Decadal climate variability in the tropical Pacific: characteristics, causes, predictability and prospects

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Structured Abstract

BACKGROUND

Tropical Pacific Decadal climate Variability and change (TPDV) affects the global climate system, extreme weather events, agricultural production, streamflow, marine and terrestrial ecosystems, and biodiversity. While major international efforts are underway to provide decadal climate predictions, there is still a great deal of uncertainty about the characteristics and causes of TPDV, and the accuracy to which it can be simulated and predicted. Here we critically synthesize what is currently known and what is not known, and provide recommendations to improve our understanding of TPDV and our ability to predict it.

ADVANCES

TPDV is evident in instrumental records, paleoclimate records over past millennia, and climate models. TPDV can occur spontaneously as "internal" variability, as is largely the case in the central equatorial Pacific, or in response to "external" forcing. While internal TPDV arises to a large extent as a residual of independent El Niño-Southern Oscillation events, it can also result from oceanic processes occurring at decadal timescales involving the upper-ocean overturning circulation known as subtropical-tropical cells, and in response to internal atmospheric variability in the extra-tropical Pacific and changes in sea surface temperature in other ocean basins. "Externally-forced" TPDV, in the form of mean-state changes that unfold on decadal timescales or forced decadal variability, can be driven by anthropogenic (e.g., greenhouse gas (GHG) increases, sulphate aerosols changes) and natural processes (e.g., volcanic eruptions). External forcing can also affect the behavior and characteristics of internal TPDV.

In the western tropical Pacific, GHG-forced warming has reached levels that are unprecedented in the historical record. Further greenhouse warming in the equatorial Pacific will ensure that record-setting high temperatures will be experienced for decades to come. Increases in equatorial precipitation and in precipitation variability in parts of the tropical Pacific, and a southward expansion of the southern hemisphere Hadley Cell, are projected by climate models with some confidence. Yet projected changes in eastern equatorial Pacific surface temperature, and changes in the strength of the Walker Circulation and trade winds, remain very uncertain.

Skill in decadal predictions of temperature in the western Pacific is apparent, though it appears to be largely underpinned by GHG warming. There are also indications of multiyear skill in predicting some biogeochemical quantities important for fisheries and the global carbon budget.

The limited length of the instrumental records, the scarcity of paleoclimate data, and TPDV representation biases in climate models have so far prevented a complete characterization and understanding of TPDV and have limited our ability to predict TPDV.

OUTLOOK

While several mechanisms have been proposed to explain TPDV, their relative importance as sources of decadal prediction remains unclear. Issues in need of greater understanding include the role played by the upper ocean overturning circulation in controlling tropical Pacific sea surface temperatures at decadal timescales, the impact of external forcing on the Walker circulation and characteristics of internally-generated TPDV, and the extent to which sea surface temperature variability in other basins drives TPDV. A better understanding of the origin and spatial pattern of current predictive skill is also needed. Improving predictions and projections requires improvements in the quality, quantity, and length of instrumental and paleoclimate records, in the performance of climate models and data assimilation methods used to make predictions.

Introduction

Climate variability in the tropical Pacific affects global climate on a wide range of timescales. On interannual timescales, the tropical Pacific is home to the El Niño-Southern Oscillation (ENSO), the most energetic and influential climate phenomenon in the world (*1*). Less well known is that decadal variations and changes in the tropical Pacific, referred to here collectively as "Tropical Pacific Decadal Variability" (TPDV), also profoundly affects the climate system. In the following, we will use TPDV to refer to any form of decadal climate variability or change that occurs in the atmosphere, the ocean and over land within the tropical Pacific. "Decadal" is used here in a broad sense to encompass multiyear through multidecadal timescales, including variability about the mean–state on decadal timescales, externally forced mean-state changes that unfold on decadal timescales, and decadal variations in the behavior of higher-frequency modes like ENSO.

Naturally occurring, spontaneously generated TPDV can arise in the absence of any change to external forcing (e.g., greenhouse gas (GHG) increases or volcanic eruptions). Climate scientists refer to such variability as "internally-generated" or "internal" variability, and will be referred to here as "internal TPDV" (*2*). Internal TPDV affected the rate at which globally-averaged surface air temperature rose over the past century. This was dramatically illustrated by the recent and highly publicized "global warming slow-down", when decadal surface cooling in the eastern equatorial Pacific (shading in Fig. 1A) associated with a major redistribution of heat in the subsurface ocean offset the anthropogenic global warming trend at the turn of the 21st century (*3*, *4*) (bottom curve on Fig. 1D). Trade winds intensification associated with this cooling also contributed to rapid sea-level rise in the western Pacific during recent decades (*5*) (contours in Fig. 1A). More generally, internal TPDV has further been reported to modulate drought, wildfire, floods, extreme weather, polar sea-ice extent (*6*, *7*), decadal variations in the impact that ENSO has on rainfall, river flow and agricultural production, and the skill with which ENSO impacts can be predicted, as demonstrated for Australia (*8*). Uncertainty in the magnitude of internal TPDV simulated in global climate models may also be linked to uncertainty in simulated climate sensitivity (*9*) – a measure of the degree of global warming that occurs in response to anthropogenic increases in atmospheric GHG concentrations (*10*).

The tropical Pacific also changes in response to external forcing, including GHG increases, volcanic eruptions and anthropogenic aerosols. This component of TPDV will be referred to as "external TPDV". The observed low-frequency sea-surface temperature (SST) evolution over the western tropical Pacific warm-pool is dominated by a long-term warming trend similar to the global anthropogenic warming signal (bottom curves of Fig. 1D), that has been linked to a drying trend in the East Asian monsoon (*11*). Further warming in the region is also expected to reduce coastal fish populations, shift tuna distribution eastward, cause record-breaking high temperatures to occur more often (*12*) and fundamentally alter coral reefs, with major impacts on biodiversity, Pacific Island communities, and livelihoods (*12*, *13*).

Major international efforts are underway to provide decadal climate predictions that are intended to help decision makers plan for coming years and decades (*14*) that take both internally generated and externally-forced TPDV into account, as they will both influence future climate. The enormous challenges currently faced by groups producing decadal predictions demand a better understanding of the mechanisms of TPDV. To that end, here we synthesize our current understanding of TPDV, its spatial and temporal characteristics, its many proposed mechanisms – both natural and anthropogenic and the interactions between them, and the current ability of state-of-the-art modeling and prediction systems to simulate and predict TPDV. A wide and diverse array of evidence is used, from historical records, instrumental and paleoclimate observations, mathematical models of Earth's climate, and decadal prediction systems, to assess the degree of confidence we have in proposed mechanisms and the extent to which those processes provide a degree of predictability (*2*, *14*, *15*).

Advances

Observed TPDV

Decadal SST fluctuations peak in the equatorial central/eastern Pacific (contours in Fig. 1B), alternating between decadal periods of anomalously warm and cold phases (top panel of Fig. 1D). This evolution broadly matches the positive and negative phases of the Interdecadal Pacific Oscillation (*8*) (represented as vertical shading in Fig. 1D), characterized by opposite SST and sea-level signals in the eastern and western tropical Pacific (Fig. 1A). While important on decadal timecales, this variability only modestly contributes to total SST variations in the equatorial eastern Pacific (shading in Fig. 1B), which are largely dominated by ENSO-related interannual SST fluctuations. The relative contribution of TPDV is considerably larger in the western Pacific, where the low-frequency SST signal is dominated by a long-term warming trend similar to the global anthropogenic warming signal (bottom curves of Fig. 1D). Consequently, internal TPDV, estimated here in the 8-40 years range, dominates in the central Pacific and in off-equatorial bands in the eastern part of the basin, especially in the northern Hemisphere. Internal TPDV has a weak signature in the western tropical Pacific (Fig. 1C), where the longer timescales of external TPDV prevail instead.

Confidently characterizing TPDV is complicated by the short historical record. Indeed, historical observations of the tropical Pacific are sparse before the mid-20th century, which creates uncertainty in tropical Pacific SST records prior to 1950. Paleoclimate records offer key complementary information extending further into the past (Fig. 1D). A recent synthesis of dozens of monthly- to annually-resolved Pacific coral records exhibit strong decadal variability over the last four centuries (*16*). In particular, isotopic measurements from corals in the central and southwest tropical Pacific (*17*, *18*) (white dot and star in Fig. 1A) display a monotonic trend toward warmer and wetter conditions over the twentieth century (blue curves in Fig. 1D), supporting the central Pacific rainfall increase in response to anthropogenic forcing found in models. On shorter timescales, these timeseries display opposite signals, capturing the contrast between warm/wet and cold/dry regions related to the internal TPDV pattern (Fig. 1A). Recent advances in paleoclimate data assimilation have enabled the construction of gridded tropical Pacific SST fields extending through the last millennium (*19*), that match qualitatively well the observed SST evolution over the instrumental period (Fig. 1D). These reconstructions, however, exhibit increasing uncertainty as fewer records become available back in time (Fig. 1D, gray envelopes).

Internal TPDV

The dominant internal TPDV SST signal can be characterized by the leading empirical orthogonal function and related Principal Component of 8-40 year variability of tropical Pacific SST (Fig. 2, A and B), which accounts for about half of the tropical Pacific SST variability in the 8-40 year timescale (contours in Fig. 1C). The related SST pattern throughout the entire Pacific basin can then be obtained through linear regression upon this principal component. This internal TPDV SST pattern (Fig. 2A; shading) strongly resembles the ENSO SST pattern in the tropics (Fig. 2E), but has a generally broader latitudinal extent (*20*, *21*). This pattern is also associated with a zonal seesaw in tropical Pacific mean sea-level pressure, as described by the Southern Oscillation index (Fig. 2B), a measure of the difference in sea level pressure between Tahiti and Darwin, leading to the anti-correlation between this index and the SST-based internal TPDV index at decadal timescales (Fig. 2B). The internal TPDV SST pattern (Fig. 2A) is consistent with the patterns of variability associated with the Interdecadal Pacific Oscillation (*8*) over the Pacific basin and the Pacific Decadal Oscillation in the North Pacific (*22*), highlighting the important role of the tropical Pacific in forcing and synchronizing decadal variability in both hemispheres (*22*).

The simplest explanation for internal TPDV - the *null hypothesis* - is that it arises as a residual of largely independent ENSO events (*21*, *23*, *24*). We hence first establish the extent to which observed TPDV might result from decadal averages of ENSO events that are randomly distributed, without modification by independent decadal dynamics or decadal clustering through nonlinear interactions. In this view, the random occurrence of decadal epochs with a larger number of El Niño (La Niña) can be expected to result in an El Niño (La Niña)-like residual SST anomaly (*21*). The null hypothsis is supported by the good correspondence between the time series of the leading pattern of internal TPDV and the relative number of El Niño and La Niña events during partially-overlapping 8-year periods (Fig. 2B). In addition, each ENSO event is not a static pattern, but undergoes an evolution from a precursor phase (Fig. 2D), through a mature phase (Fig. 2E), to a decay phase (Fig. 2F), so that the average over this seasonal evolution across multiple events can result in a latitudinally broader pattern (Fig. 2C) very similar to the pattern in Fig. 2A (*24*).

This picture is further modified by ENSO asymmetries. For example: the strongest El Niño events are larger than the strongest La Niña events; La Niña events tend to last longer than El Niño events; and strong El Nino events tend to occur further east than strong La Niña events, impacting the details of TPDV (*25*). Differences in spatial patterns, with some events having greatest amplitude in the central or eastern tropical Pacific (*1*, *26*) may result in mean pattern differences during different decadal epochs (*25*), which may themselves occur purely by chance (*25*, *27*).

Whether decadal changes in the background state, even if randomly forced, feedback and modulate ENSO characteristics is a focus of current research (*28*). To go beyond the null hypothesis, therefore, we would need evidence that slow oceanic processes provide sources of decadal predictability beyond the ENSO timescale. For example, the ocean integration of ENSO-related surface fluxes may result in low-frequency SST variations with enhanced decadal predictability, as illustrated in a modeling context (*21*).

In addition, changes in the strength of the wind-driven upper-ocean overturning circulation, known as the Subtropical-Tropical Cells (STCs), which connect the subtropical and equatorial regions, have been related to decadal variations of equatorial SSTs in both observations (*29*) and models (*30*, *31*). As schematically depicted in Fig. 3A, the STCs include subsurface equatorward flow, equatorial upwelling, and poleward flow in the surface Ekman layer, so that a strengthening (weakening) of the STCs results in enhanced (reduced) equatorial upwelling of cold subsurface waters, impacting equatorial SSTs. The adjustment of the STCs to changes in surface wind forcing is accomplished through the propagation of oceanic Rossby waves (*30*) that travel to the western ocean boundary, and then along the boundary to the equator as coastal-trapped waves, where they alter the depth of the equatorial thermocline and influence SST anomalies (Fig. 3A) (*32*, *33*). Since Rossby waves are more efficiently excited by wind anomalies with larger spatial scales and longer timescales, they can dynamically "filter" the wind forcing, and contribute to an enhancement of low-frequency power (*34*).

Other modeling studies suggest that temperature anomalies subducted in the subtropics can reach the equatorial thermocline and influence equatorial SSTs (*35*), especially when they are density-compensated by associated salinity anomalies (so-called "spiciness" anomalies) and can then propagate toward the equator along mean density surfaces with minimal dissipation (*36*). While the ability of spiciness anomalies to reach the equator from their source regions has been recently demonstrated in a modeling context (*36*), their impact on equatorial SSTs in nature remains to be determined.

The above ocean processes occurring on decadal timescales are mostly wind-forced. In particular, modeling studies (*31*) indicate that subtropical winds play a key role in altering the strength of the STCs, but the origin of these anomalous winds is still unclear. Extra-tropical influences could be a source of sub-tropical wind variations. For example, internal atmospheric variability in the northern midlatitudes during winter can create subtropical SST and wind anomalies that persist through summer due to strong air-sea coupling (*37*), developing into a SST pattern that extends from the coast of California toward the central-western equatorial Pacific (Fig. 2D), known as the "North Pacific Meridional Mode" (*38*). Similarly, an anomalous SST pattern, known as the South Pacific Meridional Mode (*39*), can develop along the coast of South America (Fig. 2D). These

Meridional Modes are considered ENSO precursors, but their associated winds could also provide anomalous forcing for the slow tropical oceanic processes described above (*40*). As ENSO precursors, they are also part of a seasonal progression from the extra-equatorial ENSO precursor stage, to ENSO development, to extra-tropical ENSO teleconnections that can act as a filter of decadal variance in the Pacific basin (*41*). Climate model sensitivity experiments, where the North and South Pacific Meridional Modes were alternatively suppressed (*42*), suggest a potentially more important influence of the South Pacific on internal TPDV, consistent with other model-based studies (*43*, *44*). SST anomalies in the Atlantic and Indian Oceans could also influence these tropical Pacific winds (*45*, *46*), as discussed below.

Finally, changes in subtropical-tropical winds may arise as a response to the equatorial SST anomalies themselves, as shown in some modeling studies (*32*, *47*). In this view, atmospheric teleconnections triggered by the tropical SST anomalies at decadal timescales alter the extra-equatorial atmospheric circulation and produce wind anomalies of the opposite sign that force a phase reversal of the decadal cycle. This view of internal TPDV as arising from low-frequency processes that are independent of ENSO, with important implications for decadal predictability, remains very challenging to demonstrate observationally, due to the insufficient duration of the instrumental record in the presence of climate noise that may obscure the various deterministic links.

Representation of internal TPDV in climate models

In practice, evaluating internal TPDV simulated by climate models is challenging because: (i) the instrumental record is relatively short (e.g., Fig. 1D); (ii) relatively few multi-century paleoclimate records exist for the core regions of internal TPDV; (iii) internal TPDV in climate model simulations exhibits large changes from one century to the next (*48*); and (iv) the characteristics of internal TPDV vary markedly from model to model (Fig. 4).

As illustrated in Fig. 4, climate models still display major deficiencies in simulating key aspects of internal TPDV (*49*, *50*). For example, most models capture to first order the observed SST pattern but the equatorial Pacific warming extends too far to the west (compare shading in Fig. 4A and Fig. 4B; see also (*49*)), as do simulated ENSO SST patterns (*51*). Models also markedly underestimate sea-level signals in the tropical western Pacific and extra-tropical central Pacific associated with internal TPDV (compare contours on Fig. 4A and Fig. 4B). Similarly, the magnitude of simulated internal TPDV varies considerably from one model to another and is underestimated by a majority of models not only in terms of SST (Fig. 4C), but also in terms of trade wind strength (Figs. 4A vs. 4B) and associated mean-sea-level pressure gradients in the tropical Pacific atmosphere (*4*, *52*). This underestimation partly arises because ENSO simulations in most models tend to be too quasi-biennial and not persistent enough (*53*), impeding the ability of models to generate decadal anomalies through the null hypothesis (*52*). As a consequence, while all models exhibit some link between ENSO decadal variability and internal TPDV, they strongly underestimate the strength of this relationship (Fig. 4D).

Sources of externally-forced TPDV

As mentioned above, external radiative forcing from natural (e.g., volcanic eruptions and solar variability) and anthropogenic (e.g., GHGs, ozone and sulfate aerosols) sources also contribute to TPDV. The resulting external TPDV is directly related to decadal variability in the forcing (e.g., intermittent volcanic eruptions, slowly-increasing GHGs, varying anthropogenic aerosols emission), with possible contributions from the slow adjustment timescale of the ocean. Here, we examine the expected tropical Pacific responses from both anthropogenic and natural external forcing, which are represented schematically in Figure 3B.

GHGs such as carbon dioxide are the major source of anthropogenic climate warming and have been increasing steadily over past decades. Despite the spatially uniform nature of well-mixed GHGs, the warming of the ocean surface simulated by climate models exhibits substantial spatial variations (*54*). Most models project an enhanced warming in the equatorial Pacific (Fig. 3B), giving rise to tropical rainfall changes (*54*) altering global teleconnection patterns, increasing the frequency of extreme ENSO events (*55*) and regulating the magnitude of climate sensitivity (*56*). One study concluded that a GHG-forced enhancement of oceanic stratification leads to increasing Rossby wave speed, which decreases the amplitude and shortens the period of internal TPDV (*57*), whereas another study using a single model found GHG enhanced the amplitude of internal decadal variability (*56*).

Unlike GHGs, anthropogenic tropospheric aerosols display large spatio-temporal variations because of localised emission sources, and act to cool global surface temperature by reflecting sunlight. Models suggest that they induce SST and rainfall changes that are similar in pattern but opposite in sign to those of GHGs, especially in the tropical Pacific (*59*), hence weakening the GHG-induced warming.

Large volcanic eruptions can also contribute to external TPDV by injecting aerosols into the stratosphere. This cools the troposphere for a year or more (*2*) and the ocean for up to a decade - thereby temporarily reducing the rate of global thermosteric sea-level rise (*60*). While the impact of volcanic eruptions on global temperature is evident, their contribution to external TPDV is less clear (*61*, *62*). Volcanic eruptions have been suggested to (i) influence ENSO (*63*) and, by inference, TPDV, and (ii) to contribute to cooling the western Pacific warm pool on decadal scales (*64*). Models tend to simulate enhanced, long-term cooling in the eastern equatorial Pacific, but observations are still too sparse to adequately test these model results (*65*).

Confidence in the attribution of observed changes and future projections

Although GHG forcing generally dominates external TPDV at multi-decadal and longer timescales, anthropogenic aerosols and volcanic eruptions may have significantly contributed to regional tropical SST variations over recent decades (*61*, *62*). Relatively small decadal changes in top-of-atmosphere solar irradiance have presumably a smaller influence than GHG, although the 11-yr solar cycle, amplified by coupled atmosphere-ocean processes, has been proposed to modulate the Walker Circulation on decadal timescales (*66*). Timescales involved in internal and external TPDV overlap, which makes them difficult to distinguish from one another, especially when considering the relatively short climate record and potential errors in models. As a result, there are varying degrees of confidence in the attribution of some of the observed trends to either internal or external forcing.

In the following section, we discuss key aspects of future model projections in the tropical Pacific, comparing them with the observational record.

- ***Western Pacific warming***

The western Pacific exhibits a prominent warming trend since the 1950s (Fig. 1D; Fig. 5A), which dominates the evolution of SST in this region (Fig. 1B). This warming trend is accurately captured by historical simulations (compare Fig. 5A and Fig. 5B) and clearly stands out against the weak background natural variability in this region (Fig. 5C), reflecting the fact that the signal-to-noise ratio for this projected warming is among the highest in the world (*12*). Coral-based SST estimates indicate that such a warming period is likely unprecedented in the western Pacific region throughout the last 1,250 years (*67*). The warming trend for air temperatures over land in west Pacific island countries is so large that every year since the early 1990s has been warmer than all years prior to 1970 (*68*). The resulting increase of the western Pacific warm-pool size has confidently been attributed to GHG forcing arising from human activity (*68*, *69*) although remote influence from the natural multidecadal climate variability in the Atlantic (*70*) and major volcanic eruptions (*64*) may also have modulated the SST warming rate there.

- ***Hadley Cell***

While recent observational datasets significantly differ before the 1950’s, they consistently report a southward expansion of the southern edge of the Southern Hemisphere Hadley Cell since 1979 (Fig. 5D; (*71*)). Although internal climate variability also contributed, this widening over the last 40 years can confidently be attributed to the combined effect of ozone depletion and rising GHGs (Fig. 3B; Fig. 5D; (*71*)). The mechanism behind this widening is still subject to debate but likely reflects how subtropical atmospheric baroclinic eddies respond to tropospheric (GHGs) and stratospheric (ozone) changes in the atmospheric background state (*71*). This southward expansion is associated with a lower rate of warming (Fig. 5AB) and ocean acidification (*54*, *72*) in the southeastern tropical Pacific than in the rest of the tropics, probably driven by an intensification of the southeastern Pacific trade winds, which strengthen the Peru-Chile upwelling system near the coast, increase heat loss through air-sea fluxes and modulate the oceanic mixed layer offshore (68). Models also project a widening of the Northern Hemisphere Hadley Cell that is currently not yet detectable in observations due to a larger influence of internal climate variability (*71*, *73*).

- ***The Walker Circulation and equatorial SST gradients***

As illustrated in Fig. 5B, E and F, most state-of-the-art models project a weakening of the equatorial trade winds and Walker Circulation and a faster warming rate at the equator, in particular in the eastern equatorial Pacific (*55*). In agreement with instrumental observations and historical simulations (*51*, *74*) central tropical Pacific corals also point to a wet trend over the 20th century (Fig. 1D), accompanied by even wetter periods during positive phases of the Interdecadal Pacific Oscillation (*18*). A leading explanation for the Walker Circulation weakening is that rainfall increases less in models than predicted by the Clausius-Clapeyron relation, implying increased atmospheric stability and a reduced mass-flux between the boundary layer and free atmosphere, resulting in a weakened Walker Circulation (*75*). The enhanced equatorial eastern Pacific warming has been explained by a feedback loop between the weaker evaporative cooling in the cold tongue (*54*) and reduced trade winds, and a limitation of the SST increase by cloud feedbacks over the West Pacific (*55*). Recent studies also suggest that the subtropical anthropogenic warming also contributes to the enhanced equatorial warming by slowly making its way to the equatorial thermocline through the oceanic STCs (*76*, *77*). There is, however, no consensus to date on the dominant mechanism responsible for the projected equatorial Pacific SST gradient changes.

A key uncertainty of external TPDV is that simulated changes do not match recent observed historical trends over, e.g., 1981-2012 (*4*, *52*), which are characterized by a marked strengthening of the Walker Circulation over this period. Such signals are typical of internal TPDV (Fig. 4AB). Indeed, recent studies attribute a large part of this recent observed evolution in the central equatorial Pacific to internal TPDV (*4*, *52*, *78*), which is a strong contributor to SST variations in this region (Fig. 1C). This is illustrated by the relatively large model ensemble spread displayed in Figures 5 E and F, which largely encompass the observed SST and surface wind evolution.

On the other hand, many recent studies suggest plausible mechanisms by which external forcings might also have contributed to the recent strengthening. For example, model results indicate that the reduction in tropospheric sulfate aerosol emissions from North America and Europe and the concurrent increase in China - perhaps augmented by changes driven by volcanic eruptions (*62*, *79*) – might have contributed to the recent tropical Pacific cooling (*61*). Other modeling studies suggest that the observed faster warming in the Indian and/or Atlantic relative to the Pacific Ocean are conducive to enhanced trades in the Pacific and reinforced the recent tropical Pacific cooling (*46*). Increasing GHGs likely contributed to this observed Indian-Pacific differential warming, but their contribution to the enhanced Atlantic warming is unclear (*80*). Finally, some models reproduce the observed Walker Circulation strengthening and equatorial cooling (*81*), with a plausible mechanism related to the poleward export of the added equatorial Pacific heat by the sustained meridional divergence of the near-equatorial upper-ocean currents (*82*, *83*). Model-based studies further suggest that the fast equatorial cooling related to this oceanic thermostat mechanism will be followed by a slower transition to an enhanced equatorial warming and Walker Circulation weakening, in response to subtropical warm anomalies advected into the equatorial thermocline by the STCs (*76*, *77*).

It is thus unclear from current literature if the recent observed Walker Circulation and cold tongue strengthening is a response to external forcing that is only reproduced by a few models, or if it simply arises from internal variability hiding a subtle opposite secular trend (*78*). This results in a rather low confidence in the projected weakening of the Walker Circulation and related enhanced equatorial eastern Pacific warming in climate models. Several studies indeed argue that the enhanced equatorial warming in most climate projections may arise from common present-day climate model biases within the tropical Pacific (*84*) or from an underestimation of interbasin interactions (*45*, *46*, *84*). Confidence in these projections is further reduced by the large uncertainties on the impact of aerosols on radiation, cloud microphysics and SST (*85*). These caveats imply that it is currently not possible to conclude with confidence whether GHG forcing has weakened, strengthened, or had no effect on the Walker Circulation and equatorial upwelling.

- ***Changes in ENSO***

Improving the reliability of these projections is key, partly because projected changes in the equatorial zonal SST gradient strongly influence ENSO in climate models (*55*). The projected warming pattern in the equatorial Pacific in most climate models indeed increases ENSO-driven and decadal precipitation anomalies in part of the tropical Pacific (*51*, *55*, *74*), and is tied to an increase in the amplitude of ENSO anomalies (*55*). Recent paleo-climatic evidence suggests that the increase in ENSO variability since the 1950s stands out in the context of the past millennia (*86*), lending support to the inter-model agreement on increased ENSO-driven precipitation variability under greenhouse warming. These findings have significant implications, given the large societal impacts of projected changes in ENSO, and the fact that any increase in ENSO-driven precipitation variability (*51*) or the frequency of extreme ENSO states (*55*) may energize internal TPDV through the various forms of our null-hypothesis (*21*, *24*, *25*).

Outlook

Predicting the climate of the tropical Pacific over the next decade and beyond, including precipitation, temperature, sea-level, and biogeochemistry, would have far-reaching societal and environmental benefits. However, because of the partially chaotic nature of the climate system, decadal predictions can, at best, provide an outlook of annual to multi-year average conditions or risks, rather than a more detailed picture of daily or seasonal conditions (*2*). A decadal prediction would be typically expressed in terms of probabilities, such as the probability that temperature in the tropical Pacific averaged over the next five years will exceed the temperature in the tropical Pacific averaged over the past 30 years. While the changes in average conditions may be small, they can produce marked differences in the probability of extremes (*12*).

Experimental prediction systems have been developed (*2*, *14*) to exploit any predictability arising from the mechanisms discussed in the previous sections. Results from an ensemble prediction system suggests that initialisation with observations in much of the tropical Pacific tends to contribute towards predictive skill for surface temperature, for forecast lead times only up to approximately two years (Fig. 6A) and is mostly associated with predictability arising from ENSO (*87*), though another study concluded that trans-basin climate variability connected with TPDV can be predicted up to three years ahead (*46*). It might also be that climate models underestimate the degree of skill that actually exists in the real world (*88*). At longer lead times, skill arises mainly from external forcing (*2*, *89*) (Fig. 6A).

While predictive skill of decadal average SST is found in most of the tropical Pacific (*15*, *87*) (Fig. 6B), it is not evident everywhere. In particular, there is limited skill in the central tropical Pacific north of the equator, extending to the northeast Pacific (Fig. 6B). This is an important region because SST variability there can impact climate in many parts of the world. This low skill may be because the intrinsic predictability of internal variability beyond two years is genuinely low there and any predictable forced response is weak compared with unpredictable internal variability. Alternatively, the combined impact of internal variability and the externally-forced signal may be predictable but the models might miss or misrepresent key mechanisms underpinning the predictability. If this is the case, then the impact of TPDV on ENSO behaviour might also be currently underestimated.

A significant advancement identified in this review is that skill in decadal predictions of SST in the western Pacific is apparent in the last two generations of dynamical decadal prediction systems (*2*) (Fig. 6B). While it is likely that this primarily arises from anthropogenic warming, climate models also simulate substantial externally-forced decadal variability in this region about the long-term warming trend (Fig. 5C). This suggests that other types of external forcing have also contributed to TPDV in west Pacific SSTs. Whether this enhances predictability in West Pacific SSTs or not is still unclear.

There are indications that in the tropical Pacific, multi-year variability in some biogeochemical quantities important for fisheries and the global carbon budget such as net primary production and carbon dioxide uptake can be predicted with greater skill than SST (*90*, *91*). This may be because the biogeochemical quantities are more influenced by subsurface and spatially integrated quantities, which tend to exhibit greater predictability than does SST (*21*). Limited evidence also suggests that there may be some skill in predicting atmospheric sea-level pressure and sea-surface height (*92*), changes in the phase of the Interdecadal Pacific Oscillation (e.g.; (*93*, *94*), related precipitation averaged over the Asian-Australian monsoon, Australia more broadly, and western North America (*95*), and soil moisture – with implications for drought and wildfire – over parts of the southwestern U.S. (*6*).

In summary, our review of TPDV predictability finds that although responses to anthropogenic GHG increases offer predictability in some variables (e.g., Fig. 5C; Fig. 6A and B), confidence in the modeled response in the tropical Pacific is generally low; predictability from tropospheric aerosols is still debated; volcanic eruptions likely provide predictability immediately after the eruption has occurred (*63*); changes in anthropogenic aerosols (e.g., due to industrial growth and pollution aerosols) provide longer-timescale forcing; and TPDV arising from solar forcing likely exists but is small in models compared with other sources of external forcing and unlikely to be a significant source of predictability.

The Way Forward

This review has highlighted some important advances in our understanding of the tropical Pacific climate variability and change at decadal and longer timescales. It has also highlighted the complexity of the interactions between variations that occur naturally and those that are forced by external factors of both natural and anthropogenic origin, and the knowledge gaps and uncertainties associated with both components and their interactions. While several plausible mechanisms for both internal and externally-forced TPDV have been proposed, their relative importance and relevance to predictability needs to be further clarified. Specific open science questions include:

1. How important are oceanic processes involving the STCs in driving predictable decadal climate variations? Do the mechanisms involving STC variability and the associated wind forcing arise independently of ENSO? How large is the predictability associated with these oceanic processes?
2. How robust are climate model projections in the tropical Pacific and what are the dominant processes driving these changes? In particular, how will the Walker Circulation, equatorial SST and internal variability respond to future greenhouse gas increases?
3. Why do forecast systems appear to offer predictive skill in the western and southern tropical Pacific, but not in the north-eastern tropical Pacific?

Improvements in the quality, quantity, and length of observational records available for characterizing decadal variability are critical to address these science questions, and to initialize and verify decadal prediction systems. This will require sustaining and enhancing the ocean and climate observing systems, data rescue efforts to recover historical observations from data-sparse regions, and the development of new monthly- to annually-resolved paleoclimate records from

TPDV centers of action, with a focus on obtaining multiple records in those regions to enhance signal-to-noise ratios. Continued advances in paleoclimate data assimilation (*19*) will also be critical for the integration of paleoclimate and instrumental observations with models to obtain more complete and reliable fields.

While substantial model improvements have been made in recent decades for some features of the climate system (*10*), models are still limited in their ability to accurately represent observed TPDV and there are large model-to-model differences in the magnitude of simulated TPDV. As noted in the Introduction, there is evidence suggesting that there may be a link between these differences and model-to-model differences in global climate sensitivity. Improving the simulation of TPDV might therefore yield a narrower range in climate sensitivities and greater clarity on our climatic future.

Despite their shortcomings, climate models are essential tools for advancing our ability to understand and predict future change in the tropical Pacific. The underlying causes of the shortcomings are still elusive and dedicated efforts using novel approaches are required to identify the major sources of errors in both local and remote feedbacks. Enhanced efforts on the specific role of the STCs in driving TPDV in models may facilitate improved understanding of the mechanisms involving variability of the STCs and their associated wind forcing. In the longer term, improving climate models will be essential for achieving more realistic simulations, as well as more reliable predictions and projections, of TPDV. Advances are expected from improvements in: the representation of subgridscale processes; data assimilation into forecast systems; and computing technology enabling higher spatial resolution, less reliance on parameterizations, longer model runs, and larger ensemble sizes.

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Figure captions

Fig. 1. Observed decadal variability in the tropical Pacific. (A) 1992-2009 linear trend of annual SST (shading, 0.1°C decade^{-1}) and sea surface height (black contours, 2cm decade^{-1}, dashed contours indicate negative trends, solid contours denote positive trends, and the zero contour is omitted). **(B)** 8 yr lowpass and **(C)** 8-40 yr bandpass filtered SST variance (black contours, in 10^2 °C^2) and ratio of the filtered SST variance to total SST variance (shading). **(D)** 8 yr lowpass filtered timeseries of SST averaged over the Niño34 region (5°N-5°S; 170°W-120°W), the western tropical Pacific (10°N-10°S; 120°E-150°E) and over the globe from instrumental observations (black lines) and Last Millennium Reconstruction ((*19*); mean: grey line; interquartile range: light grey shading) and of δ^{18}O at Palmyra and Fiji islands (plain and dashed blue lines; positions indicated in **(A)**; (*17*, *18*)). Vertical red and blue bands indicate positive and negative phases of the Interdecadal Pacific Oscillation. SST data: HadISST (*96*). SSH data: ORAS4 dataset (*97*).

Fig. 2. Internal TPDV - the null hypothesis. (A) Pacific SST pattern associated with internal TPDV, obtained by regressing the 8-40 year band-pass filtered SST anomalies onto the internal TPDV index. The latter is obtained as the time series (or Principal Component) of the leading EOF of SST anomalies in the 8-40 year band, over the tropical Pacific (24°S-24°N; 120°E-80°W). **(B)** Timeseries of SST anomalies averaged in the Niño34 region (5°S-5°N, 170°W-120°W; N3.4), a commonly used SST ENSO index; the Southern Oscillation Index (SOI; (*18*)), a measure of the Walker Circulation strength; the internal TPDV index, and the E-L index, defined as the number

of El Niño years minus the number of La Niña years over 8-year running periods. ENSO events are identified using the December Niño3.4 index and an amplitude threshold of 1 standard deviation. Thick black lines in (B) indicate the 8-40year band-pass filtered time series. **(C)** Average of ENSO-related SST anomalies over the year preceding the peak of an El Niño event (year 0) and the year following the El Niño event (year 1), defined by computing lagged regressions of SST onto the November-December-January averaged N3.4 index from lags of -11mo to +12mo, and averaging over all 24 resulting maps. **(D)**, **(E)**, and **(F)** show individual SST maps from these monthly regressions, illustrating precursor anomalies during the February-March-April (FMA, D) prior to the peak of an event, peak anomalies during October-November-December (OND, E) of the ENSO event, and anomalies during the decay phase in June-July-August (JJA, F) of the years following the peak of an ENSO event. The SST data are from HadISST (*96*) over the period 1900-2020. Filtering was performed using 5 and 53 point Hanning filter weights.

Fig. 3. Mechanisms of internal and external TPDV. **(A)** Schematic representation of the ocean processes associated with internal TPDV. The climatological upper ocean overturning circulation (the Subtropical-Tropical Cells, transparent blue arrows) consists of a subtropical subduction component, equatorward subsurface transport, equatorial upwelling, and a poleward surface return flow driven by the equatorial easterly trade winds (large blue arrow), which are the surface component of the Walker Circulation. A positive phase of internal TPDV with warm SST in the tropical Pacific (shading) is associated with a weaker Walker Circulation, reduced equatorial winds, and weaker oceanic overturning circulation. Extra-equatorial wind anomalies may play an important role in driving the changes in the Subtropical-Tropical Cells, whose adjustment is

accomplished through the westward propagation of oceanic Rossby waves. After reaching the western boundary, Rossby waves can continue along the boundary to the equator as coastal Kelvin waves and along the equator as equatorial Kelvin waves. The extra-equatorial wind anomalies may be purely stochastic, arise from extra-tropical influences, or as a response to equatorial SST anomalies (see text for details). **(B)** Schematic representation of projected changes associated with external TPDV. The map shows the late 21st century multi-model-mean change in CMIP6 SST, which is dominated by increases in greenhouse gases. High (low) confidence in these projected changes is indicated by solid (dashed) lines. Icons indicate the major external forcings involved in these changes. Greenhouse gas increases and ozone changes induce a robust southward expansion of the Hadley Cell in the southern hemisphere and reduced southern subtropical Pacific warming, in both model projections and observations. The prominent western Pacific warming and the central Pacific rainfall increase detected in models and observations can confidently be attributed greenhouse gas increases. While the projected weakening and enhanced tropical warming is evident in most CMIP6 models, confidence in these projections is low because of inconsistent signals in observations, model biases and the complexity of the mechanisms involved. Volcanic eruptions and changes in solar insolation may also cause decadal variations in the tropical Pacific, though their amplitude is likely small.

Fig. 4. Evaluation of internal TPDV in CMIP models. Maps of the 1st EOF of 8-40yrs bandpass filtered SST over the tropical Pacific (shading), and associated sea-level (contours) and 2m wind (vectors) variability for **(A)** observations (*96*, *98*, *99*) and **(B)** a multi-model mean of (*10*). Box plot showing median, interquartile range, maximum and minimum of CMIP6 historical simulations for (**C**) the standard deviation of the TPDV index, and (**D**) the correlation coefficients

between E-L and the internal TPDV index. E-L is a measure of the extent to which El Niño dominates each 8-yr period and is defined as n(EN) - n(LN), where n(EN)= the number of El Niño years and n(LN)=the number of La Niña years in eight-year blocks. ENSO events are defined using a threshold of 1 STD of Nino3.4 SST. The TPDV index is defined here as the first principal component of the 8-40yrs bandpass filtered SST EOF analysis. Observations are shown as a red star.

Fig. 5. Detection and attribution of long-term trends in the tropical Pacific. (A) Observed (*96*, *98*, *99*) and **(B)** multi-model mean (*10*) maps of 1900-2009 linear trends of SST (shading) and surface winds (vectors) over the Tropical Pacific. Annual time series for CMIP6 historical simulations (grey) and observations (colored) of the SST averaged over **(C)** over the Niño34 region (5°N-5°S; 170°W-120°W) and **(E)** the western tropical Pacific (10°N-10°S; 120°E-150°E), the latitude of southern hemisphere Hadley Cell's poleward edge **(D)** and the strength of equatorial zonal (east-west) winds (**F**). The latitude of southern hemisphere Hadley Cell's poleward edge the latitudinal anomalies of the latitude where zonal mean precipitation-evaporation is zero while the strength of equatorial zonal (east-west) winds is diagnosed from the 10 m zonal wind anomalies in the Niño3.4 region (positive values indicate a weakening Walker Circulation). CMIP6 results: ensemble mean (black lines); 60% (dark blue shading) and 90% (light blue shading) confidence intervals using a t-distribution. Reanalysis: NOAA-20C (red) (*99*) and ERA-20C (blue) (*100*); red lines: annual anomalies (thin lines); and 8-yr running averages (thick lines). SST data: HadISST (*96*). Notice how the spread of model simulations is larger in the Niño3.4 region than in the western Pacific. The Hadley Cell is calculated over all longitudes, not just the Pacific.

Fig. 6. Predicting TPDV. (A) Actual (solid lines) and potential (dashed lines) correlation skill for the surface air temperature averaged over the tropical Pacific as a function of lead time, for initialized forecasts (red) and for uninitialized simulations (blue), estimated using methods described previously (*15*). The difference between the initialized and uninitialized simulations is an indication of the potential for forecast improvement (*15*). **(B)** Correlation skill score using 8-year running mean observations of near-surface air temperature and forecast years 2-9 from initialised multi-model decadal predictions. Skill is measured using the mean of 71 ensemble members from seven modelling systems (*89*). Darker red indicates higher estimated skill. Hindcasts (*2*) starting every year from 1960 to 2005, with observations described previously (*89*). Stippling: outside 95% confidence interval.