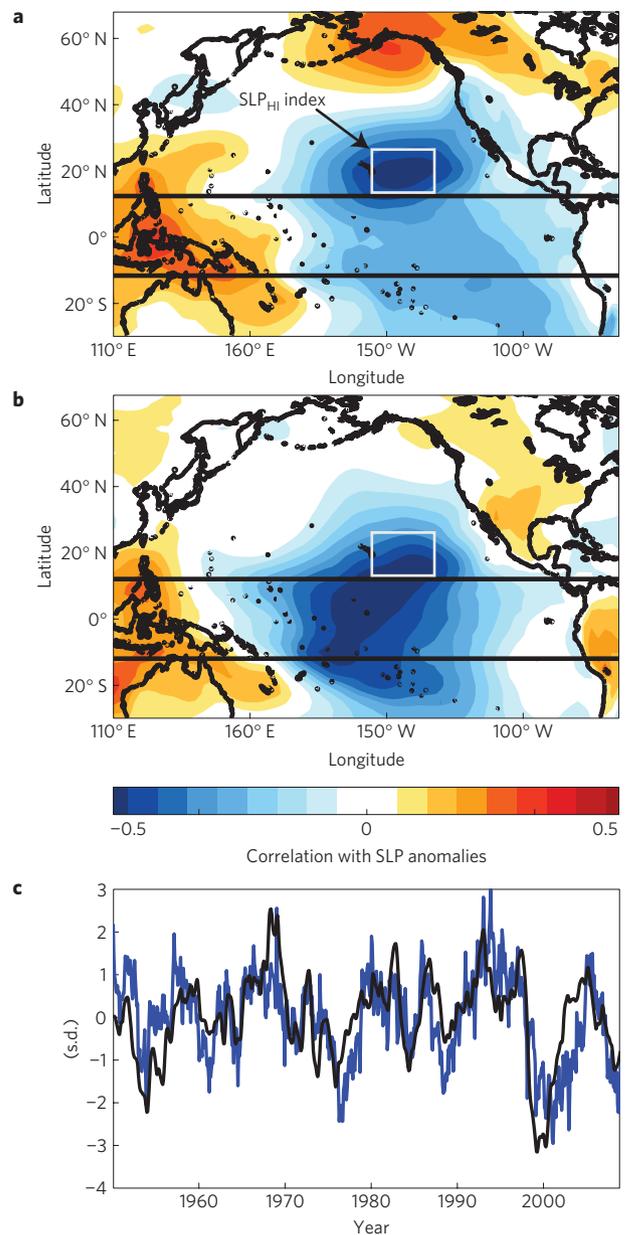


Figure 2 | The atmospheric forcing of the NPGO. a. Correlation of the NPGO index with monthly NCEP SLP anomalies. The SLP anomalies averaged over the white rectangle east of Hawaii are used to derive an index of the atmospheric forcing of the NPGO, referred to as the SLP_{HI} index. **b.** Correlation map of the CPW index with NCEP SLP anomalies. **c.** The NPGO index (blue) is reconstructed (black) using an AR1 model forced by the SLP_{HI} index. The units are in standard deviations (s.d.). The significance of correlation ($R = 0.65$; >99%) of the raw monthly values is estimated using a Monte Carlo test for time series with a corresponding red spectra (see the Methods section).

map that emerges from the 45-member ensemble reveals a significant correlation pattern in the tropical Pacific (maximum $R = 0.65$; >99%; Fig. 3a). The maximum positive correlations are located in the central tropical Pacific between 220° W and 150° W, which is a defining characteristic of the JFM SST anomaly pattern associated with the CPW (Fig. 3b). The link to the CPW is also evident from the significant correlation between the CPW index and the AGCM–ML SLP_{HI} ensemble mean ($R = 0.6$; >99%; Fig. 3c). It is important to note that the AGCM–ML atmospheric ensemble members have no feedback onto tropical Pacific SST

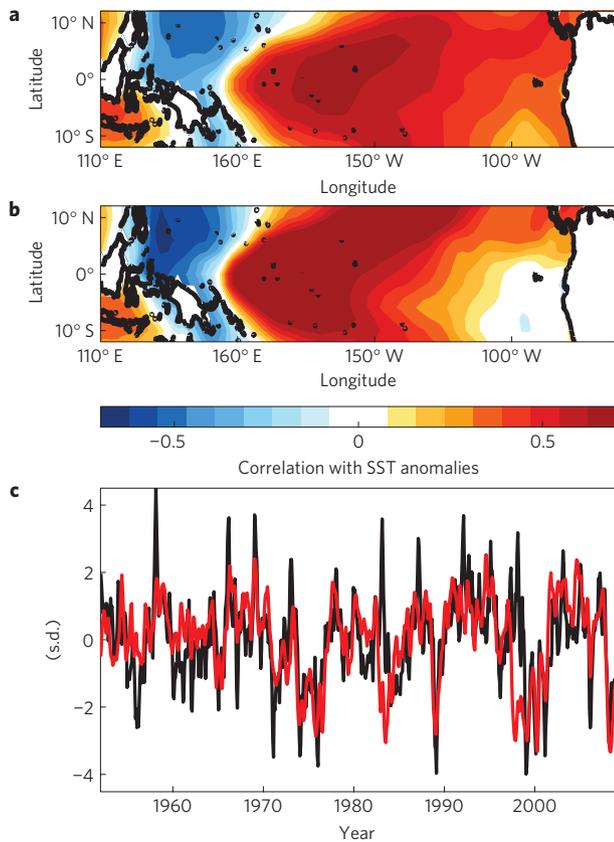


Figure 3 | Tropical Pacific SST anomaly forcing pattern for the AGCM-ML SLP_{HI}. **a**, Ensemble average correlation map of the AGCM-ML SLP_{HI} index with SST anomalies in the tropical Pacific (12° S–12° N) during winter time (JFM). The correlation is computed separately for each AGCM-ML realization of the SLP_{HI} and then all correlation maps are averaged together so that the average correlation retains both the signal and noise of the AGCM-ML. **b**, The correlation pattern of the CPW index with SST anomalies during winter (JFM). **c**, Time series of the AGCM-ML SLP_{HI} ensemble mean (black) and the CPW index (red). Indices are normalized by their standard deviations and are correlated $R = 0.6$ ($>99\%$). The significance of correlation of the raw monthly values is estimated using a Monte Carlo test for time series with a corresponding red spectra (see the Methods section).

anomalies; therefore, the significant correlations observed between the modelled SLP_{HI} index and the tropical Pacific SST indicate a one-way forcing from the tropical Pacific to the extratropics. These correlations suggest that $>25\%$ of the SLP_{HI} variability is forced by CPW and imply that the low-frequency variability of SLP_{HI}, and by extension the NPO, is forced by tropical SST variability.

To quantify how much of the NPGO variance is driven by the tropically forced component of the SLP_{HI} we apply the AR1 model introduced above to each of the 45 model-derived SLP_{HI} indices (see also the Methods section). The ensemble mean reconstruction of the NPGO index is significantly correlated with the original NPGO index⁴ ($R = 0.55$, $>99\%$; Fig. 4). The correlations between the modelled and original NPGO indices are maximized on low-frequency (>8 yr) timescales (Fig. 4; $R = 0.85$; $>99\%$). The low-frequency character of the modelled NPGO indices is a direct result of tropical SST forcing—if we remove the ensemble mean SLP_{HI} from each ensemble member, thereby removing that component of tropically forced response common to all of the AGCM-ML SLP_{HI} time series, we find that the individual ensemble members' reconstructed NPGO indices are uncorrelated to the original NPGO index ($R = 0.04$). Therefore, we conclude that the forced

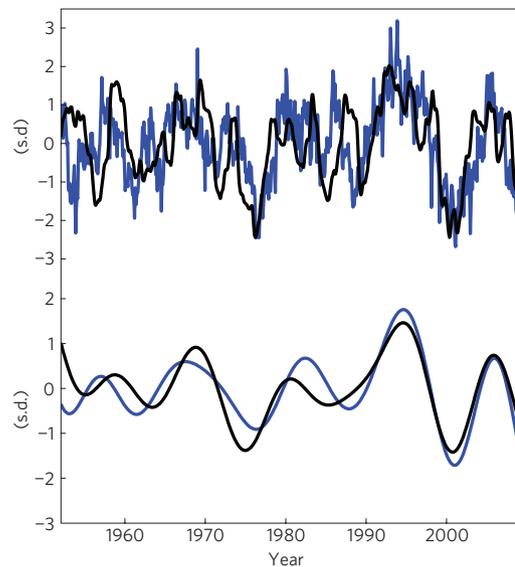


Figure 4 | Reconstruction of NPGO variance originating from the tropical Pacific. The NPGO index (blue) is reconstructed (black) by forcing an AR1 model with the time series of the AGCM-ML SLP_{HI} ensemble mean, which represent the deterministic variability driven by the central tropical Pacific. The units are in standard deviations (s.d.). The significance of correlation of the raw monthly (top panel) ($R = 0.55$; $>99\%$; top) and 8-year low-pass-filtered (bottom panel) ($R = 0.85$; $>98\%$; bottom) values is estimated using a Monte Carlo test for time series with red spectra (see the Methods section).

component of SLP_{HI} variability that drives the NPGO originates from SST anomalies in the equatorial Pacific.

Taken together, our results suggest that the low-frequency character of the NPGO, an important source of ocean climate and ecosystem variability in the Pacific, originates from coupled ocean–atmosphere interactions associated with the CPW phenomenon. The NPGO–CPW dynamical link proposed here echoes that previously identified to explain the relationship between the PDO and ENSO. Several studies have linked the midlatitude variability of the PDO to the canonical expression of ENSO, both statistically and dynamically^{12–14,22,23}. The dynamics that link ENSO to PDO are referred to as the ‘atmospheric bridge’¹², whereby atmospheric teleconnections to the extratropics excited by ENSO project onto the atmospheric variability of the Aleutian Low, which then drives the ocean PDO pattern. Employing the same modelling approach used to isolate the ‘atmospheric bridge’, this study demonstrates that a similar dynamical chain is triggered by central tropical Pacific SST anomalies (CPW or Modoki El Niño). CPW drives changes in the large-scale atmospheric circulation in the central North Pacific (for example, NPO), which are then integrated by the ocean to yield the NPGO. Whereas the impacts of the PDO on Pacific marine ecosystems and North American climate patterns are extensively documented¹, the impacts of the newly discovered NPGO across the Pacific Basin are just beginning to emerge^{4,9–11,15,24}.

These findings imply that a large fraction of low-frequency climate variability in the North Pacific is driven by tropical Pacific climate variability. Therefore, large uncertainties of the tropical Pacific's response to climate change²⁵ may limit the predictability of future changes in Pacific decadal-scale climate. However, if climate model projections suggesting an increase in the frequency of CPW under anthropogenic global warming scenarios are accurate⁸, then NPGO variance may also increase. Consistent with this view, NPGO variability has intensified in the late twentieth century⁴, explaining a growing number of late-twentieth-century climate and ecosystem indices across the North Pacific basin^{4,9–11,15,24}. As an

important indicator of physical (for example, strength of gyre-scale circulation, eastern-boundary upwelling) and biological (nutrients, chlorophyll *a*, fish species) fluctuations in the North Pacific at both the coastal and basin scales, an increase in NPGO power would have broad implications. This is especially true for marine ecosystems, which amplify decadal-scale environmental fluctuations into strong state transitions and therefore may exhibit a high sensitivity to ongoing climate change.

Methods

The observational analyses use monthly anomalies of SLP from the National Centers for Environmental Prediction (NCEP) Reanalysis II²⁶ and SST from the National Oceanic and Atmospheric Administration (NOAA) Reanalysis²⁷. The monthly anomalies are computed by removing the climatological monthly means.

The CPW index and pattern are defined by computing the first principal component of tropical SST anomalies between 20° S and 20° N after removing the canonical ENSO using regression of the SST variability associated with the Niño3 index (<http://www.cpc.naa.gov/data/indices>).

The NPGO index²¹ (<http://www.o3d.org/npgo>) is defined as the second principal component of sea surface height anomalies in the northeast Pacific (180°–110° W; 25° N–62° N) and was originally obtained from an ocean model hindcast⁴ forced by the NCEP Reanalysis II²⁶ surface fluxes. This method of computing the NPGO index is valid to the extent that the NPGO is predominantly an ocean response to large-scale atmospheric forcing over the North Pacific, as suggested by previous studies¹⁰. We confirmed this finding with an independent estimate of the NPGO index from the Japanese Earth Simulator global eddy-resolving ocean model²⁸ (OFES). The OFES model hindcast was also forced by the NCEP fluxes and its monthly NPGO index shares >70% of variance ($R = 0.86$) with the original NPGO index⁴. This shared variance can be interpreted as one estimate of the amount of NPGO variance that is forced by the atmosphere. We also quantified the sensitivity of the NPGO atmospheric forcing pattern by comparing the patterns that emerge from the NCEP SLP Reanalysis (Fig. 2a) and Hadley SLP2 Reanalysis²⁹. These forcing patterns were computed by correlating the NPGO index with the SLP anomalies of the NCEP and Hadley data sets. We find that these SLP patterns are significantly correlated ($R = 0.98$).

The oceanic NPGO response to atmospheric forcing is quantified using an autoregressive model of order 1 (AR1),

$$\frac{d\text{NPGO}_{\text{rec}}(t)}{dt} = \text{SLP}_{\text{HI}}(t) - \frac{\text{NPGO}_{\text{rec}}(t)}{\tau_{\text{NPGO}}}$$

where the rate of change of the NPGO index is forced by the SLP_{HI} , defined as the time series of average NCEP SLP anomalies over the Hawaiian region (158° W–135° W; 13° N–24° N; Fig. 2a, white rectangle). The SLP_{HI} is here used as an index of the atmospheric forcing of the NPGO. The ocean memory to the SLP_{HI} perturbations is represented in the damping term (second term on the right-hand side). The timescale of the damping τ_{NPGO} is computed from the decorrelation timescale of the NPGO index (~10 months), consistent with previous studies¹⁰. We also forced the AR1 model with the Hadley SLP2 data²⁹ to quantify whether errors in the NCEP reanalysis could affect our ability to reconstruct the NPGO. We found that the NCEP and Hadley NPGO reconstructions are essentially identical, with correlations of 0.96, with only minor discrepancies in the early 1950s.

The significance of the correlation coefficients is estimated from the probability distribution functions of the correlation coefficient of two red-noise time series with the same autoregression coefficients as estimated from the original signals. The probability distribution functions are computed numerically by generating 3,000 realizations of the correlation coefficient of two random red-noise time series.

The AGCM–ML simulations are carried out using the International Center for Theoretical Physics atmospheric general circulation model coupled to an ocean mixed-layer of 50 m fixed depth²¹. This model was selected on the basis of its ability to capture the observed large-scale atmospheric variability and tropical teleconnection as demonstrated within the Climate of the 20th Century CLIVAR project²¹.

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Author contributions

E.D.L. and N.S. carried out the analysis. E.D.L., K.M.C., N.S. and B.A. contributed to the writing of the paper. A.B. and J.C.F. contributed to the coupled ocean–atmosphere model. M.A.A. and D.V. contributed to the experimental design and analysis of the atmospheric teleconnection patterns. All authors discussed and commented on the layout and the results of the manuscript.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at <http://npg.nature.com/reprintsandpermissions>. Correspondence and requests for materials should be addressed to E.D.L.