Perspective

Possible shift in controls of the tropical Pacific surface warming pattern

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Changes in the sea surface temperature (SST) pattern in the tropical Pacific modulate radiative feedbacks to greenhouse gas forcing, the pace of global warming and regional climate impacts. Therefore, elucidating the drivers of the pattern is critically important for reducing uncertainties in future projections. However, the causes of observed changes over recent decades, an enhancement of the zonal SST contrast coupled with a strengthening of the Walker circulation, are still debated. Here we focus on the role of external forcing and review existing mechanisms of the forced response categorized as either an energy perspective that adopts global and hemispheric energy budget constraints or a dynamical perspective that examines the atmosphere–ocean coupled processes. We then discuss their collective and relative contributions to the past and future SST pattern changes and propose a narrative that reconciles them. Although definitive evidence is not yet available, our assessment suggests that the zonal SST contrast has been dominated by strengthening mechanisms in the past, but will shift towards being dominated by weakening mechanisms in the future. Finally, we present opportunities to resolve the model–observations discrepancy regarding the recent trends.

Earth's surface temperature has warmed by about 1.1 K since the pre-industrial era, and this warming has been unequivocally attributed to human-induced emissions of greenhouse gases[1]. The past warming has caused changes in many aspects of the climate system, including sea level, the cryosphere, land surface environments, regional precipitation patterns and weather extremes, all affecting human society. These regional impacts largely depend on the spatial pattern of tropical SST changes, a primary driver of the large-scale atmospheric circulation, especially in the Pacific. However, considerable uncertainty remains in the physical origins of the multi-decadal-scale SST warming pattern.

The tropical Pacific SST trend over the recent decades reveals warming in the west and cooling in the east, intensifying the climatological zonal SST contrast (Fig. 1a,b). The period of 1979–2013, a focus in many previous studies, shows the largest strengthening trend in the equatorial zonal SST gradient since 1900. The trend in terms of the pattern and the magnitude is similar when the period is extended to 2022 except for the lack of cooling in the northern subtropical eastern Pacific. The index of the equatorial zonal SST gradient shows a linear trend of 0.21 and 0.17 K per decade for 1979–2013 and 1979–2022, respectively, indicating that the mean zonal SST gradient has strengthened by approximately 30% relative to the twentieth-century average (Fig. 1c). The strengthening of the zonal SST gradient accompanies an enhanced Pacific Walker circulation (PWC), which is identified using different reanalysis datasets (Fig. 1d). The magnitude of the trend depends on the exact period and length chosen[2,3], but the observations reveal that the recent strengthening of the SST gradient and the PWC has lasted for more than four decades even after the 2015–2016 El Niño and the triple-dip La Niña in 2020–2022 (see also ref. 4). The recent multi-decadal SST trend is not subject to observational uncertainty, unlike the centennial trend, which has large uncertainty[5]. Despite the small difference in the magnitude of the SST gradient trend across multiple SST datasets, they all indicate the strengthening over the recent decades and this observational uncertainty is small compared to discrepancies with climate model simulations explained below[6,7].

The tropical Pacific SST warming pattern regulates regional precipitation changes through the warmer-get-wetter mechanism (Box 1) and alters tropical cyclone tracks[8]. Recent studies also show that global climate feedbacks vary depending on the tropical Pacific warming pattern[9–12]. This so-called pattern effect[13] (Box 1) describes the influence of the SST warming pattern on the Earth's energy budget at the top of the atmosphere, leading to the recognition that the estimate of climate sensitivity is affected by the SST pattern change during both the historical period and a future with further warming[14–16]. Hence, it is of critical importance to attribute how much of the pattern change is due to radiatively forced responses and how much is due to internally generated climate variability.

As the Pacific SST trend pattern for 1979–2013 bears a similarity to the Interdecadal Pacific Oscillation (IPO), a decadal–interdecadal mode of natural variability[17,18], it has been argued that the past SST pattern change can be explained primarily by internal variability. Indeed, some individual realizations in large ensembles of Coupled Model Intercomparison Project phases 5 and 6 (CMIP5 and CMIP6) historical

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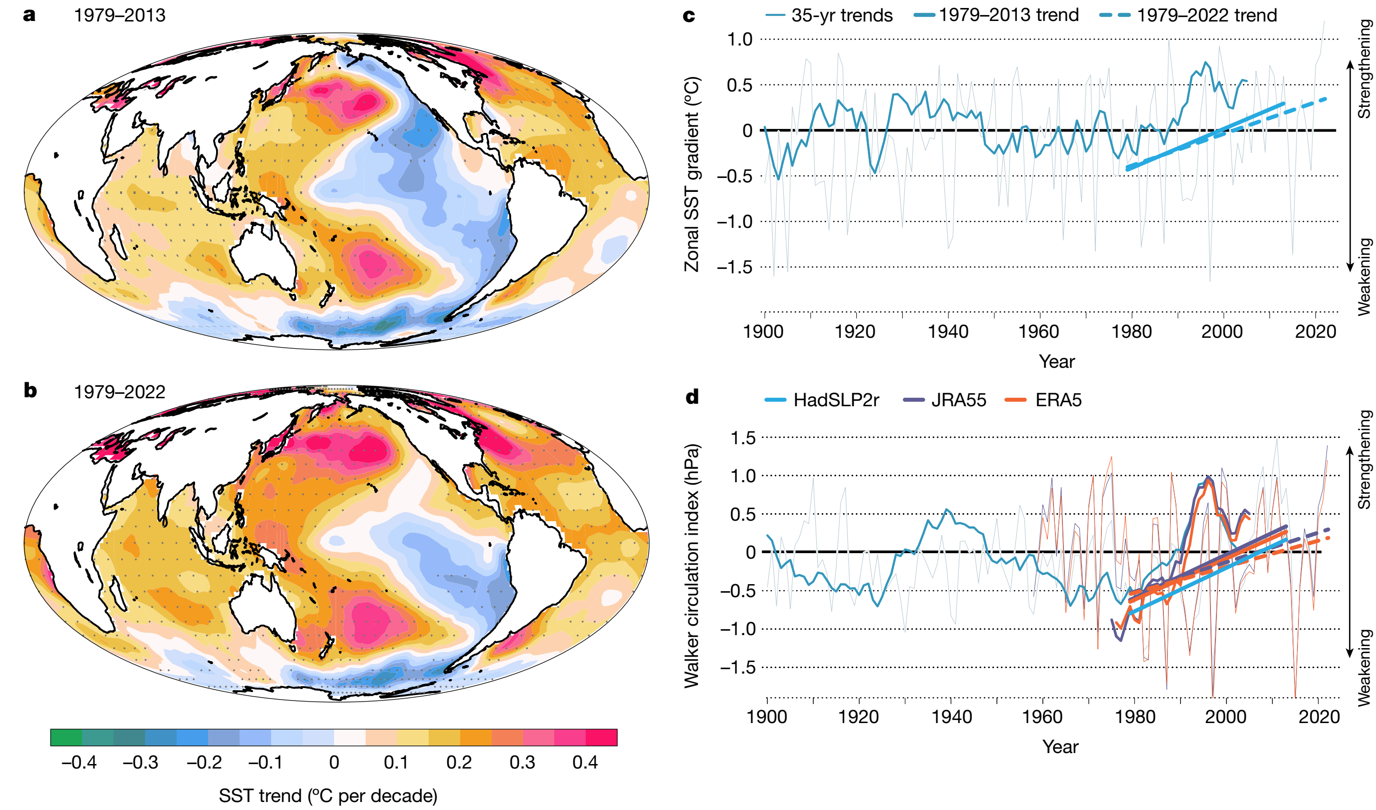

Fig. 1 | Observed changes in the Pacific SST pattern and the Walker circulation. a,**b**, SST trends for 1979–2013 (**a**) and 1979–2022 (**b**), based on the Extended Reconstructed Sea Surface Temperature (ERSST) v5 data. Stippling indicates that the trend is statistically significant at the 95% level against the null hypothesis of no trend. **c**,**d**, Time series of the zonal SST gradient in the equatorial Pacific, defined as the SST difference between western (5° S–5° N, 80°–150° E) and eastern (5° S–5° N, 180°–80° W) regions[69] (**c**), and the Walker circulation index (equivalent to the conventional Southern Oscillation index) defined by the zonal contrast of sea-level pressure between the eastern (5° S–5° N, 160°–80° W) and western (5° S–5° N, 80°–160° E) equatorial Pacific[36] (**d**). The grey curves are annual means after 1900 and the blue curves are the 35-year trend with sliding windows (plotted at the centre of the period). Thick solid lines indicate the linear trend for 1979–2013 and thick dashed lines show the trend for 1979–2022. HadSLP2r, Hadley Centre Sea Level Pressure dataset; JRA55, Japanese 55-year Reanalysis dataset; ERA5, European Centre for Medium-Range Weather Forecasts Reanalysis v5 dataset.

simulations can capture the observed strengthening of the zonal SST gradient and the enhanced PWC[6,19,20]. However, a thorough analysis of large-ensemble simulations shows that the SST trend for 1979–2020 is very unlikely (less than 5% probability) to be explained by internal variability alone[21]. Furthermore, the SST trend pattern for a more recent period (for example, 1979–2022) has deviated from the canonical IPO pattern (Fig. 1b). This indicates that part of the observed trends in the recent decades may be explained as being a response to external forcing[21,22], which may not be well represented in the climate models[7,23]. Unlike observations, models tend to show a weakening of the gradient over these periods and it continues into the future projections with increasing magnitude[24].

Given the above discussion, we raise two main issues in this paper. First, we seek to evaluate the forced mechanisms that strengthen the zonal SST gradient and the PWC in the recent decades, and then to reconcile the past strengthening with the future weakening as simulated by climate models. Second, we seek to identify the processes that are missing or not well presented in models and discuss how we can resolve the model–observation discrepancy. While noting a potentially important contribution of internal variability, here we focus on the forced responses because they are the most relevant for increasing confidence in future projections.

Our scope is to review the different mechanisms in the literature that explain the SST pattern change as a forced response and assess their relative importance in the past trends of tropical Pacific SST and PWC. We categorize various mechanisms proposed so far into two perspectives: the energy budget perspective that provides global or hemispheric energy constraints and the coupled dynamical perspective that seeks to explain regional circulation changes (Fig. 2). They are then combined to propose a storyline that reconciles discrepancies between past and future changes of the tropical Pacific surface warming pattern. Finally, we discuss opportunities to resolve the model–observations discrepancy.

Energy budget perspective

The energy budget equation at the top of the atmosphere used to estimate the equilibrium climate sensitivity and the transient climate response consists of changes in global-mean quantities of radiative forcing, surface temperature, the energy imbalance equivalent to ocean heat content change and the climate feedback parameter[15,25]. For a given increase of radiative forcing due to increasing concentrations of atmospheric carbon dioxide (CO_2) or other radiative forcing agents, the climate system reacts by adjusting with surface warming leading to increased radiative flux to space at a rate defined by the climate feedback parameter. In reality, the global-mean energy budget is not independent of the spatial pattern of surface temperature change. On one hand, the pattern of temperature change modulates the climate feedback and therefore the equilibrium climate sensitivity and the transient climate response[9–12]. On the other hand, uniform radiative forcing can give rise to spatially non-uniform patterns of surface temperature change through several pathways (blue arrows in Fig. 2). In the transient response, the surface warming pattern is also affected by the ocean heat uptake changes[26–28], which can be explicitly coupled to

Box 1

Key paradigms

Warmer-get-wetter. Precipitation pattern changes in a warming climate are determined by both dynamical and thermodynamic processes. In the zonal-mean sense, the thermodynamic process is known to dominate in the precipitation increase over regions where climatological mean precipitation is rich in the present climate, called the wet-get-wetter mechanism[31]. However, the effect of circulation change (that is, the dynamical process) is more important in determining the spatial pattern of precipitation change. Precipitation increases owing to moisture convergence that occurs where SSTs warm relative to the surrounding area and it is called the warmer-get-wetter mechanism[48,135].

Pattern effect. There is evidence that the climate feedback to surface warming is not constant. In abrupt CO_2 quadrupling simulations using coupled models, the net negative feedback generally weakens in the later stages[136]. Conversely, atmospheric model simulations driven by observed boundary conditions reveal that the climate feedback was more negative in recent decades[9]. In both cases, the modulation of the global feedback parameter occurs because of changes in the surface warming pattern, especially in the tropical Pacific. The above time dependence of the climate feedback parameter is collectively called the pattern effect.

Global hydrological constraint. The global atmospheric column water vapour is known to increase with global-mean surface warming, following the Clausius–Clapeyron relationship, at a rate of about 7% per degree of warming. However, the global-mean precipitation increase is constrained by the atmospheric energy budget[137]. With increasing atmospheric water vapour, the atmosphere emits more longwave radiation, overwhelming an increasing absorption of incoming shortwave radiation. This additional net radiative cooling is compensated by increasing surface latent heat release (that is, evaporation), which is equal to precipitation, leading to a precipitation increase estimated at 2–3% per degree of global-mean surface warming, subject to uncertainty in the shortwave absorption, and cloud effects[138].

Bjerknes feedback. The tropical Pacific mean state is characterized by cold SSTs in the east due to equatorial upwelling, associated with a zonal thermocline slope in the ocean subsurface, and easterly trade winds that are in balance with the zonal atmospheric pressure gradient. If the trade winds weaken, the slope of the zonal thermocline relaxes, leading to the reduced upwelling and Ekman pumping that otherwise act to cool the eastern equatorial Pacific. The resulting reduced zonal SST gradient further weakens the trade winds. This is the positive Bjerknes feedback that explains ENSO growth and can also be an important process in projected future changes of the mean state.

WES feedback. Consider a warm SST anomaly in the Northern Hemisphere subtropics. The resulting low sea-level pressure anomalies[139] lead to surface southeasterly wind anomalies to the south, which weaken the climatological trade winds and thereby reduce evaporation. The reduced latent heat fluxes amplify the warm SST anomaly. This is the key mechanism for the WES feedback, which is further modulated by changes in boundary layer stability[140] and low-level clouds[141]. For the future mean-state change in the tropical Pacific, the WES feedback has been argued to explain the enhanced pattern of equatorial warming and the Southern Hemisphere subtropical cooling[48,142].

the pattern effect in a simple theory[29], but it is difficult to distinguish them in observations and climate model simulations[30].

Constraint on the hydrological cycle

A theoretical argument regarding the global-mean atmospheric circulation change in response to global warming has been built on the basis of the hydrological budget, which consists of changes in precipitation, column water vapour and vertical mass flux at the top of the boundary layer, the last of these determined by the competition between the first two[31] (Box 1). As global precipitation cannot increase more than global water vapour, mass flux has to weaken by 4–5% per 1 K warming. Although this budget is an approximate form assuming that the precipitation efficiency is unity[32], the predicted change in mass flux has been supported by both idealized and realistic climate change simulations[33–35], and used to interpret the centennial slowdown of the tropical circulation in the historical period[36]. However, it was stated in ref. 31 that "the reduction in the global mass flux does not necessarily entail a weakening of the mean tropical circulation". Indeed, several studies reported that the mass flux has reduced whereas the PWC has strengthened over the past decades[37–39]. This apparent inconsistency is reconciled by the SST pattern effect on the PWC (but not on the global mass flux) and by the fact that the weakening constrained by the hydrological budget has not emerged at the present global warming level[40] (Fig. 3a). An alternative explanation to this constraint has been provided using the moist static energy budget, called the anomalous gross moist stability (GMS) mechanism[41]. Associated with the rise of tropopause due to surface warming, roughly following the moist adiabat, GMS is expected to increase, which acts to weaken the PWC[42–45]. Recent theoretical advances demonstrated that the two mechanisms embody essentially the same physics[46].

Differential evaporative damping

Another energy perspective mechanism that could explain the weakening of the zonal SST gradient in response to global warming has been proposed on the basis of the surface heat budget[47,48]. The so-called differential evaporative damping mechanism can be induced by uniform warming imposed on the climatological SST pattern; as surface evaporation depends on the total local SST, the damping of the same SST anomaly due to latent heat release will be larger over the warm pool than over the cold tongue, leading to a weakening of the zonal SST contrast. The efficiency of this mechanism has not yet been identified in observational records, but this mechanism has been clearly detected in idealized model experiments in which ocean dynamics are excluded[49] and explains about 30% of the SST gradient weakening in response to imposed CO_2 forcing in a fully coupled model[50].

Southern Ocean cooling and aerosol forcing

In addition to the above mechanisms based on the global budgets, the interhemispheric energetics framework that constrains meridional shifts in the Hadley circulation and the tropical rain band called the intertropical convergence zone (ITCZ)[51–53] has been applied to explain the remote influence of extratropical thermal forcings to the tropical SST pattern and PWC[54–56]. When a hemispheric contrast exists in the thermal forcing (for example, more heating in the Northern Hemisphere and/or more cooling in the Southern Hemisphere), the Hadley cell shifts to induce a cross-equatorial energy flow in its upper branch, acting to reduce the thermal contrast. The Hadley cell shift is accompanied by a shift of the ITCZ towards the warmed hemisphere. Associated northward displacement of the cross-equatorial surface winds tends to preferentially cool the central-eastern tropical Pacific

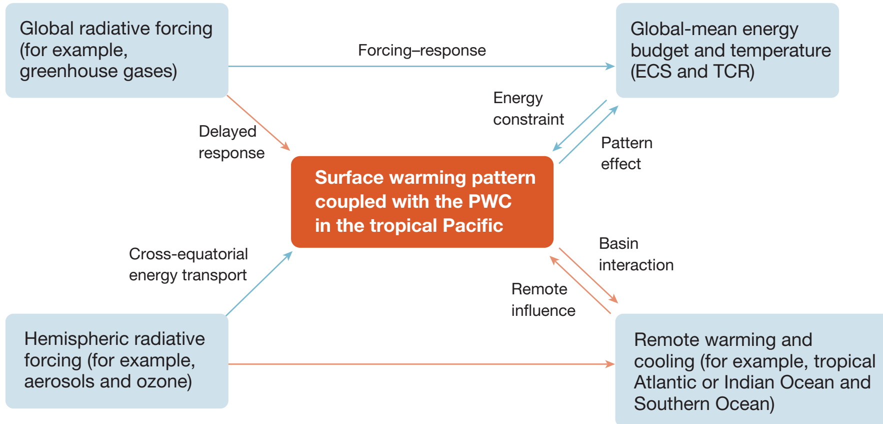

Fig. 2 | Framing associated with the tropical Pacific surface warming pattern. The diagram shows the radiative forcing and climate response on the horizontal axis, with different spatial scales on the vertical axis. Arrows indicate the direction of processes, and those in blue can be constrained by energy budgets whereas those in red can be explained by the atmosphere–ocean coupled dynamics. The surface warming pattern in the tropical Pacific, outlined in red, is the target for understanding. ECS, equilibrium climate sensitivity; TCR, transient climate response.

through coupled dynamical processes and cloud effects[55,57], thereby strengthening the zonal SST gradient; this relationship is supported by observational evidence[58]. This is a robust mechanism identified across various timescales, ranging from interannual variability to centennial climate change[59].

For explaining the past trend in the observational records, the effects of Southern Ocean cold anomalies on the tropical Pacific have received increasing attention[60] (Fig. 1a,b). In addition to the zonal-mean interhemispheric energetics framework, recent studies have identified the surface cooling in the Pacific sector of the Southern Ocean as an effective conduit for cooling the tropical southeastern Pacific through wind-driven advection and atmosphere–ocean feedback[54,61], in which the teleconnection may be interactive[62]. However, this teleconnection mechanism is probably underestimated in climate models owing to too weak subtropical cloud feedback near the coast of South America[60,63] (Box 2), and the Southern Ocean cooling has not even been reproduced in historical simulations by climate models[21]. The effectiveness of the Southern Ocean cooling in modulating the zonal gradient of equatorial Pacific SST and the PWC strength is unclear, perhaps owing to differences in experiment design such as the latitudinal–longitudinal location of the forcing[54,60].

Anthropogenic sulphate aerosols emitted mainly from the Northern Hemisphere extratropics are also potential drivers of the tropical Pacific SST pattern change through the interhemispheric energy transport[64,65]. Sulphate aerosols cool the climate system, but the increase and decrease of emissions, observed before and after the 1980s, may have caused cooling and warming trends with changes in the zonal SST contrast in the tropical Pacific. Idealized model experiments with aerosol emission increase and decrease over the Northern Hemisphere show that the eastern equatorial Pacific first warms and then cools associated with the meridional shifts in the Hadley circulation and ITCZ[54,56,66]. Realistic simulations suggest that the reduction in volcanic and anthropogenic aerosol emissions over the Euro-American regions after the 1980s acted to warm the western tropical Pacific and thereby contributed to the strengthening of the zonal SST gradient and the PWC[67–69]. The shift of the emission maxima from the Euro-American regions to East Asia since the 1980s has also been suggested to have affected the IPO-like SST pattern change in an idealized experiment[70], but the role of zonal redistribution of aerosol emissions needs to be elaborated in more realistic simulations[71,72].

Dynamical perspective

Atmosphere–ocean coupled processes are integral in shaping SST variability and change in the tropical Pacific and beyond. Here we review the dynamical mechanisms that can alter the zonal SST gradient, starting from the tropical Pacific, and then extending our view to connections with the extratropics and other tropical basins (red arrows in Fig. 2).

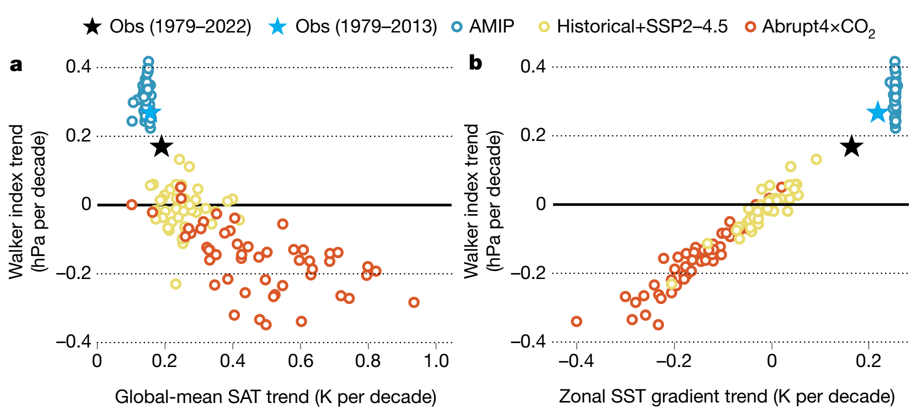

Fig. 3 | Inter-model relationship between the Walker circulation change and temperature-related metrics. a,**b**, Linear trend in the Walker circulation index (hPa per decade) against global-mean surface air temperature (SAT; **a**) and the equatorial Pacific SST zonal gradient trends (**b**; both in K per decade). The linear trends were computed for 1979–2022 in observations (Obs; ERA5 and ERSST v5; black stars) and 54 CMIP6 historical+SSP2-4.5 simulations (yellow circles), and for 1979–2013 in observations (blue stars) and 39 Atmospheric Model Intercomparison Project (AMIP) simulations (blue circles). The trends for 150 years in 51 abrupt4×CO_2 simulations (orange circles) are also plotted.

Box 2

Role of clouds

Changes in clouds affect not only the equilibrium climate sensitivity and the transient climate response but potentially also warming patterns[143]. In the tropical Pacific, convective high clouds over the warm pool act to warm the surface owing to the greenhouse effect, whereas low clouds over the eastern subtropics reflect insolation and have a cooling effect. Associated with the tropopause rise due to greenhouse warming, high clouds shift upward and result in positive longwave feedback. This process itself has been assessed with high confidence[15], but the net radiative effect may be small owing to cancellation with the Planck and the lapse rate feedbacks[144,145]. Subtropical low clouds are projected to decrease with local surface warming and might therefore act to amplify part of the observed SST trend pattern[146]. The local positive cloud shortwave feedback will be similarly seen if the eastern subtropical Pacific warms in the future[50] but with uncertainty in the magnitude[147]. Although there are model-based suggestions that the low-cloud feedback acts to weaken the zonal SST gradient in future projections[148–150], we do not have sufficient confidence yet about the role of local cloud feedback in the recent SST pattern change.

Two main coupled feedback processes exist in the tropical Pacific (Box 1). One is the Bjerknes feedback, arising from a tight coupling between the zonal SST gradient, the equatorial trade winds associated with the PWC, and the zonal thermocline slope[73]. The Bjerknes feedback is critical in forming both the tropical Pacific climate mean state and the El Niño/Southern Oscillation (ENSO)[74]. Another important coupled process observed in the tropics and subtropics is the wind–evaporation–SST (WES) feedback, which is associated primarily with changes in the meridional instead of zonal SST gradients[48,75]. The WES feedback was proposed to explain the mean ITCZ position[75] and can apply to the radiatively forced SST pattern formation[48]. The Bjerknes and WES feedbacks are the heart of the coupled dynamics in the tropics and subtropics and are important in forming the pattern of SST change[50], but they cannot determine the direction of a forced change in the SST pattern and the PWC. This can be understood by recalling the role of water vapour in global warming as an analogy: water vapour acts as positive radiative feedback to amplify greenhouse gas-induced warming, but it is an internal process of the climate system and not the external driver of the warming. However, the strength of the Bjerknes feedback varies across climate models and it affects the magnitude of the trends in the zonal SST gradient and the PWC[76] (Fig. 3b).

Ocean dynamical thermostat

The wind-driven shallow overturning of the Pacific subtropical cells (STCs), which link the extratropical and tropical Pacific Ocean and include a subducting branch in the subtropics and an upwelling branch along the Equator, provide several mechanisms that can alter the zonal SST gradient in response to uniform warming. The first mechanism, called the ocean dynamical thermostat[77–79], relies on the time delay in the warming response of the surface and subsurface ocean. Whereas the western equatorial Pacific can warm immediately when exposed to radiative forcing, warming in the eastern Pacific is delayed as the temperature is at least partly set by the upwelling of cool subsurface water that has not been exposed to the surface warming for approximately 5–10 years[80]. The ocean dynamical thermostat mechanism has been shown to operate in climate models, although it is most apparent as an initial response (about 10 years) to large changes in radiative forcing[24,69].

Oceanic tunnel

Changes in the heat transport by STCs provide the mechanism often called the oceanic tunnel, which can lead to differences in tropical SSTs and their zonal gradients[49,81]. These SST changes arise from either modulation of the rate of wind-driven overturning, with a faster overturning strengthening the zonal SST gradient through enhanced upwelling of subsurface cool water in the eastern Pacific or vice versa[82], or a change in the water properties (for example, temperature anomalies transported by the climatological STCs[49,83,84], which may also be density compensated and are known as spiciness anomalies[85]). When viewed as a mechanism for transporting temperature anomalies, anthropogenically warmed extratropical water advected by the mean STCs probably contributes to the projected weakening of the equatorial zonal SST contrast[54,56,86]. Although both STC mechanisms can modulate equatorial temperature, the timing of this response can be different as changes in the wind-driven STCs occur on sub-decadal timescales[87] whereas the advection by mean STCs occurs on decadal and longer timescales[88]. Projection simulations suggest a weakening of the STCs in the Northern Hemisphere and a strengthening in the Southern Hemisphere in response to surface wind stress changes[89,90]. The total equatorial subsurface convergence and surface divergence of the STCs are projected to decrease[91], probably contributing to the weakening of the equatorial zonal SST gradient although the efficiency of this process remains uncertain[92].

Tropical basin interaction

Tropical atmospheric teleconnections that link ocean basins have also been proposed to play a role in modulating the PWC and hence the zonal SST gradients[93] (Fig. 2). Observational analyses and modelling studies of varying complexity all suggest that relative warming in both the Indian and Atlantic basins leads to stronger equatorial Pacific trade winds and hence to an enhanced zonal SST gradient[3,94–99]. These interbasin relationships exist on interannual and decadal timescales and extend to include the response to human-induced warming. Recent studies suggest that the pan-tropical basin interaction is underestimated in many climate models[21,93,94]. Models that include a stronger, more realistic influence from the Atlantic and Indian Ocean to the Pacific tend to mitigate the future weakening of the Pacific zonal SST gradient by other mechanisms.

ENSO-related processes

It has long been recognized that changes in the tropical Pacific climatological mean state can affect the characteristics of ENSO[100], such as its amplitude, pattern and periodicity[101,102]. However, it has also been suggested that changes in ENSO variability, in turn, affect the mean state through nonlinearities in the air–sea coupled processes, such as nonlinear dynamical heating[100,103,104]. Therefore, uncertainties in future changes of ENSO variance translate to uncertainties in the tropical Pacific mean-state change[105,106]. Although there is an indication that global warming will increase the number of extreme El Niño events[107], it is still uncertain how other ENSO characteristics will change in the future. Yet, ENSO-induced rainfall variability will robustly increase in a warming climate regardless of the change in ENSO characteristic[108–111], which can act to suppress the ocean upwelling in the central-eastern equatorial Pacific through increased freshwater flux[112]. Although this mechanism has not been verified for the historical period, increasing rainfall variability in the eastern tropical Pacific has been identified from recent observations[113], which provides an additional argument as to why one might expect the weakening of the zonal SST gradient in the future.

Reconciling past and future changes

The above discussion highlights mechanisms that act to either strengthen or weaken the zonal SST gradient and PWC (Fig. 4).

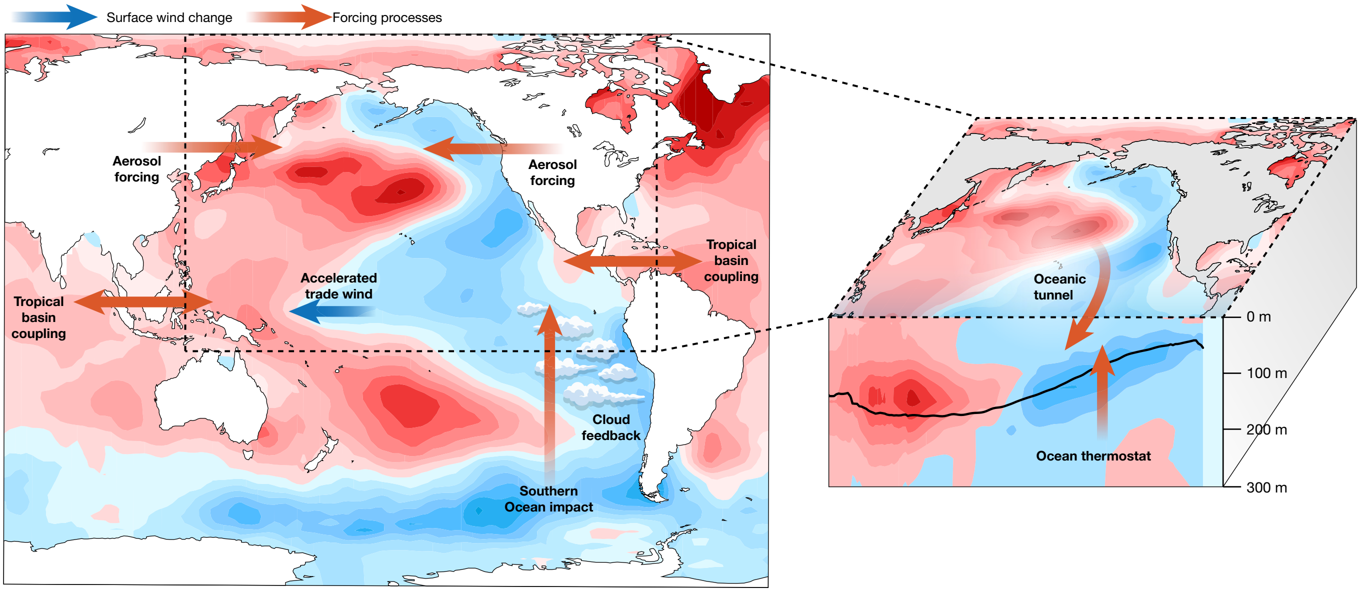

Fig. 4 | Schematic illustration of possible forced mechanisms for the tropical Pacific changes in the zonal SST contrast and associated trade winds. The processes operating in the atmosphere and the surface (left) and in the ocean (right) are shown separately. Red arrows represent the forcing processes whereas the blue arrow indicates the past strengthening of the PWC. The background shading shows the SST and equatorial ocean temperature trends for 1979–2013.

Table 1 summarizes our assessment of how different mechanisms have contributed to shaping the tropical Pacific SST pattern change over the recent past, as well as its long-term projection. We emphasize that they are based on multiple lines of evidence: climate model simulations, theory, observationally constrained coupled simulations often called pacemaker experiments, emergent constraints and, more importantly, our fundamental understanding of physical processes, altogether used to reconcile the past strengthening trend with the projected weakening of the zonal SST gradient in the future.

The ocean dynamical thermostat is a relatively fast-acting process, which suppresses surface warming in the eastern equatorial Pacific until the subsurface warms and diminishes this process. There is a suggestion that the current generation of climate models underestimate this effect[114]; nevertheless, our process understanding suggests that this mechanism is not dominant in the long-term response to greenhouse gas forcing, because it has a relatively fast timescale[24,69]. Effects of aerosol radiative forcing on the SST pattern change depend on the amount and location of emissions as well as their rate. Although aerosol forcing has been highlighted as a driver of the past SST trend pattern, it is expected to be less so in the long-term projections as most of the future socio-economic scenarios assume a continuous decline of anthropogenic aerosol emissions[1]. The observed Southern Ocean cooling trend (Fig. 1a,b) is a peculiar feature not reproduced in climate model simulations[4,21]. This has probably occurred owing to a combination of local ocean heat uptake, the Antarctic ozone hole[115], meltwater flux from the Antarctic ice sheet and multi-decadal variability of the Southern Ocean deep convection[116]. Although the degree to which Antarctic meltwater causes Southern Ocean cooling is subject to large uncertainty[117], heat uptake is expected to weaken as the ocean interior warms further, turning the cooling into a warming in the future climate[15]. Relatively larger warming of the tropical Indian Ocean and Atlantic, which has contributed to strengthening of the zonal SST gradient and PWC in the past, may remain in the future projections as the pattern of the warming on those tropical basins is largely influenced by radiative forcing[114]. However, as most of the above mechanisms leading to the strengthening trend operate only temporarily in the course of global warming, they are not expected to play a dominant role in the long-term future (Table 1), although the timing of when the importance of these mechanisms decreases is still uncertain.

There are two key mechanisms that can result in a weakening of the zonal SST gradient: the global hydrological constraint (also called the GMS mechanism) and differential evaporative damping. Both mechanisms are supported by theory and considered robust processes that scale with the global warming level. Even though these mechanisms have probably not been efficient during the historical period[40,49], their importance is expected to be enhanced in future warming in the central-eastern tropical Pacific as Earth's surface continues to warm. Other mechanisms contributing to a weakening of the zonal gradient (that is, rainfall-induced freshwater forcing and oceanic tunnels) affect the efficiency of dynamical cooling in the equatorial Pacific by altering ocean stratification. They are dependent on the regional changes in SST and precipitation that are not directly related to the global warming level, but scale with the mean SST increase in the tropical Pacific[49,108]. Furthermore, the weakening of the zonal SST gradient in the future warm climate is supported by palaeoclimate evidence, which shows that the zonal SST gradient was weaker during the Pliocene warm period[118–121].

Given that the mechanisms explaining the future weakening of the SST gradient are robust both in climate model projections and supported by our process understanding, there are three possibilities to explain its past strengthening: transient forced responses summarized above; large internal variability; and a combination of them. Many studies that analysed large climate model ensembles have shown that the spread of the past SST and PWC trend patterns due to internal variability is larger than the difference of the forced response across models, supporting an active role of internal variability[6,7,19,20]. Nevertheless, the multiple lines of evidence suggest that the observed recent SST trends are in part due to external forcing (Table 1). As the first and second possibilities are not exclusive but can coexist, the most plausible hypothesis is the third one (namely, that their combination explains the past strengthening of the zonal SST gradient and the PWC).

Although definitive evidence has not yet been provided, our current understanding of the physical mechanisms reviewed above suggests that the strengthening mechanisms have been efficient in the recent

Table 1 | Summary of existing mechanisms of the forced tropical Pacific response to uniform and non-uniform external drivers, and their importance in the past and future

Mechanism	Direction for the zonal SST gradient and PWC	Role in the past (1979–2022) (possible model bias)	Role in the future (by 2100)	Lines of evidence
Energy budget constraint on the hydrological cycle or anomalous GMS mechanism[31,41,46]	Weakening	Inefficient[39,40]	More important[33–35,42–44]	Climate models, theory and process understanding
Differential evaporative damping[47,48]	Weakening	Not identified	Important[48–50]	Climate models, theory and process understanding
Rainfall-induced freshwater forcing[112]	Weakening	Inefficient[111,113]	More important[108–110]	Climate models and process understanding
Oceanic tunnel[49,81]	Weakening	Potentially important[82–84]	More important[49,86–92]	Climate models and process understanding
Ocean dynamical thermostat[77]	Strengthening	Potentially important[80] (underestimated[114])	Less important[24,56,78,79]	Climate models, observations and process understanding
Relative warming of the tropical Atlantic or Indian Ocean[3,93–99]	Strengthening	Important[3,94–99] (underestimated[21,93])	Remains equally important[93]	Climate model pacemaker experiments and process understanding
Aerosol forcing[64–66]	Strengthening	Important[67–69]	Less important[1]	Climate models
Southern Ocean cooling[54–63]	Strengthening	Important[60,61] (not well represented[60,63])	Reverses in sign[125–127]	Climate model pacemaker experiments and emergent constraints
ENSO nonlinear rectification[100,103,104]	Strengthening or weakening	Not identified	Important if ENSO skewness changes[105–107]	Climate models and process understanding

Direction defines the change in the tropical Pacific zonal SST gradient and the PWC. The importance of individual mechanisms in the past and the future was evaluated on the basis of the lines of evidence shown in the last column. Mechanisms that are probably underestimated or not well represented in climate models are indicated by brackets.

past, whereas the weakening mechanisms that will dominate at large global warming levels have so far been less efficient. This narrative reconciling the past and future SST pattern changes in the tropical Pacific is testable in future studies, and we cannot rule out the possibility that the narrative becomes irrelevant if there are strengthening mechanisms that have not been identified and are severely underestimated in current climate models.

Resolving model–observations discrepancy

Attribution of the recent tropical Pacific SST pattern change and associated PWC strengthening to external forcing and internal climate variability remains a challenge[22]. As the relative contribution of internal variability depends on the model's ability to represent the externally forced response adequately, the estimate may be biased if models do not represent the transient forced responses well[122]. There is also a possibility of internal variability being too weak in models. Indeed, a recent palaeoclimate reconstruction suggests that the 1992–2011 PWC intensification was not unprecedented over the past 800 years[123], although this PWC intensification appears near the tail of the probability distribution. The null hypothesis that the observed recent trend can be explained solely by internal variability still needs to be tested carefully using, for example, an ensemble of long control simulations. Much focus has been on testing this null hypothesis on the basis of SST patterns. However, natural variations could be more easily distinguished from the forced response by looking at other climate variables such as the ocean subsurface temperature and precursor patterns of surface fluxes.

Regarding the discrepancy between observations and models, some of the model errors that prevent them from producing the past SST trend have been identified (for example, equatorial Pacific[23] or tropical Atlantic[94] mean states and subtropical cloud feedback[63]). These errors may explain the underestimation of the trans-basin coupling[93] and the Southern Ocean cooing impact[60] that would otherwise act to strengthen the zonal SST gradient in climate models (Table 1). If models are improved to eliminate such errors or emergent constraints on existing model ensembles are devised, then we need to re-evaluate the contribution of internal variability and the extent to which future projections are modified. Any emergent constraint would probably involve some process-based variables derived from observed interannual variability, which is correlated well with the mechanisms that operate on longer timescales. Some of the mechanisms discussed in Table 1 do have counterparts that operate on shorter timescales, so the prospect of a process-based emergent constraint could be promising. Ultimately, we hope to build a comprehensive theory for the forced changes in SST and circulation[46].

Complications arise as various local and remote mechanisms operate at different timescales (Table 1). Hence, a necessary step for resolving the problem is to quantify the characteristic timescale and the relative roles of individual mechanisms. For example, the hydrological budget argument is a robust constraint to the PWC weakening, but the efficiency may depend on other factors such as the tropical land–ocean warming contrast[124]. For decomposing the mechanisms, it may be useful to apply a technique that overrides surface winds (or heat fluxes) to historical or abrupt CO_2 quadrupling simulations[50]. It is also possible that processes that would have potentially played a role in shaping the tropical Pacific pattern during the historical warming period are missing from models. For example, the Southern Ocean cooling trend in climate models may have occurred if models incorporated interactive ice sheets with which Antarctic meltwater can cause the cooling[125–127]. Another example is the incomplete knowledge of historical aerosol radiative forcing. A recent study shows that, in addition to sulphate aerosols, aerosols due to biomass burning that is highly uncertain in models may have caused a bias in the tropical Indian Ocean warming that then affects the Pacific SST pattern change[128,129].

Reducing persistent biases in the individual air–sea coupled feedbacks in the tropical Pacific is important for narrowing uncertainties in both future ENSO and tropical Pacific mean-state changes[23,106,130,131]. Oceanic processes that might be responsible for the observed warming pattern are potentially sensitive to whether a model resolves ocean eddies or not. Hence, historical simulations with oceanic eddy-resolving resolutions, which are already available, can provide valuable insight into the model–observations discrepancy in the recent past trends[132,133]. Even if these model biases cannot be fully eliminated in the short term, it should be possible to better understand their role in determining the magnitude and timescales of the feedbacks and mechanisms proposed. A further challenge is to utilize kilometre-scale coupled models that would represent the Bjerknes feedback better and also reduce the mean-state error[134]. Another crude yet effective way to test the role of mean-state bias is to adopt coupled models with surface flux corrections. This presumably has only limited usage as the actual processes responsible for creating biases (for example, cloud feedback; Box 2) are not improved, but it is a necessary step for testing whether the model–observations discrepancy is the result of mean-state bias.

As the global climate continues to warm, nature may give us an answer to the puzzle of the mechanisms leading to the tropical Pacific warming pattern change, but climate science should not wait for such changes to appear and instead should take action to improve models as well as to develop theory, diagnostic techniques and attribution methodology for quantifying the physical mechanisms of the tropical Pacific warming pattern changes.

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Additional information

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