Strengthening western equatorial Pacific and Maritime Continent atmospheric convection and its modulation on the trade wind during spring of 1901–2010

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Abstract
Changes in the tropical atmospheric overturning circulation can strongly influence the global weather pattern via affecting the location, extent, and strength of tropical convective heating. However, due to limitations in obtaining reliable global data before the satellite era, there are still uncertainties on long-term changes in the tropical overturning features, such as the Walker Circulation. By analysing the 20th century reanalysis products, ship-based observations and gauge-based land precipitation data, robust intensification of convection is found over the western equatorial Pacific and Maritime Continent (WEP-MC; 90°E–150°E/15°S–15°N), where rainfall and total cloud cover increased by 15–20% in boreal spring during 1901–2010. The signal is noticeably seasonally dependent, and both rainfall and cloud cover show consistent and significant increasing trends only in the boreal spring season. General circulation model (GCM) experiments were conducted using two different reconstructed SST data sets as forcing; results from both runs indicate springtime intensification of WEP-MC convection, even with relatively uniform SST warming. Further, numerical experiments using a simplified model show that the Pacific trade wind can be accelerated by intensifying cumulus heating; however, this can be sensitive to the location of convection, and only occurs if the latter is within ±5° in latitude along the equator. Our findings suggest that the secular change in the Walker Circulation is potentially discovered from the current reanalysis and observational data sets if “regional-up” approaches are applied.

KEYWORDS
20th century, observational uncertainty, Pacific trade wind, tropical convective feedback, Walker Circulation

1 | INTRODUCTION
The Pacific Walker Circulation is a key cell of the large-scale tropical overturning circulations. The characteristic east–west differences in sea-level pressure (SLP) and sea surface temperature (SST) across the tropical Pacific are associated with deep convection over the western Pacific ascending regions, especially the western equatorial
The observed intensification of the Walker Circulation in recent decades may still within the range of natural variability (Sohn et al., 2013; Kim and Ha, 2017). Although considerable difficulties exist in extracting convincing large-scale signals from the existing observations before the satellite era, longer observational data may reveal a more significant secular trend signal versus natural variability. Reconstructed bucket-sampled SST and nocturnal marine surface air temperature display a reduced zonal SST gradient in the tropical Indo-Pacific Oceans, a change consistent with the Walker Circulation slowdown during 1950–2009 (Tokinaga et al., 2012). On the contrary, after removing the El Niño signal, consistent and robust trend among all reconstructed SST data sets represented a strengthening of the equatorial Pacific SST gradient during 1900–2009 (Solomon and Newman, 2012).
changes of deep convection over the western Pacific Ocean displayed strong seasonal dependence, as precipitation strengthens most significantly in boreal spring, accounting for more than 40% of the 35-year climatological MAM mean rainfall of the WEP-MC. In contrast, the other seasons only show slightly increasing trends (Li et al., 2016). Spring is the ENSO developing or decaying season when the equatorial pressure gradient was the weakest, undertaking the lowest variation among the annual cycle (Yang et al., 2018). As the dominant inter-annual variability in the climate system is ENSO, the unique low variability feature of boreal spring is potential to provide a larger signal-to-noise ratio when calculating long-term trend. The study aims to extend the seasonal change analysis based on Li et al. (2016) to the whole 20th Century, to capture any robust signals regarding changes in the Walker Circulation via validation in multiple data sets and model experiments.

2 | DATA, METHODS, AND MODEL EXPERIMENTS

2.1 | Data sets and analysis methods

Two globally-gridded SST data sets are used: one from the UK Hadley Centre which provides monthly mean SST and sea-ice concentration on a 1° × 1° spatial resolution (Rayner et al., 2003), and the other from the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed (ER) analysis version 5 (Huang et al., 2017). The monthly NOAA 20th Century Reanalysis (20CR) (Compo et al., 2006), a four-dimensional global atmospheric data set approximately on 1.875° × 1.875° resolution, generated from a state-of-the-art data assimilation system, is used to analyse the atmospheric state spanning from 1901 to 2010. The ECMWF twentieth century reanalysis (ERA-20CR) covering 1901–2010 is also used for validation (Poli et al., 2016). The International Comprehensive Ocean–Atmosphere Data Set (ICOADS; Woodruff et al., 2011) on a 2° × 2° grid resolution, the most extensive collection of marine surface data set covering the past 3 centuries, is used for providing surface wind and total cloud cover observations to corroborate results derived from the reanalysis data. The surface gauge-based Global Precipitation Climatology Centre (GPCC) Reanalysis Product V7 covering the period from 1901 to 2010 (Schneider et al., 2014) is also used in this study. The GPCC data is constructed onto a 0.5° × 0.5° resolution and land-covered only. To facilitate the demonstration of large-scale features indicative of the Walker Circulation in the WEP-MC, the GPCC data were representatively upscaled to 2.5° × 2.5° resolution. The upscaling condition is that at least one station record can be traced back to 1930 or earlier within the upscaled grid domain (5 × 5 original sub-grids), and the filled value in upscaled grid domain is weighted by the distances between all available stations within the domain to the centre sub-grid; otherwise the upscaled grid will be masked by a missing value.

Considering that a trend analysis is quite sensitive to the selected starting and ending points, following the study of He et al. (2016), we use the differences between the climatological states in the recent 30 years (1981–2010) and the beginning 30 years in 20th century (1901–1930) to investigate the changes in climate system in the last century. A trend analysis has also been implemented, the results of which, in general, support those from the 30-year-mean subtraction analysis.

2.2 | Models and numerical experiments

The atmospheric component of the Community Earth System Model Version 1.2.2, Community Atmospheric Model (CAM) Version 4 (Hurrell et al., 2008), is used to evaluate the dependence of convection change signal on zonal SST gradient change in two different SST data sets. The model experimental design is summarized in Table 1. A control (CTRL) run was forced by the monthly climatological SST and sea ice calculated over the 1981–2010 period. The other Early 20th Century (E20C) run was forced by monthly climatological SST and sea ice calculated for the 1901–1930 period. Both the Hadley SST and the NOAA ERSST were used to drive the model; the corresponding runs are labelled as Had_E20C, Had_CTRL, ER_E20C, and ER_CTRL (see Table 1). In all experiments, CAM was integrated for 30 years, and the outputs from year 6 to year 30 were used for investigating the model responses to specific SST forcing.

To test the effect of convective heating change, we further carried out a suite of idealized experiments using simplified physics. The model is constructed based on the dynamical core of CAM with idealized dry physics (Held and Suarez, 1994). In the idealized simulations, both the IDL_CTRL run and the IDL_HEAT run are initiated from default initial conditions, but then a persistent grid nudging operation with 10-day relaxation time-scale is invoked to restrict the model state towards the MAM mean. The length of integration is 180 days. Note that the IDL_HEAT represents a suite of sensitive experiments, with the heating centre placed in different locations (see Table 1). The difference between IDL_HEAT (each individual member) and IDL_CTRL reflects the atmospheric responses to various convective heating locations over the WEP-MC.
### TABLE 1 Model experiment design

| Experiments  | Configurations                                                                 |
|--------------|---------------------------------------------------------------------------------|
| Had_E20C     | CAM4 physics, driven by 30 year climatological SST for 1901–1931 based on the Hadley SST data set, 30 year integrated; outputs from year 6 to year 30 are used for analysis |
| Had_CTRL     | Same as HAD_E20C but with climatological SST for 1981–2010 based on the Hadley SST data set |
| ER_E20C      | Same as HAD_E20C but with climatological SST based on the ERSST v5 data set |
| ER_CTRL      | Same as HAD_CTRL but with climatological SST based on the ERSST v5 data set |
| IDL_CTRL     | CAM dynamical core, nudged to MAM mean UVT, with 10-day relaxation timescale and for 180-day integration. |
| IDL_HEATa    | An suite of sensitive experiments with CAM dynamical core and same settings as in IDL_CTRL, with prescribed diabetic heating in each member of the runs (see Figures 4 and 5b for details). |

*a A suite of experiments instead of an individual run.

### 3 RESULTS

#### 3.1 Strengthening of atmospheric convection

Following Li et al. (2016), we first examine the changes in various large-scale parameters in March–April–May (MAM) in the 20th century. Figure 1a shows the differences in rainfall and 10-m wind between 1981–2010 and 1901–1930 in the NOAA 20CR data set. Strong anomalous surface easterly wind prevails over the equatorial Pacific, indicating intensified Pacific trade wind in the NOAA 20CR. Associated with the easterly anomalies, enhanced rainfall can be found over the tropical eastern Indian Ocean, the Indo-China Peninsula, and southern South China Sea. Therefore, the NOAA 20CR supports the intensification of Pacific trade wind and convective activity over the WEP-MC in boreal spring, consistent with stronger zonal overturning circulation.

Given the limited amount of ground-based and radiosonde data assimilated, there are high uncertainties in the reanalysis data before the satellite era. To verify the change over the WEP-MC in boreal spring, Figure 1b shows the distribution of MAM upscaled gauge-based PRCC land precipitation. It can be seen that the overall precipitation increases significantly over the southern Malay Peninsula, Sumatra, Sulawesi, and the Philippines. Although the statistical significant areas are limited in Sulawesi, Java, and part of Sumatra and Malay Peninsula, further analysis reveals that, over the region of WEP-MC (90°E–150°E/15°S–15°N), the ratio of rainfall-increased grids to rainfall-decreased grids is 1.38 (40:29). Furthermore, the ratio of averaged magnitude of increased rainfall to decreased rainfall is 1.41 (0.4 to −0.29 mm-day⁻¹). Therefore, both the rainfall spatial distribution and intensity statistics suggest intensified convection over the WEP-MC.

In addition to the evidences from reanalysis data and gauge-based rainfall, indirect evidence from the ICOADS data also supports the above conclusion. Consistent with the sea surface warming, total cloud cover increases in almost all data-covered sea grids, and the most significant increase occurs in the Indian Ocean, the South China Sea, and the Philippine Sea. Previous study focusing on summertime cloud cover change shows similar results.
during 1949–2008 (He et al., 2016). Although there are little observations over the equatorial region, on a broader region over the Pacific Ocean, most available surface wind record contains easterly wind component, implying a high possibility of enhanced trade wind in spring.

To verify the robustness of difference analysis between the two states, we examine the time series of MAM averaged precipitation over the WEP-MC (90°E–150°E/15°S–15°N) based on ERA and also NOAA 20CR (Figure 2a). The original MAM mean precipitation time series shows strong interannual fluctuations, with high consistence between the NOAA and ERA 20CR data sets. To filter out the interannual variations, an 11-year running filter was applied to the original data. Significant decadal fluctuations as well as long-term trends can be found (blue solid curve in Figure 2a). Linear regression (short dashed blue curve) clearly shows an increasing trend, with around 15% enhancement in one century.

Sensitivity tests over the bands of 20°S–20°N, 10°S–10°N, and 5°S–5°N are also performed; it was found that the trend is robust among all the tests.

To verify the seasonal dependence of the trend signal, the NOAA 20CR precipitation and the ICOADS total cloud cover are used to calculate the trend during 1901–2010, for each calendar month by taking the three-month rolling average (Figure 2b). It can be seen that peak changes of precipitation and total cloud cover occur in different months in the annual cycle. Precipitation changes peak in April–May–June, with 20% increase in one century. Note that negative trends can be found in boreal winter, indicating that the precipitation change strongly depends on the season, and there are high uncertainties in reanalysis products. However, the changes in ship-based total cloud cover observation peak in January–February–March, ~18% increase in one century. The phase differences between precipitation and cloud cover can be attributed to different factors. One possible mechanism is that when the marine boundary layer is more stable in a warming climate (Richter and Xie, 2008), the frequently occurred inversion in wintertime is more effective in trapping moisture, permitting greater stratus cloud cover (Wood and Bretherton, 2006). Recent study by Roxy et al. (2019) reported rapid warming over the tropical oceans during 1981–2018 has warped the MJO life cycle in boreal winter to spring, with its residence time decreasing over the Indian Ocean by 3–4 days, and increasing over the Indo-Pacific Maritime Continent by 5–6 days. The altered MJO is potential to modulate both rainfall and cloud cover pattern in boreal winter and spring. As high consistence of positive precipitation and cloud cover changes is observed in spring, we further follow the ‘regional-up’ perspective to verify whether the springtime convection intensification relies on the increasing zonal SST gradient or a robust response to the uniform SST warming.

3.2 Dependence on zonal SST gradient enhancement

To test the dependence of enhanced convection to the Pacific zonal SST gradient change, both the Hadley SST and the NOAA ERSST are used to drive the CAM model (see Data and methods). Figure 3a,b show the climatological MAM SST differences between 1981–2010 and 1901–1930 in the Hadley SST and the ERSST V5. The most remarkable difference between the results from the two runs appears in the central Pacific; in this location, the Hadley SST displays cooling, while the ERSST gives moderate warming. Thus, there is an intensified zonal SST gradient in the Hadley SST in the last 110 years, while the ERSST does not show any significant trend. Although the reconstructed ship-based observation from Tokinaga et al. (2012) features a reduced zonal gradient, in this study we only focus on the dependence of the intensified convection signal to the increasing zonal SST gradient, without considering the biases in the SST data sets.

**FIGURE 2** (a) Time series of MAM averaged precipitation over the Maritime Continent and the western equatorial Pacific (90°E–150°E/15°S–15°N) based on ERA and NOAA 20CR data sets. (b) NOAA 20CR precipitation and ICOADS cloud cover percentage change per century during 1901–2010 based on three-month rolling average throughout the calendar year.
Figure 3c,d display the differences in precipitation and 1,000-hPa wind between the Had_CTRL and the Had_E20C, and between the ER_CTRL and the ER_E20C, respectively. In accord with the SST gradient change, Figure 3c shows considerable acceleration of trade wind over the equatorial Pacific. As expected, a broad region of enhanced rainfall can be found straddling from the equatorial Indian Ocean to the WEP-MC. Interestingly, enhanced rainfall can also be found over the equatorial Indian Ocean and the South China Sea in the runs driven by ERSST, even though there is only a relatively uniform warming, and no significant zonal SST gradient change according to this data set (see Figure 3d). Although the magnitude is much weaker and the location shifts westward compared with Figure 3c, the results imply that relatively uniform warming over the equatorial Pacific Ocean also supports the convection enhancement over the WEP-MC. Note that the tropical eastern Indian Ocean is around 0.2°C warmer than WEP-MC; such a pattern which is consistent among the Hadley SST and the ERSST may induce the westward shift and intensification of atmospheric convection (Meng et al., 2012). Meanwhile, studies showed that in tropical Indo-western Pacific Ocean regions where the atmosphere contributes to the observed SST changes, the specified SST simulations produce excessive local rainfall–SST correlation (Wu et al., 2006; Wu and Kirtman, 2007). Therefore, careful consideration in the AGCM produced responses is still needed before further reasoning.

3.3 | Effect on the Pacific trade wind

The above results clearly show the enhancement of springtime convection during 1901–2010, as supported by multiple observational data sets. Moreover, although limited by the AGCM overestimation in local rainfall–SST correlation, the springtime convection can enhance in uniform SST warming without zonal SST gradient change over the equatorial Pacific. Here we raise another question: When only taking the atmospheric feedback processes into consideration, to what extent can the relatively enhanced convective heating affect the Pacific trade wind, or even the Walker Circulation? Using the atmospheric dynamical core simulation with vertical and horizontal distribution of idealized heating displayed in Figure 4, we showed the effects of prescribed heating on the SLP, mid-level vertical velocity, and surface wind (Figure 5a). It can be seen that when the heating centre is located at the equator, the responses resemble the Gill-Mastuno model (Gill, 1980). That is, associated with the prescribed heating, forced ascending motion induces Ekman pumping in the PBL, and strong surface wind convergence occurs around the heating centre. More importantly, an easterly response prevails along the western-central equatorial Pacific region, implying an influence of convective heating on the Pacific trade wind.

An array of experiments are then conducted to test the sensitivity of trade wind response to the location of the prescribed heating centre. Here diabetic heating is located at various locations (see circles in Figure 5b representing the locations of heating centres) for each member in the suite of experiments in IDL_HEAT. Shading in the circles shows the differences in averaged easterly wind speed (m·s⁻¹) between the IDL_HEAT and the IDL_CTRL over 140°E–180°E/5°S–5°N (see black box in Figure 5b) among Day 31–180. It is noteworthy that the trade wind response is rather sensitive to the meridional location of the heating centre, and a northward or
By analysing the NOAA and ERA 20CR data sets, the ICOADS ship-based observations, and the PRCC gauge-based land precipitation, we have revealed a robust strengthening of springtime atmospheric convection over the western Pacific and its dependence on uniform SST warming instead of the enhancement of Pacific zonal SST gradient. We have also explored its possible influence on the Pacific trade wind. The main results obtained are summarized below:

1. Results from the 20CR data, the ICOADS ship-based observations, and the PRCC gauge-based land precipitation all confirm a robust convective intensification over the broad updraft region of the WEP-MC, indicating more organized and concentrated convection in boreal spring under a warming climate. Specifically, over the region of 90°E–150°E/15°S–15°N, rainfall and total cloud cover increase by 15–20%. The signal is also noticeably seasonally dependent, as the rainfall and cloud cover show a consistent and significant trend only in the boreal spring rather than the other seasons, which may relate to altered MJO life cycle by expanding western Pacific warm pool.
2. Climate model experiments forced by the Hadley SST and the NOAA ERSST both support the convection enhancement over the WEP-MC in the boreal spring, even though the ERSST displays only relatively uniform warming without significant change in the Pacific zonal SST gradient. Based on AGCM simulations driven by reconstructed SST data, a relatively uniform warming over the equatorial Pacific Ocean in 1901–2010 can induce the nonuniform convection enhancement concentrated over the WEP-MC ascending region. Still, we emphasize that the zonal SST gradients play a vital role in low-level convergence and the convection over the WEP-MC, and the result should be interpreted in view of the AGCM overestimation in local rainfall–SST correlation.

3. The role of the enhanced convective heating under springtime circulation background is then tested by idealized simulations. Results show that only when the convection intensification is organized near the equator, the enhancement of Pacific trade wind is significant. The zonal location of the enhanced convection also influences the strength of trade wind response: easterly wind enhances as the heating centre moves from the eastern Indian Ocean to the WEP-MC.

Our findings show that changes in the large-scale circulation can be highly sensitive to the spatial distribution of heating, even on the regional scale. In addition to springtime convection, other physical variables might also be potential indicators for the changing tropical overturning circulation. Regional heterogeneity and seasonal dependence, thus, cannot be overlooked when investigating the Pacific Walker Circulation change. For instance, the complex and unique land-sea thermal contrast in the eastern and western boundaries (Yim et al., 2017), the inter-basin effect between the Indian Ocean and the Pacific Ocean (Wu et al., 2010; Meng et al., 2012) and between the Atlantic Ocean and the Pacific Ocean (Latif, 2001) are factors that could modulate the Walker Circulation. Further studies using such a “regional-up” approach can potentially provide new perspectives about the changing general circulation and its relation with various forcing factors.

ACKNOWLEDGEMENTS
The comments and suggestions from two anonymous reviewers are helpful for improving the overall quality of this paper. This study was supported by the National Key Research and Development Program of China (2016YFA0602703), the National Natural Science Foundation of China (Grants 41690123, 41690120 and 41705050), Guangdong Province Key Laboratory for Climate Change and Natural Disaster Studies (Grant 2020B1212060025), and the Jiangsu Collaborative Innovation Center for Climate Change. Computing resource for the CESM was provided by the high-performance grid computing platform of Sun Yat-sen University and the “Tianhe-2” in the National Supercomputer Centre in Guangzhou. The 20th Century Reanalysis V2 data was provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at https://www.esrl.noaa.gov/psd/.

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**How to cite this article:** Li Z, Yang S, Tam C-Y, Hu C. Strengthening western equatorial Pacific and Maritime Continent atmospheric convection and its modulation on the trade wind during spring of 1901–2010. *Int J Climatol*. 2021;41:1455–1464. [https://doi.org/10.1002/joc.6856](https://doi.org/10.1002/joc.6856)