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ABSTRACT

In this study, long-term structural changes in the intertropical convergence zone (ITCZ) and associated precipitation–radiation–circulation feedback processes are examined using multiple sources of reanalysis data for temperature, winds, moisture, and observed precipitation and outgoing longwave radiation (OLR) during 1980–2014. Consistent with CMIP5 climate model projections of the “deep tropical squeeze” under greenhouse warming, this period witnessed a warming and wetting (increased specific humidity) global trend, characterized by a narrowing of the ITCZ core with increased precipitation, coupled to widespread tropospheric drying (deficient relative humidity), increased OLR in the subtropics and midlatitudes, a widening of the descending branches of the Hadley circulation, and a poleward shift of the jet streams in both hemispheres. The widespread tropospheric drying stems from 1) a faster rate of increased saturated water vapor with warming, relative to the increase in ambient moisture due to convective and large-scale transport, and 2) enhanced anomalous subsidence, and low-level moisture divergence in the subtropics and midlatitudes. The long-term trend in enhanced precipitation (latent heating) in the ITCZ core region is strongly coupled to increasing OLR (radiative cooling to space) in the expanding dry zones, particularly over land regions in the subtropics and midlatitudes, arguably as a necessary condition for global thermodynamic energy balance. Analyses of the trend patterns in vertical profiles of $p$ velocity, temperature, and relative humidity with respect to ITCZ precipitation rate and OLR reveal that the contrast between the wet and dry regions in the troposphere has been increasing globally, with the ITCZ core getting wetter and contracting, while the marginal convective and dry zones are getting drier and expanding.

KEYWORDS: Hadley circulation; Subsidence; Precipitation; Humidity; Latent heating/cooling; Longwave radiation

1. Introduction

Anthropogenic climate change and natural climate variability are intrinsically linked through complex interactions among radiation, clouds, precipitation, and circulation as well as interface exchanges of energy and water among components of the coupled atmosphere–ocean–land system (IPCC 2013). These complex interactions have spurred large uncertainties regarding regional impacts such as floods and droughts. Notwithstanding these uncertainties, a number of long-term (multidecadal) observed global trends have generally been recognized by scientific consensus as highly likely attributable to GHG warming (IPCC 2013). These include, among others, warmer and wetter tropics (Santer et al. 2000; Fu et al. 2004; Lau and Wu 2007; Adler et al. 2017), a rise of the tropical tropopause coupled to an expansion of the Hadley circulation (HC; Seidel et al. 2001; Santer et al. 2003; Lu et al. 2007; Seidel and Randel 2007; Lu et al. 2009), a widening of subtropical dry zones (Hu...

Furthermore, observational evidences have also revealed a multidecadal trend indicating a sharpening (narrowing meridional width and increased precipitation) of the intertropical convergence zone (ITCZ) over the central and eastern Pacific, and increasing contrast between dry and wet extremes globally during the last several decades (Lau and Wu 2007, 2011; Zhou et al. 2011; Gu et al. 2016; Wodzicki and Rapp 2016; Wu and Lau 2016). This trend in the ITCZ has been attributed to various mechanisms such as “wet-getting-wetter” (Chou and Neelin 2004; Chou et al. 2009), “warm-getting-wetter” (Xie et al. 2010; Chadwick et al. 2013; Huang et al. 2013), the upper-ante effect (Neelin et al. 2003; Lintner and Neelin 2007), the circulation response to radiative forcing of clouds and water vapor (Voigt et al. 2014; Voigt and Shaw 2015), and the efficiency of interhemispheric energy transport (Donohoe et al. 2019). Others have attributed the increased precipitation of the ITCZ to a tightening of the ascending branch of the HC (Su et al. 2017) and enhanced advection of moist static energy in the deep tropics (Byrne and Schneider 2016; Byrne et al. 2018). Based on analyses of model experiments from phase 5 of the Coupled Model Intercomparison Project (CMIP5), Lau et al. (2013) and Lau and Kim (2015) found a canonical response of the global precipitation and circulation under 2xCO2 forcing, that is, the “deep tropical squeeze” (DTS), linking the narrowing and intensification of the ITCZ to an overall reduced relative humidity (drying) of the global troposphere, except in the deep tropics and polar regions. The DTS posits that a dynamical moisture convergence feedback in the tropics induced by GHG warming can lead to a narrowing and intensification of the ITCZ, coupled to a rise in the altitude of the maximum divergent outflow in the upper troposphere, together with a widening of the subsiding branch of the HC. In a more recent study using a superparameterized GCM (i.e., one with embedded cloud-resolving models), Lau et al. (2019) found that cloud–radiation–convection–circulation interaction, via convective aggregation in the tropics, can play fundamental roles in enhancing the diabatic heating contrasts that drive circulation changes connecting the wet and dry regions in a global climate system, perturbed by cloud radiation feedback. However, observational evidence of DTS and relationships among precipitation, radiation, and circulation changes, as well as linkage to GHG warming, is still lacking. The objectives of the present study are 1) to detect the fingerprints of DTS and associated large-scale circulation changes from long-term observations and 2) to shed new light on underlying physical processes, and possible connections to GHG warming.

2. Data and analysis methods

A variety of observational datasets from multiple independent sources for the period 1980–2014 are used in this study. For global precipitation, we use monthly data from the Global Precipitation Climatology Project (GPCP) v2.3 (Adler et al. 2003), which consists of combined satellite-based precipitation estimates and in situ observations over land on a 2.5° × 2.5° grid. Monthly mean satellite-based outgoing longwave radiation (OLR) observations are obtained from the National Oceanic and Atmospheric Administration (NOAA) interpolated OLR dataset on a 2.5° × 2.5° grid for the same period as precipitation (Liebmann and Smith 1996; Lee 2014).

For temperature, moisture, relative humidity (RH), and winds, we use reanalysis data products. To increase reliability, six reanalysis datasets are used, including the European Centre for Medium-Range Weather Forecast (ECMWF) interim reanalysis (ERA-Interim, herein ERAI; Dee et al. 2011), the Japanese 55-Year Reanalysis (JRA-55; KOBAYASHI et al. 2015), the Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA2; Gelaro et al. 2017), the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis (NCEP1; Kalnay et al. 1996), and NCEP–U.S. Department of Energy Atmospheric Model Intercomparison Project II reanalysis (NCEP2; Kanamitsu et al. 2002), and the NOAA–Cooperative Institute for Research in Environmental Sciences (CIRES) Twentieth Century Reanalysis V2c (20CR; Compo et al. 2011). More detailed descriptions of the six reanalysis datasets can be found in Table S1 in the online supplemental material. All reanalysis datasets used are remapped onto a uniform 2.5° × 2.5° grid by using bilinear interpolation to calculate the multireanalysis ensemble mean (MRE). For estimates of the long-term change, linear trends (also referred to hereinafter as anomalies) of all quantities are computed based on annual mean during 1980–2014. Statistical significance is estimated using the standard two-tailed Student’s t test with an effective degree of freedom accounting for autocorrelation in a given time series (Zwiers and von Storch 1995). The Theil–Sen trend estimation method (Sen 1968) and Mann–Kendall test (Gilbert 1987) are also used. Since all methods produce consistent results, only those for linear trend and Student’s t test are shown in this study. It is important to point out that during our data period,
previous studies have shown significant signals not only in linear trend global pattern of surface temperature and precipitation, but also in multidecadal variations associated with Pacific decadal oscillation (PDO), including a tendency for more La Niña–like cooling of the eastern equatorial Pacific associated with the “global warming hiatus” of 1998–2013 (Gu and Adler 2013; Gu et al. 2016; Kosaka and Xie 2013; Trenberth and Fasullo 2013). Here, our focus is on cloud–radiation–convection–circulation feedback associated with global warming, as conveyed by linear trend analyses of diverse quantities from observations and multiple reanalysis products during a relatively short recent data period. Separation into effects of global warming versus interdecadal variations require longer data periods and is outside the scope of this work.

3. Results

a. Zonal mean precipitation, large-scale circulation, and RH

Figure 1a shows the latitudinal profile of zonal mean precipitation trend and climatology. Strong climatological ITCZ precipitation (annual mean $\geq 3$ mm day$^{-1}$) appears in the tropics with the maximum centered around $5^\circ$–$7^\circ$N of the equator. The trend profile shows enhanced precipitation near the climatological ITCZ maximum, flanked by drying areas in both hemispheres. The drying is more pronounced over the Northern Hemisphere, extending into the subtropics and midlatitudes. In association with the ITCZ precipitation change, the trend of MRE vertical velocity shows significant enhanced rising motions in the deep tropics near the ITCZ core, accompanied by anomalous subsidence near the tropical and extratropical boundaries of climatological sinking motions, respectively in both hemispheres (Fig. 1b). The trend indicating expansion of the HC is also evident in the meridional mass streamfunction pattern (Fig. 1c) with the anomalies tightly packed around the ITCZ core, and also found beyond the outer boundaries of the sinking region, represented by the zero lines in the climatological MRE near $35^\circ$N/S (Hu and Fu 2007; Hu et al. 2011; Allen et al. 2014; Davis and Birner 2017; Grise et al. 2018). The poleward expansion of the HC can also be seen in the decrease (increase) of zonal mean wind anomalies on the equatorward (poleward) flank of the climatological jet stream core near $35^\circ$–$45^\circ$N/S (Fig. 1d). The jet stream changes arise, in part, from increased momentum and heat transport from the subtropics to midlatitudes by transient storm track activities in the upper troposphere (Fig. S1). A strong increasing trend in zonal westerlies in the Southern Hemisphere extratropics ($>50^\circ$S) can be seen in Fig. 1d. This trend has been noted in previous studies and is attributed to

FIG. 1. (a) Latitudinal profile of annual GPCP precipitation (mm) for linear trend (bar; decade$^{-1}$) and climatology (black line) during 1980–2014. Latitude–height profile of annual MRE (b) vertical $p$ velocity ($10^{-3}$ Pa s$^{-1}$), (c) meridional mass streamfunction ($10^{10}$ kg s$^{-1}$), and (d) zonal winds (m s$^{-1}$) for linear trend (shading; decade$^{-1}$) and climatology (contour) during 1980–2014. Bars with outlines and dots indicate that the significance level reaches 90%.
increased polar stratospheric cooling from reduced absorption of ultraviolet radiation due to ozone depletion that occurred during the present data period (McLandress et al. 2011; Perlwitz 2011; Polvani et al. 2011; Shaw et al. 2016). In this study, we focus only on the tropical influences. Possible polar stratospheric forcing is outside the scope of this investigation.

The aforementioned structural changes in the ITCZ and HC are associated with a trend in global tropospheric RH deficit, except in the middle and lower troposphere in the deep tropics near the ITCZ core region (Fig. 2a). The latitude–height zonal mean RH trend pattern resembles those reported previously in climate model projections under GHG warming (Wetherald and Manabe 1980; Sherwood et al. 2010; Lau and Kim 2015). However, judging from the specific humidity and temperature pattern (Figs. 2b,c), it is also clear that during the present data period, the global troposphere has been getting warmer and wetter, and the lower stratosphere cooler and slightly drier, consistent with signature GHG warming and moistening (Soden et al. 2005; Dessler and Davis 2010; Chung et al. 2014). This dichotomy in apparent global wetting and drying can be explained in terms of the temperature-saturated water vapor constraint governed by the Clausius–Clapeyron (CC) relationship:

\[ dR_h = dq/q_s - \alpha R_h dT, \]

where \( \alpha = 6.5\% \text{ K}^{-1} \), \( q \) is the specific humidity, \( q_s \) is the saturated specific humidity, \( R_h \) is the relative humidity, and \( T \) is the temperature. Essentially, under the effects of GHG forcing, the saturated moisture in a warming atmosphere increases as a function of temperature much faster than the actual increase in the ambient specific humidity, which depends on efficiencies of convection and atmospheric moisture transport. In the tropics, warm air from below rises following the moist adiabatic lapse rate, and water vapor is transported upward by deep convection to the upper troposphere, which occurs relatively infrequently. As a result of the CC constraint, the upper troposphere of the deep tropics and much of the extratropics warms much faster than the lower troposphere, and gets drier, RH-wise (\( dq/q_s \ll -\alpha R_h dT \)).

In the mid- to lower troposphere and near the surface of the subtropics and midlatitudes, additional drying occurs due to dynamical effects (i.e., increased anomalous subsidence bringing drier air from above). Moreover, adiabatic warming and drying of the subsiding air further exacerbate the RH deficit (Lau and Kim 2015). These effects are reflected in the characteristic feature of the two arms of anomalous RH deficit extending from the upper troposphere in the deep tropics to the
middle and lower troposphere in the extratropics, and "squeezing" back toward the tropics near the surface, in both hemispheres (Fig. 2a). In the lower stratosphere (Fig. 2a) where upward moisture by deep convection is negligibly small \( \frac{dq}{qs} \approx 0 \), the increase in RH is due mostly to the thermodynamic cooling effect \( -aRdT > 0 \).

In the ITCZ region, RH below 300 hPa increases as a result of enhanced specific humidity from anomalous moisture convergence (Fig. 2d), while RH above 300 hPa decreases due to the warmer upper troposphere, relative to below (Figs. 2a,c). Moisture divergence anomalies, arising from large-scale dynamical adjustment processes also contribute to low-level drying near 40°S, 20°S–0°, 15°N, and 30°–50°N (Fig. 2d), coinciding with the subsidence anomalies (Fig. 1b). As a result, a pronounced tropospheric RH deficit is found located at the poleward flanks of climatological RH minima in both hemispheres (Fig. 2a), consistent with the projected expansion of subtropical dry zones (RH < 30%) over the Pacific.

\[ aRdT < 0 \]

\[ \frac{dq}{qs} \approx 0 \]

\[ -aRdT > 0 \]

In summary, RH represents a critical control factor in delineating the competing effects of long-term changes in temperature, moisture transport, and circulation change.

We have examined the latitude–height RH trend pattern in individual reanalysis (Fig. S6) and found large inter-reanalysis diversity, particularly in the upper troposphere. This is likely due to the lack of direct observations of RH to constrain reanalyses outputs. As an example, in the upper troposphere of the tropics, JRA-55 and NCEP2 show significant positive and negative RH anomalies, respectively (Figs. S6c,f), which can be largely explained by the difference in specific humidity and moisture convergence (Figs. S7c,f and S8c,f). Notably, the anomalous RH deficit in the subtropical middle to lower troposphere is consistently captured in all reanalysis datasets (Fig. S6), and good agreement in reduced subtropical RH anomalies can also be found in the relevant 500-hPa spatial patterns (Fig. S9).

b. Trend patterns of RH, precipitation, vertical motion, and OLR

In this section, the interrelationships among trend signals in RH, precipitation, vertical motion and OLR are examined (Fig. 3). In the deep tropics (20°S–20°N), the 500-hPa RH trend (Fig. 3a) displays a pattern of alternating wetting and drying of the troposphere circumscribing the equatorial regions, featuring a pronounced east–west dipole anomaly encompassing the Maritime Continent/central Pacific region, coupled to two secondary dipoles over the eastern equatorial Pacific/northwestern South America/South Atlantic region and the West Africa/Indian Ocean region, respectively (Fig. 3a). In the subtropics (20°–35°N, S), the RH deficit is most pronounced near the poleward edge of the climatological dry zones (RH < 30%) over the Pacific.
and the Atlantic. Strong and negative RH anomalies indicating extensive drying are found over the midlatitudes (30°–60°N), with the most pronounced signal over the extratropical land regions of Eurasia. Significant midtropospheric drying is also found in the Southern Hemisphere subtropics and midlatitudes (25°–60°S), albeit less pronounced compared to the Northern Hemisphere.

In the deep tropics (20°S–20°N), the RH anomalies are consistent with the trend pattern in precipitation and 500-hPa $p$ velocity $\omega$, with RH wetting (drying) matching well with the regions of enhanced (reduced) precipitation, and anomalous rising (sinking) motions (Figs. 3b,c). The respective pattern correlation (pcr) of RH to precipitation (0.53), $\omega$ ($-0.78$), and OLR ($-0.50$) is highly significant ($p < 0.001$). The excellent pcr values can be attributed to the robust dipole anomalies in precipitation and vertical motions associated with multidecadal changes in the Walker circulation and sea surface temperature, noted in numerous previous studies (England et al. 2014; McGregor et al. 2014; Ma and Zhou 2016; Chung et al. 2019). In the subtropics and extratropics (20°–60°N, S), the spatial match (pcr = 0.26, $p > 0.02$) between RH and precipitation is insignificant, while that for RH and $\omega$ remains strong (pcr = 0.40, $p < 0.003$). On the other hand, for RH and OLR in the subtropics and extratropics (20°–60°N/S), the match in the trend pattern remains strong (pcr = 0.53, $p < 0.001$) and even slightly better compared to the deep tropics. Overall, positive OLR anomalies are stronger and much more widespread, compared to negative OLR (Fig. 3d), especially in the Northern Hemisphere extratropical land regions, where the surface warming trends are strong (Fig. S10). An increase in OLR at the top of the atmosphere in conjunction with a reduction in RH signals a net loss in longwave radiation energy to space from reduced cloudiness and increased exposure of the warmer atmosphere–Earth surface. The overall increase in precipitation in the ITCZ regions in the deep tropics and the expansion of areas with RH deficit are consistent with the notion of increasing contrast between the wet and dry regions as a fundamental response of the climate system stemming from diabatic heating–circulation interactions under a major global radiative perturbation, regardless whether the source of the perturbation is natural or anthropogenic (Stephens et al. 2018; Lau et al. 2019). The trend patterns also support the notion that loss in radiation energy in extended regions of anomalous RH deficit acts as “radiator fms” in order to balance the increased latent heating by precipitation in the “furnace” region of ITCZ (Pierrehumbert 1995; Lau and Kim 2015).

To further explore the furnace–radiator paradigm, we have computed the linear trend magnitudes of 500-hPa $p$ velocity $\omega$, precipitation, RH, and OLR averaged over regions with ascent ($\omega < 0$ Pa s$^{-1}$), and descent ($\omega > 0$ Pa s$^{-1}$) in the tropics respectively for each reanalysis dataset, and for the MRE (Fig. 4a). Within the tropics, strong increases in precipitation and RH, together with reduced total OLR, can be identified in the ascent regions, and the opposites are found in the descent regions. In the ascent regions, the troposphere is warmed by the residual imbalance between enhanced latent heating (from increased precipitation) and adiabatic cooling due to ascent. The warmer air will increase OLR cooling to space. However, increased precipitation means more deep convection with cold cloud tops, and increased water vapor from moisture convergence. Both effects trap more longwave radiation, leading to decreased OLR, and warming. The net effect is a slight negative OLR (warming effect), amplifying the warming due to latent heating (Fig. 4a, left panel). In contrast, in the descent regions, increased subsidence warms the air by adiabatic compression, suppresses precipitation and clouds, and reduces RH. These all work to increase OLR; that is, there is strong cooling to space from longwave radiative loss (Fig. 4a, right panel). Figures 4b and 4c show that within the tropics, precipitation in the ascent areas is highly correlated with RH and total OLR in the descent areas with highly significant ($p < 0.01$) correlation coefficient of $-0.65$ and 0.67, respectively (Table 1). These strong correlations attest to the strength of the east–west overturning circulation in controlling the heating contrast in the wetter (latent heating) and drier (radiative cooling) regions. Precipitation in the tropical ascent regions is also strongly correlated with RH and total OLR in the extratropical descent regions with correlation coefficients ($p < 0.01$) of $-0.57$ and 0.49, respectively (Figs. 4d,e). The trends of $\omega$, RH, vertical motion, and OLR time series in the descent areas that are linearly congruent with the ITCZ precipitation in the ascent areas have been estimated. This is done by regressing the time series of these quantities onto the time series of rain rates, and then multiplying the linear trend of rain rate for ascent areas in the ITCZ, following the method of Thompson et al. (2000). Congruent trend analyses for precipitation in the tropical ascent regions have been carried out for $\omega$, RH, and OLR in descending areas over select large-scale domains that include, respectively, the tropics (30°S–30°N), the tropics and extratropics (60°S–60°N), and separately the extratropics of the Northern (30°–60°N) and Southern Hemisphere (30°–60°S). Analyses of variance of the regressed time series (Table 1) show that the long-term trend of precipitation in the ascent regions of the ITCZ contributes to significant portions (15%–40%) of the total variance of RH and OLR, respectively, in the descent regions within the
global tropics (30°S–30°N), as well as within the tropics and extratropics (60°S–60°N). Remarkably, a large portion of the total variance of RH (69.6%), and OLR (27.5%) in the northern extratropics (30°–60°N) can be explained by the linear trend of precipitation in the ascent regions of the ITCZ. This reflects the important roles of expanded drier, less cloudy, and warmer land areas (e.g., deserts and semideserts) in the Northern Hemisphere extratropics, acting as longwave radiator fins in balancing the increased latent heating in the tropics (see Fig. 3d and Fig. S10).
expansion of deserts and arid and semi-arid areas, has been well documented in numerous recent studies (Dai 2011; Feng and Fu 2013; Fu and Feng 2014; Sherwood and Fu 2014; Feng and Zhang 2015; Huang et al. 2016).

c. Vertical profile changes

To further quantify the increasing contrast between wet and dry regions, the long-term trends in vertical profile of $p$ velocity, temperature, and RH over the region from 60°S–60°N as a function of the precipitation rate $P$ and OLR have been constructed (Fig. 5). Anomalous upward motions are dominant over the ITCZ core region ($P > 10$ mm day$^{-1}$), most intense for extreme precipitation (Fig. 5a). The anomalous ascent weakens rapidly over the marginal convective zone (MCZ; $1 < P < 10$ mm day$^{-1}$). Note that the MCZ as defined includes not only regions with moderate rainfall in the tropics, but also midlatitude storm track regions, near the outer boundaries of the descending branch of the HC. Beyond the MCZ, the vertical motions reverse sign, and anomalous downward motions develop in the middle and lower troposphere over the dry zone (DZ; $P < 1$ mm day$^{-1}$), with most pronounced descent found over the driest part of the DZ. As defined, the DZ covers not only the subtropics, and also a large part of the extratropical oceans and continents of both hemispheres (cf. Fig. 3b). The temperature–precipitation cross section (Fig. 5b) exhibits overall tropospheric warming and stratospheric cooling with the strongest signal in the ITCZ core region, and in the DZ consistent with the zonal mean pattern (Fig. 2c). In addition, warming in the upper troposphere and lower stratosphere, and cooling in the lower troposphere is found near the MCZ. This warming/cooling pattern is likely associated with increased midlatitude storm track activities near the poleward edge of the HC (30°–50°N, S), in conjunction with the poleward migration of the jet streams (see Fig. 1d). These activities are associated with net increase in upward and poleward heat and moisture transport due to enhanced cloud–radiation–circulation interactions, resulting in warming of the lower stratosphere and upper troposphere, and cooling below (Lau et al. 2019). Consistent with the constraint by the CC relationship, RH is reduced in the upper troposphere of the ITCZ core and wetter portion of the MCZ, except in the most extreme precipitation of the ITCZ core, where penetrative deep convection occurs (Fig. 5c, see also Fig. 2a). Strong drying (negative RH anomalies) is found in the upper troposphere in the transition region of the MCZ and DZ, where the mean vertical motion is relative weak, and drying is due mostly to the effect of warmer temperature, that is, the $-aRdT$ term in Eq. (1). Near the surface, pools with RH deficit in the ITCZ core and MCZ are found, due to increased moisture divergence (see Fig. 2d). In contrast, in the DZ where anomalous sinking motion is strong, adiabatic compression provides strong warming and drying in the middle and lower troposphere (Figs. 5b,c). In regions with strong RH deficit in the troposphere (i.e., the DZ), the MCZ, and the outer portion of the ITCZ core, OLR anomalies are positive, indicating increased cooling to space, due to reduced trapping of longwave radiation from suppressed clouds and exposure of the warmer surface (Fig. 5d). Also notable is a strong negative OLR in the transition zone between the MCZ and DZ, suggesting positive feedback to warming of the upper troposphere. This may be a result of anomalous upward and poleward moisture and heat transport stemming from increased midlatitude storm track activities near the poleward edge of the HC, due to cloud–radiation–circulation interaction. Such interaction increases the frequency of high clouds with colder tops, and hence reduces OLR, resulting in warming of the upper troposphere and cooling below (Lau et al. 2019). Interestingly, strong ascent coupled to a large increase in RH up to 100 hPa, and substantial reduction in OLR can be seen in the most extreme precipitation in the ITCZ core (Figs. 5a,c,d), suggesting the presence of strong penetrative deep convection. This region features strong low-level moisture convergence, and increased water vapor in the atmospheric column (see Figs. 2b,d), which warms the atmosphere by trapping longwave radiation, providing positive feedback to the increased latent heating. However, strong RH increase in the ITCZ extreme precipitation region does not reach significance level in the MRE, probably due to the diversity and insufficient frequency of occurrence of these extreme precipitation events among the reanalysis datasets. The functional relationships of vertical motion, temperature, and RH with precipitation have also been examined for individual reanalysis, and for

### Table 1. Correlation coefficients and explained variance of linear trend for precipitation $P$ in rising areas within 30°S–30°N to 500-hPa $p$ velocity $\omega$, RH, and OLR in different sinking areas during 1980–2014. Correlation coefficients with asterisks indicate that the significance level reaches 99%.

<table>
<thead>
<tr>
<th>Region</th>
<th>$P$ and $\omega$</th>
<th>$P$ and RH</th>
<th>$P$ and OLR</th>
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</thead>
<tbody>
<tr>
<td>60°S–60°N</td>
<td>0.52*</td>
<td>-0.73*</td>
<td>0.62*</td>
</tr>
<tr>
<td>30°S–30°N</td>
<td>0.67*</td>
<td>-0.65*</td>
<td>0.67*</td>
</tr>
<tr>
<td>30°–60°N/S</td>
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<td>-0.57*</td>
<td>0.49*</td>
</tr>
<tr>
<td>30°–60°N</td>
<td>0.16</td>
<td>-0.53*</td>
<td>0.48*</td>
</tr>
</tbody>
</table>

Explain variance

<table>
<thead>
<tr>
<th>Region</th>
<th>$P$ and $\omega$</th>
<th>$P$ and RH</th>
<th>$P$ and OLR</th>
</tr>
</thead>
<tbody>
<tr>
<td>60°S–60°N</td>
<td>14.85%</td>
<td>36.81%</td>
<td>14.87%</td>
</tr>
<tr>
<td>30°S–30°N</td>
<td>38.09%</td>
<td>21.70%</td>
<td>39.41%</td>
</tr>
<tr>
<td>30°–60°N/S</td>
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<td>49.22%</td>
<td>16.45%</td>
</tr>
<tr>
<td>30°–60°N</td>
<td>0.25%</td>
<td>69.58%</td>
<td>27.50%</td>
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different selected four reanalysis ensembles. Overall, the increase in contrast between the dry and the wet regions are consistent among different selections of reanalyses for the MRE statistics (Figs. S11–S16).  

4. Summary and discussion

In this study, the observed long-term change in structure of the ITCZ and relationships among changes in precipitation, circulation, temperature, RH, and OLR, are investigated based on multiple observational and reanalysis datasets for the period 1980–2014. We find significant multidecadal trends featuring a narrowing and intensification of the ITCZ precipitation, with increased ascent in the rising branch of the HC coupled to an expanded and drier sinking branch of the HC, and a poleward shift of the jet streams in both hemispheres. These features are in general agreement with the DTS and changes in storm tracks found in CMIP5 global climate models under GHG warming (Yin 2005; Kidston and Gerber 2010; Lau and Kim 2015; Su et al. 2017). The DTS is also manifest in a robust global drying trend, reflected by a deficit in tropospheric RH within 60°S–60°N as a function of precipitation (in log10 units and actual values; mm day⁻¹) during 1980–2014. Climatology of vertical velocity, temperature, and relative humidity is shown in contours; climatology of outgoing longwave radiation is shown by a line. Bars with outlines and dots indicate that the significance level reaches 90%.

![FIG. 5. Linear trend of MRE for (a) vertical velocity (Pa s⁻¹ decade⁻¹), (b) temperature (K decade⁻¹), (c) relative humidity (% decade⁻¹), and (d) outgoing longwave radiation (W m⁻² decade⁻¹) within 60°S–60°N as a function of precipitation (in log10 units and actual values; mm day⁻¹) during 1980–2014. Climatology of vertical velocity, temperature, and relative humidity is shown in contours; climatology of outgoing longwave radiation is shown by a line. Bars with outlines and dots indicate that the significance level reaches 90%.

Coherent long-term trends in precipitation, large-scale circulation, and OLR are closely linked to RH trends, reflecting competing effects of changes in temperature, specific humidity, and moisture convergence. Changes in tropical precipitation in anomalous ascent regions are significantly correlated with OLR variations in regions with anomalous subsidence, indicating strong longwave cooling to space in regions with strong RH deficit, with the largest contributions coming from the subtropics and extratropics of the Northern Hemisphere land regions. Analyses of vertical structures of RH, temperature, and vertical motion as a function of precipitation rate and OLR reveal that there has been increasing contrast between a wetter and contracted ITCZ core, coupled to a drier marginal convective zone, and expanded dry zones in the subtropical and extratropics, associated with a poleward shift of midlatitude storm activities in recent decades. Strong longwave radiation cooling to space in the extended dry zones in the subtropics and extratropics, most pronounced over land regions of the Northern Hemisphere, acts as “radiator fins” releasing heat from the increased latent heating in the “furnace
region” of the ITCZ core, as the global circulation adjusts toward quasi-equilibrium of a warmer climate (Pierrehumbert 1995; Lau et al. 2019).

While the observational trend patterns and relationships revealed here are largely consistent with signals of GHG warming from previous studies, it is worth noting that the feedback processes described here are not necessarily attributable to GHG warming exclusively. As discussed in section 2, the negative phase of the PDO and anomalous cooling associated with more La Niña–like sea surface temperature variability in the equatorial eastern Pacific during the “global warming hiatus” (1998–2013) may have also contributed to the linear trend found in our study. Another important issue raised by our study is that while climate models projected a weakening of the Walker circulation under GHG warming (Vecchi and Soden 2007; Tokinaga et al. 2012), our observational analyses revealed a strengthening of Walker circulation with increased precipitation, relative humidity, rising motion, and reduced OLR over the equatorial western Pacific and Indian Ocean, coupled to anomalies of the opposite signs over the equatorial central and eastern Pacific during 1980–2014 (see Fig. 3). The discrepancy between observations and model projections regarding changes of the Walker circulation under GHG warming has been noted in previous studies, and is still a subject of debate, involving possibly the latency of the GHG warming signal in observations, being masked by natural sea surface temperature variability in the Pacific (Collins et al. 2010; Xie et al. 2010) and remote forcing from outside the Pacific Ocean (McGregor et al. 2014; Sohn et al. 2019). Indeed, the trend signals (~35 years) in various control variables reported in this study could possibly represent in part a contribution from a longer multidecadal natural variation of sea surface temperature that cannot be disentangled from the radiative effects due to increased anthropogenic GHG and aerosol emissions.

Finally, it should be noted that this study is focused on the ITCZ structural changes and feedback driven by tropical processes. Climate changes at higher latitudes such as Arctic warming have been shown to spur radiation–circulation interactions affecting the midlatitudes and the ITCZ (Broccoli et al. 2006; Kang et al. 2008, 2009; Seo et al. 2014). The seasonality of the expansion of Hadley circulation may also play important roles (Kang and Polvani 2011). More in-depth studies, including seasonal dependence of the cloud–radiation–circulation feedback, are needed to better understand and to disentangle the effects of natural versus anthropogenic forcing, and the relative importance of tropical versus polar forcing in giving rise to the observed changes in the ITCZ, and associated feedback processes.

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REFERENCES


