Indian Ocean warming modulates Pacific climate change

Jing-Jia Luo[a,b,c,1], **Wataru Sasaki**[a], and **Yukio Masumoto**[a]

[a]Research Institute for Global Change and Application Laboratory, Japan Agency for Marine-Earth Science and Technology, Yokohama, Kanagawa 236-0001, Japan; [b]Centre for Australian Weather and Climate Research, Bureau of Meteorology, Melbourne, VIC 3008, Australia; and [c]State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an 710075, China

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It has been widely believed that the tropical Pacific trade winds weakened in the last century and would further decrease under a warmer climate in the 21st century. Recent high-quality observations, however, suggest that the tropical Pacific winds have actually strengthened in the past two decades. Precise causes of the recent Pacific climate shift are uncertain. Here we explore how the enhanced tropical Indian Ocean warming in recent decades favors stronger trade winds in the western Pacific via the atmosphere and hence is likely to have contributed to the La Niña-like state (with enhanced east–west Walker circulation) through the Pacific ocean–atmosphere interactions. Further analysis, based on 163 climate model simulations with centennial historical and projected external radiative forcing, suggests that the Indian Ocean warming relative to the Pacific's could play an important role in modulating the Pacific climate changes in the 20th and 21st centuries.

centennial trends | interbasin influence | multidecadal fluctuations | El Niño change

The tropical Pacific climate has considerable environmental and socioeconomic influence over the globe. How the tropical Pacific climate changes under increasing greenhouse gases (GHGs) forcing is a matter of concern to both the general public and climate specialists. Up until recently, theory and observational analyses suggested that the atmospheric east–west Walker circulation in the tropical Pacific weakened during the 20th century (1–3). It has also been suggested, on the basis of multimodel projections, that it will further weaken in the 21st century under global warming (4–6). The slackened trade winds associated with the weakening Walker circulation may affect the ocean mean state in a coupled way, leading to a shallowing and flatter thermocline in the equatorial Pacific. However, recent evidence based on high-quality observations suggested that the tropical Pacific trade winds may have actually strengthened over the past two decades (7–12) despite the continuous increase of GHGs emissions. This has cooccurred with a rapid surface warming in the Indian Ocean (IO) (Fig. 1). Satellite and in situ measurements show that the sea level height in the western tropical Pacific has rapidly risen since the mid-1990s in response to the strengthening of the easterly trade winds (10–12). The increasing easterlies have reversed previous multidecadal trends and enhanced the Indonesian Throughflow, the Leeuwin Current west of Australia, and gyre circulations in the tropical northwestern Pacific over the past decade (8–10).

The recent enhancement of the tropical Pacific winds is evident in the decadal mean anomalies during the 2000s (Fig. 2*A*) (13). (The latest strong La Niña years of 2010–2011 were excluded to reduce the impact of uneven El Niño/La Niña events on the decadal mean. Results based on the linear trends of 1982–2009 are similar.) The sea surface temperature (SST) averaged during the period 2000–2009 displays cold anomalies in the eastern Pacific and warm anomalies in the west (Fig. 2*A*). This SST anomaly pattern is closely coupled with stronger-than-normal easterlies in the Pacific and wet (dry) conditions in the west (east). The shift toward a La Niña-like state in the last decade is affirmed by a strengthening Walker circulation and increased thermocline tilt, with subsurface cooling (warming) in the eastern (western) Pacific (Fig. 2 *B* and *C*). The La Niña-like state in the 2000s corresponds to a hiatus period of increase in the global mean surface temperature. In fact, a not-uncommon link between a La Niña-like state and a decade of relative cooling globally was recently discovered in both model projections and historical records (14). This is not surprising, because a La Niña condition usually acts to decrease global surface temperature via atmospheric bridges and oceanic meridional overturning circulations (14). Understanding the recent tropical climate changes is therefore vital as a way of improving both regional and global climate prediction/projection during the 21st century.

Underlying reasons for the recent change to a La Niña-like state (enhancing central-Pacific easterlies and Walker circulation) are unclear. El Niños in the 2000s display distinctive features compared with those in previous decades. The sea surface warm pool (characterized by the 28 °C isotherm) associated with the four El Niños in the 2000s never extended to the eastern Pacific. This feature corresponds to persistently weaker surface westerly anomalies in the central Pacific and less eastward extension of deep convection and subsurface warming (Fig. S1). A null hypothesis is that such El Niño behaviors might be related to natural chaotic variability, which contributes to the recent decadal mean background (13). However, results based on long-historical records suggest the following: changes of the tropical Pacific mean state caused by decadal/interdecadal El Niño/La Niña variability bear no resemblance to the La Niña-like state (15, 16). A paradox is that the El Niño variability may not determine but instead be controlled by the Pacific mean-state change (5, 17, 18). How El Niño/La Niña and the mean state interact and how their interactions impact the mean state remains a long-standing riddle. We find that the central-Pacific trade winds were persistently stronger during both El Niños and La Niñas in the 2000s (Fig. S2); this finding suggests that the recent Pacific climate changes are unlikely to have been caused by natural El Niño/La Niña variability (7, 10, 12). It is noteworthy that the enhanced mean central-Pacific easterlies might help to suppress warm oceanic Kelvin waves and eastern Pacific warming, and hence favor the occurrence of a central-Pacific type of El Niño and La Niña.

Other potential mechanisms for the tropical Pacific mean-state changes include the following: (*i*) natural decadal/multidecadal variability associated with the influence of extratropical oceans (19, 20); (*ii*) Pacific response to global warming (1, 21) and solar forcing (22); or (*iii*) a superposition of natural and human-induced

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[1]To whom correspondence should be addressed. E-mail: j.luo@bom.gov.au.

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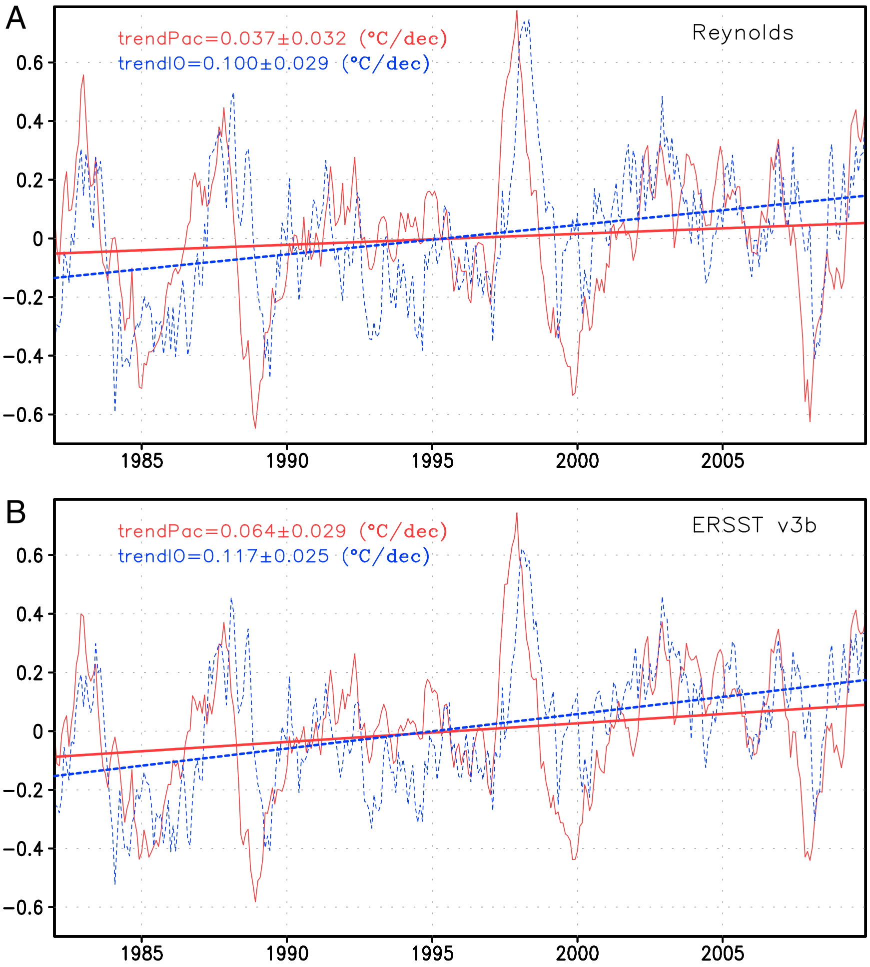

Fig. 1. Warming rates in the tropical IO and Pacific over the past three decades. Shown are monthly anomalies and linear trends of observed SST in the tropical Pacific (120°–280°E, 20°S–20°N, red lines) and IO (40°–120°E, 20°S–20°N, blue lines) based on two independent analyses (*A*, *B*). The linear trends of the IO-minus-Pacific SST differences are 0.063 ± 0.031 and 0.053 ± 0.027 °C per decade, respectively. Error bars denote 95% confidence intervals according to Student *t* test. Results based on HadISST 1.1 data (Fig. S8) and averaged over different latitude bands (e.g., 10°S–10°N or 30°S–30°N) are similar.

changes. The Pacific natural multidecadal processes do not seem to adequately account for the recent climate change. For example, although a previous study (20) displayed equatorward propagation of large subsurface cooling in the South Pacific during the 1990s, which could have provided a favorable condition for the La Niña-like state in the 2000s, we do not find similar features according to multiple ocean reanalysis datasets (Fig. S3); in those, the equatorial Pacific basin-mean heat content is actually above normal in the 2000s (Fig. 2*C*). Besides, it is controversial as to whether atmospheric or oceanic processes might dominate to generate a weaker or stronger Walker circulation under global warming (1, 21). It is also unclear as to whether the recent low decadal solar activity might act to decrease or enhance the La Niña-like climate shift (22). Here we attempt to provide a new plausible mechanism by examining the influence of the tropical IO multidecadal warming trend on the Pacific climate. The IO SST has risen rapidly in recent decades, partly owing to the increasing GHGs forcing (23), two to three times faster than the warming in the tropical Pacific according to two multidecadal analyses of SST (Fig. 1). We note, however, that exact factors contributing to the faster warming in the IO remain unclear (24, 25).

Results

Fig. 3 depicts the impacts of multidecadal IO warming on the Pacific climate according to two sets of climate model experiments (*Methods*; external radiative forcing in the model is fixed). In the first set of coupled model experiments, we simulate the atmospheric response to observed SST in the tropical IO and prescribe climatological SST elsewhere. In the second set of experiments, we prescribe climatological SST in the IO but allow free ocean–atmosphere interactions elsewhere (control run). We superimpose on the control run four different warming trends in the IO that represent the possible range of warming differences between the IO and the Pacific. We find that the multidecadal IO warming induces excessive surface easterlies in the western Pacific via modifying the atmospheric Walker circulation, and this leads to a La Niña-like state through the Pacific ocean–atmosphere coupling (Fig. 3 and Figs. S4–S6). The IO warming also induces easterly anomalies in the North Pacific, which help to strengthen the subtropical oceanic overturning circulation and enhance the La Niña-like state (26). These results suggest that the enhanced IO warming (in addition to other possible processes) is likely to have contributed to the recent La Niña-like climate shift in the Pacific.

We further examine the IO warming influence on the Pacific, using multimodel simulations for climate in the 20th and 21st centuries, with historical radiative forcing and eight different scenario-projected GHGs forcing, provided by "phase-3 and phase-5 of the Coupled Model Intercomparison Project" (CMIP3 and CMIP5; *Methods*). The simulated IO and Pacific warming is

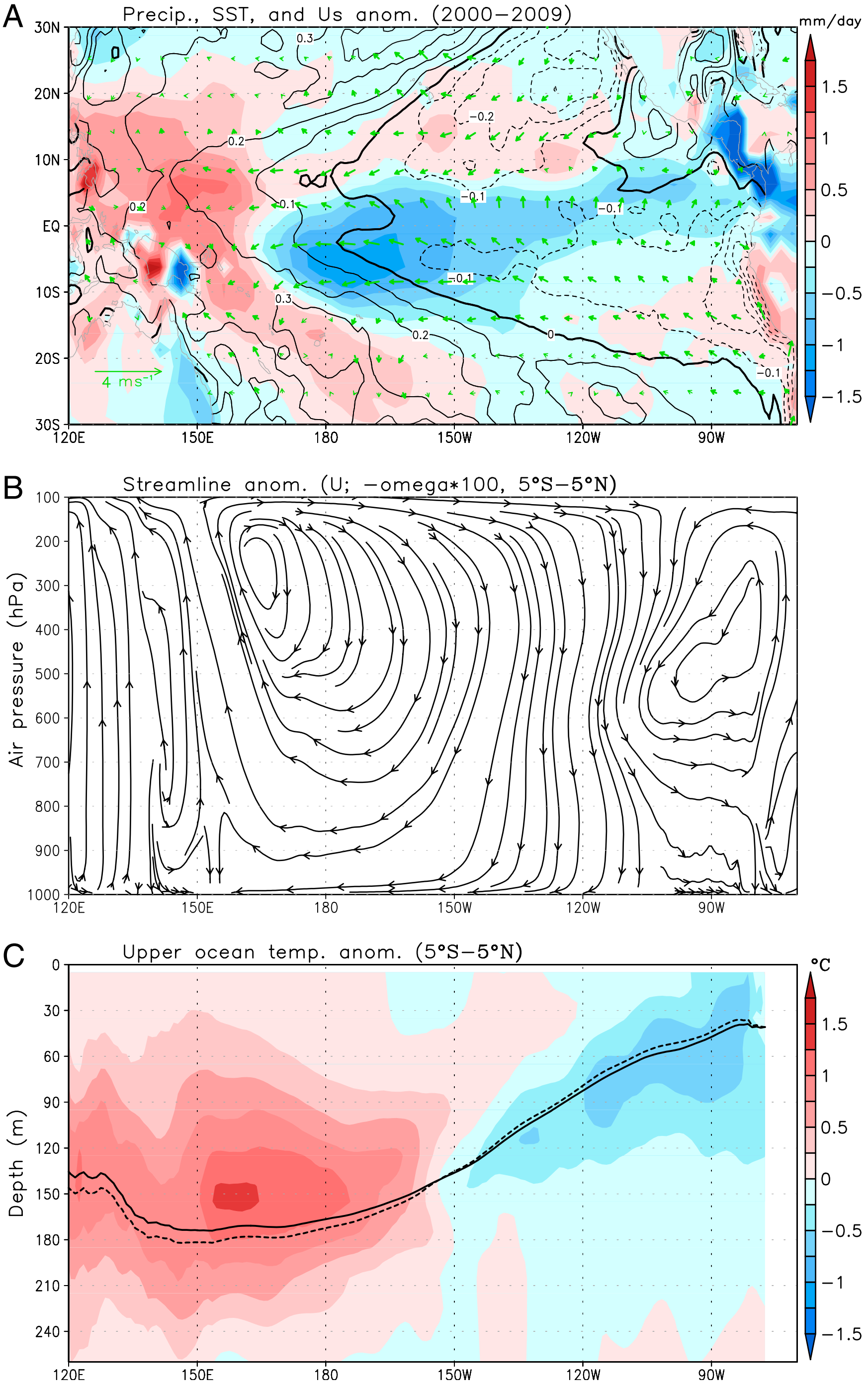

Fig. 2. Pacific climate change in recent decades. Shown are 2000–2009 mean anomalies of (*A*) SST (contour), surface winds (thick vectors indicate ≤5% significance according to one-tailed Student *t* test), and precipitation (mm/d, color shaded) in the tropical Pacific, (*B*) the atmospheric Walker circulation, and (*C*) upper ocean temperature in the equatorial Pacific (5°S–5°N). The anomalies are calculated relative to the climatology of 1983–2006. The solid (dashed) line in (*C*) denotes climatological (2000-2009 mean) 20 °C isotherm, which represents the thermocline depth. Results based on the linear trends of these fields during 1982–2009 and other available ocean and atmosphere reanalysis datasets (Fig. S10) are similar.

proportional to imposed anthropogenic forcing, with more warming corresponding to stronger GHGs forcing. However, the Pacific trade wind changes do not follow the monotonic basin warming. We find that the Pacific wind changes actually correspond to the interbasin warming contrast between the eastern Pacific and the IO, according to the 163-model multiexperiment ensemble simulations (Fig. 4). Both the centennial linear trends and multidecadal changes display in-phase relations between the Pacific winds and interbasin warming contrast, with median correlation coefficients of ∼0.6–0.9. This result suggests that the IO warming, relative to the Pacific's, could be an important process that modulates the Pacific climate changes in the 20th and 21st centuries.

Ninety-nine of the 163 models produce centennial trends of weakened Pacific winds (i.e., positive wind trend) under various GHGs forcing (Fig. 4*A*). A prevailing theory to explain this trend

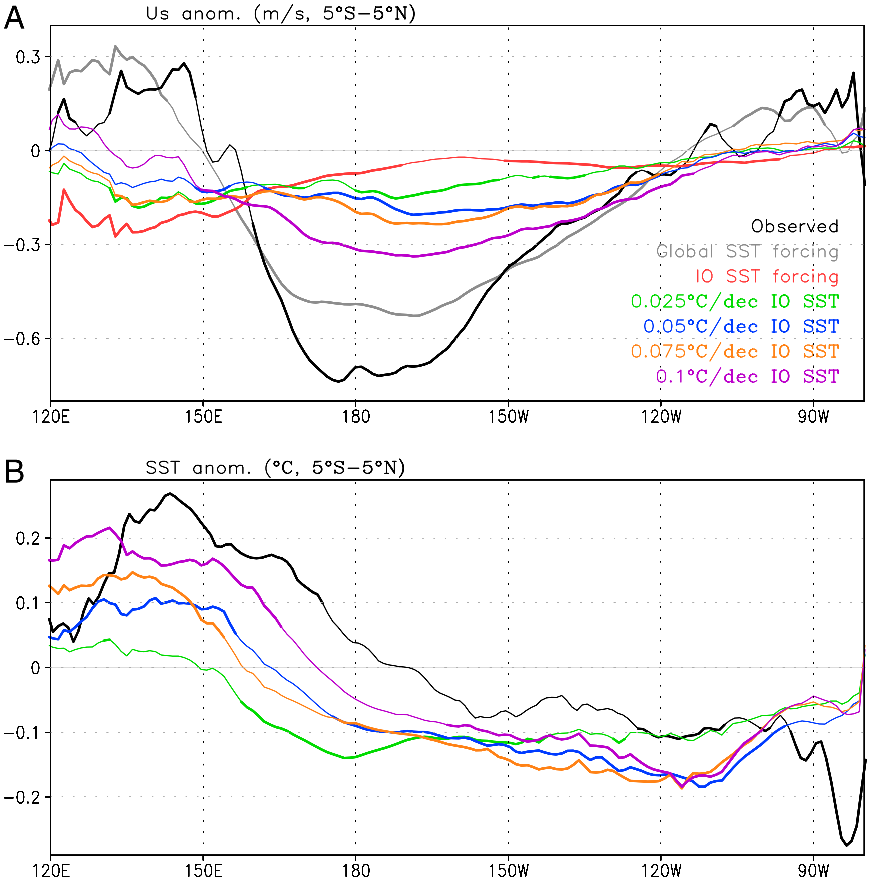

Fig. 3. Influence of multidecadal IO warming on the Pacific climate. Shown are (*A*) zonal surface wind and (*B*) SST changes in the equatorial Pacific (5°S–5°N). Black lines denote the observed anomalies of 2000–2009. Gray line in *A* denotes the wind anomalies reproduced by the SINETX-F climate model with global observed SST forcing (Fig. S9*A*). The red line in *A* displays the influence of the IO SST rise (2000–2009 minus 1982–1999) on the Pacific surface wind via atmospheric processes, based on model experiments in which only the tropical IO observed SST is assimilated into the coupled model, whereas climatological SST is prescribed elsewhere. The green (blue, orange, and purple) lines indicate influences of the IO warming in presence of the Pacific local ocean–atmosphere coupling, based on model sensitivity experiments in which 0.025 (0.05, 0.075, and 0.1) °C per decade warming trend is prescribed in the tropical IO. These are 50-y mean differences between the sensitivity experiments and the control run; in those simulations, we prescribe SST in the IO but keep elsewhere free ocean–atmosphere coupling (*Methods*). Thick lines indicate ≤10% significance according to Student *t* test.

is that atmospheric general circulations would slacken in response to global surface warming (1). Here we find that the weakened Pacific winds in 63 of the 99 models correspond to less IO warming compared with the eastern Pacific. Similarly, 54 of the remaining 64 models show that enhanced Pacific trade winds are closely linked with stronger IO warming. The results suggest that both a stronger and a weaker centennial warming rate in the IO (relative to the Pacific's) could influence the Pacific climate change, and that the stronger IO warming seems to have a more robust influence than the weaker IO warming.

In Fig. 4*B* we depict multidecadal changes of the Pacific winds in the model simulations/projections for climate in the 20th and 21st centuries. Consistent with recent observations (7–12), the 20th century simulations with historical radiative forcing based on 20 CMIP3 climate models show that the Pacific easterlies have intensified since the 1980s (significant at the ≤10% level despite large intermodel spreads). The increasing trade winds correspond to the fact that the IO has warmed faster than the Pacific over the past two to three decades. (Similar results are found from the historical simulations based on 20 CMIP5 models.) This finding suggests that the observed recent climate change toward the La Niña-like state in the tropical Pacific may be partly influenced by the multidecadal fluctuations. Model projections based on the CMIP3 Special Report on Emission Scenarios (SRES) A1B scenario show that the multidecadal changes would help to enhance the Pacific easterlies in coming decades, weaken them from the 2030s to the 2050s, and increase them again from the mid-2060s to the mid-2080s. [Model projections based on SRESA2, SRESB1, and Representative Concentration Pathways (RCP) 45 scenarios show similar results.] It is true that the precise phase of the multidecadal changes may differ in different model simulations and under different external radiative forcing. Nevertheless, from the 10 experiments of the 20th and 21st century climate simulations, we find ubiquitous in-phase relations between the multidecadal fluctuations of the Pacific winds and the IO-eastern Pacific warming contrast, despite the spreads among individual models (Fig. 4*C*). This suggests that the multidecadal IO warming (relative to the Pacific's) may play a role in the multidecadal Pacific climate changes.

Discussion

Before the present study, the importance of multidecadal and centennial IO warming in affecting the Pacific climate had not been well recognized. Previous studies have focused on the response of local ocean–atmosphere processes in the Pacific to increasing GHGs emissions (1, 6, 21). We find that stronger (weaker) IO warming, relative to the Pacific's, helps to enhance (weaken) the Pacific trade winds by modulating the atmospheric Walker circulation. The induced wind changes in the Pacific are subsequently amplified via ocean–atmosphere positive feedbacks in the Pacific between the east–west SST gradient and trade winds. Averaging the eastern and western Pacific SST warming (and hence diminishing the contributions of the Pacific local air–sea interactions) gives results that are similar (Fig. S7), although they have lower correlations than those achieved when the eastern Pacific SSTs are used.

The IO influence on interannual Pacific climate variability has been studied previously (27–29). It is also known that Pacific signals that vary year to year strongly influence the IO climate (30). For example, the El Niño signal usually warms the IO; this helps to increase the Pacific trade winds and hence weaken the El Niño. As a result, the interannual tropical climate variations are influenced by the intrinsic interactions between the IO and the Pacific (28). The interbasin coupling may also act on the

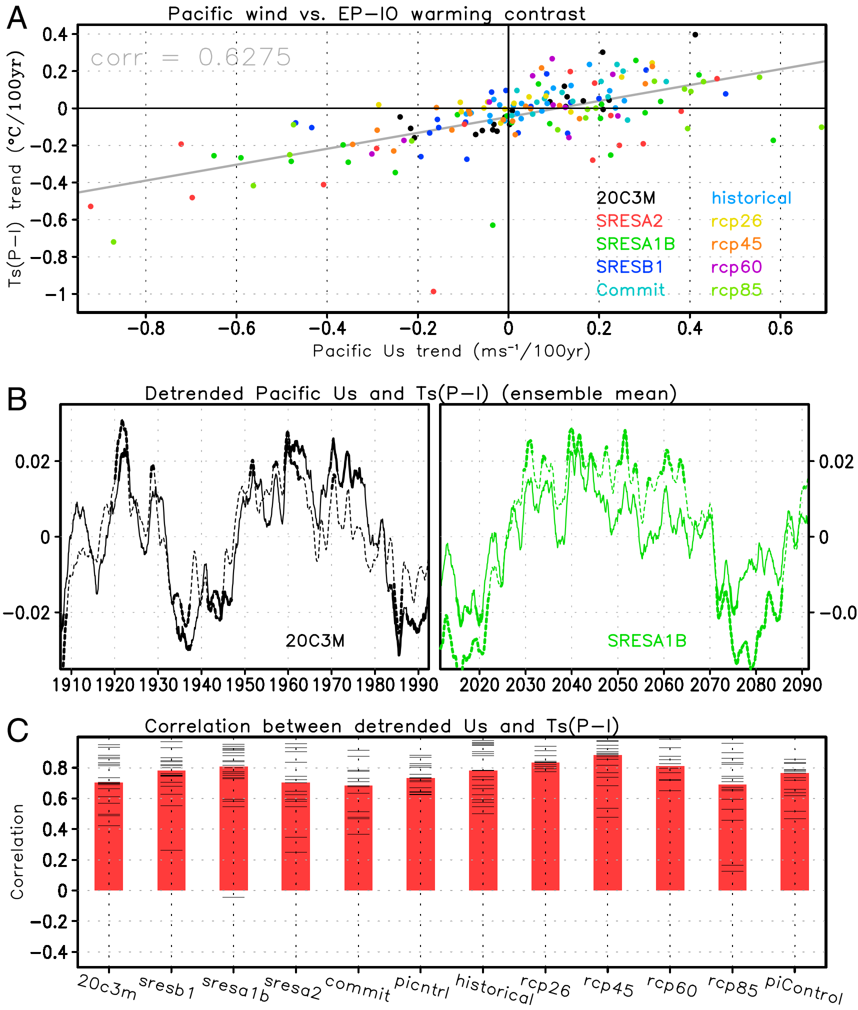

Fig. 4. Pacific wind changes modulated by the IO warming in the simulations of the CMIP3 and CMIP5 models. (*A*) Scatter plot of the linear trends of the Pacific zonal wind (150°–240°E, 10°S–10°N) vs. those of the SST warming difference between the tropical eastern Pacific (200°–280°E, 20°S–20°N) and IO (40°–120°E, 20°S–20°N). Gray line denotes the least-square linear fit of the trends based on 163 models of 10 climate simulation/projection experiments (correlation is 0.63). (*B*) Multidecadal changes of the Pacific wind (solid lines) and eastern Pacific-minus-IO warming difference (dashed lines), with the linear trends being removed. These are multimodel ensemble mean results based on the CMIP3 20C3M and SRESA1B experiments. Thick lines indicate ≤10% significance according to one-tailed Student *t* test. (*C*) Correlations between the multidecadal Pacific zonal wind and eastern Pacific-minus-IO SST difference. Red bars (black lines) denote the median (individual model) correlations.

Indo-Pacific centennial and multidecadal changes. Interestingly, results based on two control experiments with fixed preindustrial GHGs forcing indicate that the multidecadal covariability of the interbasin SST differences and the Pacific winds can also originate from natural ocean–atmosphere processes (the picntrl and piControl in Fig. 4*C*). Extended atmospheric reanalysis shows trends of both enhancing Pacific trade winds and increasing IO-minus-Pacific warming contrast in the 20th century, superimposed with multidecadal covarying fluctuations (Fig. S8). Neither the centennial trends nor multidecadal fluctuations are well reproduced by the CMIP model historical simulations. It is unclear whether the discrepancy could be ascribed to natural multidecadal variability, observational errors, model biases, and/or external radiative forcing uncertainties.

It is suggested that the multidecadal variability could be modulated or partly forced by anthropogenic radiative forcing, particularly the offset effects between GHGs and aerosol (31, 32). However, the signal-to-noise ratio (i.e., the ratio of the variance of multimodel ensemble mean to the variance of intermodel spreads) is small; this indicates uncertainties in attributing the multidecadal changes to external forcing. Besides, understanding exact mechanisms responsible for the multidecadal fluctuations and how global warming might modulate the multidecadal changes remains a challenge. Extratropical ocean processes and the Indonesia Throughflow could play an important role in redistributing the tropical Indo-Pacific interbasin upper-ocean heat content (33) under global warming. To explore this issue requires long-term ocean observations and models with high resolutions for better Indonesia Throughflow simulation. In addition to its direct influence via modifying the Walker cell, the IO warming also affects the North Pacific and Atlantic climate (23), which may subsequently influence the tropical Pacific. Further studies are warranted to clarify these issues. Nevertheless, our results suggest that differences in the response to anthropogenic forcing over individual ocean basins, together with the interinfluence between the tropical IO and the Pacific, may affect not only the centennial trends but also multidecadal changes of the Pacific climate. Correctly reproducing these processes in models would help to reduce uncertainties in the climate projections for the 21st century.

Methods

Observational Datasets. We adopt the high-quality Reynolds SST data, which combined both in situ and satellite observations from 1982 to 2010 (www.emc.ncep.noaa.gov/research/cmb/sst_analysis/). We also use Extended Reconstructed Sea Surface Temperature (ERSST) v3b analysis (www.ncdc.noaa.gov/ersst/), which has excluded satellite observations. Surface winds and atmospheric circulation data are obtained from the "Japanese 25-Year Reanalysis" (jra.kishou.go.jp/JRA-25/index_en.html), precipitation from the National Centers for Environmental Prediction (NCEP, www.cpc.ncep.noaa.gov/products/global_precip/html/wpage.cams_opi.html), and the ocean reanalysis from the NCEP global data assimilation system (www.cpc.ncep.noaa.gov/products/GODAS/). Observed anomalies are calculated relative to the monthly climatology of 1983–2006.

Model Experiments. We use the SINTEX-F global ocean–atmosphere coupled model, which shows excellent performance in simulating and predicting the tropical Indo-Pacific climate (ref. 34 and references therein). Model real-time forecasts of El Niño/La Niña at lead times of up to 2 y are provided monthly at www.jamstec.go.jp/frcgc/research/d1/iod/e/seasonal/outlook.html. The atmospheric component has a resolution of 1.1° (T106) with 19 vertical σ-pressure levels. Its oceanic component has a 2° Mercator horizontal mesh (finer meridional resolution of 0.5° around the equator) with 31 vertical levels. All external radiative forcing in the model is fixed at present-day levels so that the impacts of anthropogenic and natural radiative forcing changes have been explicitly excluded.

To examine the influence of multidecadal IO warming (relative to the Pacific's) on the Pacific climate, we perform two sets of model experiments. In the control of the first set of experiments, we assimilate observed SST into the coupled model with nine ensemble members (34). The model with global SST forcing realistically reproduces the enhanced central-Pacific easterlies (a La Niña-like state with enhanced Walker circulation) in the 2000s (Fig. S9). In the sensitivity experiment of the first set, we assimilate observed SST only in the tropical IO (20°S–20°N) (28) and prescribe monthly observed climatological SST elsewhere. The nine-member ensemble mean would represent the deterministic (i.e., externally forced) atmospheric response in the Pacific to the IO warming forcing. In the second set of model experiments, we first integrate the freely coupled model for 100 y. According to this, we prescribe the last 50-y climatological SST in the tropical IO but keep elsewhere free ocean–atmosphere coupling. We run the model in this way for 50 y starting from the 51st y (control run). We conduct four sensitivity runs. They are similar to the control run, but we add four linear SST warming trends in the tropical IO (0.025, 0.05, 0.075, and 0.1 °C per decade), which represent the possible range of the warming differences between the IO and the Pacific.

World Climate Research Programme (WCRP) CMIP3 and CMIP5 Model Datasets. Centennial-length climate simulations/projections of 193 coupled models are obtained from the Program for Climate Model Diagnosis and Intercomparison (Tables S1 and S2). From CMIP3 we use the 20th century simulation with historical external radiative forcing (20C3M) and the 21st century projections based on the SRESB1, -A1B, and -A2 as well as the commitment experiment (commit: all GHGs' concentrations are fixed at year 2000 values) (35). From CMIP5 we use the 20th century simulation with historical anthropogenic and natural forcing (historical) and the 21st century projections based on the RCP26, -45, -60, and -85 (36). These are conducted by 163 models in total. In addition, 300-y model simulations with fixed preindustrial GHGs forcing (CMIP3 picntrl and CMIP5 piControl) are analyzed (30 models in total). We select as many models as possible for each simulation/projection based on the availability of SST and surface winds provided by each model. An ensemble mean for each model (with the numbers of members varying from 1 to 10) is used. Model monthly anomalies are calculated relative to the century (or 300-y) climatology and smoothed using a 15-y running mean to display multidecadal changes.

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