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Key Points:
- We propose a probabilistic framework for tracking the ITCZ on seasonal to decadal scales
- Our approach is longitudinally and seasonally explicit and allows for joint consideration of multiple variables to define the ITCZ
- We reveal a statistically significant southward trend in the ITCZ location over the central Pacific in the late twentieth century

Supporting Information:
- Supporting Information S1

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A Multivariate Probabilistic Framework for Tracking the Intertropical Convergence Zone: Analysis of Recent Climatology and Past Trends

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Abstract Due to its importance for water availability in the tropics and subtropics, efficient tracking of the seasonal and long-term shifts of the intertropical convergence zone (ITCZ) is of great value. Current approaches, which are based on tracking changes in the annual mean of single variables, ignore the intra-annual dynamics, while more sophisticated methods are computationally intensive. Here we propose a new probabilistic framework to track the ITCZ, which is based on tracking the location of maximum precipitation and minimum outgoing longwave radiation in overlapping longitudinal windows. Our framework is seasonally and longitudinally explicit, allows for joint consideration of multiple variables to define the ITCZ, and is flexible in its implementation, thus, it can be used in analyses of different scales and scopes. We apply our framework to analyze the recent climatology of the ITCZ and report a southward trend in its location over central Pacific in the late twentieth century.

Plain Language Summary The zone of deep air convection and heavy precipitation in the Earth's tropics, known as the intertropical convergence zone (ITCZ), is characterized by seasonal southward and northward movement, following Sun's radiation, as well as long-term meridional shifts, which greatly affect water availability in many regions around the world. This study proposes and applies a new probabilistic framework to track the ITCZ by jointly considering multiple physical variables to define its location. It also allows for detailed analysis of the intra-annual dynamics in all longitudes of the globe, while being computationally efficient and flexible in its implementation. We reveal a statistically significant southward trend in the location of the ITCZ over the central Pacific.

1. Introduction

The intertropical convergence zone (ITCZ) is the area where the northeasterly and southeasterly trade winds converge to the low-pressure zone on the equator. It is collocated with the ascending branch of the atmospheric meridional overturning circulation in the tropics (i.e., the Hadley circulation) and is characterized by deep convection and high amount of precipitation (Schneider et al., 2014), greatly affecting the tropical and subtropical hydroclimatic variability.

On seasonal timescales, the ITCZ migrates toward the warmer hemisphere, leading to the expansion of the Hadley cell and increasing the meridional heat transport toward the cooler hemisphere, which flattens the tropical temperature gradient (Adam et al., 2016a, 2016b; Bischoff & Schneider, 2014, 2016; Donohoe et al., 2013; Schneider et al., 2014). The location and intra-annual variability of the ITCZ vary with longitude (Waliser & Gautier, 1993; Waliser & Somerville, 1994), and generally depend on the geometry and distribution of the continents, and the sea surface temperature (see, e.g., Chao & Chen, 2001; Graham & Barnett, 1987; Philander et al., 1996; Schneider et al., 2014; Trenberth, 2011). In particular, the ITCZ migrates more over continental regions, where it collocates with the trough of the global monsoon (see Trenberth et al., 2000), and it is driven by the seasonal change of the solar heating. In contrast, over the Atlantic and eastern Pacific oceans, the ITCZ does not migrate seasonally between the two hemispheres and resides north of the equator during most of the year (Philander et al., 1996). In the western Pacific, apart from the northern ITCZ, the so-called south Pacific convergence zone (SPCZ) is also prominent from the equatorial region north of Australia poleward and eastward toward 30°S in the central Pacific, with seasonally varying strength, which picks during boreal winter (see Berry & Reeder, 2014; Haffke & Magnusdottir, 2013, 2015; Widlansky et al., 2011). It should be also noted that although the ITCZ in the northern Pacific and Atlantic oceans is mainly a zonal feature, the

SPCZ as well as the south Indian Ocean convergence zone (Cook, 1998, 2000) and the south Atlantic convergence zone (Carvalho et al., 2004) are diagonally oriented.

On decadal and longer scales, local features like the geometry of coastlines are not likely to be affecting the variability in the location of the ITCZ (Schneider et al., 2014). Instead, the ITCZ is influenced by the heating contrast between the two hemispheres, or more generally, the energetic asymmetry of the globe, and it tends to move toward the warmer hemisphere, mimicking its seasonal migration (Allen et al., 2015; Arbuszewski et al., 2013; Bischoff & Schneider, 2014; Broccoli et al., 2006; Broecker & Putnam, 2013; Chiang & Bitz, 2005; Kang et al., 2008; Sachs et al., 2009; Schneider et al., 2014).

Due to its importance for efficient water resources management in tropical and subtropical regions, and for the sustainability of ecosystems and rainforests, efficient detection and tracking of the ITCZ on seasonal to decadal scales, as well as reliable assessment of changes in its dynamics are of high interest. Usually, the latter is based on tracking changes in the outgoing longwave radiation (OLR) or precipitation using global-zonal and annual averages (Allen, 2015; Hwang et al., 2013), thus not offering much insight into the changes of the intra-annual dynamics of the ITCZ and not facilitating assessment of regional changes. Moreover, in particular seasons or regions of the Earth, the detection of ITCZ is rather subjective and the use of a single variable can be questionable (Nicholson, 2009, 2018). In the light of the above, more rigorous methods to objectively detect the ITCZ have been recently proposed (see method proposed by Bain et al., 2011), which consider multiple physical variables to assess the probability of any point being part of the ITCZ using Bayesian inference. Although more insightful and theoretically consistent, these methods are computationally intensive, and require the use of manually identified ITCZ points as training data sets, both of which limit their applicability only in specific longitudinal sectors and over short time periods, and are not offered for straightforward analysis of the extensive observational, reanalysis, or climate simulation products available, which is essential for climate change assessment studies.

Here, recognizing the fact that the ITCZ location has to be inferred based on physical variables (e.g., precipitation, OLR, cloud cover, etc.) which vary stochastically in space and time, we propose a new probabilistic approach for tracking the ITCZ. This approach allows for detailed analysis of the intra-annual dynamics in all longitudes of the globe, while being computationally efficient and flexible in its implementation. Our approach is based on the following principles:

i The location of the ITCZ is longitudinally and seasonally explicit: at each longitude and in each month/season, there are latitudes at which the ITCZ is most likely to prevail.
ii The ITCZ is a large-scale feature and isolated features of deep convection are not parts of it (Bain et al., 2011). Accordingly, we consider zonal means of the defining variables (e.g., precipitation or OLR) to reduce the likelihood of detecting small-scale, isolated patterns of convection as ITCZ points.
iii In particular seasons or regions of the Earth, the definition of ITCZ based on the use of a single variable may be questionable (Nicholson, 2018), and thus, the joint consideration of multiple variables is necessary to increase robustness and physical causality.

Principles (i)–(ii) become less robust on finer than monthly/seasonal temporal scales, where tropical waves like the Madden-Julian Oscillation (Madden & Julian, 1971) can disturb the large-scale features of deep convection in the Indo-Pacific basin. Thus, our analysis is focused on seasonal to decadal scales. The proposed probabilistic framework is used to determine the recent climatology of the ITCZ, particularly its annual mean location as an explicit function of longitude, its intra-annual variability, and its overall probability distribution, that is, the frequency at which every point within the ITCZ zone experiences the physical conditions used to define it, for example, extreme precipitation, minimum OLR, and so forth. We also assess changes in ITCZ dynamics since the mid of the twentieth century and report longitudinal trends.

2. Data

For our analysis, we use both observations and reanalysis products. Particularly, to study the recent climatology of the ITCZ, we use a high-resolution data set of satellite precipitation (monthly precipitation series in 1983–2012 and on a 0.25° × 0.25° grid, see Ashouri et al., 2015) developed by the Center for Hydrometeorology and Remote Sensing, and referred to as the PERSIANN-CDR data set, and monthly records of OLR developed by the Physical Sciences Division of NOAA (monthly OLR series in 1983–2012 and on a 1° × 1° grid, see Lee, 2014) referred to as the PSD-CDR data set. To study the ITCZ trends since the mid twentieth century, we use reanalysis products obtained from the 20th Century Reanalysis V2c project (monthly series of precipitation, OLR, omega velocity, and cloud cover in 1948–2014 and on a 2° × 2° grid, see Compo et al., 2011), which is here referred to as the 20C data set, and from the National Centers for Environmental Prediction–National Center for Atmospheric Research (monthly series of precipitation, OLR, omega velocity, and cloud cover in 1948–2014 and on a 2° × 2° grid, see Kalnay et al., 1996), which we here refer to as the NCEP/NCAR data set. See supporting information Table S1 for more information on the data used.

3. Probabilistic Tracking of the ITCZ

Many different variables have been used in the literature to define the location of the ITCZ, including pressure, surface wind convergence, precipitation, OLR, and cloudiness (see Nicholson, 2018, and references therein). Yet the most commonly used variables are precipitation and OLR, since both are indicative of deep convection which takes place along the ITCZ (see, e.g., Adam et al., 2016a, 2016b; Bain et al., 2011; Bischoff & Schneider, 2014, 2016; Donohoe et al., 2013; Sachs et al., 2009; Schneider et al., 2014; Zhang & Wang, 2015, among others). Thus, we use here the latter two variables to track the ITCZ, but our framework is general and applicable in considering any single variable, and/or jointly distributed multiple variables to define the ITCZ.

Let X denote the variable (e.g., precipitation) used for defining the ITCZ location and $X_w^{l,t}$ the zonal average of X within the longitudinal window $[l - w/2, l + w/2]$ of width w and during month/season t. The latitudinal distribution of $X_w^{l,t}$ can be obtained from observations or model outputs (see example in Figure S1a). For a specified probability of nonexceedance a, we define $x_{w,a}^{l,t}$ to be the a^{th} quantile of $X_w^{l,t}$, that is,

$$F\left(x_{w,a}^{l,t}\right) \equiv \Pr\left[X_w^{l,t} \le x_{w,a}^{l,t}\right] = a,$$

where F is the cumulative distribution function (CDF) of $X_w^{l,t}$. We define the random variable $Y_{w,a}^{l,t}$ to be the location (in degrees of latitude) at which the ITCZ is most likely to prevail, at longitude l and in month/season t. A sample of $Y_{w,a}^{l,t}$ may then be the set of latitudinal points $y_{w,a}^{l,t}$ (hereafter labeled as *ITCZ points*) at which the value of $X_w^{l,t}$ exceeds the a^{th} quantile $x_{w,a}^{l,t}$, that is:

$$\begin{aligned} &\left\{y_{w,a}^{l,t}\right\} : \; X_w^{l,t}\left(y_{w,a}^{l,t}\right) > x_{w,a}^{l,t} = F^{-1}(a) \\ &\text{or} \\ &\left\{y_{w,a}^{l,t}\right\} : \; F\left(X_w^{l,t}\left(y_{w,a}^{l,t}\right)\right) > a. \end{aligned} \tag{1}$$

In other words, we track the position of ITCZ based on the upper $(1 - a) \times 100\%$ of the zonal precipitation in longitude l and month/season t, using the points $y_{w,a}^{l,t}$ (see example in Figures S1a–S1b). When considering the OLR to track the ITCZ, the negative zonal OLR is used, since deep convection associates with minimum (not maximum) OLR. Such an approach is rather computationally efficient and allows the analysis of both the mean annual location and the intra-annual variability of the ITCZ, simply by obtaining the ITCZ points, $y_{w,a}^{l,t}$, for each calendar month $t = 1, 2, \ldots, 12$ (see Figure S1c) or each season.

When jointly considering multiple (e.g., $N \ge 2$) variables $\mathbf{X} = [X_1, X_2, \ldots, X_N]$ to track the ITCZ, the ITCZ points, $y_{w,a}^{l,t}$, also satisfy equation (1), but F is now the joint CDF of $\mathbf{X}_w^{l,t}$. This joint CDF can be estimated using copulas which offer the flexibility to express the joint distribution of multiple variables in terms of the quantiles of their marginal distributions (e.g., Nelsen, 1998; Salvadori & De Michele, 2007). Figure 1 illustrates an example where zonal precipitation and negative zonal OLR have been jointly used (i.e., $N = 2$) to detect the location of the ITCZ during January (i.e., $t = 1$), at longitude $l = 175°$E (and with $w = 15°$), in the period 1983–2012 (the latter is the period which all data sets cover; see Table S1). Note that in order to obtain results for the entire period, we have used the climatological mean precipitation and OLR (see also Figure S1). In this example, the zonal precipitation and −OLR are strongly correlated ($r = 0.98$) as indicated by the scatter plot and the copula function (see Figures 1b–1c), which means that the ITCZ is well defined, and similar results would have been obtained by using the marginal distribution of either variable. Yet this is not the case in all longitudes or seasons (see next section), and thus, the use of joint statistics becomes necessary. Using $a = 90\%$, the ITCZ in

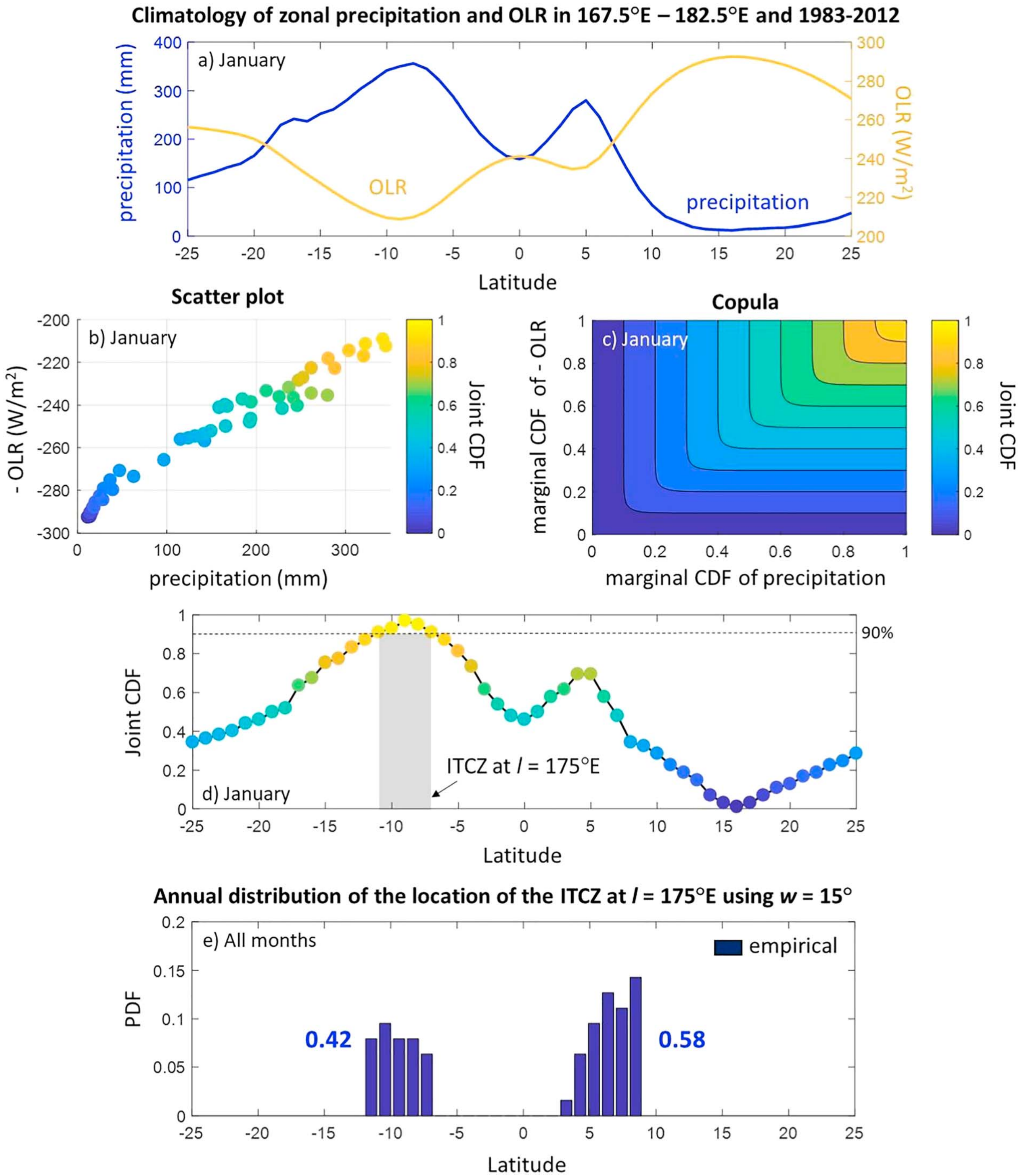

Figure 1. Probabilistic tracking of the ITCZ at longitude l = 175°E, based on the joint distribution of the monthly precipitation and OLR. (a) The zonally averaged (167.5°E–182.5°E) precipitation (blue curve; from PERSIANN-CDR) and OLR (orange curve; from PSD-CDR) in January, 1983–2012 (climatological means are presented). (b) Scatter plot of the points in (a). Coloring indicates the value of the joint CDF of precipitation and −OLR. (c) The joint distribution is modeled using the Frank copula. (d) The value of the joint CDF of precipitation and −OLR as a function of latitude. The location of the ITCZ is also indicated based on the probability of nonexceedance a = 90%. (e) Annual PDF of the location of the ITCZ at longitude l = 175°E, using *ITCZ points* obtained in each calendar month (t = 1, 2, …, 12). For a = 90%, five ITCZ points are tracked in each calendar month; see for example, panel (d). The probability of ITCZ residing in the northern (southern) hemisphere during the year is 0.58 (0.42). OLR = outgoing longwave radiation; CDF = cumulative distribution function; ITCZ = intertropical convergence zone; PDF = probability density function.

January is located close to 10°S (Figure 1d). By obtaining the samples $y_{15,90\%}^{175,t}$ for each calendar month $t = 1, 2, \ldots, 12$, the annual distribution of the location of the ITCZ is obtained (see Figure 1e). It is shown that during the year, the ITCZ is slightly more likely to be established in the northern hemisphere with probability 58%. Moreover, its annual average location is at 1°N, while its intra-annual variability (defined here as twice the standard deviation of the distribution of the ITCZ points, and measured in degrees of latitude) is about 15° of latitude. The use of the standard deviation to quantify the intra-annual variability of ITCZ is preferred here against more complicated metrics (like the bimodal separation) which may be sensitive to outliers.

The proposed framework is physically motivated, straightforward, and flexible in its implementation. Moreover, by using different values of the parameters N, w, and a, the sensitivity of the results for a considered problem (regional analysis of ITCZ dynamics, analysis of trends, etc.) can be investigated. In the next sections we use the proposed framework to analyze the climatology of the ITCZ in the entire globe in the period 1983–2012, and the trends in the location of the ITCZ since the mid-twentieth century. For this purpose, we choose here to use $N = 2$ (precipitation and OLR), $w = 15°$, and $a = 90\%$ (or in some cases $a = 85\%$). The choice of $w = 15°$ is important, since larger longitudinal windows (e.g., $w > 30°$) may not allow the tracking of nonzonal (diagonal) ITCZ features like the SPCZ, the south Indian Ocean convergence zone, and the south Atlantic convergence zone. However, we note that depending on the region, season, scale, and scope of the investigation, future analysts may decide to use different/more variables (e.g., cloud cover, divergence, diabatic heating, pressure, vertical velocity, and/or a joint combination of them), different width of the longitudinal window w, and different probability of nonexceedance a, to define the ITCZ, and no universally optimal values of these parameters exist.

4. Recent Climatology of the ITCZ

By obtaining the samples $y_{15,90\%}^{l,t}$ in all longitudes $l = 0°, r_l, 2\,r_l, \ldots, 360° - r_l$ (r_l is the longitudinal resolution), and all calendar months $t = 1, 2, \ldots, 12$ (we use climatological mean precipitation and OLR for each calendar month), the seasonal and annual distributions, and basic statistics of the location of the ITCZ in the entire globe are obtained for the period 1983–2012 (Figures 2 and S2). Results are generally consistent using either precipitation or OLR, with slight discrepancies being apparent over the Indian Ocean and East Asia (compare Figure S2a to S2b). When using OLR, some outliers are obtained over Mexico, and generally, the results when jointly considering both precipitation and OLR are more robust (see Figure 2).

Our results are consistent with the known physics of the ITCZ. Concerning the intra-annual variability, our framework shows that the ITCZ is more migratory over continental regions (compare Figures 2a–2b and see Adam et al., 2016a, 2016b), with the deep convection zone being mostly evident in the northern hemisphere during April–September (Figure 2a), and migrating to the south mainly over Africa and America, during October–March (Figure 2b). Also, the SPCZ is shown to increase in strength during October–March; note, for example, that during April–September, the subtropical part of the SPCZ is not tracked (see also Figure 1 in Waliser & Gautier, 1993; Figures 2, 4, 5, and 8 in Trenberth et al., 2000; Figure 1 in Widlansky et al., 2011; and Figure 1 in Adam et al., 2016a, 2016b). Both these remarks are in accordance with the suggestion that the ITCZ collocates with the trough of global monsoon, which seasonally follows solar heating (Trenberth et al., 2000).

Concerning the longitudinal variability, the ITCZ resides in the northern hemisphere (Philander et al., 1996), apart from the area of the Indian and western Pacific Oceans, and the Amazon (see Figures 2 and S2). Over Indian Ocean, the ITCZ is positioned in the southern hemisphere during most of the year (see Figures 2d and S2d and Waliser & Gautier, 1993), while in boreal summer, it is difficult to define, as its interaction with the Indian monsoon is still under debate (note the noisy patterns over India in Figures 2a and S2a). Particularly, although the traditional view is that the Indian monsoon is driven by land-sea thermal contrast, recent studies support that it is a manifestation of the seasonal migration of the ITCZ toward India (Bordoni & Schneider, 2008; Chao & Chen, 2001; Fleitmann et al., 2007; Gadgil, 2003). In the western and central Pacific, the ITCZ consists of two distinct and much distant zones, the northern ITCZ and the SPCZ, which coexist almost year-round, however, with high intra-annual variability in their strengths (see Figure 2 and Waliser & Gautier, 1993). As proposed recently by Mamalakis et al. (2018), the large intra-annual variability of the ITCZ and of the overturning meridional circulation (see Figures 2, 5, and 8 in Trenberth et al., 2000) over

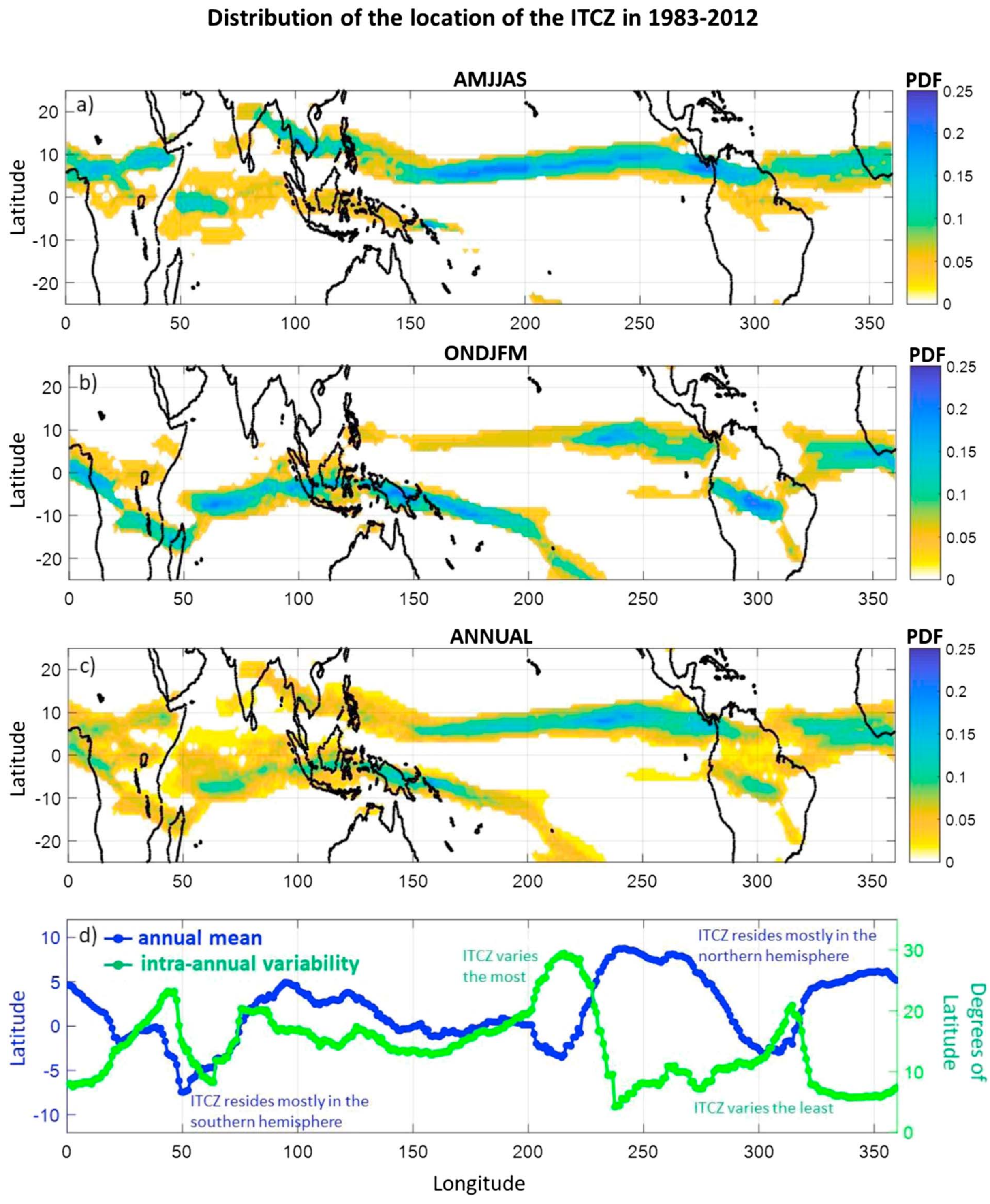

Figure 2. The location of the ITCZ around the globe in 1983–2012. (a) The empirical PDF of the location of the ITCZ during April–September, as computed in overlapping longitudinal windows of width $w = 15°$, based on the upper 10% (probability of nonexceedance $a = 90\%$) of the joint distribution of zonal precipitation (from PERSIANN-CDR) and zonal −OLR (from PSD-CDR); we use the long-term climatology of precipitation and OLR in each month, see also Figure 1.
(b) Same as in (a), but for October–March. (c) Same as in (a), but the annual distribution is presented. (d) The annual mean (blue color) and the intra-annual variability (twice the standard deviation of the distribution of the *ITCZ points*; green color) of the location of the ITCZ as a function of longitude. ITCZ = intertropical convergence zone; PDF = probability density function.

the western and central Pacific can establish interhemispheric climate connections through the accompanied expansion of the regional Hadley cell (atmospheric bridge; see also Alexander et al., 2002, and Liu et al., 2010). Accordingly, studies suggest that the longitudinal zone around the globe where the most significant interhemispheric interaction occurs is the region of east Australia to East Asia (Liu et al., 2010; Tao & Xu, 1962; Wang & Zhao, 1987). Over the eastern Pacific and Atlantic Oceans, observations suggest that the ITCZ is least variable (Figure 2d), tending to stay in the northern hemisphere during the whole year (see Figure S2d and Waliser & Gautier, 1993), although a double ITCZ may form during boreal spring in the eastern Pacific (see Figure 2 and Adam et al., 2016b; Bischoff & Schneider, 2016; Haffke et al., 2016; Yang & Magnusdottir, 2016).

The ITCZ climatology has also been obtained based on monthly products from the 20CR and the NCEP/NCAR data sets (see Figures S3 and S4, respectively). Particularly, to illustrate the generality of our framework, we have used many different variables to track the ITCZ (i.e., precipitation, OLR, joint statistics of precipitation and OLR, total cloud cover, and omega velocity), and the corresponding distributions of the location of ITCZ are shown to be very similar with that presented in Figure 2, especially when using products from the 20CR data set. The general agreement of the results in Figures 2 and S2–S4 indicates the effectiveness of the reanalysis data sets in capturing the ITCZ dynamics, and thus, their suitability to be used in assessing decadal changes in the ITCZ location.

Another important result is that when one investigates the annual distribution of the ITCZ based on season by season analysis in 1983–2012 (i.e., $t = 1, 2, \ldots, 119$), or month by month analysis (i.e., $t = 1, 2, \ldots, 360$), results are very similar (see Figure S5a–S5b and S6, respectively) to the case of using monthly climatology of precipitation and OLR (Figure 2), indicating the robustness and consistency of our framework. However, we note that in months when the Madden-Julian Oscillation is active, it may introduce biases in the tracking of the ITCZ, thus, the seasonal tracking is more accurate.

The physical consistency of the tracking framework is also illustrated by exploring the effect of El Niño-Southern Oscillation on the ITCZ location. As an example, Figure S5c presents the sampled ITCZ points in all seasons in 1983–1992, at l = 175°E. Our results show that in almost all seasons two ITCZs are tracked (one in each hemisphere; the northern ITCZ and the SPCZ), and reveal a dependence between the El Niño-Southern Oscillation and the location of the SPCZ in the central/western Pacific (here at l = 175°E), as shown by the covariation of the latter with the series of the Niño 3.4 index. It is shown that during El Niño (La Nina) years, the derived ITCZ points are located northern (southern) than average (see, e.g., Adam et al., 2016a, 2016b; Berry & Reeder, 2014; Trenberth & Shea, 1987; Widlansky et al., 2011).

5. ITCZ Trends

Time series (2-yr averages of the seasonal series) of the location of the ITCZ for the entire globe and for the period 1948–2014 are presented in Figure 3, based on reanalysis products from the 20C data set (Figure 3a) and the NCEP/NCAR data set (Figure 3b). Generally, there are evident changes in several regions, with the most prominent and consistent (i.e., identified in both reanalysis products) change being a southward shift/trend of ITCZ in the central and western Pacific Ocean (see also Berry & Reeder, 2014). Specifically, differences in the distribution of the location of the ITCZ in the period 1991–2010 relative to the period 1951–1970 clearly indicate the southward shift, which is more profound in the results of NCEP/NCAR (see Figures 3c–3d). In terms of annual precipitation, a similar southward shift has been reported and studied in the literature. Particularly, during the late twentieth century, the tropical rainbelt shifted southward, due to the decrease of the interhemispheric temperature gradient (Allen et al., 2015; Chung & Soden, 2017; Friedman et al., 2013; Hwang et al., 2013; Polson et al., 2014). The latter was mainly driven by the increased anthropogenic release of sulfate aerosols in the northern hemisphere, which counteracted the effect of the greenhouse gases (Friedman et al., 2013) and altered the cloud radiative properties (Chung & Soden, 2017; Hwang et al., 2013), making the north-to-south temperature difference decrease. Our results clearly support these precipitation trends, but we additionally report similar changes when the ITCZ is defined using OLR and/or multiple variables (note that similar trends are obtained when using total cloud cover and omega velocity to define the ITCZ from either reanalysis data set; not shown here). More particularly, over the region of 150–220°E, results derived from the 20CR data set indicate southward trends from −0.5° to −1° of latitude per decade, while the NCEP/NCAR results indicate trends from −1° to −1.5° of latitude per decade (see Figure S7a). Time series for a specific longitude l = 200°E are

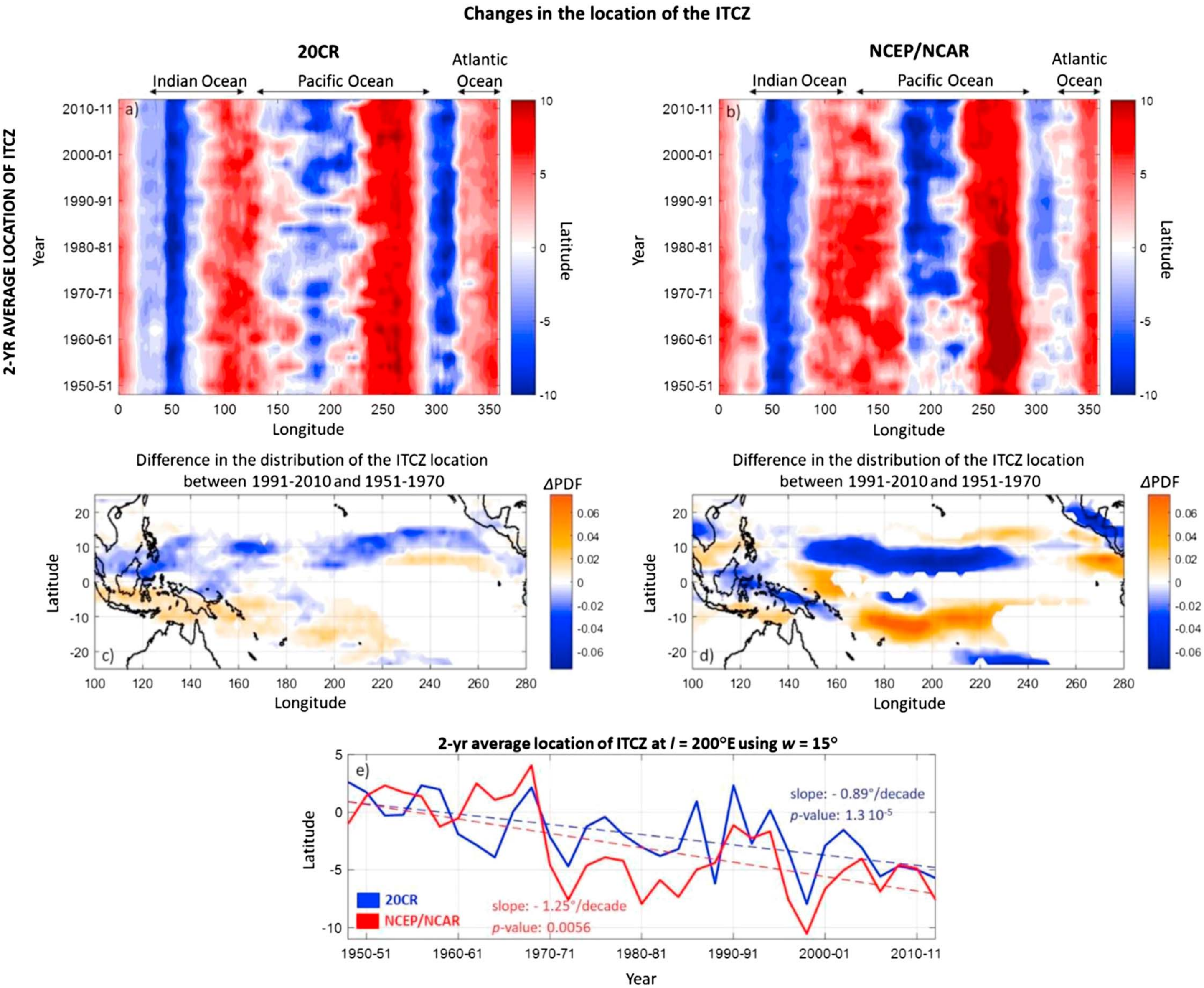

Figure 3. Changes in the location of the ITCZ. (a) Two-year average of the seasonal series of the location of the ITCZ as a function of longitude, for 1948–2014. The location of the ITCZ is obtained in each season using overlapping longitudinal windows of length $w = 15°$, based on the upper 15% of the joint distribution of zonal precipitation and −OLR. Data are from the 20CR data set. (b) Same as in (a), but data are from the NCEP/NCAR data set. (c) Difference in the probability distribution of the location of the ITCZ (ΔPDF) between the periods 1991–2010 and 1951–1970. Data are from the 20CR data set. (d) Same as in (c), but data are from the NCEP/NCAR data set. The central Pacific region is where results from the two data sets show the most prominent trends, indicating a southward shift of the ITCZ. (e) The ITCZ series at $l = 200°$E (using $w = 15°$) and the corresponding linear trends. ITCZ = intertropical convergence zone; PDF = probability density function.

also presented (see Figure 3e), and results from applying a simple linear regression (considering also the autocorrelation of the series) confirm the statistical significance of the trends.

6. Conclusions

Due to its high importance in water resources management and sustainability of ecosystems in tropical and subtropical regions, efficient tracking of the changes in the seasonal and decadal dynamics of the ITCZ at different longitudes is necessary. In the light of the limitations of existing approaches, here we proposed and applied a new probabilistic framework which facilitates detailed analysis of changes in the seasonal dynamics of the ITCZ, and offers the ability to use multiple variables to define it, which adds to its physical rigor. Moreover, it is rather computationally efficient and flexible in its implementation, which makes it useful for the analysis of multimodel ensembles in climate change assessment studies.

Competing interests

The authors declare no competing financial or nonfinancial interests.

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References

Adam, O., Bischoff, T., & Schneider, T. (2016a). Seasonal and interannual variations of the energy flux equator and ITCZ. Part I: Zonally averaged ITCZ position. *Journal of Climate*, *29*, 3219–3230. https://doi.org/10.1175/JCLI-D-15-0512.1

Adam, O., Bischoff, T., & Schneider, T. (2016b). Seasonal and interannual variations of the energy flux equator and ITCZ. Part II: Zonally varying shifts of the ITCZ. *Journal of Climate*, *29*, 7281–7293. https://doi.org/10.1175/JCLI-D-15-0710.1

Alexander, M. A., Blade, I., Newman, M., Lanzante, J. R., Lau, N.-C., & Scott, J. D. (2002). The atmospheric bridge: The influence of ENSO teleconnection on air-sea interaction over the global oceans. *Journal of Climate*, *15*, 2205–2231. https://doi.org/10.1175/1520-0442(2002)015<2205:TABTIO>2.0.CO;2

Allen, R. J. (2015). A 21st century northward tropical precipitation shift caused by future anthropogenic aerosol reductions. *Journal of Geophysical Research: Atmospheres*, *120*, 9087–9102. https://doi.org/10.1002/2015JD023623

Allen, R. J., Evan, A. T., & Booth, B. B. B. (2015). Interhemispheric aerosol radiative forcing and tropical precipitation shifts during the late twentieth century. *Journal of Climate*, *28*, 8219–8246. https://doi.org/10.1175/JCLI-D-15-0148.1

Arbuszewski, J. A., deMenocal, P. B., Cléroux, C., Bradtmiller, L., & Mix, A. (2013). Meridional shifts of the Atlantic intertropical convergence zone since the Last Glacial Maximum. *Nature Geoscience*, *6*, 959–962. https://doi.org/10.1038/NGEO1961

Ashouri, H., Hsu, K. L., Sorooshian, S., Braithwaite, D. K., Knapp, K. R., Cecil, L. D., et al. (2015). PERSIANN-CDR: Daily precipitation climate studies data record from multisatellite observations for/hydrological and climate studies. *Bulletin of the American Meteorological Society*, *96*, 69–83. https://doi.org/10.1175/BAMS-D-13-00068.1

Bain, C. L., de Paz, J., Kramer, J., Magnusdottir, G., Smyth, P., Stern, H., & Wang, C. C. (2011). Detecting the ITCZ in instantaneous satellite data using spatiotemporal statistical modeling: ITCZ climatology in the east Pacific. *Journal of Climate*, *24*, 216–230. https://doi.org/10.1175/2010JCLI3716.1

Berry, G., & Reeder, M. J. (2014). Objective identification of the intertropical convergence zone: Climatology and trends from the ERA-interim. *Journal of Climate*, *27*, 1894–1909. https://doi.org/10.1175/JCLI-D-13-00339.1

Bischoff, T., & Schneider, T. (2014). Energetic constraints on the position of the intertropical convergence zone. *Journal of Climate*, *27*, 4937–4951. https://doi.org/10.1175/JCLI-D-13-00650.1

Bischoff, T., & Schneider, T. (2016). The equatorial energy balance, ITCZ position, and double-ITCZ bifurcations. *Journal of Climate*, *29*, 2997–3013. https://doi.org/10.1175/JCLI-D-15-0328.1

Bordoni, S., & Schneider, T. (2008). Monsoons as eddy-mediated regime transitions of the tropical overturning circulation. *Nature Geoscience*, *1*, 515–519. https://doi.org/10.1038/ngeo248

Broccoli, A. J., Dahl, K. A., & Stouffer, R. J. (2006). Response of the ITCZ to Northern Hemisphere cooling. *Geophysical Research Letters*, *33*, L01702. https://doi.org/10.1029/2005GL024546

Broecker, W. S., & Putnam, A. E. (2013). Hydrologic impacts of past shifts of Earth's thermal equator offer insight into those to be produced by fossil fuel CO_2. *Proceedings of the National Academy of Sciences of the United States of America*, *110*(42), 16,710–16,715. https://doi.org/10.1073/pnas.1301855110

Carvalho, L. M., Jones, C., & Liebmann, B. (2004). The South Atlantic convergence zone: Intensity, form, persistence, and relationships with intraseasonal to interannual activity and extreme rainfall. *Journal of Climate*, *17*, 88–108. https://doi.org/10.1175/1520-0442(2004)017<0088:TSACZI>2.0.CO;2

Chao, W. C., & Chen, B. (2001). The origin of monsoons. *Journal of the Atmospheric Sciences*, *58*, 3497–3507. https://doi.org/10.1175/1520-0469(2001)058<3497:TOOM>2.0.CO;2

Chiang, J. C. H., & Bitz, C. M. (2005). Influence of high latitude ice cover on the marine intertropical convergence zone. *Climate Dynamics*, *25*, 477–496. https://doi.org/10.1007/s00382-005-0040-5

Chung, E.-S., & Soden, B. J. (2017). Hemispheric climate shifts driven by anthropogenic aerosol-cloud interactions. *Nature Geoscience*, *10*, 566–571. https://doi.org/10.1038/NGEO2988

Compo, G. P., Whitaker, J. S., Sardeshmukh, P. D., Matsui, N., Allan, R. J., Yin, X., et al. (2011). Review article, The twentieth century reanalysis project. *Quarterly Journal of the Royal Meteorological Society*, *137*, 1–28. https://doi.org/10.1002/qj.776

Cook, K. H. (1998). On the response of the Southern Hemisphere to ENSO. In *Proc 23rd Climate Diagnostics and Prediction Workshop* (pp. 323–326). Miami, FL: American Meteorological Society.

Cook, K. H. (2000). The south Indian convergence zone and interannual rainfall variability over southern Africa. *Journal of Climate*, *13*, 3789–3804. https://doi.org/10.1175/1520-0442(2000)013<3789:TSICZA>2.0.CO;2

Donohoe, A., Marshall, J., Ferreira, D., & McGee, D. (2013). The relationship between ITCZ location and cross-equatorial atmospheric heat transport: From the seasonal cycle to the last glacial maximum. *Journal of Climate*, *26*, 3597–3618. https://doi.org/10.1175/JCLI-D-12-00467.1

Fleitmann, D., Burns, S. J., Mangini, A., Mudelsee, M., Kramers, J., Villa, I., et al. (2007). Holocene ITCZ and Indian monsoon dynamics recorded in stalagmites from Oman and Yemen (Socotra). *Quaternary Science Reviews*, *26*, 170–188. https://doi.org/10.1016/j.quascirev.2006.04.012

Friedman, A. R., Hwang, Y.-T., Chiang, J. C. H., & Frierson, D. M. W. (2013). Interhemispheric temperature asymmetry over the twentieth century and in future projections. *Journal of Climate*, *26*, 5419–5433. https://doi.org/10.1175/JCLI-D-12-00525.1

Gadgil, S. (2003). The Indian monsoon and its variability. *Annual Review of Earth and Planetary Sciences*, *31*, 429–467. https://doi.org/10.1146/annurev.earth.31.100901.141251

Graham, N. E., & Barnett, T. P. (1987). Sea surface temperature, surface wind divergence, and convection over tropical oceans. *Science*, *238*(4827), 657–659. https://doi.org/10.1126/science.238.4827.657

Haffke, C., & Magnusdottir, G. (2013). The South Pacific convergence zone in three decades of satellite images. *Journal of Geophysical Research: Atmospheres*, *118*, 10839–10849. https://doi.org/10.1002/jgrd.50838

Haffke, C., & Magnusdottir, G. (2015). Diurnal cycle of the South Pacific convergence zone in 30 years of satellite images. *Journal of Geophysical Research: Atmospheres*, *120*, 9059–9070. https://doi.org/10.1002/2015JD023436

Haffke, C., Magnusdottir, G., Henke, D., Smyth, P., & Peings, Y. (2016). Daily states of the March-April east Pacific ITCZ in three decades of high-resolution satellite data. *Journal of Climate*, *29*, 2981–2995. https://doi.org/10.1175/JCLI-D-15-0224.1

Hwang, Y.-T., Frierson, D. M. W., & Kang, S. M. (2013). Anthropogenic sulfate aerosol and the southward shift of tropical precipitation in the late 20th century. *Geophysical Research Letters*, *40*, 2845–2850. https://doi.org/10.1002/grl.50502

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., et al. (1996). The NCEP/NCAR 40-year reanalysis project. *BAMS*, *77*(3), 437–471. https://doi.org/10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2

Kang, S. M., Held, I. M., Frierson, D. M. W., & Zhao, M. (2008). The response of the ITCZ to extratropical thermal forcing: Idealized slab-ocean experiments with a GCM. *Journal of Climate*, *21*, 3521–3532. https://doi.org/10.1175/2007JCLI2146.1

Lee, H.-T. (2014). Climate algorithm theoretical basis document (C-ATBD): Outgoing longwave radiation (OLR)—Daily. NOAA's Climate Data Record (CDR) Program, CDRP-ATBD-0526 (46 pp.)

Liu, G., Ji, L., Sun, S., & Zhang, Q. (2010). An inter-hemispheric teleconnection and a possible mechanism for its formation. *Advances in Atmospheric Sciences*, *27*(3), 629–638. https://doi.org/10.1007/s00376-009-8172-x

Madden, R. A., & Julian, P. R. (1971). Detection of a 40–50 day oscillation in the zonal wind in the tropical Pacific. *Journal of the Atmospheric Sciences*, *28*, 702–708. https://doi.org/10.1175/1520-0469(1971)028<0702:DOADOI>2.0.CO;2

Mamalakis, A., Yu, J.-Y., Randerson, J. T., AghaKouchak, A., & Foufoula-Georgiou, E. (2018). A new interhemispheric teleconnection increases predictability of winter precipitation in southwestern US. *Nature Communications*, *9*. https://doi.org/10.1038/s41467-018-04722-7

Nelsen, R. B. (1998). *An introduction to copulas*, *Lecture Notes in Statistics, 139*. New York: Spinger-Verlag.

Nicholson, S. E. (2009). A revised picture of the structure of the "monsoon" and land ITCZ over West Africa. *Climate Dynamics*, *32*, 1155–1171. https://doi.org/10.1007/s00382-008-0514-3

Nicholson, S. E. (2018). The ITCZ and the seasonal cycle over equatorial Africa. *BAMS*, *99*, 337–348. https://doi.org/10.1175/BAMS-D-16-0287.1

Philander, S. G. H., Gu, D., Lambert, G., Li, T., Halpern, D., Lau, N.-C., & Pacanowski, R. C. (1996). Why the ITCZ is mostly north of the equator. *Journal of Climate*, *9*, 2958–2972. https://doi.org/10.1175/1520-0442(1996)009<2958:WTIIMN>2.0.CO;2

Polson, D., Bollasina, M., Hegerl, G. C., & Wilcox, L. J. (2014). Decreased monsoon precipitation in the Northern Hemisphere due to anthropogenic aerosols. *Geophysical Research Letters*, *41*, 6023–6029. https://doi.org/10.1002/2014GL060811

Sachs, J. P., Sachse, D., Smittenberg, R. H., Zhang, Z., Battisti, D. S., & Golubic, S. (2009). Southward movement of the Pacific intertropical convergence zone AD 1400–1850. *Nature Geoscience*, *2*, 519–525. https://doi.org/10.1038/NGEO554

Salvadori, G., & De Michele, C. (2007). On the use of copulas in hydrology: Theory and practice. *Journal of Hydrologic Engineering*, *12*(4), 369–380. https://doi.org/10.1061/(ASCE)1084-0699(2007)12:4(369)

Schneider, T., Bischoff, T., & Haug, G. H. (2014). Migrations and dynamics of the intertopical convergence zone. *Nature*, *513*, 45–53. https://doi.org/10.1038/nature13636

Tao, S. Y., & Xu, S. Y. (1962). The characteristics of the zonal and meridional circulation over tropical and subtropical regions in eastern Asia in summer (in Chinese). *Acta Meteorologica Sinica*, *32*, 91–103.

Trenberth, K. E. (2011). Changes in precipitation with climate change. *Climate Research*, *47*, 123–138. https://doi.org/10.3354/cr00953

Trenberth, K. E., & Shea, D. J. (1987). On the evolution of the Southern Oscillation. *Monthly Weather Review*, *115*, 3078–3096. https://doi.org/10.1175/1520-0493(1987)115<3078:OTEOTS>2.0.CO;2

Trenberth, K. E., Stepaniak, D. P., & Caron, J. M. (2000). The global monsoon as seen through the divergent atmospheric circulation. *Journal of Climate*, *13*, 3969–3993. https://doi.org/10.1175/1520-0442(2000)013<3969:TGMAST>2.0.CO;2

Waliser, D. E., & Gautier, C. (1993). A satellite-derived climatology of the ITCZ. *Journal of Climate*, *6*, 2162–2174. https://doi.org/10.1175/1520-0442(1993)006<2162:ASDCOT>2.0.CO;2

Waliser, D. E., & Somerville, R. C. J. (1994). Preferred latitudes of the intertropical convergence zone. *Journal of the Atmospheric Sciences*, *51*(12), 1619–1639. https://doi.org/10.1175/1520-0469(1994)051<1619:PLOTIC>2.0.CO;2

Wang, S. W., & Zhao, Z. C. (1987). The interaction between the two hemispheres and long-term forecasting. In *Foundation of long-term weather forecasting* (in Chinese) (pp. 116–130). Shanghai: Shanghai Science & Technology Press.

Widlansky, M. J., Webster, P. J., & Hoyas, C. D. (2011). On the location and orientation of the South Pacific Convergence Zone. *Climate Dynamics*, *36*, 561–578. https://doi.org/10.1007/s00382-010-0871-6

Yang, W., & Magnusdottir, G. (2016). Interannual signature in daily ITCZ states in the east Pacific in boreal spring. *Journal of Climate*, *29*, 8013–8025. https://doi.org/10.1175/JCLI-D-16-0395.1

Zhang, G., & Wang, Z. (2015). Interannual variability of tropical cyclone activity and regional Hadley circulation over the northeastern Pacific. *Geophysical Research Letters*, *42*, 2473–2481. https://doi.org/10.1002/2015GL063318