Strengthening of the Walker Circulation in recent decades and the role of natural sea surface temperature variability

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Abstract
In response to global warming, climate model simulations suggest a weakening of the Walker Circulation (WC), which is supported by long-term sea level pressure observations over the 20th century. Here, we show the observations and multiple reanalyses yield the opposite trend from 1979 to present—a WC intensification. Atmosphere-only simulations driven by the real-world evolution of sea surface temperatures (SSTs) simulate this observed intensification, whereas coupled ocean atmosphere simulations do not. Thus, the recent WC intensification is related to real-world SST evolution. Assuming the multi-model mean SSTs from 20th century coupled climate model simulations accurately represent the externally forced response, the observed SSTs can be decomposed into a forced and an unforced component. Idealized Community Atmosphere Model version 5 (CAM5) simulations driven by the unforced component of SSTs yield significant WC strengthening, whereas negligible WC changes occur when driven by the forced component of SSTs. Although coupled climate models may be deficient in their tropical response to anthropogenic warming, our results suggest natural SST variability, and in particular a La Niña-like SST pattern, is primarily responsible for the strengthening of the WC since 1979.

1. Introduction

The Walker Circulation (WC) is a large-scale zonal-vertical atmospheric circulation in the equatorial Pacific. Its variations are tied to the sea surface temperature (SST) gradient across the tropical Pacific. For example, during El Niño, the tropical Pacific SST gradient is weakened, as is the strength of the WC. In contrast, the tropical Pacific SST gradient and the WC are strengthened during La Niña. Similarly, changes in the sea level pressure (SLP) gradient across tropical Pacific is an indicator of changes in the vertical motion of the WC, including the descending branch over cooler eastern Pacific and the ascending branch over the warm western Pacific. Variations in the strength and structure of the WC are closely tied to the southeast Asian monsoon [1], precipitation in adjunct regions [2, 3], drying of eastern Africa [4] and fishery stocks related to nutrient supply brought by upwelling of cold water. Thus, understanding long-term changes in the WC are important for water resource management, ecosystems and agriculture.

The long-term temporal trend in WC strength is a popular and highly-debated subject. A weakened Walker Circulation in the twentieth century as response to greenhouse gas emissions is expected to cause ~7% °C⁻¹ increase in water vapor, based on the Clausius-Clapeyron relationship. However, increases in tropical precipitation occur at a slower rate (~3% K⁻¹) [43]. This implies the tropical overturning circulation, which includes the WC and the easterly trade winds, slows down [12]. Furthermore, the Bjerknes feedback, a positive feedback between trade wind intensity and the zonal SST gradient, implies that the above changes will
lead to a reduced zonal SST gradient over the tropical Pacific and an El Niño-like response to warming. Such an SST pattern may lead to atmospheric dynamical changes, including enhanced divergence in the central and eastern tropical Pacific, a southeastward shift of North Pacific jet stream, and an increase in wintertime precipitation for California [13].

In contrast to the above studies, strengthening of the Walker Circulation is simulated by atmosphere-only climate models (AMIP) driven by observed SSTs over the 20th century [14, 15], particularly since the late second half [16, 17]. This strengthening is further supported by various observational data sets [17–20]. In more recent decades, a stronger WC is also supported by cooling of the central and eastern tropical Pacific SSTs (a La Niña-like pattern) [2]. Observed and unprecedentedly strengthening of the easterly trade winds [21, 22] and cooling in the eastern equatorial Pacific [2] contribute to an acceleration of tropical atmospheric overturning—opposite what coupled climate models suggest. The abnormally strong wind stress is found to be regulated by internal climate variability in the 2000s, and the east Pacific cooling is dominated by decadal variability, suppressing the effect of anthropogenic forcing [22].

Projected WC weakening in response to anthropogenic warming is found to be doubtful due to lack of consistent weakening in coupled climate models [23]. No conclusive projection for El Niño and the Southern Oscillation (ENSO) exists in global climate models [24–26]. Thus, whether a La Niña-like (related to WC strengthening) or a El Niño-like (related to WC weakening) tropical Pacific SST pattern will dominate this century is undetermined. In turn, the dominant driver of the Walker Circulation, whether anthropogenic emissions or natural variability, is not well constrained.

The aim of this study is to quantify the contribution of multi-decadal SST variations on recent changes in the Walker Circulation. We investigate the imprints of both anthropogenic warming and decadal internal climate variability on real world SSTs directly, instead of changes in surface air temperature forced by wind stress [22]. Idealized climate model experiments are conducted with the Community Atmosphere Model version 5 (CAM5) [27] to quantify the effects of forced versus unforced SST evolution. The response to the forced signal is estimated based on coupled model climate simulations. This paper is organized as follows: section 2 describes our data and methods; results follow in section 3. A discussion and conclusions follow in section 4.

2. Data & methods

2.1. Trend

The strength of the Walker Circulation is estimated by trends of the east minus west SLP anomaly differences across the tropical Pacific, which is associated with vertical motions of the WC. The described region over the tropical Pacific is 4.74°S—4.74°N in latitude, and 128.39°E—151.05°E and 211.47°E—231.61°E in longitude for the western and eastern tropical Pacific edge, respectively. We also examined additional regions, which yield similar results (Supplementary table 1 available online at stacks.iop.org/ERC/1/021003/mmedia). Anomalies are calculated by removing the long term monthly mean at each grid point. Trend significance for the time series and spatial plots is examined by a standard two-tail student t-test, accounting for the influence of serial correlation by using the effective sample size, \( n(1 - \eta)(1 + \eta)^{-1} \), where \( n \) is the number of years and \( r_n \) is the lag-1 auto-correlation coefficient. Trend uncertainty will be estimated as twice the standard error, \( 2 \times \sigma / \sqrt{n} \), where \( \sigma \) is the standard deviation of the trends, and \( n \) is the number of model realizations.

2.2. Observation and Reanalysis data

Observation-based WC trends are estimated from the Met Office Hadley Centre’s Sea Level Pressure version 2 (HadSLP2) [28], NCEP/National Center for Atmospheric Research Reanalysis (R1) [29], ERA-Interim [30], MERRA2 [31], CFSR [32] and Japan Reanalysis (JRA55) [33]. WC trends are estimated from 1979 to 2014, except JRA-55 which ends in 2013, and MERRA2 which starts in 1980. Since the spatial resolution varies among our data sets, we unify all to a 1.9° × 2.5° resolution—same as the Community Atmosphere Model version 5 (CAM5) model—before commencement of the analysis. Observed SST trends are estimated from Hadley Centre SST data set version 3 (HadSST3) [34][44].

Monthly mean data from the Coupled Model Intercomparison Projection version 5 (CMIP5) [35] archive is utilized, including 22 atmosphere-only (AMIP) models and coupled ocean atmosphere (CMIP) models. Supplementary table 2 lists the 22 models used in this study. Both CMIP and AMIP simulations use identical external forcings, including temporal evolution of greenhouse gases, anthropogenic aerosols, solar insolation and volcanic aerosols. AMIP simulations are driven by the observed evolution of SSTs and sea ice. CMIP5 simulations nominally end in 2005. Representative Concentration Pathway 4.5 (RCP4.5) is used to extend the CMIP5 simulations through 2008. Only models from the CMIP5 archive that contain both AMIP and CMIP simulations are utilized. Furthermore, the same number of realizations for each AMIP and CMIP experiment is
used. Since most AMIP simulations end in 2008, our analysis of CMIP5 simulations is focused on the 1979–2008 time period. Other analyses, however, are based on a longer time period, from 1979–2014.

Analogous sets of AMIP-type simulations are conducted with CAM5. CAM5 AMIP simulations are based on 10 ensemble members with varying initial conditions, by applying a random surface temperature perturbation. Simulations are initiating from 1970 to allow initial state of the atmosphere to diverge as a result of internal atmospheric variability. Ensemble members are extended to 2014 using RCP 4.5 time varying forcing, including solar radiation, estimated concentrations of greenhouse gases, volcanic aerosols, ozone and primary emissions of sulfur dioxide and black and organic carbon.

We also analyze 40 CMIP simulations from Community Earth System Model Large Ensemble Project (CESM LENS) models [36]. CESM LENS simulations, referred as CAM5 CMIP in this manuscript, were downloaded from the Earth System Grid at the National Center for Atmospheric Research (NCAR). These simulations were extended from 2005 to 2014 using RCP 8.5 – the only available future pathway. CAM5 CMIP simulations feature identical forcing, but different initial conditions. Both CAM5 AMIP and CMIP simulations allow assessment of natural climate variability. Note that ensemble mean averages out the internal variability and hence represents the forced signal.

2.3. Idealized CAM5 experiment

It is assumed that the observed SST evolution is composed of two components, including an unforced (UFSST) and forced (FSST) component. The unforced component is due to the natural variability of SSTs (e.g., El Niño and La Niña), and the forced component is due to external forcing (i.e., anthropogenic emissions). The forced component is obtained from the ensemble mean SSTs from the CMIP5 coupled ocean atmosphere models. Solar radiation and volcanic aerosols are considered as external factors. The unforced component is obtained by removing the forced SST trend from the observed SST at each grid point using linear regression. To do so, the trend of monthly FSST is estimated by taking a least squares trend at each grid point, multiplying this slope by the corresponding year, and then subtracting this SST estimate from the observed SST. We perform CAM5 experiments using forced (CAM5 FSST) and unforced (CAM5 UFSST) SST fields. CAM5 FSST and CAM5 UFSST show the role of SST evolution on variability of the Walker Circulation, including the relative roles of externally forced and unforced SST evolution.

The occurrence of a more El Niño-like mean state of the tropical Pacific is a likely response to anthropogenic warming [37]. However, coupled climate models may be deficient in their tropical response to warming [18, 38]. Uncertainty lies in whether the tropical response will resemble a more La Niña-like SST pattern (as has occurred since ~1979), or a more El Niño-like pattern. Changes in the tropical Pacific mean state depend on the relative strength of amplifying effects associated with ocean energy balance (including an increase in SST gradient and stronger ENSO events), and damping effects associated with atmospheric dynamics (including weakening zonal winds, upwelling and weaker ENSO events) [24].

3. Results

Based on HadSLP2 observations, the WC strengthens from 1979–2014, which is statistically significant at the 99% confidence level based on a standard t-test (figure 1(A)). Observed eastern tropical Pacific SLP yields positive trends, while negative trends prevail over the western tropical Pacific (figure 1(B)). Over the same time period, a La Niña-like SST trend pattern exists (figure 1(C)). This result is robust to the eastern and western tropical Pacific box definitions (Supplementary table 1). Observations over a shorter period, 1979–2008, also depicts WC strengthening, but not as strong as that over longer period (4.65 versus 6.08 hPa century$^{-1}$) (table 1, Supplementary figure 1). These observational results are further supported by reanalyses data, which also show intensification of the WC (figure 1), though with magnitude differences. Furthermore, only trends based on R1 and JRA55 are significant. The spatial pattern of observed SLP trends is also captured by reanalyses (not shown). A shorter time period (1979–2008) also yields positive trends of the SLP gradient, with only HadSLP2 yielding a significant WC intensification (table 1). 1979–2008 trends of the SLP gradient are generally weaker than those over the longer, 1979–2014 time period (except MERRA2). This is likely related to a strong La Niña event during late 2007 to early 2008, leading to a larger SLP gradient over the tropical Pacific.

Figure 2 shows the 1979–2014 ensemble mean simulated change in the strength of the WC in CAM5 AMIP and CESM LENS (referred as CAM5 CMIP) simulations. CAM5 AMIP yields a positive trend but weaker than that from observation, with ensemble mean of 2.3 hPa century$^{-1}$ significant at the 90% confidence level (table 1, figure 2(A)). Trends of SLP gradient estimated from CAM5 AMIP realizations ranges from 2.15 to 2.59 hPa century$^{-1}$ (figure 3(A)). The corresponding SLP trend pattern is also consistent with that from observation and reanalyses (figure 2(C)). In contrast, CAM5 CMIP simulations yield a general increase in SLP over most of the tropical Pacific (figure 2(D)), and a weakly negative ensemble mean WC trend (figure 2(B)). CAM5 CMIP also
yields a larger range of trends (−3 to 1 hPa century⁻¹) than CAM5 AMIP, and there is no consensus on the sign of the SLP gradient trend derived from CAM5 CMIP simulations (figure 3(A)). About two thirds of the CAM5 CMIP simulations yield WC weakening, and one third yield WC strengthening. Individual trends from CAM5 CMIP realizations largely underestimate those from observation and reanalyses, except CFSR. Thus, we find robust results across CAM5 AMIP simulations that are consistent with observations. This implies the real-world evolution of SSTs is important to the observed strengthening of the WC. HadSLP2 observation shows that WC weakening dominants the bulk of the 20th century (1920–2000) (Supplementary figure 2). This weakening is captured by the CAM5 CMIP (CESM LENS) simulations, with a robust ensemble mean trend at −0.25 hPa century⁻¹. This is in agreement with previous work arguing the long-term WC weakening is a greenhouse gas (GHG) forced response [6, 8]. This also implies that the effect of GHG warming is not the major cause of recent WC strengthening, which may be counteracted by the natural variability.

**Figure 1.** 1979–2014 trends of tropical Pacific SLP gradient, SST and SLP pattern from observation and reanalyses. (A) Time series of east (4.74°S–4.74°N, 211.47°E–231.61°E) minus west (4.74°S–4.74°N, 128.39°E–151.05°E) tropical Pacific SLP. Black lines represent HadSLP2; red lines represent NCEP/NCAR (R1) reanalysis; green lines represent CFSR reanalysis; purple lines represent ERA-Interim reanalysis; blue lines represent JRA55 (which ends in 2013) and orange lines represent MERRA2 reanalysis (which starts in 1980). Also included is the least squares linear trend corresponding to each data set. (B) Observed SLP trend (hPa century⁻¹) pattern. Thin black lines represent climatological SLP (hPa). Purple boxes denote the western and eastern tropical Pacific regions used in (A). (C) Observed SST trend (°C century⁻¹) pattern based on HadSST3. Symbols in (B, C) represent trend significance at the 90 % (diamond), 95% (X) or 99% (+) confidence level, accounting for autocorrelation. Warm (cold) colors represent positive (negative) trends.
Table 1. Walker Circulation trends based on multiple data sets and model simulations. Trends in 1979–2014 and 1979–2008 are based on observations (HadSLP2), reanalyses including R1 (NCAR/NCEP), JRA55, CFSR, ERA-Interim and MERRA2, and atmosphere-only (AMIP) and coupled ocean atmosphere (CMIP) simulations from CAM5 and CMIP5 (only available in 1979–2008). Idealized CAM5 unforced (UFFST) and forced (FSST) trends are also included in both periods. Symbols represent trend significance at the 90% (diamond), 95% (X) or 99% (+) confidence level, accounting for autocorrelation, and thin black lines represent climatological SLP (hPa). Warm (cold) colors represent positive (negative) SLP trends.

| Data                     | 1979–2014 | 1979–2008 |
|--------------------------|-----------|-----------|
| HadSLP2                  | 6.08°     | 4.65°     |
| R1                       | 4.89°     | 3.8       |
| JRA55                    | 3.51°     | 3.35      |
| CFSR                     | 0.50      | 0.38      |
| ERA-Interim              | 3.21      | 3.00      |
| MERRA2                   | 3.20      | 4.87      |
| CMIP5 AMIP               | —         | 3.1       |
| CMIP5 CMIP               | —         | −0.15     |
| CAM5 AMIP                | 2.3°      | 2.32      |
| CAM5 CMIP (CESM LENS)    | −0.32     | −0.16     |
| CAM5 UFFST               | 2.59°     | 2.54      |
| CAM5 FSST                | −0.21     | −0.09     |

Figure 2. 1979–2014 CAM5 AMIP and CAM5 CMIP (CESM LENS) ensemble mean SLP trends. Left panel (A), (C) CAM5 AMIP and right panel (B), (D) CAM5 CMIP. (A), (B) time series of east minus west tropical Pacific SLP gradient. Gray shading represents uncertainty across realizations, estimated as twice the standard error. Also included is the least squares linear trend corresponding to each data set. (C), (D) SLP trend (hPa century$^{-1}$) pattern. Purple boxes denote the western and eastern tropical Pacific regions used in (A), (B). Symbols in (C), (D) represent trend significance at the 90% (diamond), 95% (X) or 99% (+) confidence level, accounting for autocorrelation, and thin black lines represent climatological SLP (hPa). Warm (cold) colors represent positive (negative) SLP trends.
We also conducted the same analysis with CAM5 simulations over the shorter period—1979 to 2008, and similar results are obtained (Supplementary figure 3). WC strengthening is simulated from CAM5 AMIP, with an ensemble mean trend of 2.32 hPa century$^{-1}$, nearly the same as that over the longer period (table 1, Supplementary figure 3(A)). The SLP trend patterns in CAM5 AMIP also resembles a La Niña-like pattern, consistent with that from observations (Supplementary figure 3(C)). CAM5 CMIP, however, yields a much smaller and negative ensemble mean trend at $-0.16$ hPa century$^{-1}$ (table 1, Supplementary 3(B) and (D)). A wider distribution of CAM5 CMIP trends also exists, ranging from $-2.75$ to $2.5$ hPa century$^{-1}$. 45% of CAM5 CMIP realizations yield positive trends and 55% yield negative trends (Supplementary figure 4(A)). Thus, similar to observations, CAM5 simulations yield similar results over both time periods, although WC strengthening is less statistically significant over the 1979–2008 time period.

Results based on 1979–2008 CAM5 simulations are further supported by those from CMIP5 (Supplementary figure 5). CMIP5 AMIP yields a positive ensemble mean trend nearly as large as that from observations, at 3.1 hPa century$^{-1}$, although it is not significant at the 90% confidence level (table 1, Supplementary figures 5(A) and (C)). All CMIP5 AMIP simulations yield WC strengthening, ranging from 1.75 to 4.25 hPa century$^{-1}$, which agrees well with the observed trends (figure 3(B)). In contrast, a small negative CMIP5 CMIP ensemble mean trend is obtained at $-0.15$ hPa century$^{-1}$ (table 1, Supplementary figures 5(B) and (D)) and 73% of these realizations depict WC weakening (figure 3(B)). Therefore, similar to CAM5 AMIP,

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**Figure 3.** Histogram of tropical Pacific SLP gradient trends. Trends based on (A) 1979–2014 CAM5 simulations, (B) 1979–2008 CMIP5 simulations and (C) 1979–2014 CAM5 USST and FSST simulations. Blue bars represent trends from CMIP simulations in (A), (B) and unforced SST component (USST) in (C). Red bars represent trends from AMIP simulations in (A), (B) and forced SST component (FSST) in (C). Dash lines represent trends from ensemble mean of AMIP/USST (blue) and CMIP/FSST (red) simulations. In (A), stars represent trends from observation (black), NCEP/NCAR (R1) (red), JRA55 (orange), MERRA2 (gold), CFSR (olivegreen) and ERA-Interim (light green) reanalysis. Units is hPa century$^{-1}$. 

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CMIP5 AMIP simulates WC strengthening that agrees with observations, while CAM5 CMIP and CMIP5 CMIP do not. Robust results from both CAM5 and CMIP5 simulations over the shorter time period provide additional evidence that WC intensification is related to real-world SST variations, rather than anthropogenic emissions.

The real-world evolution of SSTs is composed of an unforced and a forced component. The unforced SSTs are controlled by internal variability of SSTs, such as El Niño Southern Oscillation (ENSO). The forced SSTs are driven by external forcing due to anthropogenic emissions, volcanic eruptions and solar radiation variations. We assume that the observed SSTs can be decomposed into a forced component. All CAM5 FSST SLP gradient trends yield WC strengthening and exhibit a relatively narrow distribution than those based on CAM5 UFSST, with a range of −0.21 to −0.09 hPa century$^{-1}$ for both periods (figure 3(C) and Supplementary figure 4(A)). The CAM5 FSST ensemble mean yields a positive SLP gradient trend of ∼2.5 hPa century$^{-1}$ over both time periods (table 1). From 1979–2014, this trend is significant at the 95% significance level (table 1). Trends simulated from CAM5 FSST fall in a narrow range of 2.34 to 2.7 hPa century$^{-1}$ for both periods (figure 3(C) and Supplementary figure 4(B)). The CAM5 UFSST ensemble mean trend pattern resembles the observations over the tropical Pacific, with positive trends dominating in the eastern tropical Pacific and negative trends prevailing in the western tropical Pacific (figure 4(C) and Supplementary figure 6(C)). In contrast, the CAM5 FSST ensemble mean yields weakly negative and insignificant SLP gradient trends of −0.25 to −0.08 hPa century$^{-1}$ for both periods (figure 3(C) and Supplementary figure 4(B)). The corresponding 1979–2014 SST trend pattern from these simulations were examined by [39] (Supplementary figure 7). A cold ENSO-like SST trend pattern is associated with FSST (Supplementary figure 7(B)), consistent with the observed SST trend pattern (figure 4(C), Supplementary figure 7(A)). However, a spatially uniform warming pattern is produced by FSST (Supplementary figure 7(C)). Thus, CAM5 UFSST captures the observed WC intensification. It suggests the
recent intensification of the Walker Circulation is largely due to natural SST variations, primarily due to a La Niña-like SST pattern.

4. Discussion and conclusions

Through observations, multiple reanalyses and climate model simulations, we have showed the importance of real-world SST evolution to recent intensification of the Walker Circulation. Since 1979, observations and reanalyses yield positive SLP gradient trends over the equatorial Pacific, suggesting an intensified Walker Circulation. CAM5 atmosphere-only (AMIP) simulations also simulate significant strengthening of the SLP gradient over tropical Pacific, while CAM5 coupled atmosphere-ocean (CMIP) models yield relatively small, negative ensemble mean trends. A large range of of trends—including both positive and negative— is also found with CAM5 CMIP simulations. CMIP5 AMIP and CMIP5 CMIP simulations yield similar results over a shorter time period (1979–2008), with CMIP5 AMIP simulations capturing the observed strengthening of the Walker Circulation, though not statistically significant. These results imply that the real-world evolution of SSTs is important for the observed intensification of the Walker Circulation. Note that the observed WC trend is not captured by either AMIP or CMIP simulations. Furthermore, the range of WC trends from AMIP simulations does not overlap that from CMIP. This suggests that models, particularly the coupled ocean atmosphere models, tend to underestimate the strength of tropical interdecadal SST variability. Given a sufficiently large ensemble of CMIP simulations, the observed value should at least be within the tail of the simulated distribution, but this is not the case. Therefore, CMIP may be able to accurately simulate the long-term mean response to anthropogenic perturbations, but may not be able to simulate the strength of the interdecadal variability in tropical SST and WC intensity. Underestimating decadal variability may produce a response with a narrow spread around the mean value and a potential underestimation of extremes at the regional scale.

Idealized experiments were conducted with CAM5, to isolate the forced and unforced component of real-world SST evolution. Robust results are obtained from simulations driven by the unforced SSTs, where a significant strengthening of the Walker Circulation is obtained. UFSST resembles the observed SSTs, and in particular, the La Niña-like SST pattern over the same time period [39]. This further implies the unforced component of real-world SST evolution is the dominant driver of the recent intensification of the Walker Circulation. Since 1979, natural SST variability has played a larger role in long-term evolution of the WC than anthropogenic emissions, contrary to that over the entire 20th century.

A caveat to our results is that models may not accurately simulate the tropical response to warming. The observed cooling in the central and eastern tropical Pacific in recent decades cannot be well captured by coupled models [40]. If the true forced SST signal is more La Niña-like than what we show, a more positive SLP gradient trend would be estimated from CAM5 FSST. Therefore, a smaller positive trend of SLP gradient over equatorial Pacific would be simulated by CAM5 UFSST, and the intensification of the Walker Circulation by natural SST variations would be smaller than what we show here.

Consistent with previous studies, a strengthened Walker Circulation is captured from simulations forced with observed tropical Pacific SSTs and external forcing, accompanied by a ‘faux pause’ in global mean surface temperature increase [2]. A negative phase of Pacific Decadal Oscillation (PDO) and more La Niña events is suggested to be an important cause of the recent warming hiatus [41]. Radiative effects from GHGs are superimposed with natural variability over this period. In recent decades, natural variability related to the observed La Niña-like SST pattern is found to be exceptionally strong, as compared to CMIP5 control runs [42]. We also note that as the PDO transitions to the opposite phase, it is likely that the strengthening of the Walker Circulation will weaken in the next decade. Furthermore, as GHGs continue to accumulate in the atmosphere, the forced signal will become more important through this century, implying weakening of the Walker Circulation. Regardless, future changes in the strength of the Walker Circulation will be heavily modulated by natural SST variability related to ENSO/PDO cycles.

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datasets/data/interim-mdfa. JRA55 is obtained from https://rda.ucar.edu/datasets. MERRA2 is obtained from https://disc.gsfc.nasa.gov/datasets. CSFR is obtained from https://climatedataguide.ucar.edu/climate-data.

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References

[1] Wang B, Liu J, Kim H J, Webster P J and Yim S Y 2012 Clim. Dyn. 39 1123–35
[2] Kosaka Y and Xie S P 2013 Nature 501 403
[3] Liu J, Wang B, Cane M A, Yim S Y and Lee J Y 2013 Nature 493 656
[4] Williams A P and Funk C 2011 Clim. Dyn. 37 2417–35
[5] Held I M and Soden B J 2006 J. Clim. 19 5686–99
[6] Vecchi G A, Soden B J, Wittenberg A T, Held I M, Leetmaa A and Harrison M J 2006 Nature 441 73
[7] Power S B and Smith I N 2007 Geophys. Res. Lett. 34 L18702
[8] Power S B and Kociuba G 2011 J. Clim. 24 6501–14
[9] Power S B and Kociuba G 2011 Clim. Dyn. 37 1745–54
[10] Tokinaga H, Xie S P, Deser C, Kosaka Y and Okumura Y M 2012 Nature 491 439
[11] Collins Mat et al 2010 The impact of global warming on the tropical Pacific Ocean and El Niño Nature Geoscience 3 391–397
[12] Soden B J, Jackson D L, Ramaswamy V, Schwarzkopf M and Huang X 2005 Science 310 841–4
[13] Allen R J and Luptowitz R 2017 Nat. Commun. 8 16055
[14] Meng Q, Latif M, Park W, Keenlyside N S, Semenov V A and Martin T 2012 Clim. Dyn. 38 1757–73
[15] Sandeep S, Sordal F, Sardeeshmukh P D and Compo G P 2014 Clim. Dyn. 43 103–17
[16] Ma S and Zhou T 2016 J. Clim. 29 3097–118
[17] Sohn B, Yeh S W, Schmetz J and Song H J 2013 Clim. Dyn. 40 1721–32
[18] Karnauskas K B, Seager R, Kaplan A, Kushner Y and Cane M A 2009 J. Clim. 22 4316–21
[19] Solomon A and Newman M 2012 Nat. Clim. Change 2 691
[20] L’Heureux M L, Lee S and Lyon B 2013 Nat. Clim. Change 3 571
[21] England M H, McGregor S, Spence P, Meehl G A, Timmermann A, Cai W, Gupta A S, McPhaden M J, Purich A and Santoso A 2014 Nat. Clim. Change 4 422
[22] Watanabe M, Shigama H, Tatebe H, Hayashi M, Ishii M and Kimoto M 2014 Nat. Clim. Change 4 893
[23] Plesca E, Gritzmann V and Buehler S A 2018 J. Clim. 31 81–97
[24] Collins M et al 2010 Nat. Geosci. 3 391
[25] Cane M A 2005 Earth Planet. Sci. Lett. 249 227–40
[26] DiNezio P, Clement A and Vecchi G 2010 En. Transactions American Geophysical Union 91 141–2
[27] Neale R B et al 2012 Description of the NCAR Community Atmosphere Model (CAM 5.0) NCAR Tech. Note NCAR/TN-486+STR 1
[28] Allan R and Ansell T 2006 J. Clim. 19 5816–42
[29] Kalnay E et al 1996 Bull. Am. Meteorol. Soc. 77 437–71
[30] Dee D P et al 2011 Q. J. R. Meteorol. Soc. 137 553–97
[31] Gelaro R et al 2017 J. Clim. 30 5419–54
[32] Saha S et al 2010 Bull. Am. Meteorol. Soc. 91 1015–38
[33] Kobayashi S et al 2015 Journal of the Meteorological Society of Japan. Ser. II 93 5–48
[34] Kennedy J, Rayner N, Smith R, Parker D and Saunby M 2011 Reassessing biases and other uncertainties in sea surface temperature observations measured in situ since 1850. 2. Biases and homogenization Journal of Geophysical Research: Atmospheres 116 D14104
[35] Taylor K E, Stouffer R J and Meehl G A 2012 Bull. Am. Meteorol. Soc. 93 485–98
[36] Kay J E et al 2015 Bull. Meteo. Soc. 96 1333–49
[37] Cai W et al 2015 Nat. Clim. Change 5 849
[38] Fyfe J C, Gillett N P and Zwiers F W 2013 Nat. Clim. Change 3 767
[39] Allen R J and Kovilakam M 2017 J. Clim. 30 6329–50
[40] Kociuba G and Power S B 2015 J. Clim. 28 20–35
[41] Tremberth K E and Basu S 2013 Earthas Future 1 19–32
[42] Amaya D J, Siler N, Xie S P and Miller A J 2018 Clim. Dyn. 51 305–19
[43] Held I M. and Soden B J. 2006 Robust Responses of the Hydrological Cycle to Global Warming Journal of Climate 19 (21) 5686–5699
[44] Kennedy J. J., Rayner N. A., Smith R. O., Parker D. E. and Saunby M. 2011 Reassessing biases and other uncertainties in sea surface temperature observations measured in situ since 1850: 1. Measurement and sampling uncertainties J. Geophys. Res. 116 D14103