Mechanisms of Tropical Pacific Decadal Variability

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Abstract

Naturally-occurring tropical Pacific variations at timescales of 7-70 years—Tropical Pacific Decadal Variability (TPDV)—describe basin-scale sea surface temperature (SST), sea level pressure and heat content anomalies. Several mechanisms are proposed to explain TPDV, which can originate through oceanic processes, atmospheric processes, or as an ENSO residual. In this Review, we synthesise knowledge of these mechanisms, their characteristics and contribution to TPDV. Oceanic processes include off-equatorial Rossby waves, which mediate oceanic adjustment and contribute to variations in equatorial thermocline depth and SST; variations in the strength of the shallow upper-ocean overturning circulation, which exhibit a large anti-correlation with equatorial Pacific SST at interannual and decadal timescales; and the propagation of salinity-compensated temperature ("spiciness") anomalies from the subtropics to the equatorial thermocline. Atmospheric processes include midlatitude internal variability inducing (sub)tropical wind anomalies, which result in equatorial SST anomalies, and in atmospheric feedbacks that enhance persistence; and atmospheric teleconnections from Atlantic and Indian Ocean SST variability, which induce winds conducive to decadal anomalies of the opposite sign in the Pacific. Although uncertain, the tropical adjustment through Rossby wave activity is likely a dominant mechanism. A deeper understanding of the origin and spectral characteristics of TPDV-related winds is a key priority.

Key points

- Tropical Pacific decadal variations are linked to basin-scale sea surface temperature and sea level pressure anomalies, and are associated with a zonal reorganization of tropical Pacific heat content.
- Salinity-compensated temperature anomalies ("spiciness anomalies") can reach the equatorial thermocline, but their amplitude appears small and their influence on equatorial sea surface temperatures remains uncertain.
- Variability of the Pacific upper-ocean overturning circulation exhibits a large anti-correlation with equatorial Pacific SSTs at both interannual and decadal timescales, suggesting that similar mechanisms are operating at both timescales.
- Internally generated subtropical/tropical wind anomalies can create equatorial SST anomalies, which in turn can reinforce the wind anomalies locally and through atmospheric teleconnections to increase their persistence.
- Decadal SST anomalies in the Atlantic and Indian Oceans can induce wind anomalies in the tropical Pacific conducive to the formation of decadal SST anomalies of the opposite sign.

Introduction

The tropical Pacific exhibits variability over a broad range of timescales from seasonal to centennial. While the El Niño Southern Oscillation (ENSO) is the dominant mode of variability at interannual timescales (about 2-7 years), "natural" variations arising from processes internal to the climate system are also observed in the "decadal" range, namely at timescales longer than the ENSO timescales, but shorter than the centennial trend resulting from anthropogenic forcing. Internal variations at periods longer than 7 years can occur at both quasi-decadal and multi-decadal timescales[1], and hence we define Tropical Pacific Decadal Variability (TPDV) as variability in the 7-70 years range.

TPDV is the tropical expression of large-scale patterns of variability like the Pacific Decadal Oscillation (PDO)[2] in the North Pacific, and the Interdecadal Pacific Oscillation (IPO)[3] over the entire Pacific basin. The positive phase of TPDV is characterized by warm SSTAs in the tropical Pacific, and along the western coasts of the Americas, and by negative anomalies in the central/western midlatitudes of both hemispheres, while the negative TPDV phase exhibits SSTAs of the opposite sign.

Such TPDV could just result as a residual of interannual ENSO variability[4], but various oceanic and atmospheric processes could also produce variability at decadal timescales, with important implications for the potential predictability of TPDV. Since the equatorial Pacific is connected to the subtropics through an oceanic pathway (Box 1), temperature anomalies created in the subtropics can reach the equatorial pycnocline and be brought to the surface by equatorial upwelling, a mechanism known as the "$\bar{v}T'$ hypothesis", with $\bar{v}$ indicating the time mean circulation and T' the temperature anomaly. Alternatively, changes in the ocean circulation could result in equatorial SSTAs through changes in equatorial upwelling (Box 1), a mechanism termed the "$v'\bar{T}$ hypothesis". These oceanic changes are part of a slow oceanic adjustment to atmospheric variability, which is mediated by oceanic wave activity occurring at decadal timescales. Atmospheric processes include influences from the extratropical Pacific, atmospheric response to equatorial SSTAs, and interactions with the Atlantic and Indian Oceans. However, no consensus exists on the effectiveness and relative importance of these processes.

TPDV modulates ENSO characteristics[5,6] and some of its global impacts[4,7,8], and has been linked to the rate of change of the globally-averaged surface temperature[9,10]. Thus, the ability to predict the occurrence of different decadal epochs in the tropical Pacific has important societal implications, which has motivated the development of major decadal prediction efforts in several centres around the world. However, TPDV predictability remains elusive, hence the need to better understand its underlying mechanisms. A better understanding of TPDV is also needed to more robustly separate the forced climate response from internally-generated climate variability and to achieve more reliable future projections of tropical Pacific climate, which has implications for the global climate[9]. Some climate models used for both predictions and projections appear to underestimate internally-generated decadal variations[11-13]. Although this conclusion may be severely hampered by the relatively short duration of the observational record, as indicated by paleoclimate data (Box 2), an assessment of model fidelity in realistically reproducing the relevant mechanisms of decadal variability is essential.

In this Review, we critically synthesise the current state-of-knowledge of the mechanisms proposed for TPDV, based on observations, ocean reanalyses, dynamical models, and paleoclimate evidence. Relative to other reviews on this topic[4], which have considered both internal and anthropogenically-forced low-frequency variability, this synthesis focuses on *internal* decadal variations in order to allow for in-depth developments of the key concepts. We will describe salient features of TPDV in the context of the decadal phase transition that occurred in the late 1990s, followed by a description of the leading oceanic and atmospheric processes relevant for TPDV. We end with recommendations for future research and some hypotheses on how TPDV may change in a warmer world.

Observed tropical Pacific decadal changes

Before reviewing the mechanisms proposed to explain TPDV, it is important to identify the key oceanic and atmospheric changes accompanying decadal phase transitions. To illustrate such changes, we consider the dramatic shift to colder equatorial SSTs that occurred during 1999-2014 relative to 1984-1999, concurrent with phase transitions of both the PDO and IPO. The spatial structure of these SST changes (Fig. 1a, shading) is characterized by cold conditions in the equatorial Pacific, and warm anomalies in the central/western midlatitudes. This pattern is similar to that obtained through a statistical definition of TPDV, as the leading EOF of 7-70 years band-pass filtered SSTAs in the tropical Pacific (25°S-25°N). The basin-wide TPDV pattern is then determined through linear regression of SSTAs on the associated principal component--the TPDV index (Fig. 1a, contours). The decadal SST pattern in the tropical Pacific is "ENSO-like", but with a broader meridional extent and with the largest equatorial variability shifted further west than the interannual ENSO variance[4,14]. The large-scale SST changes from 1984-1999 to 1999-2014 are accompanied by sea level pressure anomalies in the extra-tropics of both hemispheres (Fig. 1b), and by wind anomalies that include an enhancement of the easterly trade winds in the tropics.

This trade wind intensification has led to changes in the ocean density structure and circulation[15,16], resulting in a reorganization of the tropical Pacific heat content[11,17]. Such reorganization is captured by the changes in SSH (Fig. 1c), a quantity dynamically linked to upper ocean heat content and thermocline depth. Positive SSH differences (higher heat content, deeper thermocline) occur in the western tropical Pacific, with maxima located off the equator, while negative SSH differences (reduced heat content, shallower thermocline) are found in the central and eastern part of the basin. These SSH differences are consistent with the SSH signature of TPDV (Fig. 1c, contours), and are also consistent with typical SSH decadal patterns[1]. Increased heat content is seen in the western tropical Pacific at the depth of the thermocline (Fig. 1e), and is primarily associated with westward-propagating Rossby waves[18], while decreased heat content is found in the upper ocean east of the dateline (Fig. 1f). Oceanic changes during negative-to-positive decadal transitions largely mirror the surface and subsurface changes shown here[18,19]. Positive SSH anomalies are also present in the Indonesian Seas and eastern Indian Ocean (Box 1), suggesting a transfer of heat from the Pacific to the Indian Ocean in conjunction with negative TPDV phases[20,21]. Indeed, the Indian Ocean heat content exhibits a decadal modulation that is in phase with Pacific decadal variations, likely associated with changes in the western Pacific winds and their influence on the transport of the Indonesian Throughflow (ITF, Box1)[22-24].

The decadal transition after 1999 occurred in the presence of tropical trends[11] (Fig. 1b), which are particularly pronounced in the SSH field[25-27] (Fig. 1c, d). This SSH trend seems to have accelerated since 2000[21], and is particularly evident in the western Pacific, Indonesian Seas and eastern Indian Ocean (Fig. 1d), as a result of the tropical easterly surface trade wind intensification. This wind intensification and the zonal SSH gradient are not captured by state-of-the-art climate models, introducing a large uncertainty in the attribution of the trend to either internal low-frequency variability or to climate change[24,28-30]. This ambiguity highlights the importance of a deepened understanding of internal low-frequency variability for robustly separating the two components.

To that end, we now revisit the leading mechanisms proposed for TPDV. We first discuss the possibility that TPDV arises as a residual of interannual ENSO variations, and then consider mechanisms involving oceanic and atmospheric processes, including the $\bar{v}T'$ and the $v'\bar{T}$

hypotheses, as well as the atmospheric influences from the extra-tropics and from the Atlantic and Pacific Oceans. The pattern of TPDV that emerges from a statistical EOF approach (Fig. 1a, contours) of anomalies spanning a broad range of timescales (7-70 years) does not presume that a single set of dynamically-related physical processes is responsible for it, as demonstrated for the PDO, which results from the combination of different dynamical modes with different timescales[31]. The purpose of this paper is to elucidate the nature and relative importance of these processes.

TPDV as an ENSO residual

Since the tropical Pacific climate is dominated by interannual ENSO variations, a plausible hypothesis is that TPDV arises as a residual of ENSO. Indeed, the "ENSO-like"[14] spatial pattern of TPDV can be reconstructed from decadal averages of evolving ENSO patterns, from their developing to decaying phases, and random event-to-event variations of those patterns[4,32]. In addition, uneven numbers of warm (El Niño) or cold (La Niña) events, can randomly occur during different decadal epochs (Fig. 2a), resulting in El Niño-like, or La Niña-like decadal conditions because of the differences in amplitude and spatial asymmetry of ENSO events. Also, uneven numbers of events with largest anomalies centered either in the Eastern (EP) or Central (CP) Pacific[33] (Fig. 2a) can contribute to low-frequency background changes[34]. Similar to the influence of stochastic sub-seasonal disturbances on the development of El Niño[35,36], ENSO events could also act as triggers for TPDV phase transitions, either through changes of off-equatorial winds responsible for discharging the heat content anomalies in the western Pacific[37], or through low-frequency equatorial Pacific changes induced by nonlinear dynamical heating[38]. Off-equatorial western Pacific heat content anomalies (Fig. 1c) are a necessary condition for an ENSO event to trigger a TPDV transition[37,39].

The interpretation of TPDV as an ENSO residual also involves subsurface anomalies. Western Pacific heat content exhibits a decadal modulation, with a reduced heat content during periods of positive TPDV (prevailing negative anomalies during 1976-1999 in Fig. 2c, when the TPDV index in Fig. 2d is predominantly positive) and *vice versa* (prevailing positive anomalies during 1999-2014 in Fig. 2b, associated with a predominantly negative TPDV). These low-frequency variations are punctuated by the heat content changes associated with the recharge-discharge activity of individual ENSO events (Fig. 2b), which are the dominant signal in the eastern part of the basin (Fig. 2c). The decadal modulation of tropical Pacific heat content could thus be interpreted as the low-frequency envelope of interannual ENSO variations.

However, ENSO characteristics also depend upon the mean state[40,41]. The warm phase of TPDV, characterized by weaker trade winds and a deeper thermocline in the eastern equatorial Pacific, favours more frequent and stronger El Niño events of EP-type, as seen during 1976-1999 (Fig. 2a, warm anomalies extending to the far-eastern part of the basin), while negative TPDV phases, like the 1999-2014 period, are characterized by weaker El Niño events with peak anomalies in the central Pacific (Fig. 2a). Dynamical model sensitivity experiments have indeed highlighted the impact of the initial background conditions on ENSO evolution and predictive skill[42,43]. The decadal modulation of ENSO, as captured in climate models by the second EOF of decadal SSTAs[5,44,45] is significantly lag-correlated with TPDV[45], with a large inter-model dependence[44]. ENSO decadal modulation appears to lead the opposite phase of TPDV by about two years, suggesting its possible role as precursor of TPDV phase transitions[45]. However, TPDV also leads the same phase of ENSO decadal modulation by two years with a higher correlation[45], indicating that ENSO modulation by TPDV may be more prominent than the influence of ENSO activity on TPDV.

The $\bar{v}\,T'$ hypothesis and wave processes

The $\bar{v}\,T'$ hypothesis considers the effect of equatorward advection of temperature anomalies within the pycnocline as a driver of TPDV (Fig. 3a). This mechanism was originally proposed for anomalies that leave the surface mixed layer to enter the subsurface ocean in the northern mid-latitudes[46], and are advected by the mean circulation (the northern subsurface branches of the STC, Box1) toward the equator, where they are upwelled to the surface, altering SSTs and leading to a change of the TPDV phase. However, observational and modelling results based on temperature observations only showed that these anomalies decayed prior to reaching the equator[47], casting doubt on the feasibility of this mechanism. Further works suggested that the South Pacific could be more suitable for the $\bar{v}\,T'$ mechanism[48-50], due to its larger and more direct equatorward transport[51-54], Indeed, the presence of the Intertropical Convergence Zone (ITCZ) in the tropical North Pacific alters the depth of the pycnocline and creates a "potential vorticity barrier"[54] that limits the interior equatorward flow[54,55] (Fig. 3).

Moreover, a more careful examination of the mechanisms by which subtropical signals reach the equator highlighted two different types of mechanisms: spiciness anomalies advected as passive tracer by the mean circulation, and non-compensated temperature anomalies propagating as planetary waves.

Advection of spiciness anomalies

Ocean density increases with decreasing temperature and increasing salinity. Temperature anomalies with a density compensating salinity signal ("spiciness anomalies"[56]), do not affect density and can propagate along isopycnals as a passive tracer[57] (Fig. 3a). These warm-salty or cold-fresh anomalies appear to be predominantly generated in the eastern subtropics of the Pacific basin[58,59] through either shifts in spiciness gradients induced by wind-forced anomalous ocean currents[57], or through buoyancy-forced penetrative mixing[59]. At large spatial scales, theoretical arguments suggest that pycnocline advection may result in a frequency spectrum of spiciness anomalies reaching the equator that has enhanced power in the decadal range[60]. Based on fully coupled model experiments[57,61] a mechanism for TPDV was proposed, in which spiciness anomalies generated in the off-equatorial regions by changes in the tropical trade winds are advected toward the equator, where they are upwelled to the surface, rearrange equatorial sea surface temperatures, winds and the slope of the pycnocline (Box 1)[61], and induce off-equatorial atmospheric forcing of spiciness anomalies of the opposite sign, resulting in a 10-year cycle.

Spiciness generation and pathways from the eastern subtropics towards the western tropical Pacific are supported by observations[62-67]. Observations also show that spiciness anomalies undergo some decay during their propagation to the tropical region[65,67,68]. However, whether these anomalies are advected all the way to the equator and reach the surface at the equator is much less clear. The complexity of the LLWBCs and the high level of mixing and water mass transformation occurring in some parts of these swift currents[69] cast doubt on the feasibility of a western boundary pathway. Modelling results using a Lagrangian approach however suggest that spiciness anomalies can reach the eastern equatorial band[55], with a clear dominance of southern hemisphere pathways. A heat budget analysis of the modelled equatorial Pacific mixed layer reveals a potential influence of spiciness anomalies on TPDV[68], yet with a small magnitude, leaving the efficiency of this mechanism unclear.

Wave propagation of non-compensated temperature anomalies

Oceanic Rossby waves cause isopycnal displacements that appear as temperature anomalies over time-mean isopycnal surfaces. Rossby wave activity has been related to decadal subsurface temperature anomalies in the tropical Pacific with maxima around 10°-15°N and 10°-14°S[18,48,49,70-72] (Fig. 2c). These anomalies can reach the equatorial thermocline via the western boundary and propagate eastward along the equator as equatorial Kelvin waves altering equatorial SSTs. However, the origin of the decadal timescale remains unclear since the Rossby wave transit time at the latitudes of the Rossby wave maxima is only 2-3 years. One hypothesis is that the latitudes of the Rossby wave maxima coincide with areas of high zonal coherence of the wind forcing, which may be more efficient in exciting larger amplitude waves at decadal timescales[71]. In addition, these latitudes coincide with the equatorward boundaries of the subtropical gyres, where instability processes may energize planetary waves originating in the eastern midlatitudes of both hemispheres with longer transit times in the decadal range[72]. Finally, equatorial signals have a slow eastward propagation due to the coupling of the oceanic waves with the local winds[48]. More generally, decadal timescales cannot be expected to coincide with the transit time of one single wave, but result from the collective effect of multiple waves generated over relatively broad latitude bands at different times, which may lead to a longer adjustment timescale.

Coupled climate model experiments suggest that a mix of both advection and planetary wave activity contributes to the equatorward propagation of temperature anomalies with a potentially larger impact of anomalies from the Southern Hemisphere[49,50]. CGCM sensitivity experiments, where oceanic temperature and salinity anomalies were blocked from reaching the equator in both hemispheres, indicated that the southern $\bar{v}\,T'$ process acts as a delayed negative feedback for bi-decadal (12-25yr) variability, whereas oceanic wave adjustment has a dominant influence in the decadal range (9-12yr)[50]. The role of decadal anomalies from the South Pacific was further illustrated by their influence on the evolution of El Niño events during the first decade of the 2000s, as noted in decadal prediction experiments[73]. Cold anomalies in the southwestern tropical Pacific related to the negative TPDV phase during 1999-2014 may have impacted the development of El Niño events[73], possibly leading to the unexpected termination of El Niño in 2014[74].

The $\mathbf{v'\overline{T}}$ hypothesis

Changes in the strength of the STCs' transport (Fig. 3b) can affect equatorial upwelling and equatorial SSTs. Specifically, an increase in the STCs' equatorward mass transport will induce enhanced equatorial upwelling, bringing colder pycnocline waters closer to the surface and cooling the equatorial SSTs, while reduced STC transport will result in warmer SSTs[75]. Originally illustrated in the context of simple models[75-78], this hypothesis has also been extensively tested in observations[19,79], ocean general circulation models[80-83] and ocean reanalyses[18,84]. The pycnocline flow, zonally averaged east of the LLWBCs ("interior transport" hereafter)[19] is used as a measure of the STCs' strength. Since 9°N is a choke point for the equatorward flow (Fig. 3b), this latitude has been chosen to estimate the interior transport in the Northern Hemisphere, and 9°S is used in the Southern Hemisphere for equatorial symmetry[19]. Observational estimates of the interior transports at these two latitudes over the second half of the 20th century show a decline of the equatorward subsurface mass convergence after the mid-seventies, which was concurrent with the tropical Pacific warming associated with the "1976-77 climate shift"[2,19](Fig. 4a, b).

Due to the sparsity of subsurface observations, [19] binned the data over multi-year periods to obtain transport estimates (Fig. 4a, b). Ocean reanalyses and ocean models forced by observationally-constrained surface fields allowed transport estimates at a higher time resolution and confirmed that increased interior equatorward mass convergence is associated with colder equatorial SSTs, and *vice versa* (Fig. 4c, d), with high correlations at both interannual and decadal timescales[18,80,84] (Fig. 5c, d). Changes in interior transport at interannual timescales encapsulate the recharge/discharge of the equatorial upper-ocean heat content, underpinning ENSO evolution[85]. The relationship between transport convergence and SST anomalies at decadal timescales suggests that similar underlying dynamics may be at play also at lower frequencies[86].

Many climate models also show correlations between transport convergence and SST anomalies that are comparable with those obtained from ocean reanalyses (Fig. 4e), although some models exhibit much weaker relationships[87,88]. In addition, the transport variability is generally weaker in the models than in observations for the same SST variability (Fig. 4f)[87,88], suggesting a higher sensitivity of modelled SSTs to STC variability.

The total equatorward pycnocline transport includes both the interior transport and the transport of the LLWBCs. LLWBCs' transport anomalies are of the opposite sign to the interior transport anomalies in both models and observational estimates[80,89-91], leading to a partial compensation of the interior mass convergence. The sign of the boundary transport anomalies has been related to the development of anomalous gyre circulations in the western tropical Pacific, as implied by the SSH anomalies in Fig. 1c for the negative TPDV phase, with a clockwise (anticlockwise) circulation in the Northern (Southern) Hemisphere[15,18,79]. Given the complexity of the LLWBCs, and the sparsity of in situ observations in these regions, it is unclear whether numerical models can realistically simulate these currents and what fraction of their anomalous transport recirculates in the western Pacific, exits the Pacific through the ITF or acts to alter the equatorial mass balance.

The strength of the ITF can also contribute to the mass and heat balance of the equatorial Pacific[92], as seen in the case of the two extreme El Niño events of 1997/98 and 2015/16, whose difference in ocean heat discharge was controlled by different strengths of the ITF[93,94]. On interannual timescales, variations in the ITF strength are related to the SSH difference between the western Pacific and eastern Indian Ocean, as well as buoyancy forcing[24,95]. They likely also respond to slow changes in the large-scale SSH and salinity fields, leading to decadal-scale anomalous heat exchanges between the two basins[21,96], and suggesting a potential oceanic pathway for the Indian Ocean influence on TPDV.

The location of the winds that are most influential on the STC decadal variations is key to understanding their role in TPDV. The seminal results obtained with simplified ocean models[75,78] suggested that wind variations in the subtropical regions could control the STC transport and remotely affect equatorial SSTs. However, meridional transport changes at each latitude appear to be established by westward-propagating oceanic Rossby waves, as part of the tropical adjustment to varying winds, and be largely controlled by the local wind forcing[18], although influences from the 15°-20° latitude band may also play a role at decadal timescales[83,97-99]. The possible origin and nature of these winds are discussed in the following sections.

Influences from Pacific extratropical atmospheric forcing

Modes of internal atmospheric variability, such as the North Pacific Oscillation (NPO)[100] in the Northern Hemisphere and the South Pacific Oscillation (SPO)[101] in the Southern Hemisphere, extend toward the tropics, and can influence the tropical Pacific climate by changing the patterns of surface winds[102,103]. Subtropical/ tropical wind anomalies in the central-eastern Pacific alter the off-equatorial turbulent heat fluxes, resulting in SST anomalies that can persist for several months through the Wind-Evaporation-SST feedback[104] to impact equatorial dynamics. These SST patterns are known as the North and South Pacific Meridional Modes (NPMM and SPMM, respectively)[105,106]. The NPMM extends southwestward from the coast of California to the central equatorial Pacific[106] (Fig. 6a), while the SPMM exhibits SST anomalies along the South American coast, elongating toward the equator[105] (Fig. 6b). The processes by which the NPMM and SPMM can impact equatorial dynamics are clearer for the NPMM. They include the excitation of Summer deep convection near the ITCZ, which can result in equatorial wind anomalies[107], and heat recharge/discharge in the equatorial pycnocline through meridional flows induced by NPMM-related wind stress curl anomalies, a process known as Tropical Wind Charging[108]. Both processes can affect ENSO development, but the Tropical Wind Charging mechanism appears to be the dominant player[109,110].

While the Meridional Modes are well-known ENSO precursors[103,105,107,111,112], they are also involved in the development of TPDV. This was first shown with atmospheric models coupled to slab ocean models, namely ocean models that provide ocean memory, but lack ocean dynamics[113,114]. In these "Atm-Slab" models, frequency spectrum reddening of weather and climate variability at decadal timescales appeared to occur through a sequence of extratropical-to-tropical influences (ENSO precursors to ENSO development) and tropical-to-extratropical feedbacks (ENSO teleconnections)[113] – a series of links supported by observational analyses[115]. Indeed, model experiments[116] indicate that ENSO teleconnections from the central equatorial Pacific can reinforce the NPMM and increase its persistence, resulting in the decadal NPMM variations detected in century-long coral time series from the northeastern subtropical Pacific[117].

TPDV anomalies obtained in Atm-Slab models are weaker and centred further south than those obtained in fully coupled climate models and observations, highlighting the effect of oceanic processes[45,114]. Additionally, the tropical wind anomalies associated with the Meridional Modes can induce meridional pycnocline flow, as illustrated by the Tropical Wind Charging mechanism, and could therefore provide the atmospheric forcing needed to alter the strength of the STCs and produce equatorial SST anomalies, as previously discussed. Sensitivity experiments with simple dynamical models also indicate that extratropical stochastic wind forcing can produce low-frequency changes in the equatorial thermocline and multi-year ENSO variations[118].

Since internal atmospheric variability typically peaks during the winter season in each hemisphere, they can independently influence the tropical Pacific. Some model results indicate a dominant influence of the Southern Hemisphere[114,119-121]. For example, a coupled model where the NPMM and SPMM were selectively disabled showed that the absence of the NPMM primarily impacted ENSO variability, while the SPMM significantly altered TPDV[119]. The prescription of heat fluxes typical of South Pacific Oscillation and North Pacific Oscillation forcing in century-long coupled model sensitivity experiments indicated a larger influence of the Southern Hemisphere on equatorial ocean dynamics responsible for TPDV[121]. Also, idealized coupled model experiments in which oceanic variability was nudged to climatological values in the 30ºS-10ºS latitude band caused a ~30% reduction in decadal-scale SST variability in the equatorial Pacific[120]. The potential importance of the South Pacific influence has also emerged in an observational and modelling study[122], which showed the important influence of South Pacific internal atmospheric variability on ENSO and Pacific decadal variability.

On the other hand, a mode of variability linking the North Pacific with the Central Equatorial Pacific via the NPMM (and thus termed NP-CP mode) at decadal timescales has been recently identified in observations and ocean reanalyses[31,38,123,124] as a source of tropical Pacific decadal variance. This mode involves SST anomalies typical of the NPMM, and includes a SSH component with a pattern similar to that typical of decadal differences[123] (Fig. 1c), implying an important role for ocean dynamical processes.

Thus, both hemispheres can potentially provide the atmospheric forcing for TPDV, but the question of which hemisphere dominates remains outstanding. The discrepancy between model- and observationally-based results regarding the influence of the North Pacific on TPDV likely reflects model deficiencies in capturing the North Pacific – Tropics interactions[125], an aspect that warrants further investigation.

Winds of Tropical Origin

Anomalous off-equatorial winds can also arise as a response to decadal SST anomalies[116]. Numerical simulations using an Atm-Slab model showed that SST anomalies prescribed in the central equatorial Pacific, where decadal anomalies are more prominent, can excite atmospheric Rossby waves, whose subtropical component may weaken the subtropical trade winds in both hemispheres[116] (Fig. 5a,b). Coupled climate model experiments with prescribed equatorial SST anomalies[126] yielded similar results. The equatorially-forced subtropical wind anomalies can then be expected to reinforce the equatorial anomaly through both thermodynamical processes, like Summer deep convection[107], or changes in equatorward mass transport induced by the anomalous winds[18], and create a feedback loop between equatorial and off-equatorial regions that can redden the spectra and contribute to the meridionally broader SST anomaly pattern found at decadal timescales[4,14].

Low-frequency equatorial SST anomalies can also alter the Walker and Hadley circulations. In particular, coupled model simulations with prescribed idealized warming along the Pacific equator, mimicking climate change conditions, show an intensification of the ascending branch of the Hadley circulation, and an enhancement of the off-equatorial trade winds. The ocean adjustment to these wind changes involves the spin-up of the STCs, leading to a cooling of the equatorial Pacific at some later time[127]. Changes in the strength of the Hadley Cells in response to equatorial decadal SST anomalies were also detected in other numerical simulations investigating the nature of Pacific decadal variability. These numerical experiments, conducted with different modelling frameworks, demonstrated that an anomalously warm tropical Pacific produces an increased poleward atmospheric energy transport[128,129], and changes in off-equatorial Ekman pumping. The resulting ocean circulation adjustment leads to variations in STCs' strength and provides a delayed negative feedback to the original equatorial SST anomalies[99,129]. The opposite is found for cold decadal conditions in the tropical Pacific. These results suggest the possibility of a feedback loop between equatorial SST anomalies and off-equatorial wind variations which would support the view of TPDV as a tropical-extratropical coupled cyclic mode of variability. However, the ability to robustly detect these links in the relatively short observational record, given the presence of a large level of atmospheric noise remains a challenging scientific task that needs to be further explored in the future.

Influences from other oceans

Outside all mechanisms internal to the Pacific basin that can influence TPDV, it has now been recognized that the Indian and Atlantic Oceans have the potential to generate variability in the Pacific[130]. Decadal SST variability in the Atlantic and Indian Oceans can generate inter-basin connections via changes in both atmospheric and oceanic circulations. The Indian to Pacific connections involve transport in the ITF (as previously discussed), while the ocean connection between the Atlantic and Pacific is considered small[131]. We thus focus on the atmospheric connections here.

Consider an SST anomaly in either the tropical Atlantic or Indian Ocean. The atmosphere responds with overlying anomalous atmospheric convection and diabatic heating, with accompanying near-surface zonal wind convergence into the convective region and a zonal wind divergence aloft (Fig. 5c, d). The diabatic heating generates an eastward-propagating equatorial Kelvin wave, and westward-propagating Rossby waves to the north and south of the heat source, inducing a descending motion throughout the rest of the tropics that is typically strongest where the Kelvin and Rossby waves meet (Fig, 5c, d). This so-called "Gill-type response"[132] alters the global Walker circulation on different timescales, from intra-seasonal through multidecadal[133-140]. These planetary waves act to spread the diabatically-generated tropospheric temperature anomaly through the entire tropics, a process commonly referred to as the "weak temperature gradient approximation"[141,142]. The resulting temperature changes away from the original heat source act to increase the vertical stability of the troposphere and reduce rainfall, a process known as the "tropospheric temperature mechanism"[143]. The two latter mechanisms provide thermodynamic explanations for the global Walker circulation changes (Fig. 5c, d). Alternate Atlantic to Pacific pathways have also been proposed to occur via the mid-latitudes along a curved pathway through the North Pacific to the western equatorial Pacific[144,145]; or through the tropics due to sea level pressure-induced surface wind changes across the Panama Isthmus[146-148]. Similarly, the linkages between the Indian to Pacific Ocean may also occur via wind changes across the Maritime Continent[27] or through stationary extratropical wave trains[149].

Idealised numerical model experiments with prescribed surface warming in either the tropical Indian or Atlantic basins confirm the Gill-type induced global Walker circulation changes, including a Pacific trade wind acceleration (Fig. 5c,d), which leads to a central/eastern Pacific sea surface cooling in coupled model settings[27,134,135,150-152] and is further amplified by the Pacific Bjerknes feedback[133,135,138]. These Pacific changes on decadal timescales can also modulate ENSO characteristics[151,153]. While the inter-basin connections from the tropical Atlantic and Indian Oceans rely on broadly similar mechanisms, the location of the Atlantic SST forcing in relation to the Pacific implies that the resulting Rossby wave-induced wind anomalies also act to modulate eastern Pacific winds. Also, the descending motion response tends to be locally reinforced in the central Pacific where the Rossby and Kelvin waves collide (Fig. 5c, d).

TPDV appears to have responded to Atlantic and Indian Ocean forcing over the historical period. Using partially coupled experiments, where SSTs are constrained by idealised observed SST in one basin, Atlantic warming was shown to play a prominent role[134,137,138,152] in the transition from TPDV+ in the 1990s to TPDV- in the early 2000s[11]. The Indian Ocean was reported as either playing a minor role[135,137] or amplifying the Pacific response to the Atlantic forcing[134]. However, observations suggest that this recent dominance of the Atlantic may have been different in the past[130]. The magnitude of the Pacific response to idealised Indian Ocean SST forcing appears to become more prominent further back in time (i.e., 1980-2010 or 1958-2010)[140,149], while the response to Atlantic Ocean SST forcing appears relatively consistent[130,144,152].

While there seems to be a reasonable understanding of this inter-basin connectivity, some questions remain regarding the exact mechanisms and their influence on TPDV. These include: What is the net effect of inter-basin coupling on TPDV amplitude? How has and will anthropogenic climate change alter these decadal inter-basin relationships[154]?

Other sources of uncertainties arise from the apparent discrepancies between some model results. For example, while inter-basin interactions are thought to amplify TPDV, model simulations in which the Atlantic or Indian Ocean influence is removed suggest instead that TPDV is intensified in the absence of Atlantic/Indian Ocean coupling[155,156]. Also, the connection between the Atlantic and Pacific becomes less clear when partially-coupled numerical experiments become more realistic[157]. These uncertainties indicate possible limitations of currently used partially-coupled experiments[158], suggesting the need for additional research.

Relative Importance of Different Mechanisms

This Review has critically explored several mechanisms proposed to explain internal decadal variations in the tropical Pacific. While it is plausible that TPDV may simply arise as a residual of random ENSO variations[4,32], modelling results indicate that TPDV leads decadal ENSO modulation by a few years[45], suggesting that ENSO decadal changes are likely a consequence of the slowly varying background conditions, rather than causing them. However, the relationship between ENSO and TPDV is complex and warrants further investigation.

Results based on observations, ocean reanalyses, and models show a strong relationship between variations in the strength of the STCs at decadal timescales, as measured by the zonally-averaged equatorward pycnocline transport, and equatorial SSTAs, in support of the $v'\bar{T}$ hypothesis. However, the largest correlations occur at zero lag, making a causal relationship between STC transport and equatorial SST changes unlikely. Instead, these results suggest that the concurrent STC and equatorial SSTs variations are both part of the tropical pycnocline adjustment to varying wind forcing. This adjustment is mediated by Rossby wave activity, whose westward propagation alters the zonal slope of the pycnocline and produces meridional transport anomalies[18]. The adjustment timescale depends on the wave transit time, which increases with latitude, as well as the characteristics of the wind forcing relevant for TPDV.

Rossby wave activity alters pycnocline depth and manifests itself as temperature anomalies that propagate on mean isopycnals without a compensating salinity anomaly, thus encapsulating the non-compensated subset of the $\bar{v}T'$ hypothesis. Apart from their transit times, these waves can also contribute to decadal timescales through their interaction with the forcing, for example by responding preferentially to the larger spatial and temporal scales of the winds[71].

Propagation of salinity-compensated temperature anomalies (“spiciness anomalies”), another component of the $\bar{v}T'$ hypothesis, is well supported by climate and ocean-only models[55,61], but the limited observational evidence available raises questions about whether these anomalies actually reach the equatorial region. In addition, an ocean-only model analysis suggests that the influence of spiciness anomalies on the heat budget of the equatorial thermocline may be small[68].

The origin of the atmospheric forcing driving the oceanic mechanisms at decadal time scales remains unclear. We have considered three main groups of atmospheric processes relevant for TPDV: The atmospheric response to decadal SSTAs in the equatorial Pacific; internal atmospheric variability in the extratropical Pacific; and atmospheric influences from the Atlantic and Indian Oceans. Current evidence suggests that these various processes may all be potentially important. Additional research is needed to more precisely assess their relative role in TPDV.

Summary and Future Perspectives

Tropical Pacific decadal variations at periods between 7 and 70 years are linked to coherent basin-scale sea surface temperature and sea level pressure anomalies, and have global impacts. Despite a more limited historical record of subsurface data, it is clear that the surface manifestations of TPDV are associated with a reorganization of tropical Pacific upper-ocean heat content, most notably in the zonal direction, suggesting the involvement of ocean dynamical processes. Our Review has highlighted mechanisms of TPDV of which we are more confident, while pointing out aspects that are less certain and in need of additional research. In particular, the relationship between STC variability and changes in equatorial SSTs, underpinning the $v'\bar{T}$ mechanism, emerges as a robust feature of TPDV across different datasets. The concurrent nature of this relationship does not support a causal influence of transport changes on SST changes, but instead highlights the importance of oceanic adjustment processes for modifying both quantities. This relationship holds for both interannual timescales associated with ENSO and for longer decadal timescales on which we have focused, suggesting that similar processes are operating on both timescales.

In spite of these similarities with ENSO, questions remain about the nature of TPDV. While ENSO is an ocean-atmosphere coupled phenomenon, whose growth and phase transitions rely on coupled feedbacks, it is not clear if this is also true for TPDV. Although there are indications that low-frequency equatorial heating[127], or individual ENSO events[37] can induce off-equatorial winds favourable for a TPDV phase reversal, there is still uncertainty about the origin and nature of the winds involved. Internally-generated wind anomalies in the subtropical/tropical regions can create equatorial SST anomalies[102], which can then reinforce the subtropical wind anomalies through atmospheric teleconnections, increasing their persistence to enhance lower-frequency variability[116]. Decadal timescale SST anomalies in the Atlantic and Indian Oceans can also induce wind anomalies in the tropical Pacific conducive to the development of SST anomalies of the opposite sign[134,137,150,152]. However, the extent to which wind forcing from the extra-tropics or from other ocean basins may itself be the result of forcing from the tropical Pacific is not clearly understood. Furthermore, the relative magnitude of these various sources of wind variability in forcing TPDV is not known. A further uncertainty is related to whether the wind variations arise from deterministic processes operating on decadal timescales, or whether the decadal timescale processes that we observe in the Pacific are simply the result of stochastic white noise forcing that the ocean integrates through its inertia to produce a red noise spectral response. A full understanding of TPDV requires that we resolve these outstanding uncertainties via further research.

Properly designed coupled model sensitivity experiments, where SSTs are prescribed in certain regions could be used to isolate the contribution of the different regional sources of wind anomalies. Since these experiments may be affected by model biases and delicate to conduct[158], they should be complemented by analyses of multi-variate empirical models[159], which are trained on observations and allow a cleaner decoupling of feedbacks among different variables and regions[160-162]. In addition, simple ocean models that capture Rossby wave dynamics[18,163] can help assess the role of different aspects of the winds, including location and spectral characteristics, in reproducing key features of TPDV.

Although spiciness anomalies do not seem to significantly affect TPDV, current evidence is based on a limited number of analyses using just over two decades of observations available from the Argo floats, and primarily conducted with ocean-only models. However, the expected concentration of variance at decadal time scales of spiciness anomalies arriving at the equator, and the resulting rearrangement of the tropical climate, suggests that spiciness anomalies could still be potentially important driver of TPDV in the coupled setting. Thus, the role of spiciness should be further investigated in the context of coupled models. Availability of long time series from model simulations with realistic mixing parameterizations, achieved through either higher spatial resolution or improved model design, would be critical to more reliably assess the impact of spiciness on TPDV.

This review has focused on the oceanic and atmospheric processes that govern TPDV arising naturally within the climate system. We have not addressed the question of how TPDV may change in response to external forcing. However, we can expect changes in the characteristics of TPDV as a result of anthropogenic forcing. Increasing surface temperatures will result in increased ocean stratification[164], leading to faster Rossby wave propagation, shorter adjustment timescales and reduced growth and predictability of Pacific decadal variability[165], which may lead to weaker, shorter timescale TPDV in the future[166]. The expected reduced influence of Atlantic variability on ENSO, due to increased tropospheric stability[167] may also reduce the influence of Atlantic decadal variability on TPDV. On the other hand, the Wind Evaporation SST feedback is projected to increase due to warmer sea surface temperatures and increased evaporative response, which can lead to an enhanced impact of the NPMM on ENSO and possibly on TPDV[168,169]. These and other possible processes, and their interactions, need to be assessed in climate models to determine how TPDV may change in a warmer world.

Box 1. Mean ocean and atmospheric circulations in the tropical Pacific

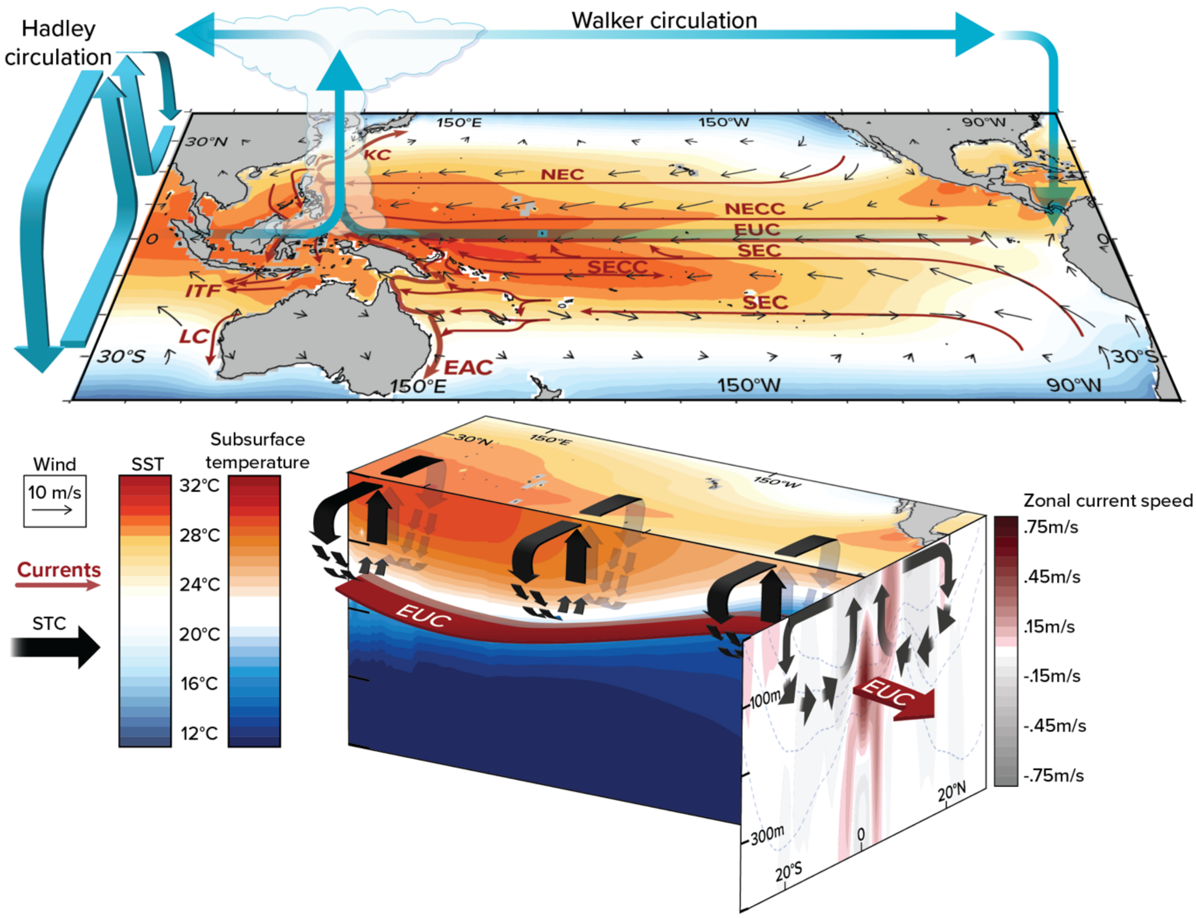
The equatorial Pacific Ocean is often described as a system with a warmer and dynamically active upper layer, and a colder and more quiescent bottom layer (shading along the equator, figure, bottom). These two layers are separated by a region of sharp vertical density (temperature) gradients, known as the pycnocline (thermocline), and are overlaid by a near-surface frictional layer – the Ekman layer.

The pycnocline links subtropical regions to the equator: subtropical waters can penetrate into the ocean interior at the latitudes where surfaces of constant density (isopycnals) meet the near surface layer, and then flow equatorward along those isopycnals (black dashed lines in bottom panel of figure, Fig. 3 for a three-dimensional perspective). At the equator, these waters are brought to the upper layers by the upward vertical velocity (a process known as upwelling), and returned to higher latitudes by the flow in the surface Ekman layer (black solid arrows in bottom panel of figure), creating shallow overturning circulations in both hemispheres termed

Subtropical Cells (STCs)[75]. Warm tropical SSTs drive the atmospheric Hadley Cells (see figure, top), with air rising near the equator, flowing poleward in the troposphere at 10-15 km above the surface, and descending in the subtropics, with an equatorward return flow near the surface that is deflected westward because of the Earth's rotation, creating the easterly trade winds.

The tropical Pacific Ocean circulation also exhibits a rich system of zonal currents, (see figure, top) with both westward and eastward flowing currents, the most noteworthy of which is the Equatorial Undercurrent (EUC), a strong eastward flowing jet centred on the equator with a core in the pycnocline (see figure, bottom). The zonal slope of the pycnocline - deeper in the west, and shallower in the east - is in balance with the easterly equatorial trade winds, and provides the pressure gradients that drives the EUC. The trade winds are the surface branch of the zonal atmospheric Walker circulation, consisting of an ascending branch over the warm waters of the western equatorial Pacific "Warm Pool", and a descending branch in the colder and dryer eastern equatorial Pacific "Cold Tongue" (see figure, top).

The interior wind-driven zonal circulation is connected in the western Pacific to the equatorward flowing Low-Latitude Western Boundary Currents (LLWBCs), which are an important conduit for the redistribution of subtropical water to the western equatorial Pacific[170] and then into the tropical current system, including the EUC and the Indonesian Throughflow (ITF).



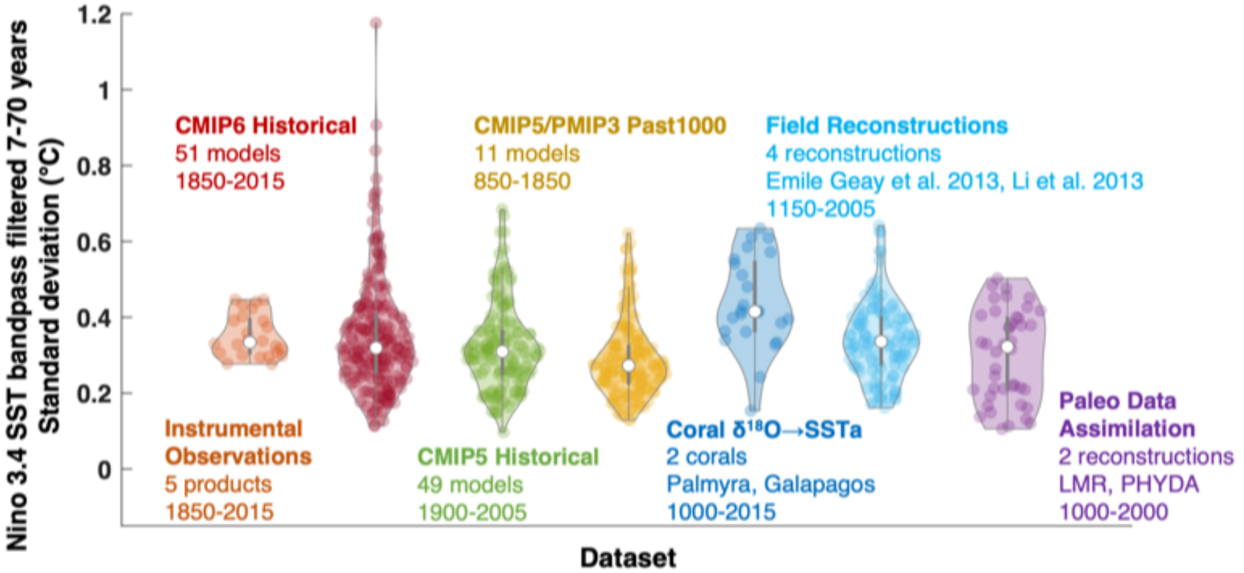
Box glossary

LLWBC: Low Latitude Western Boundary Current
NEC: North Equatorial Current;
NECC: North Equatorial Countercurrent;
EUC: Equatorial Undercurrent;
SEC: South Equatorial Current;
SECC: South Equatorial Countercurrent;
EAC: East Australian Current;
ITF: Indonesian Throughflow:
LC: Leeuwin Current;
KC: Kuroshio Current

Box 2. Paleoclimate insights

The brevity of the instrumental record limits analyses of TPDV with instrumental observations. Paleoclimate proxies, particularly tropical corals and sclerosponges, provide opportunities to track the low-frequency variations of the tropical oceans over centuries. Over the most recent phase transitions of TPDV, corals have recorded associated changes in dynamically relevant fields, including sea surface temperature[171,172], salinity[173-175], westerly wind bursts[176], and upwelling[177,178]. Proxy records have provided evidence of interactions among different ocean basins at both interannual[179] and decadal[180] timescales. Proxy records from the Eastern Tropical North Pacific, where SST anomalies may reflect NPMM activity, illustrate high levels of decadal variability coherent with the Central Equatorial Pacific records, supporting the potential involvement of the NPMM in TPDV[174].

Additionally, paleoclimate analyses provide a perspective into the range of TPDV found over centuries-millennia, which can be used to assess model simulations of TPDV. The Box Figure compares TPDV across five different instrumental products, two generations of climate models (CMIP5, CMIP6; historical and Past1000 experiments), and three different sources of paleo data using violin plots[181]. TPDV is described in terms of the standard deviation of decadal variations (7-70 years) of the Niño3.4 index (annually average sea surface temperature anomalies in the 5°S-5°N, 170°W-120°W region). Violin plots for each dataset are based on decadal standard deviations of 100-year sliding windows allowing for 50 years overlap between segments. Individual dots represent the decadal standard deviation of each unique 100-year segment. The median and interquartile range of these values is indicated by the white dots and vertical lines, respectively, while the width of the violin plot for each standard deviation indicates the corresponding frequency of occurrence. Notably, the instrumental record does not cover the full range of decadal variability suggested by both paleoclimate proxy reconstructions and climate models, although the median standard deviation is very similar among products.


Nino 3.4 SST bandpass filtered 7-70 years
Standard deviation (°C)
1.2
1
0.8
0.6
0.4
0.2
0
CMIP6 Historical
51 models
1850-2015
CMIP5/PMIP3 Past1000
11 models
850-1850
Field Reconstructions
4 reconstructions
Emile Geay et al. 2013, Li et al. 2013
1150-2005
Instrumental
Observations
5 products
1850-2015
CMIP5 Historical
49 models
1900-2005
Coral δ18O→SSTa
2 corals
Palmyra, Galapagos
1000-2015
Paleo Data
Assimilation
2 reconstructions
LMR, PHYDA
1000-2000
Dataset

Figures

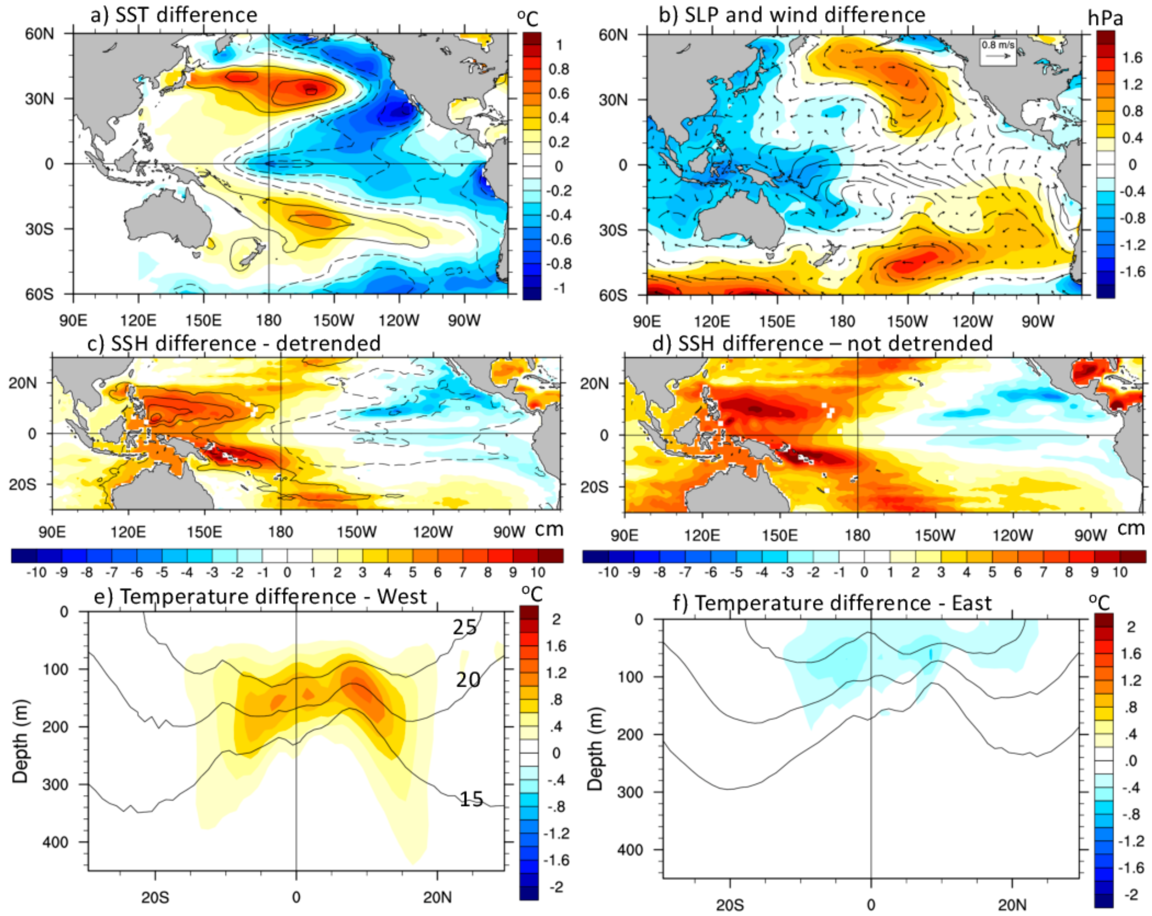


Figure 1. Observed Pacific decadal changes. a) The difference of linearly detrended SST anomalies[182] between 1999-2014 (Period 2) (shading) and 1984-1999 (Period 1), and the negative phase of the basin-wide TPDV pattern (contours). The TPDV pattern was obtained by regressing the decadal SST anomalies on the TPDV index (leading Principal Component of decadal SST anomalies in 25°S-25°N). b) Differences (Period 2 minus Period 1) of linearly detrended sea level pressure (shading) and vector wind anomalies[183] (arrows) over 1958-2020 c) Differences of linearly detrended SSH anomalies[184] (shading), and tropical SSH signature of TPDV, computed as the regression of decadal SSH anomalies on the TPDV index. d) Same as c), but for un-detrended SSH data. e) Differences (Period 2 minus Period 1) of detrended temperature anomalies zonally averaged between the western ocean boundary and the dateline, and displayed as a function of latitude and depth. Contours indicate the time mean 15°, 20°, and 25° isotherms, highlighting the thermocline layer. f) Same as e), but for temperature values averaged from the dateline to the eastern ocean boundary. SST contour interval in a) is 0.1°C, while SSH contour interval in c) and d) is 1 cm. TPDV is associated with basin-wide SST, SLP and wind anomalies, and involves a reorganization of heat content in the tropics.

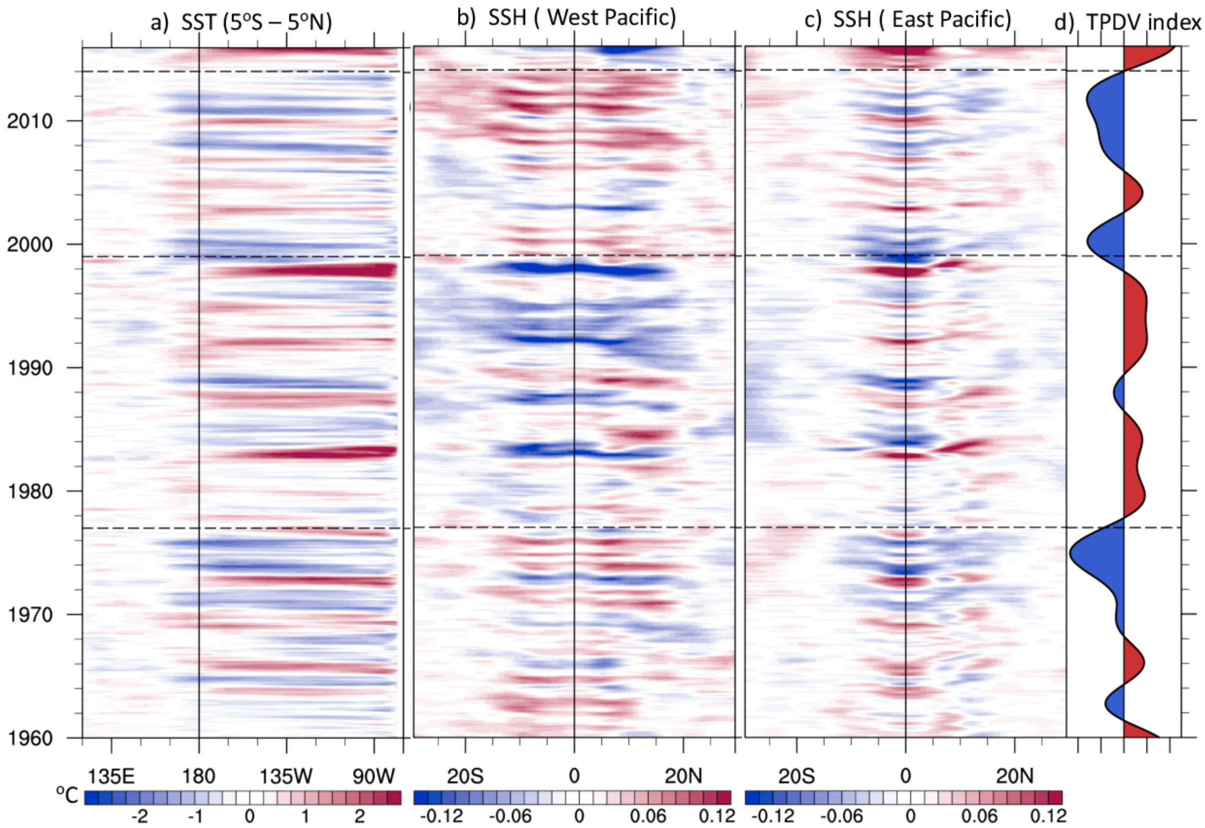


Fig. 2. Relationship between TPDV and El Niño Southern Oscillation. a) Evolution of SST anomalies[182] averaged in the equatorial band (5°S-5°N), displayed as a function of longitude (x-axis) and time (y-axis), with time increasing upward. b) Evolution of SSH anomalies[185] (m), a proxy for upper ocean heat content, averaged west of the dateline, as a function of latitude and time. c) Evolution of SSH anomalies (m) averaged east of the dateline, as a function of latitude and time. Anomalies of both SST and SSH are obtained by removing the climatological monthly mean and linearly detrending the data over the period 1958-2015. d) Time evolution of the TPDV index, computed as the leading Principal Component of decadal (7-70 years) SST anomalies in the tropical band (25°S-25°N). The index in d) is based on ERSSTv5. ENSO variability exhibits a decadal modulation with more El Niño activity and prevailing negative heat content anomalies in the western tropical Pacific during positive TPDV phases, and *vice versa* for negative TPDV phases.

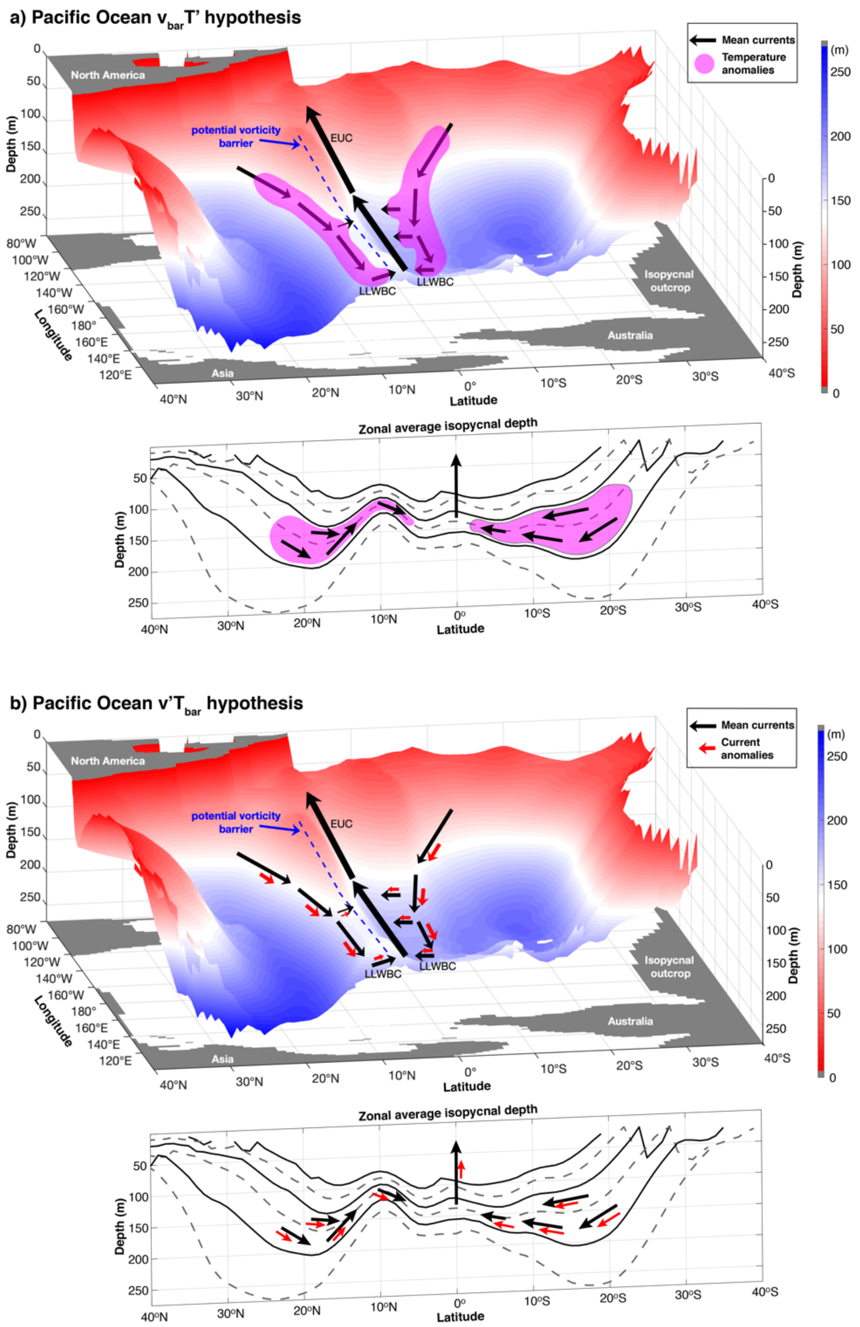


Figure 3. Subtropical Cells influence on TPDV. a) Schematic illustration of advection of spiciness anomalies (pink shading) by the mean circulation on the 25.0 kg m^{-3} isopycnal surface, illustrating the $\bar{v}\,T'$ mechanism. Shading indicates isopycnal depth[184]. A density ridge in the 5°-10°N latitude band, known as "potential vorticity barrier"[54] is indicated by the gray dashed line. Equatorward spiciness flow along these isopycnal surfaces is also highlighted on the zonally averaged isopycnal depths (from 23 kg m^{-3} to 25.5 kg m^{-3} with a spacing of 0.5 kg m^{-3}) in the latitude-depth plane on the bottom panel. b) Schematic illustration of the $v'\bar{T}$ mechanism, where the mean (black arrows) and anomalous (red arrows) flow are presented on the 25.0 kg m^{-3} isopycnal surface, which is located in the middle of the upper pycnocline. Flow along these isopycnal surfaces connects the subtropical to the tropical regions, as highlighted by the contours of zonally averaged isopycnal depth (from 23 kg m^{-3} to 25.5 kg m^{-3} with a spacing of 0.5 kg m^{-3}) in the latitude-depth plane on the bottom panel. Both $\bar{v}\,T'$ and $v'\bar{T}$ mechanisms were proposed as potential contributors to TPDV.

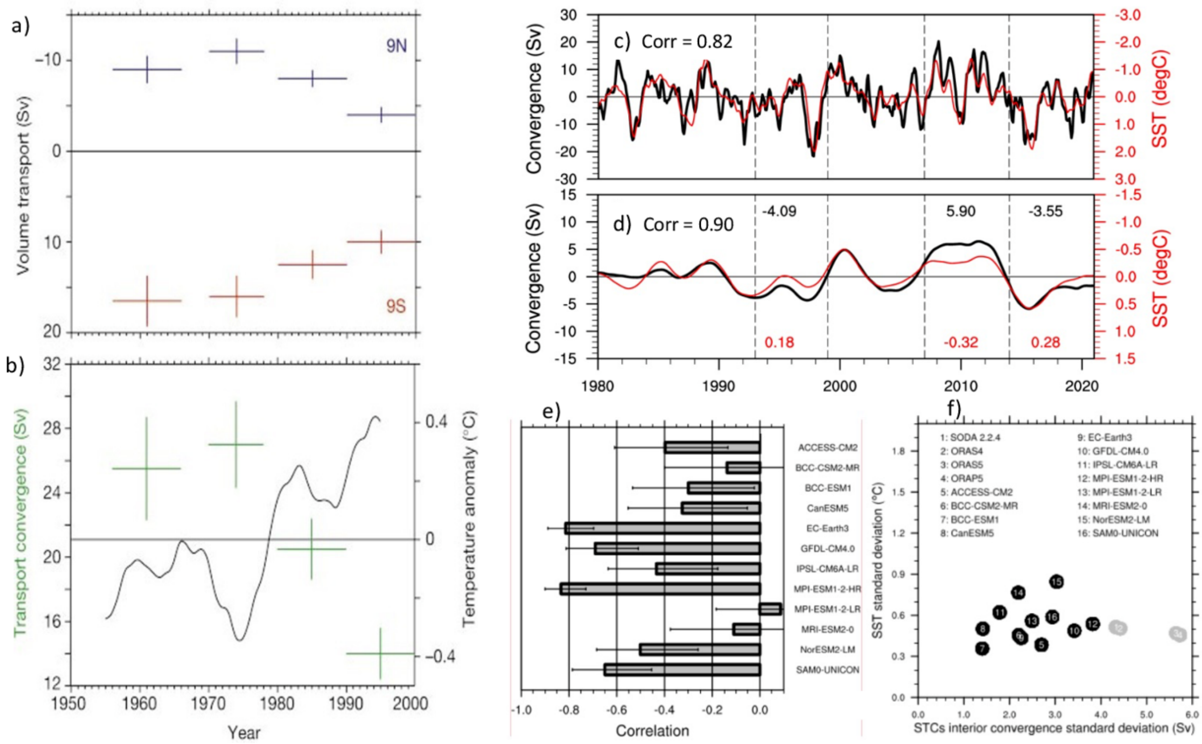


Figure 4. Assessment of the $v'\overline{T}$ hypothesis. a) Observational estimates of mean zonally-integrated interior meridional pycnocline transports at 9°N and 9°S computed over 1956-65, 1970-77, 1980-89, and 1990-99. Transport units are Sverdrups (1Sv = 10^6 m^3 s^{-1}). Error bars are for one standard deviation error. b) Mean meridional transport convergence (in Sv) across 9°N and 9°S computed as the difference between Southern Hemisphere minus Northern Hemisphere transports. SST anomalies averaged over the central and eastern equatorial Pacific (9°N-9°S, 90°W-180°W). c) Meridional transport convergence anomalies (seasonal cycle removed) across 9.5°N and 9.5°S in the Pacific from the GODAS ocean reanalysis[186] during 1980-2021. Transport convergence is compared with SST anomalies averaged over 9.5°N-9.5°S, 90°W-180°W. Meridional velocity anomalies used to compute the transports and SST anomalies are linearly detrended. Correlation at zero lag between the time series is -0.82. d) Same as c) but for 7-year low pass filtered anomalies. Correlation at zero lag is -0.90. Numerals in d) indicate values of mean decadal transport anomalies (black) and mean decadal SST anomalies (red) over the periods identified by the vertical dashed lines. e) Correlations between transport convergence at 9°N and 9°S and equatorial SST anomalies in four ocean reanalyses[184,185,187,188] and 12 CMIP6 historical simulations. For each model, the 95% confidence interval is shown. f) Standard deviation of equatorial SST anomalies vs. the standard deviation of the transport convergence at 9°N and 9°S for the ocean reanalyses and the historical CMIP6 simulations. Panels a) and b) are from [19], panels c) and d) are adapted from [18], and panels e) and f) are adapted from [88].

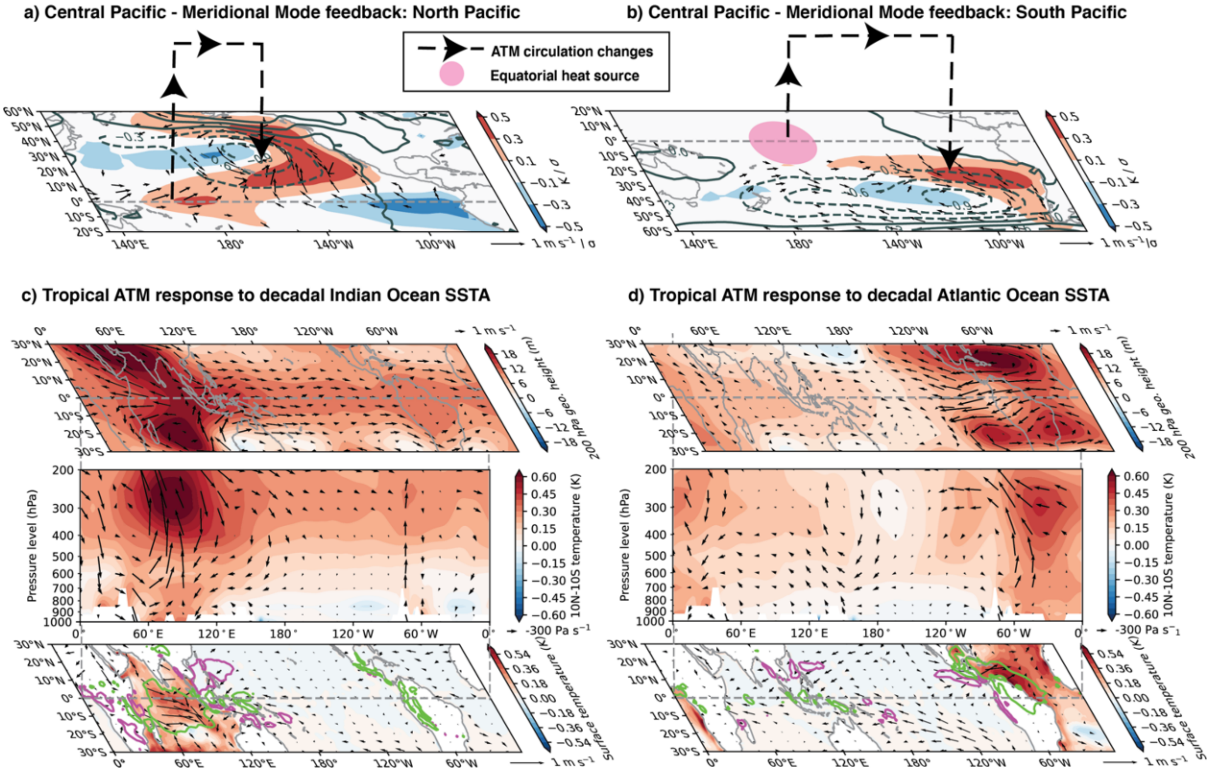


Figure 5. Atmospheric processes involved in TPDV. a) SST (shading) and sea level pressure (SLP, contours) anomalies typical of the North Pacific Meridional Mode (NPMM). The SLP anomalies are associated with changes in the off-equatorial trade winds, which produce SST anomalies through the wind-evaporation-SST feedback. b) As in a), but for the South Pacific Meridional Mode (SPMM). To calculate these indices, we linearly remove the Niño 3.4 index influence on wind and SST anomalies [106] and identify the NPMM and SPMM indices, respectively, as the first SST expansion timeseries of an SST-wind maximum covariance analysis performed over 21ºS-32ºN, 175ºE-95ºW[106] and 10ºS-35ºS, 180ºE-70ºW[189]. The tropical atmospheric response to positive interdecadal SST differences in the Indian (1999-2008 minus 1988-1998) and Atlantic (1999-2014 minus 1982–1998) Oceans is respectively presented in c) and d). The lower panel includes the forcing SST anomalies in shading, while the modelled precipitation anomalies are shown as contours (green=positive; purple=negative), and the overlaying wind vectors represent the surface zonal and meridional winds. The mid-panels present equatorial sections of temperature (shading) and zonal and vertical wind vectors (arrows), meridionally averaged in the (10ºS-10ºN) latitude band. Note that the vertical winds are magnified by a factor of 300 to ensure scale comparability with the zonal wind. The upper panel represents the 200hPa geopotential height (shading) with overlaying wind vectors representing the 200hPa zonal and meridional winds. Data presented in c) and d) are based off AGCM simulations run by [190] and Naha et at. (2023b, in revision).

Competing interests

The authors declare no competing interests

Acknowledgements

This paper is a product of the CLIVAR Pacific Region Panel working group on "Tropical Pacific Decadal Variability". The authors would like to thank CLIVAR for their sponsorship, and Ms. Jing Li at the CLIVAR Program Office for her help. The paper was finalized during a workshop held at Monash University, Australia. We acknowledge workshop funding support from the Faculty of Science and the School of Earth Atmosphere and Environment at Monash University, as well as CLIVAR and US CLIVAR. We also thank Natalie Renier from the Woods Hole Oceanographic Institution graphics team for her help in the preparation of Figure 1. A.C. was supported by the NOAA Climate Program Office's Climate Variability and Predictability (CVP) and Modeling, Analysis, Predictions, and Projections (MAPP) programs and by DOE Award #DE-SC0023228. S.M. was supported by the Australian Research Council (grant numbers FT160100162, DP200102329) and the Australian Government's National Environmental Science Program (NESP2). M.F.S. was supported by NSF grant AGS-2141728 and NOAA's Climate Program Office's Modeling, Analysis, Predictions, and Projections (MAPP) program grant NA20OAR4310445. This is IPRC publication X and SOEST contribution Y. Ag.S is supported by Australian Government's National Environmental Science Program (NESP) and was supported by the Centre for Southern Hemisphere Oceans Research (CSHOR). K.B.K. was supported by the NASA Sea Level Change Science Program, Award 80NSSC20K1123. N.J.H. was supported by funding from the ARC Centre of Excellence for Climate Extremes (Grant No. CE170100023) and acknowledges support from the National Environmental Science Program (NESP) Climate Systems Hub. M.M. was supported by Austrian Science Fund project P33177. S.S. was supported by the U.S. Department of Energy, DE-SC0019418 and the US National Science Foundation, OCE-2202794 and AGS-1805143. C.M.V. was supported by Proyecto ANID Fondecyt 3200621. A.S.T. acknowledges the ARC Centre of Excellence for Climate Extremes and the Australian Government's National Environmental Science Program (NESP). R.M.H. was supported by the Australian Research Council through grant DE21010004. C.C.U. was supported by NSF award AGS-2002083 and the *James E. and Barbara V. Moltz Fellowship for Climate-Related Research*. G.A.M. was supported by the Regional and Global Model Analysis (RGMA) component of the Earth and Environmental System Modelling Program of the U.S. Department of Energy's Office of Biological & Environmental Research (BER) under Award Number DE-SC0022070, and also by the National Center for Atmospheric Research, which is a major facility sponsored by the National Science Foundation (NSF) under Cooperative Agreement No. 1852977. N.S. acknowledges support from the joint JAMSTEC-IPRC Collaborative Research project JICore. This is PMEL contribution no. 5499.

Author contributions

A.C. and S.M. conceived the study. A.C., S.M., M.J.M., S.C., N.J.H., Y.I., S.C.S., J.S., M.F.S., M.Z. coordinated the writing of the various sections. A.C., S.M., C.C.U. and S.C.S led the analyses and the preparation of the figures. All authors contributed to the discussion and interpretation of the material and assisted with the writing of the manuscript, led by A.C.

Peer review information

Nature Reviews Earth & Environment thanks [Referee#1 name], [Referee#2 name] and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

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