The Role of Tropical Interbasin SST Gradients in Forcing Walker Circulation Trends

LEI ZHANG
Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, Boulder, Colorado

KRISTOPHER B. KARNAUSKAS
Cooperative Institute for Research in Environmental Sciences, and Department of Atmospheric and Oceanic Sciences, University of Colorado Boulder, Boulder, Colorado

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ABSTRACT

The effects of externally forced tropical sea surface temperature (SST) anomalies on long-term Walker circulation changes are investigated through numerical atmospheric general circulation model (AGCM) experiments. In response to the observed tropics-wide SST trend, which exhibits a prominent interbasin warming contrast (IBWC) with smaller warming in the Pacific than the Indian and Atlantic Oceans that includes a weak La Niña–like pattern in the equatorial Pacific, pronounced low-level easterly anomalies emerge over the equatorial Pacific. Through sensitivity experiments, the intensification of the Pacific trade winds (PTWs) is attributable to the IBWC, whereas the slightly enhanced zonal SST gradient within the equatorial Pacific plays a small role relative to the observed IBWC. It is further demonstrated that the greater Indian Ocean warming forces low-level easterly anomalies over the entire equatorial Pacific, while the greater tropical Atlantic warming-driven enhancement of PTWs is located over the central equatorial Pacific. In contrast to observations, a negligible IBWC emerges in the tropical SST trends of CMIP5 historical simulations due to a strong El Niño–like warming in the tropical Pacific. Lacking the observed IBWC (and the observed enhancement of the zonal SST gradient within the equatorial Pacific), the PTWs in the CMIP5 ensemble can only weaken.

1. Introduction

The tropical Pacific trade winds (PTWs), or the surface branch of the Walker circulation, have been strengthening since the mid-1990s (Merrifield 2011; England et al. 2014), accompanied by a prominent cooling trend in the sea surface temperature (SST) of the eastern tropical Pacific (Kosaka and Xie 2013; Trenberth et al. 2014). It has been suggested that both the enhanced PTWs and the eastern Pacific cooling are closely connected with the observed global warming hiatus occurring since the late 1990s (Meehl et al. 2011; Kosaka and Xie 2013; England et al. 2014; Watanabe et al. 2014). It has been suggested that the spatial distribution of tropical SST trends plays an important role in PTW changes (Xie et al. 2010; Meng et al. 2012; Zhang and Li 2016). In particular, it has been suggested that the observed interbasin warming contrast (IBWC; i.e., less Pacific warming compared to the Indian Ocean and the tropical Atlantic) may have contributed to the intensification of PTWs over the recent decades (e.g., Luo et al. 2012; McGregor et al. 2014). It has also been found that the warming of the Indian Ocean exceeds that of the Pacific in the past few decades, which drives low-level easterly anomalies over tropical Pacific, strengthening the PTWs (Luo et al. 2012; Han et al. 2014). Furthermore, the excessive tropical Atlantic warming compared to the adjacent eastern Pacific has been suggested to make a contribution to the enhanced PTWs as well, through anomalous zonal overturning straddling the South American continent (Kucharski et al. 2011; McGregor et al. 2014; Li et al. 2015).

Compared with the well-observed PTW changes in recent decades, the long-term changes of the Pacific Walker circulation are less clear because of sparse observations in the early period of the twentieth century.

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Corresponding author e-mail: Lei Zhang, lezh8230@colorado.edu

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(DiNezio et al. 2013). Vecchi et al. (2006) identified a weakened Walker circulation resulting from anthropogenic forcing based on the analysis of the long-term sea level pressure (SLP) trend over the period 1861–1992. By constructing an SST dataset using only bucket measurements, Tokinaga et al. (2012) found a reduced zonal SST gradient in tropical Pacific, which in turn forces a weakened Walker circulation. In contrast, Meng et al. (2012) found a strengthened Pacific Walker circulation in an atmospheric general circulation model (AGCM) forced by observed SST trends in the tropical region since 1870. It is also found that the PTWs have been strengthening in twentieth century when the ENSO-related signals were removed (Compo and Sardeshmukh 2010; Sandeep et al. 2014). Hence, how the Walker circulation responds to global warming remains uncertain, although some promising mechanistic insights have emerged from the study of decadal variability.

The physical mechanisms for the long-term changes of PTWs under global warming have also been intensively studied (Knutson and Manabe 1995; Clement et al. 1996; Held and Soden 2006; Zhang and Li 2016), which, as mentioned above, is closely associated with the differential SST warming in tropics. Several studies have found that the observed long-term linear SST trends associated with anthropogenic forcing are manifested as smaller Pacific warming compared with Indian Ocean and tropical Atlantic and a slightly enhanced zonal SST gradient in tropical Pacific (Karnauskas et al. 2009; Sandeep et al. 2014; Zhang 2016). The formation of such a trend pattern might be attributed to the so-called “ocean thermostat mechanism” associated with the warming being damped by oceanic upwelling in equatorial eastern Pacific under global warming (Clement et al. 1996; Seager and Murtagh 1997).

In contrast, it is abundantly clear that future projections from multimodel ensembles of the global climate models that participated in phases 3 and 5 of the Coupled Model Intercomparison Project (CMIP3 and CMIP5) predict an El Niño–like SST warming trend (i.e., reduced zonal SST gradient in the equatorial Pacific), and most predict a weakened Walker circulation in response to anthropogenic greenhouse gas emissions (Vecchi and Soden 2007; Xie et al. 2010; Zhang and Li 2014). A very similar spatial pattern of long-term SST trend is also found in the corresponding historical runs, which is distinctively different from most analyses of the observed SST trends based on available instrumental reconstructions (Karnauskas et al. 2009; Compo and Sardeshmukh 2010; Solomon and Newman 2012; Zhang 2016).

In this study, forced AGCM experiments are conducted to separate the contribution of internal variability from externally forced tropical SST trends, and to further separate the role of forced SST trends in each of the three major tropical ocean basins on the long-term changes of the Walker circulation or PTWs. Importantly, how the pronounced discrepancies between observations and climate model simulations of tropical SST trends may affect estimates and simulations of changes of PTWs is also examined.

2. Data and methodology

a. Observations

The instrumental SST reconstruction for the period of 1900–2013 from the Hadley Centre Sea Ice and SST dataset (HadISST; Rayner et al. 2003) was employed in this study. The extended-range SST data from the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed SST dataset, version 3b (ERSST. v3b; Smith et al. 2008) and the Kaplan SST dataset (Kaplan et al. 1998) were also analyzed for comparison. Zhang (2016) points out that the first two leading empirical orthogonal function (EOF) modes of the 5-yr running mean global SST essentially describe the externally forced global warming mode [first EOF (EOF1)] and interdecadal Pacific oscillation (IPO)-like natural variability [second EOF (EOF2)], respectively. A 5-yr running mean filter was applied to remove the influence of the strong interannual variability [i.e., El Niño and Southern Oscillation (ENSO)]. The same procedure was applied here to obtain the SST warming patterns associated with anthropogenic greenhouse warming. Interested readers can refer to Zhang (2016) for a more in-depth discussion. The spatial pattern of the EOF1 mode is almost identical to the long-term linear SST trends for both observed and model SST (figure not shown).

b. Model experiments

AGCM experiments were conducted using the Max Planck Institute (MPI) ECHAM4.6 at a T42 spectral horizontal resolution (corresponding to $2.8125^\circ \times 2.8125^\circ$ grid resolution) with 19 vertical levels (Roeckner et al. 1996). The model was integrated for 20 years and the last 15 years were analyzed. The first 5 years were discarded given that it takes some time for the model atmosphere to reach a state of statistical equilibrium. The numerical experiments are designed as follows: in addition to the control run (CTRL), which was forced by the monthly climatological SST field, the same spatial pattern of the EOF1 (EOF2) mode of smoothed global SST was included in each month to force the atmosphere (Fig. 1), which is referred to as Had1 (Had2); the ensemble mean EOF1 mode of SST from 125 CMIP5 historical runs (Table 1) within 30°N and 30°S was added as the forcing compared with the CTRL (CH1; see Table 2 for experiment names.)
We also conducted a set of experiments that separate the effects of SST trends in the different ocean basins: atmospheric responses to tropical Indian Ocean SST warming associated with the EOF1 mode for HadISST was analyzed (HadIO), and the same for the tropical Pacific Ocean (HadPac) and tropical Atlantic Ocean (HadAtl). CHPac is used to refer to the experiment forced by the climatological SST field plus the tropical Pacific SSTA associated with the ensemble mean EOF1 mode for CMIP5 historical runs. We chose 20°E, 120°E, and 80°W as the boundaries between the three ocean basins (Fig. 1a), but we confirmed through additional sensitivity experiments that the results are insensitive to minor variations in these boundaries and the manner in which they are implemented as model surface forcing (e.g., as a stepwise transition, a zonally smoothed transition zone along the boundary, or a linearly damped transition zone). There is no significant impact of artificial gradients introduced by applying forcing in one basin but not the neighboring basin(s). Each of the numerical experiments performed in this study is summarized in Table 2. In the Had2 experiment, we only used SST data in the Pacific region, given the evident discrepancies in SST data in other basins among different SST datasets (Fig. 1b; see also Figs. S1c,d in the supplemental material).

3. Results

a. Characterizing the observed and simulated tropical SST warming

EOF analysis was conducted to separate orthogonal modes of SST variability and extract the long-term trend. The first (second) dominant mode accounts for 54.9% (10.6%) of total variance. As found in Zhang (2016), the leading mode of HadISST presents as nearly ubiquitous SST warming globally (Fig. 1a), and the first principal component (PC1) is highly correlated with the time evolution of global mean SST (0.95), both of which exhibit a relatively steady rising trend (Fig. 1d). Thus, EOF1 essentially reflects the global warming signal. It is noted that the warming in the tropical Pacific basin is clearly smaller than that in the Indian Ocean and tropical Atlantic, associated with a slight enhancement of the zonal SST gradient in equatorial Pacific (Fig. 1a). The second mode exhibits an IPO-like pattern in tropical Pacific (Zhang et al. 1997; Power et al. 1999) with pronounced cooling (warming) anomalies in tropical eastern Pacific (subtropical Pacific) (Fig. 1b), with second principal component (PC2) being highly correlated with the IPO index (−0.82). PC2 switched to the positive phase in the past decade (Fig. 1d), contributing to the evident eastern Pacific cooling trend. In contrast with the instrumental observations, an El Niño–like SST warming pattern emerges in the EOF1 mode for CMIP5 historical runs, yielding no overall IBWC (Fig. 1c).

b. Simulated response to global warming and IPO

In response to the greater warming in tropical Indian and Atlantic Oceans, positive precipitation anomalies and negative SLP anomalies emerge in both ocean basins in Had1 (Figs. 2a,b). In the tropical Pacific, the zonal SLP gradient is enhanced, accompanied by low-level easterly anomalies over the equatorial central Pacific, thus strengthening the PTWs and Walker circulation. Consistently, drying anomalies occur in the equatorial central Pacific, mimicking the La Niña event (Fig. 2b). We note that there is no positive precipitation response over Maritime Continent as would be expected during a La Niña event, which may be associated with the prominent Indian
Ocean warming effect. In Had2, the substantial eastern Pacific cooling anomalies associated with the IPO forces pronounced low-level easterly anomalies over equatorial Pacific (Fig. 2c), and drying anomalies appear in equatorial central-western Pacific (Fig. 2d). Hence, both the externally forced and IPO-related SST patterns force strengthened PTWs.

As mentioned in the introduction, the PTWs have been strengthening in recent decades, accompanied by a pronounced eastern Pacific cooling trend and prominent SST warming trend in the Indian Ocean and Atlantic Ocean (Fig. 3). Consistently, the observed zonal SLP gradient in tropical Pacific is enhanced, and strong interbasin SLP gradients appear in response to the IBWC (Fig. 3b). It was suggested in previous studies that the IPO may contribute to the recent global warming hiatus and enhanced PTWs (e.g., England et al. 2014; Meehl and Teng 2014). Indeed, we note that there is a negative-to-positive phase transition in PC2 since the mid-1990s (Fig. 1d). On the contrary, the EOF1 mode may not play an important role in the recent IBWC, given that 1) the trend in PC1 during the period 1994–2013 is small compared with that in PC2 (Fig. 1d), and 2) there are discrepancies evident in the Indian Ocean and Atlantic Ocean warming patterns between Figs. 1a and 3a.

c. SST warming in each basin

In Had1, both the increased zonal SST gradient in tropical Pacific and the IBWC may contribute to the enhanced PTWs (Fig. 1a). To explore the relative roles

<table>
<thead>
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<th>Model</th>
<th>Modeling center (group)</th>
<th>AGCM resolution (lon × lat)</th>
<th>Ensemble No.</th>
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</thead>
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<tr>
<td>ACCESS1.3</td>
<td></td>
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<td>1</td>
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<td>CMCC-CMS</td>
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<td>FG0ALS-g2</td>
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<td>3</td>
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<td>MIROC5</td>
<td>Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology</td>
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<tr>
<td>MPI-ESM-LR</td>
<td>Max Planck Institute for Meteorology</td>
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<tr>
<td>MPI-ESM-MR</td>
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<td>3</td>
</tr>
<tr>
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<tr>
<td>NorESM1-M</td>
<td>Norwegian Climate Centre</td>
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of the SSTA in each basin in the intensification of PTWs in Had1, numerical simulations imposing observed SSTA trends in the tropical Pacific, Indian Ocean, and tropical Atlantic separately are analyzed here (Fig. 4). It is found that the low-level easterly anomalies are only weakly enhanced over the equatorial central and eastern Pacific in HadPac (Fig. 4a). Such a result is not surprising, given that 1) the cooling signal of the eastern equatorial Pacific associated with EOF1 is relatively weak in magnitude, and 2) the cooling anomaly is superimposed a background climatological SST that is already cool and far below the convective initiation value (Fig. 1a). Over the western equatorial Pacific, prominent westerly anomalies emerge in the HadPac simulation, which are related to the anomalous cyclonic circulation anomaly over the western North Pacific (WNP) associated with the enhanced rainfall and positive SSTA in situ (Figs. 1a, 4a, and 5a). Associated with local negative SSTAs, prominent drying anomalies emerge in the central equatorial Pacific in the HadPac experiment (Fig. 5a). In contrast, the IBWC generates pronounced low-level easterly anomalies located over equatorial western-central Pacific (Fig. 4b). The remarkable similarities between Figs. 2a and 4b across the tropics suggest that the enhancement of PTWs in Had1 is primarily driven by the SSTA in Indian Ocean and tropical Atlantic, whereas SSTA trends within tropical Pacific alone play a smaller role. Such a result suggests that, in addition to a damping mechanism associated with the oceanic upwelling in the Pacific cold tongue region, the cooling anomalies in the eastern equatorial Pacific could in fact be a response to the remotely (Indian Ocean and tropical Atlantic) driven strengthened PTWs. However, it should be remembered that the presence of a temperature contrast (i.e., the IBWC as defined here) still requires some mechanism to damp SST warming in the tropical Pacific relative to the adjacent basins.

The excessive warming in both the Indian Ocean and tropical Atlantic generates pronounced easterly anomalies over equatorial Pacific, but with some noticeable discrepancies (Figs. 4c,d). The Indian Ocean warming induces substantial local positive rainfall anomalies, negative SLP anomalies, and anomalous large-scale low-level convergent flow (Figs. 4c and 5c), and such an anomalous pattern alters the SLP gradient between the Indian Ocean and tropical Pacific, which thereby forces pronounced easterly anomalies over the entire equatorial Pacific (Fig. 4c) and drying anomalies in the western equatorial Pacific (Fig. 5c). The tropical Atlantic warming also leads to more rainfall and prominent negative SLP anomalies in situ, which in turn give rise to low-level easterly anomalies over the equatorial Pacific

<table>
<thead>
<tr>
<th>Name</th>
<th>SST forcing</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTRL</td>
<td>Monthly climatological SST</td>
</tr>
<tr>
<td>Had1</td>
<td>Climatological SST and EOF1 mode for HadISST (30°N–30°S)</td>
</tr>
<tr>
<td>Had2</td>
<td>Climatological SST and EOF2 mode for HadISST (50°N–50°S, 120°E–80°W)</td>
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<tr>
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<td>Same as Had1, but for domain 30°N–30°S, 20°–120°E only</td>
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<tr>
<td>HadPac</td>
<td>Same as Had1, but for domain 30°N–30°S, 120°E–80°W only</td>
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<tr>
<td>HadAtl</td>
<td>Same as Had1, but for domain 30°N–30°S, 80°W–20°E only</td>
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<tr>
<td>CH1</td>
<td>Same as Had1, but for EOF1 mode for CMIPS historical simulations</td>
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<tr>
<td>CHPac</td>
<td>Same as CH1, but for domain 30°N–30°S, 120°E–80°W only</td>
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The excessive warming in both the Indian Ocean and tropical Atlantic generates pronounced easterly anomalies over equatorial Pacific, but with some noticeable discrepancies (Figs. 4c,d). The Indian Ocean warming induces substantial local positive rainfall anomalies, negative SLP anomalies, and anomalous large-scale low-level convergent flow (Figs. 4c and 5c), and such an anomalous pattern alters the SLP gradient between the Indian Ocean and tropical Pacific, which thereby forces pronounced easterly anomalies over the entire equatorial Pacific (Fig. 4c) and drying anomalies in the western equatorial Pacific (Fig. 5c). The tropical Atlantic warming also leads to more rainfall and prominent negative SLP anomalies in situ, which in turn give rise to low-level easterly anomalies over the equatorial Pacific

![Fig. 2](image-url)
in HadAtl (Figs. 4d and 5d). However, it is noted that
the intensification of PTWs in response to the additional
Atlantic warming is primarily located over the central
equatorial Pacific, whereas low-level westerly anomalies
appear over the eastern equatorial Pacific in HadAtl
(Figs. 4b,d). This result is consistent with McGregor
et al. (2014) and Li et al. (2015), who also found westerly
(easterly) anomalies over the eastern (central) equato-
rial Pacific driven by the tropical Atlantic warming.

It is worth mentioning that the combination of Indian
Ocean and tropical Atlantic warming-induced changes
agrees with the results from Had1 and HadPac reason-
ably well (figure not shown), suggesting that the total
tropical SST warming effects on the PTWs are reasonably
decomposed in the AGCM experiments (see Fig. 8b).

d. Tropical SST warming in CMIP5 models

In contrast with the pronounced IBWC in Had1, the
EOF1 mode for CMIP5 historical runs is manifested as
greater Pacific warming compared with that for the
Indian Ocean and tropical Atlantic, and an El Niño–like
warming in the tropical Pacific (Fig. 1c). As a result, it is
found that low-level westerly anomalies and positive
rainfall anomalies emerge in the equatorial Pacific in
CH1 (Figs. 6a and 7a). Unsurprisingly, this result is
consistent with the forced response of the tropical at-
mospheric overturning simulation in the fully coupled
model integrations themselves (e.g., Vecchi and Soden
2007). It is further noted that the weakening of the
PTWs is much more significant in CHPac, and the PTWs
are actually enhanced when the Pacific warming effect is
excluded (Figs. 6b,c). Hence, the weakening of the
PTWs in CH1 is primarily due to the weakened zonal
SST gradient in the equatorial Pacific. Such a result also
supports the finding that the warming in the Indian
Ocean and tropical Atlantic may lead to intensification
of PTWs, except that in this case they weaken the
westerly anomalies generated by the El Niño–like SST
warming in tropical Pacific.

We note that there are pronounced low-level westerly
(easterly) anomalies over the western equatorial Pacific in
CHPac (CH1 minus CHPac), prominently weakening
(strengthening) the PTWs (Fig. 6). These zonal wind
changes are related to the cyclonic (anticyclonic) anom-
alies over WNP, which in turn associated with wetting
(drying) anomalies in situ (Figs. 6 and 7). We also note
that the rainfall changes in the Indian Ocean are opposite

![Fig. 3. Linear trends of (a) SST from HadISST (K decade⁻¹),
(b) SLP (hPa decade⁻¹) and 850-hPa wind from ERA-Interim
(m s⁻¹ decade⁻¹) over the period 1994–2013. Stippling denotes
regions where the trends are statistically significant at a 90% confi-
dence level based on the Student’s t test, and only the vector
trends that are significant at 90% level are shown. Vectors are
drawn every five grid points.](http://journals.ametsoc.org/doi/pdf/10.1175/JCLI-D-16-0349.1)

![Fig. 4. Changes of SLP (shading; hPa) and 850-hPa wind (vectors; m s⁻¹) in (a) HadPac, (c) HadIO, and
(d) HadAtl compared with the control run. (b) Differences between Had1 and HadPac. The vectors where the wind
speed is smaller than 0.1 m s⁻¹ are not shown. Black stippling (cyan contours) represent statistical significance at
90% confidence level for SLP (zonal wind) differences. Vectors are drawn every four grid points.](http://journals.ametsoc.org/doi/pdf/10.1175/JCLI-D-16-0349.1)
to that in WNP (Figs. 7b,c), which is consistent with previous studies that found an out-of-phase relationship between precipitation anomalies in the Indian Ocean and WNP (Annamalai et al. 2013; Wang et al. 2013). Thus, it is the enhanced rainfall over the WNP (Indian Ocean) in Fig. 7b (Fig. 7c) due to local SST warming that contributes to the westerly (easterly) anomalies over western equatorial Pacific. The zonal wind changes over the western equatorial Pacific in CH1 are much less significant when the SST warming in both the tropical Pacific and Indian Ocean is included (Figs. 6a,d).

4. Summary and discussion

The effects of interbasin gradients in externally forced tropical SST trends on the Walker circulation are explored by conducting numerical atmospheric model experiments. The anthropogenically forced SST warming pattern (EOF1) was obtained by conducting an EOF analysis of global SST for both HadISST and CMIP5 historical runs (60°N–60°S). It is found that both the IPO and the long-term IBWC force low-level easterly anomalies over the central equatorial Pacific on different time scales (Fig. 8). However, unlike the IPO, which...
has been suggested to play an important role in the recent strengthening Walker circulation and prominent eastern equatorial Pacific cooling trend, the externally forced SST trend may not contribute substantially to the enhanced PTWs since the mid-1990s, given that the trend in PC1 is relatively small over that period, and so are the associated SSTA and induced trade wind changes. We also note that the strengthening of PTWs in our AGCM experiments forced by EOF1 SST mode is weaker than that in the twentieth-century reanalysis dataset, which may be partly due to natural variability that is not included in the Had1 experiment.

The externally forced long-term La Niña–like SST warming trend in the tropical Pacific, however, plays a negligible role in enhancing the PTWs. It is further demonstrated that the easterly anomalies forced by the additional Indian Ocean warming occupy the entire equatorial Pacific, whereas the intensification of PTWs induced by the excessive tropical Atlantic warming occurs mainly over the central equatorial Pacific (Fig. 8a), consistent with previous studies (e.g., Luo et al. 2012; McGregor et al. 2014; Li et al. 2015). Results based on the difference between the Had1 and HadPac experiments and the combination of Indian Ocean and tropical Atlantic warming-induced changes (Fig. 8b) are very similar, which suggests that the tropical SST warming effects on the PTWs are first-order linear and reasonably well separated by this common methodology. Although the assumption of linearity may present an issue given an implied convective threshold in the tropics, this does not appear to affect our AGCM simulations in this study. One caveat of this study, however, lies in the absence of air–sea interaction, which may affect the linear additivity of the effects of three basins. For instance, the strengthening of the PTWs driven by the IBWC may be further amplified by the stronger zonal SST gradient in tropical Pacific through air–sea interaction. The effects of SST warming in each basin on Walker circulation changes will be fully explored using coupled climate model experiments in a future study.

The CMIP5 historical runs predominantly simulate an El Niño–like SST warming pattern in response to the anthropogenic forcing, which is distinctly different from the observational analyses. Furthermore, the observed IBWC is absent in the CMIP5 SST trends as the zonal SST gradient in tropical Pacific is weakened, all of which leads to prominent weakening of the PTWs or the Walker circulation. It is also shown that the westerly anomalies over equatorial Pacific in CH1 are mainly driven by the SSTA in tropical Pacific, whereas the SST warming in the Indian Ocean and tropical Atlantic act against such changes (but not strongly enough to counteract the local forcing). The causes of the discrepancies between the SST trends in instrumental observations and coupled model simulations demand further attention.

It has been suggested that there are noticeable discrepancies in the observed Pacific warming trends among different SST datasets (Meng et al. 2012; Zhang 2016). For instance, a weak La Niña–like trend emerges for the HadISST and Kaplan SST data (Fig. 1a; see also Fig. S1b), whereas the zonal SST gradient is only very slightly increased for ERSST.v3b (Fig. S1a). The IBWC, on the other hand, is pronounced and robust feature in all three SST datasets. Given the apparently negligible role of the local Pacific warming trends in modulating the strength of the Walker circulation changes on the centennial time scale as in the simulations presented here, it is not surprising that the Walker circulation also exhibits a strengthening trend in response to the ERSST.v3b and Kaplan SST datasets when used as lower boundary forcing, which is primarily due to the effects of SST warming in the tropical Indian Ocean and Atlantic (Fig. S2 in the supplemental material).

In addition to the prominent impact of the long-term SST trend on the Walker circulation change, the natural decadal variability of the tropical Pacific (IPO) may also play an important role. It has been suggested that only a handful of CMIP5 models capture the global warming hiatus since late 1990s (England et al. 2015), which is closely related to the IPO (England et al. 2014; Trenberth et al. 2014). Meehl and Teng (2014) found that with proper initialization and bias adjustment, the recent global warming hiatus may be simulated reasonably well. These results suggest that
in addition to the externally forced SST warming trend, the simulation of the IPO in CMIP5 models may also be important for climate prediction on a decadal time scale.

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