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RESEARCH LETTER

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Key Points:

- Rainfall trends from multiple observational data sets are not consistent in some regions
- Spurious rainfall trends are linked to changes in gauge density over time
- SST patterns play a strong role in determining Africa-wide rainfall trends since 1983

Supporting Information:

- Figures S1–S14 and Tables S1–S4

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Recent observed and simulated changes in precipitation over Africa

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Abstract Multiple observational data sets and atmosphere-only simulations from the Coupled Model Intercomparison Project Phase 5 are analyzed to characterize recent rainfall variability and trends over Africa focusing on 1983–2010. Data sets exhibiting spurious variability, linked in part to a reduction in rain gauge density, were identified. The remaining observations display coherent increases in annual Sahel rainfall (29 to 43 mm yr⁻¹ per decade), decreases in March–May East African rainfall (–14 to –65 mm yr⁻¹ per decade), and increases in annual Southern Africa rainfall (32 to 41 mm yr⁻¹ per decade). However, Central Africa annual rainfall trends vary in sign (–10 to +39 mm yr⁻¹ per decade). For Southern Africa, observed and sea surface temperature (SST)-forced model simulated rainfall variability are significantly correlated ($r \sim 0.5$) and linked to SST patterns associated with recent strengthening of the Pacific Walker circulation.

1. Introduction

Changes in rainfall patterns can have profound societal consequences, particularly across Africa where rainfall plays a crucial role in sustaining livelihoods and economic development. Changes in rainfall across Africa have received much attention during the last 40 years [e.g., Bunting *et al.*, 1976; Rodhe and Virji, 1976; Ogallo, 1979; Janowiak, 1988; Hulme *et al.*, 2001; Mahe *et al.*, 2001; Nicholson, 2001; Lebel and Ali, 2009; Jury, 2013], in particular, the Sahel drought during the 1970s and 1980s due to its longevity and severity [Lebel *et al.*, 2003; Dai *et al.*, 2004; Nicholson, 2005]. In addition, a decline in the long rains (March–May) over East Africa [Giannini *et al.*, 2008; Williams and Funk, 2011; Williams *et al.*, 2011; Lyon and DeWitt, 2012; Jury and Funk, 2013; Liebmann *et al.*, 2014; Yang *et al.*, 2014] has recently contributed to widespread famine across the Horn of Africa affecting over 10 million people during 2010–2011 [United Nations Office for the Coordination of Humanitarian Affairs, 2011].

Careful evaluation of precipitation change demands reliable long-term observational records, which are usually derived from in situ and/or satellite-based proxies. However, sparse and temporally inconsistent rain gauge observations [Janowiak, 1988; Nicholson, 2001; Washington *et al.*, 2006] and uncertainties in satellite algorithms [e.g., Sapiano and Arkin, 2009; Tian *et al.*, 2009; Tian and Peters-Lidard, 2010] make it difficult to quantify changes in rainfall across large domains and over many years [e.g., Lau and Wu, 2007; Yin and Gruber, 2010; Balan Sarojini *et al.*, 2012; Wan *et al.*, 2013]. Recently, the development of several long-term satellite-based data sets tailored for African research and climate monitoring [e.g., Novella and Thiaw, 2013; Maidment *et al.*, 2014] has provided an opportunity to assess recent changes in African precipitation.

While observational records are essential for detecting changes in precipitation patterns, climate models are valuable tools for understanding the physical mechanisms driving past and current climate variability and change [e.g., Lu and Delworth, 2005; Reason and Jagadheesha, 2005; Hoerling *et al.*, 2006; Washington and Preston, 2006; Williams and Funk, 2011; Yang *et al.*, 2014] and provide the only physically based method available to predict future changes in the climate [e.g., Shongwe *et al.*, 2009, 2011; James and Washington, 2012; Knutti and Sedláček, 2012]. Model projections play an important role in decision making, but evaluating present-day climate is essential for interpreting the realism of future changes [e.g., James *et al.*, 2015]. Model evaluation across Africa is particularly challenging because of the diversity of observed data sets and the lack of ground observations.

While the latest generation of climate models from the Coupled Model Intercomparison Project Phase 5 (CMIP5) can successfully simulate aspects of the present-day rainfall climatology in some regions [Haensler *et al.*, 2013; Otiemo and Anyah, 2013; Roehrig *et al.*, 2013; Vizy *et al.*, 2013], representing observed variability,

which is closely linked with evolving sea surface temperatures (SSTs) patterns, is more challenging [e.g., Roehrig *et al.*, 2013]. Robust rainfall observations are also essential in assessing model performance and in improving understanding of Africa-wide rainfall changes. Until recently, less attention has focused on continent-wide assessments—in part because of the sparsity of ground-based observations in much of Africa, especially over Central Africa. Here we examine Africa-wide precipitation variability and trends as portrayed by an array of observational data sets and CMIP5 atmosphere-only model simulations to characterize and understand robust changes in African rainfall during the last three decades (1983–2014).

2. Data

We have used three gridded gauge-only and five satellite-based precipitation data sets (summarized in Table S1 in the supporting information). The gauge-only data sets were Climatic Research Unit (CRU) [Harris *et al.*, 2014], Global Precipitation Climatology Centre (GPCC) Full Data Reanalysis (hereinafter GPCC) [Becker *et al.*, 2013; Schneider *et al.*, 2014], and the National Oceanographic and Atmospheric Administration (NOAA) PRECipitation REConstruction over Land (PREC/L) [Chen and Xie, 2002]. The satellite data sets were NOAA's African Rainfall Climatology (ARC) [Novella and Thiaw, 2013], the Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) [Funk *et al.*, 2014], the Climate Prediction Center Merged Analysis of Precipitation (CMAP) [Xie and Arkin, 1997], the Global Precipitation Climatology Project (GPCP) monthly estimates [Huffman *et al.*, 2009], and the TAMSAT African Rainfall Climatology And Time-series (TARCAT) [Tarnavsky *et al.*, 2014; Maidment *et al.*, 2014]. The satellite data sets all combine thermal infrared measurements combined with other data sources such as microwave retrievals and rain gauge measurements but apply contrasting methodologies as detailed in Maidment *et al.* [2014]; further limitations of these data sets are discussed in section 3. All data sets provide global coverage except ARC and TARCAT, which only provide estimates for Africa. All data sets were converted to a regular 2.5° latitude/longitude grid, and the submonthly data sets were summed to monthly totals. Missing time steps in ARC and TARCAT were replaced by linearly interpolating the anomaly (computed for each time step with respect to the time step climatology) across missing time steps using existing neighboring times steps and imposing this onto the climatology. For ARC, the climatology was based on monthly means which are less noisy than daily climatological values. In total, 3% (340 days) and 14% (27 dekads) of the data between 1983 and 2010 were missing for ARC and TARCAT, respectively.

Climate model simulations forced by observed SSTs and sea ice and historical radiative forcings from the CMIP5 data set [Taylor *et al.*, 2012] are exploited (see Table S1). These atmosphere-only (Atmospheric Model Intercomparison Project version 5 (AMIP5)) simulations (available until the end of 2008) demonstrate skill in reproducing observed interannual rainfall variability over tropical land [Liu *et al.*, 2012]. For ease of comparison, model monthly precipitation averages were bilinearly interpolated onto a regular 2.5° latitude/longitude grid, consistent with the observational data sets. Throughout, deseasonalized time series were obtained by calculating the difference between each monthly value and the respective monthly rainfall climatology.

3. Influence of Variation in Gauge Density on Observed Rainfall Trends

Figures 1a–1h display maps of Africa-wide annual rainfall trends (1983–2010) for each observational data set (see supporting information for annual and seasonal rainfall climatologies (also provided in Maidment *et al.* [2014]) and for seasonal rainfall trends). Spatially averaged trends for four subregions (Sahel and Central, East, and Southern Africa; see Figure 2 for domains) are provided in Table S2. All data sets indicate an increase in annual rainfall across the Sahel and Southern Africa (both discussed in section 4), while remaining parts of Africa exhibit striking differences in trend sign and magnitude, most notably across Central Africa.

Over this region, which has the lowest gauge density in sub-Saharan Africa [Washington *et al.*, 2013], inferred annual rainfall trends vary from -96 to $+39$ mm yr⁻¹ per decade. Such observational uncertainty presents a challenge for characterizing and understanding current changes in precipitation.

Figure 1i displays differences between the multiple satellite-based observational data sets and the CRU gauge-based Africa-wide mean rainfall time series. While the satellite data sets (GPCP, CHIRPS, and TARCAT) show relatively small deviations from the CRU gauge analysis, CMAP and ARC are characterized by significant time-varying jumps not found in other data sets. While inhomogeneity in the CRU data set is

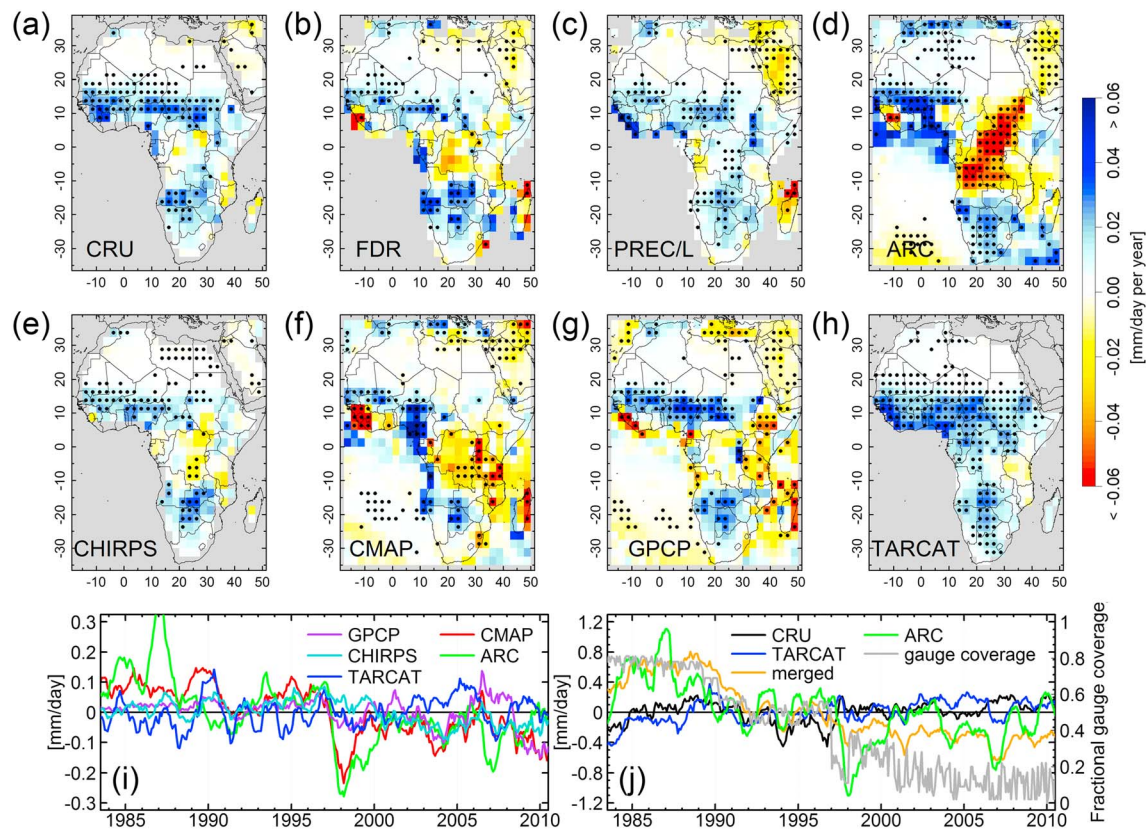


Figure 1. Spatial trends in annual rainfall from 1983 to 2010 for (a) CRU, (b) GPCP, (c) PREC/L, (d) ARC, (e) CHIRPS, (f) CMAP, (g) GPCP, and (h) TARCAT. Stippling represents statistically significant trends at the 95% confidence level using an *F* test. Deseasonalized 12 month running mean of (i) Africa-wide mean monthly rainfall difference between CRU and the other satellite-based data sets and (j) Central African mean monthly rainfall for CRU, TARCAT, merged CRU-TARCAT (see text for details), and ARC. The time evolution showing the fractional coverage across Central Africa of CRU grid squares containing at least one gauge has been superimposed (y axes on the right).

likely, agreement with satellite-based estimates (anomalies within about ± 0.1 mm/d) increases confidence in the realism of the variability and suggests that larger deviations displayed by CMAP and ARC (e.g., 1998) may be spurious. This is further indicated by the contrasting spatial structure of trends (Figures 1d and 1f).

Methodological differences, such as (i) gauge interpolation techniques (particularly in gauge sparse regions), (ii) merging of gauge and satellite records, (iii) changes in satellite sensors/spectral band, and (iv) changes in satellite estimation algorithm, can all affect the long-term stability of precipitation records [e.g., Yin *et al.*, 2004; Lau and Wu, 2007; Yin and Gruber, 2010; Balan Sarojini *et al.*, 2012; Wan *et al.*, 2013]. While changing satellite inputs, responsible for time-dependent biases in the CMAP record [Yin *et al.*, 2004], may explain some of the discrepancy between CMAP and the other data sets, this cannot alone explain the large discrepancies between data sets, especially over Central Africa.

A temporally inconsistent and sparse gauge network can potentially alias interannual variability in merged satellite-gauge products, resulting in spurious trends. To investigate this, we conducted a sensitivity analysis. Gauge-only (CRU) and satellite-only rainfall (TARCAT) data were merged by weighting these inputs based on the fraction of CRU grid squares containing at least one gauge in the Central Africa domain for each month from 1983 to 2010 (although calibrated using gauges, the interannual variability in TARCAT is driven purely by satellite observations). For the purposes of this test, CRU rainfall was systematically increased by 30% (which can be considered a typical difference between gauge to large areal averages [e.g., Grimes *et al.*, 2003; Maidment *et al.*, 2013]) in order to simulate the effect of incorporating point-based gauge information.

It is evident from Figure 1j that a reduction in gauges between the late 1980s and late 1990s coincides with declining rainfall in the merged estimate. As the number of gauges decreases, the merged monthly area average rainfall shifts from the higher gauge-mean rainfall to the lower satellite-mean rainfall, thus introducing a spurious

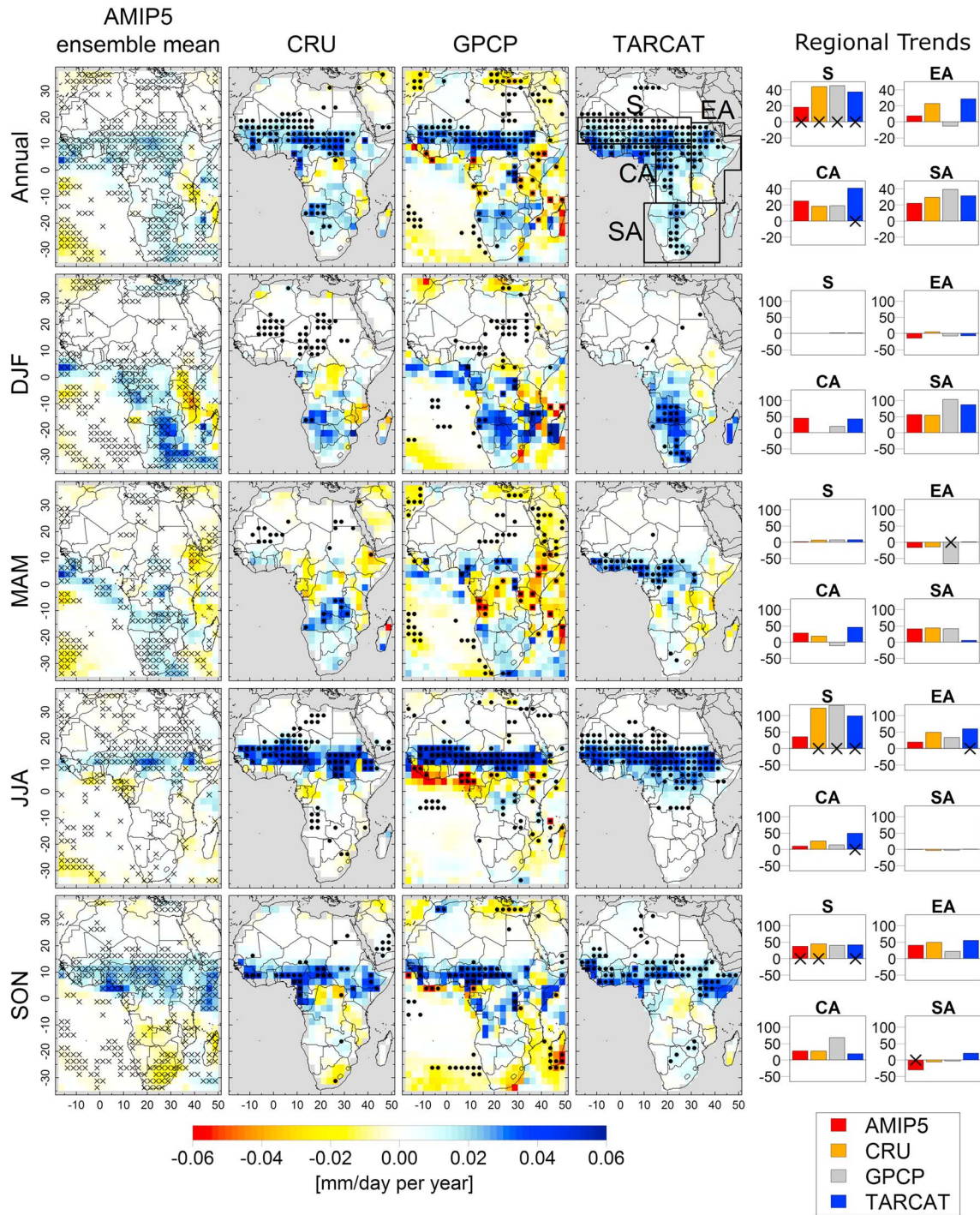


Figure 2. Spatial pattern of trends (1983–2008) in annual and seasonal rainfall for the AMIP5 ensemble mean and the observational data sets CRU, GPCP, and TARCAT. For the model ensemble means, stippling (crosses) represents grid points where at least seven out of the nine (78%) models agree of the trend sign. For the observations, stippling (dots) represents statistically significant trends at the 95% confidence level using an *F* test. Bar plots give the linear trends in rainfall (mm yr^{-1} per decade) using land-only values for the Sahel, Central Africa, East Africa, and Southern Africa (see top right figure for regional domains) for the AMIP5 model ensemble means and observational data sets (CRU, GPCP, and TARCAT). Crosses denote statistically significant trends ($P < 0.05$) using an *F* test.

negative trend. The time evolution of this merged product resembles that of ARC ($r=0.57$), a data set that merges point gauge measurements with satellite-only infrared GOES Precipitation Index estimates. The spatially coherent decrease in rainfall across Central Africa seen in ARC data [e.g., Diem et al., 2014] (and to a lesser extent in CMAP), but not in other data sets (see Figure 1), may thus be an artifact of the reduction in gauge coverage.

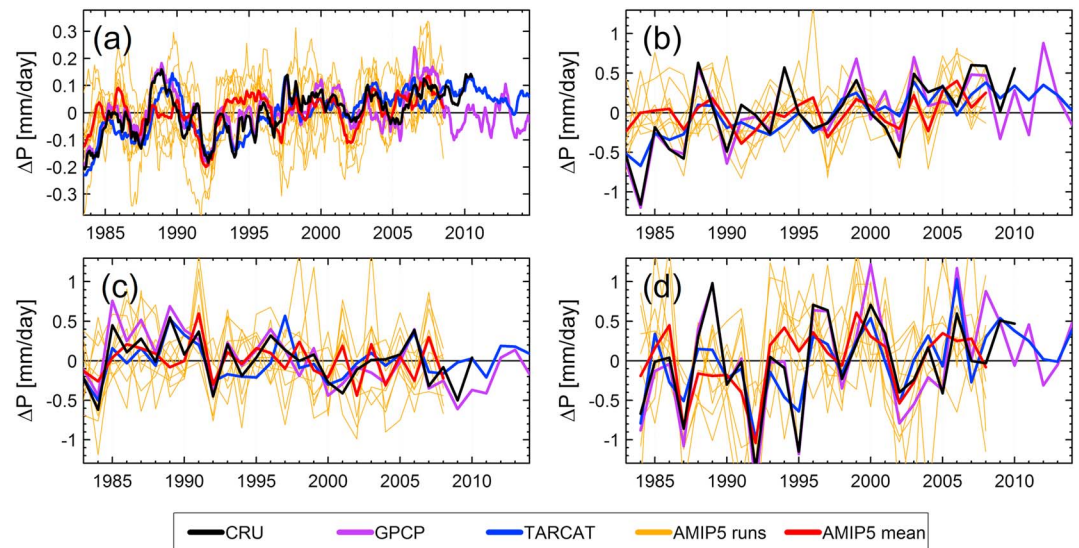


Figure 3. Time evolution of observed and simulated precipitation variability (computed for land grids only) of (a) the 12 month running mean of Africa-wide area-average monthly rainfall anomaly and seasonal rainfall anomaly for (b) JJA over Sahel, (c) MAM over East Africa, and (d) DJF over Southern Africa. The thick red line represents the AMIP5 ensemble mean across all nine models (thin orange lines represent individual model runs).

Based on the identified impact of declining gauge density, contrasting variability compared to other observational products and previous assessments [Yin *et al.*, 2004], the ARC and CMAP data sets are excluded from further analysis of rainfall trends.

4. Identifying Robust Annual and Seasonal Average Precipitation Variability and Trends in Observations and Simulations

The previous section identified several data sets that are not known to suffer from temporally dependent biases over Africa, and which can thus be used to infer long-term changes in precipitation [see also Maidment *et al.*, 2014]. These include CRU, GPCP, and TARCAT. Figure 2 shows the annual and seasonal trends (1983–2008) in each of the data sets.

For comparison, the AMIP5 multimodel mean is shown alongside the observed data. The AMIP5 trends are smaller in magnitude than the individual models since they average over the internal atmospheric variability of individual models (see supporting information and Figure 3). However, the ensemble mean annual trends generally reproduce the main observed signals, in particular, the spatial pattern given by the TARCAT data set. Pattern correlations with the observations range between 0.49 (CRU) and 0.66 (TARCAT) for annual precipitation trends (see Table S3). It is evident from Figure 2 that there are several regions in Africa, where trends in rainfall are identified consistently in the three observational data sets. Time series of monthly Africa-wide rainfall and seasonal rainfall for three of these regions—the Sahel, East Africa, and Southern Africa (locations shown in Figure 2)—are displayed in Figure 3. Roughly 25% of observed deseasonalized monthly variability in Africa-wide precipitation is explained by the AMIP5 model ensemble (see Figure 3a and Table S5). The simulated variability shown in Figure 3a is at odds with the ARC and CMAP data sets shown in Figure 1i, adding further evidence that the variability depicted by these data sets is unrealistic. Analysis of July–August (JJA) precipitation for the Sahel indicates that around 40% of the long-term variability is captured by the AMIP5 simulations. Correlations are lower during March–May (MAM) for East Africa (between 0.13 and 0.29), although they are higher during September–November (SON; between 0.45 and 0.63). This may relate to the influence of El-Niño–Southern Oscillation and local SST forcing on the short rains [Black *et al.*, 2003]. Over Southern Africa during December–February (DJF), the atmosphere-only simulations perform better than over the Sahel ($r = 0.5$, all statistically significant), clearly evident in Figure 3d. Low rainfall totals in both the observations and AMIP5 ensemble mean during 1991–1992 over Southern Africa may be linked to the eruption of Mount Pinatubo [Stenchikov *et al.*, 2006; Trenberth and Dai, 2007; Driscoll *et al.*, 2012].

Agreement between observations and AMIP-type simulations increases confidence in the observations, as well as in the models. Over parts of Central Africa, for example, where observed annual rainfall trends range between -10 and $+39$ mm yr⁻¹ per decade (based on the six remaining observational data sets given in Figure 1), there is good agreement between idealized atmosphere-only simulations and river discharge over the Central Africa region [Todd and Washington, 2004], strengthening our trust in the fidelity of the AMIP simulations for inferring long-term trends. It is notable, moreover, that the AMIP simulations agree with TARCAT more strongly than with CRU and GPCP (see Figure 2). While CRU and GPCP utilize gauge records, TARCAT's sole dependence on the satellite signal to determine year-to-year changes in precipitation arguably provides a more reliable multidecadal record over this gauge-sparse region of Africa.

Across the Sahel statistically significant ($P < 0.05$) increases in annual rainfall are evident in all observational data sets (see Figures 1 and 3), ranging from 21 to 43 mm yr⁻¹ per decade between 1983 and 2010. The increase occurs predominantly during peak monsoon (JJA) and to a lesser extent in SON rainfall. However, the spatial extent and magnitude of this rainfall increase vary between data sets, indicating that at local scales (e.g., grid scale), the observations are less consistent. The observed increase in both JJA and SON Sahel rainfall is well simulated by the majority (>75%) of the AMIP5 models.

The increase in Sahel rainfall is well documented [Hulme *et al.*, 2001; Nicholson, 2005; Olsson *et al.*, 2005; Hoerling *et al.*, 2006; Lebel and Ali, 2009; Brandt *et al.*, 2014] and indicates a recovery from drought conditions during the 1970s and 1980s. Recent studies have proposed that Sahel rainfall is sensitive to changing concentrations of Northern Hemispheric anthropogenic aerosols [Kawase *et al.*, 2010; Hwang *et al.*, 2013; Dong *et al.*, 2014], but intensification of the Saharan heat low due to greenhouse gas-induced warming [Dong and Sutton, 2015] involving positive water-vapor feedback [Evan *et al.*, 2015] and low-frequency variability associated with the Interdecadal Pacific Oscillation [Villamayor and Mohino, 2015] may also play a role.

Another region, for which all data sets display consistent trends is Southern Africa. This is a region where CMIP3 data indicate significant changes in rainfall in a warming climate [Shongwe *et al.*, 2009]. Across Southern Africa there is a marked increase in observed annual rainfall of around 35 mm yr⁻¹ per decade between 1983 and 2010 (see Figures 2 and 3). The increase is confined largely to DJF rainfall. As in the Sahel, the trend is also evident in the AMIP-type simulations, indicating that the precipitation variability is driven, at least to some extent by SSTs.

Figure 4 displays the correlation between observed SST (Hadley Centre Global Sea Ice and Sea Surface Temperature) [Rayner *et al.*, 2003] and observed (TARCAT) and simulated (AMIP5) Southern Africa rainfall for DJF. While Southern Africa rainfall covaries with the adjacent tropical Atlantic and Indian Ocean SST, higher correlations exist with Pacific SST variability, previously identified as important for rainfall variability over other regions of Africa [Yang *et al.*, 2014; Villamayor and Mohino, 2015]. Over Southern Africa, whose rainfall climate has been extensively studied [e.g., Nicholson and Kim, 1997; Reason, 2001; Fauchereau *et al.*, 2003; Usman and Reason, 2004; Reason and Jagadheesha, 2005; New *et al.*, 2006; Washington and Preston, 2006; Williams and Kniveton, 2011; Jury, 2013; Bellprat *et al.*, 2015], years with above average rainfall are associated with cooler SSTs across the central and eastern Pacific and warm SSTs over western, northern, and southern Pacific. This correlation pattern across the Pacific Ocean resembles the long-term trend (1983–2008) in mean DJF SST (Figure 4c). The increase in rainfall is also associated with coherent dynamical changes diagnosed by increased ascent at 500 hPa.

The spatial pattern in Pacific SST trend reflects the negative phase of the Pacific Decadal Oscillation (PDO) and has been characterized by an unprecedented intensification of the Pacific branch of the Walker Circulation since the early 1990s [Merrifield, 2011; L'Heureux *et al.*, 2013; England *et al.*, 2014]. Observed Southern Africa rainfall covaries moderately with the PDO index ($r = -0.38$ for GPCP between 1983 and 2014) with negative phases tending to coincide with above average rainfall (see Figure 4d). Cook [2001] noted that the strength of the Walker circulation plays a vital role in determining drought years over Southern Africa. While ENSO plays an important role on shorter time scales [Nicholson and Kim, 1997; Nicholson and Selato, 2000; Usman and Reason, 2004], we suggest that the trend to more La Niña-like conditions since 2000 is a likely contributing factor driving the increase in Southern Africa rainfall between 1983 and 2008. A consistent trend in the atmosphere-only AMIP5 model ensemble and the absence of any significant trend in the coupled CMIP5 model ensemble (not shown) suggest that Southern African rainfall changes are a consequence primarily of Pacific SST variability, the pattern of which reflects a mode of variability that is thought to originate from natural internal variability of the climate system.

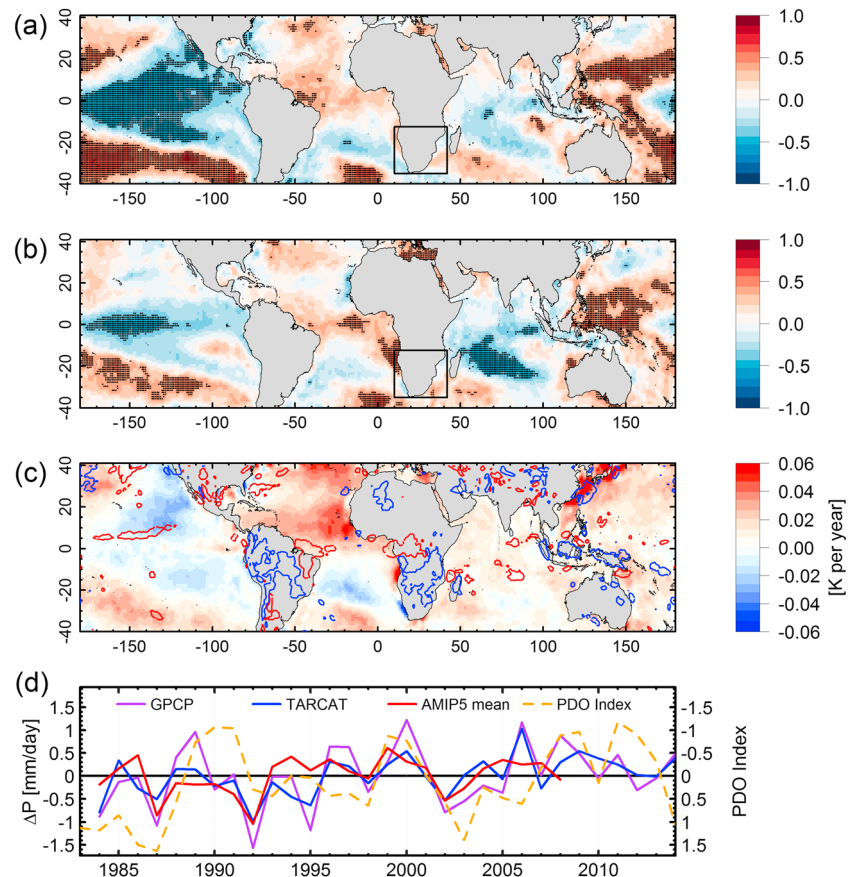


Figure 4. Correlation between DJF mean SST and DJF Southern Africa rainfall (1983–2008) from (a) TARCAT and (b) AMIP5 ensemble mean (stippling indicates statistically significant ($P < 0.05$) correlations), (c) 1983–2008 trends in DJF SST (shading) and vertical velocity (given by contours of $\pm 80 \text{ Pa d}^{-1} \text{ yr}^{-1}$) derived from mean monthly ERA-Interim 500 hPa reanalysis fields (blue contours indicate regions of increased ascent; while red contours indicate regions of decreased ascent), and (d) time series of observed Southern Africa rainfall anomalies and PDO index (<http://research.jisao.washington.edu/pdo/PDO.latest>) for DJF (year corresponding to January).

The well-documented decrease in the long rains of East Africa [e.g., Lyon and DeWitt, 2012] is evident in Figures 2 and 3. These figures show a reduction in area-average March–May (MAM) precipitation of -14 (CRU) and -65 (GPCP) mm yr^{-1} per decade (see bar plots in Figure 2). TARCAT gives a slight increase in area average rainfall, although a reduction across much of the East African domain is evident (see Figure 2). During DJF, a decrease in rainfall is largely centered over Tanzania, but this expands to the Horn of Africa during MAM. The decrease in MAM precipitation has been linked to changes in tropical Indian and Pacific Ocean SSTs [Williams and Funk, 2011; Lyon and DeWitt, 2012; Jury and Funk, 2013; Liebmann et al., 2014; Yang et al., 2014]. The drying trend over East Africa is also discernible in AMIP5 simulations, centered over Tanzania during DJF and over the Horn of Africa during MAM. However, the spatial pattern, including trend magnitude, varies considerably between models.

5. Conclusions

Recent changes (1983–2014) in African precipitation are analyzed using multiple observational data sets and atmosphere-only simulations. A reduction in rain gauge density across Central Africa is linked to an artificial reduction in precipitation which appears to particularly affect the ARC data set and to some degree the CMAP data set. Since these data sets are also outliers compared to the remaining observational and model-based estimates with regard to Africa-wide rainfall they were not considered in our assessment of regional trends. Robust regional trends include increased annual rainfall over the Sahel (29 to 43 mm yr^{-1} per decade) and

Southern Africa (12 to 41 mm yr⁻¹ per decade) and drying over East Africa (−14 to −65 mm yr⁻¹ per decade in March–May rainfall). However, considerable differences in trend sign and magnitude exist, particularly over Central Africa where annual rainfall trends range between −10 and +39 mm yr⁻¹ per decade.

Examination of nine CMIP5 models indicates that the SST-forced simulations (AMIP5) were able to capture many aspects of the observed African precipitation change. Roughly, 40% of June–August observed rainfall variability over the Sahel and 50% of December–February observed rainfall variability over Southern Africa are captured by the AMIP5 ensemble mean, indicating that SST patterns play a strong role in determining rainfall trends since 1983.

While increased Sahel rainfall since the 1980s has been linked to greenhouse gas forcing [Dong and Sutton, 2015], increases in Southern Africa rainfall of comparable magnitude are found to be associated with an unprecedented strengthening of Walker circulation [e.g., L'Heureux et al., 2013] and linked to SST patterns related to the PDO; this mode of variability, thought to relate to internal climate variability, may therefore determine low-frequency rainfall variability over Southern Africa. Continued strengthening of the Walker circulation, and therefore further associated rainfall increases across Southern Africa, is not anticipated to be sustained in the future [e.g., England et al., 2014].

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