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Key Points:
- Moisture budget decomposition indicates that CMIP5 end of 21st century projections for wetter conditions in equatorial East Africa are primarily due to a weakening of the zonal overturning circulation
- Uncertainties are associated with our limited understanding of the response of sea surface temperatures, El Niño, and monsoons to warming, as well as the realism of East African orography in the models

Supporting Information:
- Supporting Information S1

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Dynamical and Thermodynamic Elements of Modeled Climate Change at the East African Margin of Convection

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Abstract We propose a dynamical interpretation of model projections for an end-of-century wetting in equatorial East Africa. In the current generation of global climate models, increased atmospheric moisture content associated with warming is not the dominant process explaining the increase in rainfall, as the regional circulation is only weakly convergent even during the rainy seasons. Instead, projected wetter future conditions are generally consistent with the El Niño-like trend in tropical Pacific sea surface temperatures in climate models. In addition, a weakening in moisture convergence over the adjacent Congo Basin and Maritime Continent cores of convection results in the weakening of near-surface winds, which increases moisture advection from the Congo Basin core toward the East African margin. Overall confidence in the projections is limited by the significant biases in simulation of the regional climatology and disagreement between observed and modeled tropical Pacific sea surface temperature trends to date.

1. Introduction

The contrast between the increased frequency of drought that has affected equatorial East Africa since the late 1990s (Funk et al., 2015; Nicholson, 2017) and global model projections for wetter conditions by the end of this century (e.g., Christensen et al., 2007) could not be starker. This "paradox" has been noted for its practical implications, given the region's vulnerability to climate fluctuations. Should decision-makers conservatively aim to reduce the impact of the worst-case scenario based on the recent historical experience of more frequent drought (National Meteorological Agency of Ethiopia, 2008), or, trusting the most likely future outcome as projected by the multimodel mean from the Intergovernmental Panel on Climate Change (IPCC) (Niang et al., 2014), develop adaptation strategies that may include a significant investment in large-scale irrigation infrastructure to capitalize on the projected increase in water availability? We pose these rhetorical questions to frame our work, fully cognizant that we cannot evaluate the likelihood of either outcome with an analysis of model simulations alone. Instead, we focus on identifying the key physical processes operating within coupled models that lead to a model consensus of a wetter future climate. The results provide fundamental insights to the workings of these models that are known to have problems capturing important aspects of the current East African climate (Lyon & Vigaud, 2017; Otieno & Anyah, 2013; Ummenhofer et al., 2017; Yang et al., 2015a).

Understanding the physical basis of the model projections is an important advance to better predict the future climate in the region. Understanding what has occurred in nature and comparing against model projections is another requirement. In the latter regard, and in terms of the recent drying, several studies have related regional warming of the Indian Ocean (Funk et al., 2008), and of the tropical western Pacific Ocean (Funk, 2012; Liebmann et al., 2014; Lyon & DeWitt, 2012), or the increased zonal gradient in equatorial Pacific sea surface temperatures (SSTs) (Ummenhofer et al., 2017; Vigaud et al., 2017), to the recent drying of equatorial East Africa, during the March–May "long rains" season. Decadal-scale cooling of the eastern tropical Pacific Ocean (Lyon, 2014; Lyon & DeWitt, 2012; Yang et al., 2014) appears to be an important factor contributing to the recent enhancement of the zonal SST gradient. While it is too soon to determine whether the current decadal cooling in the tropical Pacific is an expression of internal variability of the climate system or the response to positive radiative forcing in the presence of dominant ocean dynamics (Cane et al., 1997; Clement et al., 1996; Coats & Karnauskas, 2017), recently observed ocean conditions clearly contain contributions from both anthropogenic forcing and natural variability, and the interaction of these two influences may itself have contributed to the recent rainfall decline in eastern Africa (e.g., Hoell et al., 2017).

Based purely on theoretical expectations of the response to warming, different mechanisms have been proposed regarding changes in tropical rainfall. First, increased atmospheric moisture content directly resulting from warming, a "thermodynamic" change, would have the effect of increasing (decreasing) precipitation minus evaporation ($P - E$) in regions where the climatological values are positive (negative), via the "wet-get-wetter" mechanism (Chou et al., 2009; Huang et al., 2013). Second, under the "upped ante" mechanism (Neelin et al., 2003) increased static stability associated with tropospheric warming (Betts, 1998) would inhibit convection in regions at the "margin" of climatological deep convection, semiarid equatorial East Africa being one such region, owing to their lower near-surface moist static energy. A reduction in rainfall in these margins would be reflected in increased subsidence and reduced moisture convergence and appear as a "dynamical" response to warming (Chou et al., 2009). Third, across the wider tropics away from deep convection, rising static stability drives a weakening of the tropical overturning (Hadley and Walker) circulations (Betts, 1998), which will cause drying (wetting) in regions of current low-level mass convergence (divergence) opposing the wet-get-wetter mechanism. Because it involves a circulation change, this is another dynamical effect.

Beyond these general changes, East African precipitation is also expected to be affected by changes in the SST distribution and by shifts in convergence zones (Huang et al., 2013; Kent et al., 2015). Here we seek to identify the main contributors to model projections of an end-of-century increase in equatorial East African rainfall through an examination of its regional moisture budget, isolating thermodynamic and dynamical contributions.

2. Methods

We use output from the 29 models participating in phase 5 of the Climate Model Intercomparison Project (CMIP5; Taylor et al., 2012) listed in Table S1 in the supporting information. These models were chosen for the completeness of the variables required to calculate terms in the moisture budget using monthly averages.

In the twentieth century or "historical" simulations, coupled ocean-atmosphere models are subjected to the best available estimates of time-varying external influences on the Earth's energy budget, of natural (e.g., top of the atmosphere insolation and volcanic aerosols) and anthropogenic (e.g., greenhouse gases and aerosols from human activity) origin. Among the 21st century projections, we chose the most extreme, Representative Concentration Pathway (RCP) 8.5, which corresponds to a top of the atmosphere radiative imbalance of 8.5 W/m^2 at the end of the 21st century (Moss et al., 2010), to ensure that a forced response could be identified.

Here twentieth century climatological values of variables are computed over the 1900–1999 period. The changes between the end of the 21st and end of the 20th centuries are computed as differences between RCP8.5 projections and historical simulations, with the end of the 21st century average computed over 2075–2099, and the end of the twentieth century average computed over 1975–1999.

3. Dynamics of the Climatological Base State

The climate of equatorial East Africa is generally defined by the alternation between two equinoctial rainy seasons, known as "long" (March–May, hereafter MAM) and "short rains" (here September–November or SON), and two comparatively dry solstitial seasons (December–February (DJF) and June–August (JJA)). The CMIP5 multimodel ensemble struggles to fully reproduce this seasonality, having a significant bias: while in observations the long rains accumulate more rain than the short rains, in models the opposite is true (Lyon & Vigaud, 2017; Tierney et al., 2015; Yang et al., 2015a, 2015b).

To assess anthropogenically forced changes in the moisture budget, we examine what processes contribute most to changes in the difference between precipitation (P) and evaporation (E), which climatologically equals convergence of the vertically integrated moisture flux:

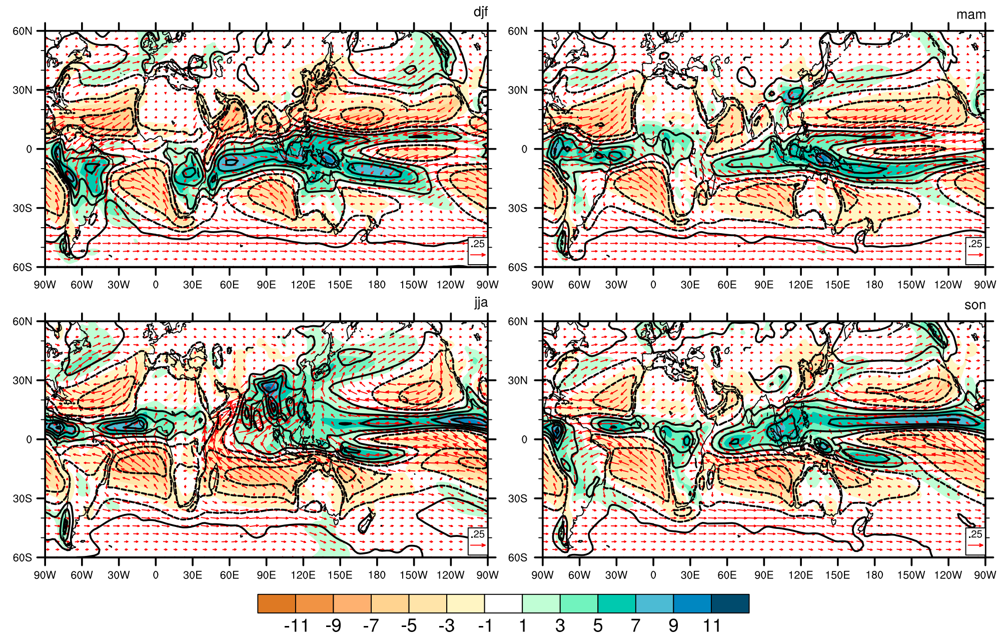

Figure 1. The twentieth century (1900–1999) or historical multimodel mean climatologies of the convergence of the column-integrated moisture flux (color, in mm/d), precipitation minus evaporation (contour, every 2 mm/d, starting at −1, 1 mm/d), and vertically integrated moisture flux from the surface to 700 hPa (vectors).

$$P - E = -\frac{1}{\rho g}\nabla\cdot\left[\int_0^{p_s} q\,\mathbf{u}\,\mathrm{d}p\right]. \quad (1)$$

Here ρ is density of water, g is gravity, q is specific humidity, and $\mathbf{u} = (u, v)$ are the horizontal components of the wind. The vertical integral is computed numerically as a discrete, weighted sum over 12 levels between the surface pressure, p_s, and 100 hPa, using the thicknesses between pressure levels as weights. Divergence is computed using centered finite differences. For reference, Figure 1 shows the twentieth century (1900–1999) climatological multimodel mean, seasonal average values of $P - E$ (black contours), the convergence of the column-integrated (surface to 100 hPa) moisture flux (shading), and the moisture flux integrated in the vertical between the surface and 700 hPa (red vectors).

During the relative dry seasons (DJF and JJA; left-hand side (LHS) of Figure 1), there is divergence of column-integrated moisture flux over equatorial East Africa, particularly along the coast. These dry seasons are shaped by large-scale monsoons: northeasterly near-surface winds sweep across the Arabian Sea in DJF; southwesterly winds flow into equatorial East Africa and then toward the South Asian subcontinent, in JJA.

During the long and short rains (MAM and SON, right-hand side (RHS) of Figure 1), there is weak column-integrated moisture convergence. The "marginal" nature of eastern Africa's climate is clear from the $P - E$ contours: even during its rainy seasons the region is at the edge, or margin, of $P - E$ maxima situated over the African "core" of convection in the Congo Basin to the west, beyond the Rift Valley, and the Maritime Continent to the east, across the Indian Ocean (Hastenrath, 1991; Hastenrath et al., 2011; Nicholson, 2017). During these wet seasons the Indo-Pacific convergence pattern is large scale: easterly winds sweep across the tropical Pacific from the west coast of South America, and, over the Indian Ocean, equatorward moving winds recurve to become westerly near the equator. During these equinoctial seasons, southeasterly and northeasterly flow comes onshore in East Africa, respectively, from the Southern and Northern Hemispheres, splitting roughly along 60°E from the dominant flow that at the equator converges toward the Maritime Continent.

The weak climatological moisture convergence during the two rainy seasons in East Africa results from the near balance between the moisture-laden onshore flow at the surface and large-scale divergence away from the margin in the vertical column. This becomes apparent when the divergence operator is taken inside the vertical integral (Trenberth & Guillemot, 1995):

$$-\nabla\cdot\left[\int_0^{p_s} q\mathbf{u}\,\mathrm{d}p\right] = -\int_0^{p_s}\nabla\cdot q\mathbf{u}\,\mathrm{d}p - q_s\mathbf{u}_s\cdot\nabla p_{s.} \tag{2a}$$

In the climatology of the current climate, the first term on the RHS of (2a), representing the vertical integral of moisture convergence, is strongly negative (divergent), even during the rainy seasons. When it is further decomposed into mass convergence and moisture advection, as follows

$$-\int_0^{p_s}\nabla\cdot q\mathbf{u}\mathrm{d}p = -\int_0^{p_s} q\nabla\cdot\mathbf{u}\,\mathrm{d}p - \int_0^{p_s}\mathbf{u}\cdot\nabla q\,\mathrm{d}p, \tag{2b}$$

it can be shown that mass convergence, the first term on the RHS of (2b), is the dominant negative contribution all along the eastern African coastline (Figure S1 of supporting information) and that moisture advection, the second term on the RHS of (2b) (Figure S2 of supporting information), further contributes to drying. Thus, the moisture flux convergence required during the rainy season results primarily from the second term on the RHS in (2a), the surface pressure gradient term, which represents the upslope flow of moist air near the surface. This second term can be computed as a residual, or difference, between the term on the LHS of (2a) and the first term on the RHS of the equation to ensure balance in the moisture budget (Figure S3 of supporting information; Seager & Henderson, 2013). Coastal topography and onshore flow ensure that the surface term provides a positive $P - E$ tendency over equatorial East Africa. Hence, convergence of onshore moisture transport occurs only near the surface and is almost entirely, but not totally opposed by column-integrated moisture divergence. The weakly positive values shaded in color in the rainy season panels of Figure 1 (i.e., during MAM and SON) thus result from the near cancellation of the large, opposing terms on the RHS of (2a).

4. Dynamics of Change

The multimodel mean projections presented in the 4th Assessment Report (AR4) of the IPCC showed an increase in equatorial East African precipitation by the end of the 21st century, with a degree of model consensus found in only a few other tropical land regions, most notably the Caribbean and Central America, which were projected to dry (Neelin et al., 2006). These results, which have puzzled climate scientists and policymakers alike in view of the recent increase in drought occurrence in eastern Africa, motivated this research. They are broadly echoed in the 5th Assessment Report (e.g., Figure 8 in the summary for policymakers; Intergovernmental Panel on Climate Change, 2014).

Here Figure 2 shows the multimodel mean percent change in seasonal precipitation between the end of the 21st (2075–2099) and 20th (1975–1999) centuries. The percent change is most marked in DJF and SON. (A second, related measure showing the number of models projecting a positive change, is provided in supporting information Figure S4.) The red stippling in Figure 2 covers grid points that receive less than 25% of annual mean rainfall during a given season (a simple indicator of a climatological dry season). Note that the largest percent change in East African rainfall, an increase upward of 75%, actually occurs during the DJF dry season. This illustrates an important caveat to the display of projected changes in precipitation: seasonality needs to be taken into account. Presumably, the most significant societal impact would be associated with changes in rainfall accumulated during the climatological rainy season(s) or with shifts in timing of onset and/or cessation, not necessarily with the largest percent change. Therefore, here we focus on model-projected changes in the two rainy seasons.

To shed light on the projected wetting of the equatorial East African margin, and the thermodynamic and dynamical contributions, we decompose the moisture budget as in Seager et al. (2010) and Seager and Naik (2012):

$$\rho g\Delta[P - E]\tilde{}\,\Delta\mathrm{TH} + \Delta\mathrm{MCD} + \Delta\mathrm{TE} + \Delta S, \tag{3}$$

where Δ represents the change between the end of 21st and end of the 20th centuries. Here the change in $P - E$ is broken into, on the RHS of (3), changes in the thermodynamic, dynamical, transient eddy, and storage terms. Following the notation of Seager et al. (2010), the thermodynamic and mean circulation dynamics contributions, derived from mean seasonal quantities, are given by

$$\Delta\mathrm{TH} = -\frac{1}{\rho g}\nabla\cdot\left[\int_0^{p_s}\Delta q\,\overline{\mathbf{u}}\,\mathrm{d}p\right] \tag{4}$$

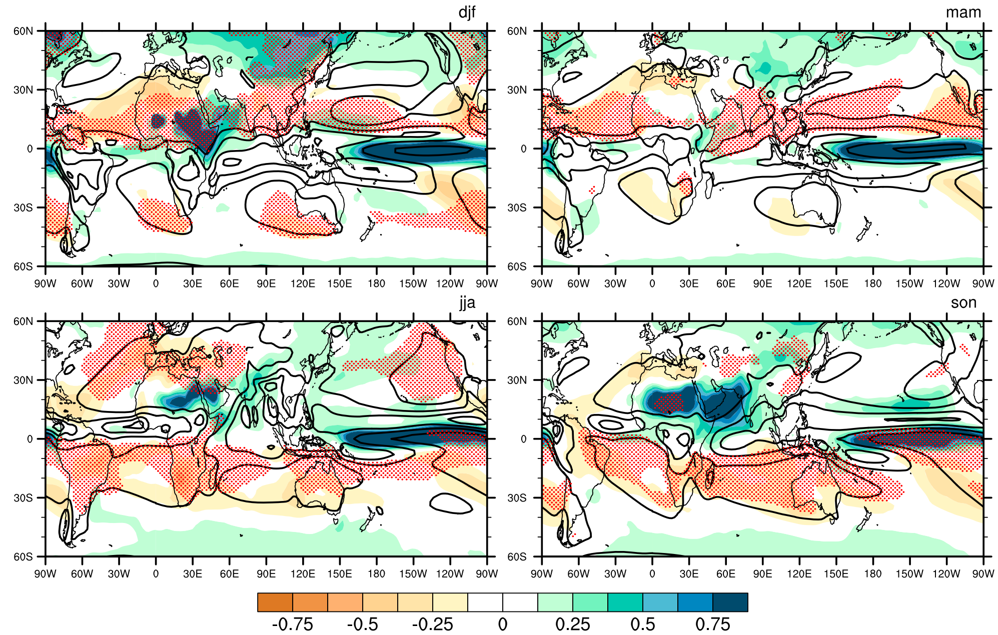

Figure 2. The change between end of the 21st and end of 20th centuries multimodel mean percent precipitation, in color, with the 20th century precipitation climatology in contour. Grid points are stippled in red where seasonal precipitation is less than 25% of the annual total.

$$\Delta \mathrm{MCD} = -\frac{1}{\rho g}\nabla\cdot\left[\int_0^{p_s}\overline{q}\,\Delta\mathbf{u}\,\mathrm{d}p\right]. \quad (5)$$

The overbar denotes a climatological average, computed at the end of the twentieth century. When equations (4) and (5) are compared to (1), it can be seen that, by definition, change in the thermodynamic term depends solely on the change in moisture (Δq), while change in the dynamical term depends solely on the change in circulation ($\Delta\mathbf{u}$). These terms are depicted in Figures 3 and 4, respectively.

The thermodynamic change term (ΔTH) is shown in Figure 3 (for MAM and SON only). In this figure, vectors represent vertical integrals, from the surface to 700 hPa, of the change in specific humidity *(Δq)* multiplied by end of the twentieth century climatologies of the horizontal wind (**u**). This term does not contribute significantly to the change in $P - E$ during equatorial East Africa's rainy seasons. A simple "rich-get-richer" expectation would imply weak wetting, when the current, weakly convergent mean moisture flux (depicted in Figure 1) strengthens due to increased humidity. Comparing Figures 1 and 3, it can be seen that projected changes in humidity do not substantially alter the spatial pattern seen in the current climate.

The dynamical change term (ΔMCD), shown in Figure 4, thus prevails and results in a positive change in $P - E$, explaining the future model wetting of eastern Africa's climate. The dynamical term includes three components: changes in the overturning circulation associated with changes in vertically integrated mass convergence, changes in vertically integrated moisture advection, and changes in the near-surface upslope flow associated with the surface pressure gradient term (see equations (2a) and (2b)). A slowdown in overturning manifests itself in the following features in Figure 4, which are common to both rainy seasons: (i) negative values in ΔMCD over the Congo Basin and Maritime Continent cores of convection and (ii) changes in winds that oppose the climatological circulation depicted in Figure 1. With regard to (i), negative values in ΔMCD over the cores of convection are consistent with weaker convergence and drying where the current climatological flow is convergent. With regard to (ii), the vectors in Figure 4 represent the vertical integral (surface to 700 hPa) of the change in the horizontal components of wind *($\Delta\mathbf{u}$)* multiplied by end of the twentieth century climatological specific humidity *(q)*. Changes in wind also show a weakening in the overturning circulation, with anomalous easterly flow across the Indian Ocean from the Maritime Continent. These easterlies recurve to southwesterly at the East African coast and flow toward South Asia. Further, there are westerly anomalies from the Congo Basin core toward its East African margin (Cook & Vizy, 2013). The latter wind anomalies help

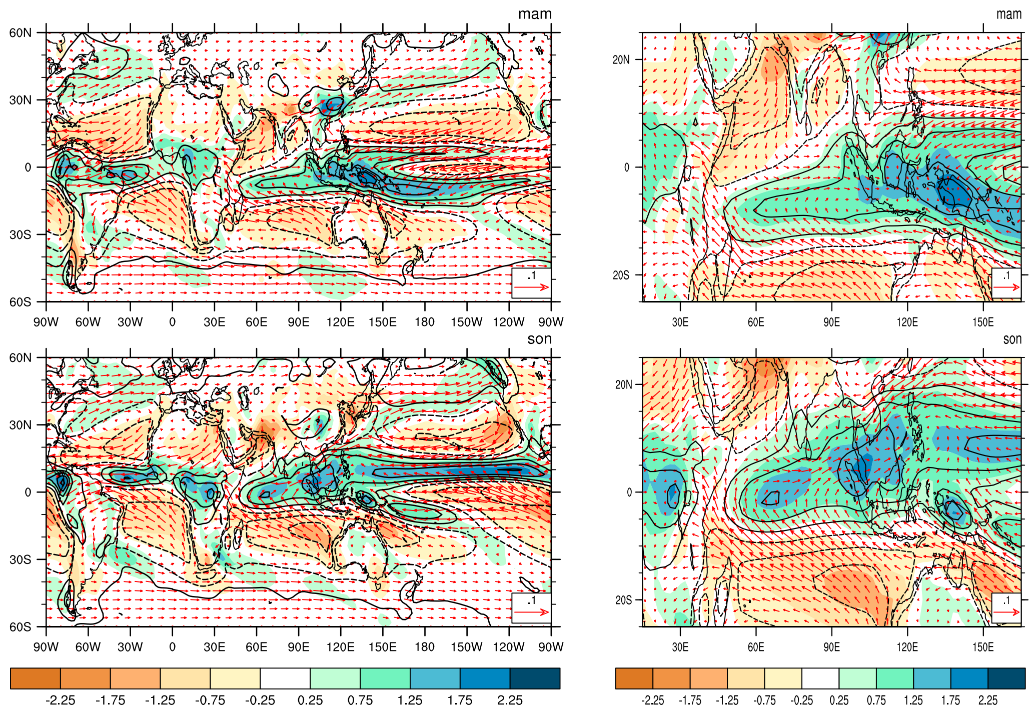

Figure 3. The change in the thermodynamic term in the moisture budget between the end of the 21st and end of the 20th centuries, in color. Contour represents the $P - E$ climatology, with contours as in Figure 1. Vectors represent the thermodynamic change in moisture flux, computed as the vertical integral of the change in specific humidity multiplying the climatological horizontal components of wind.

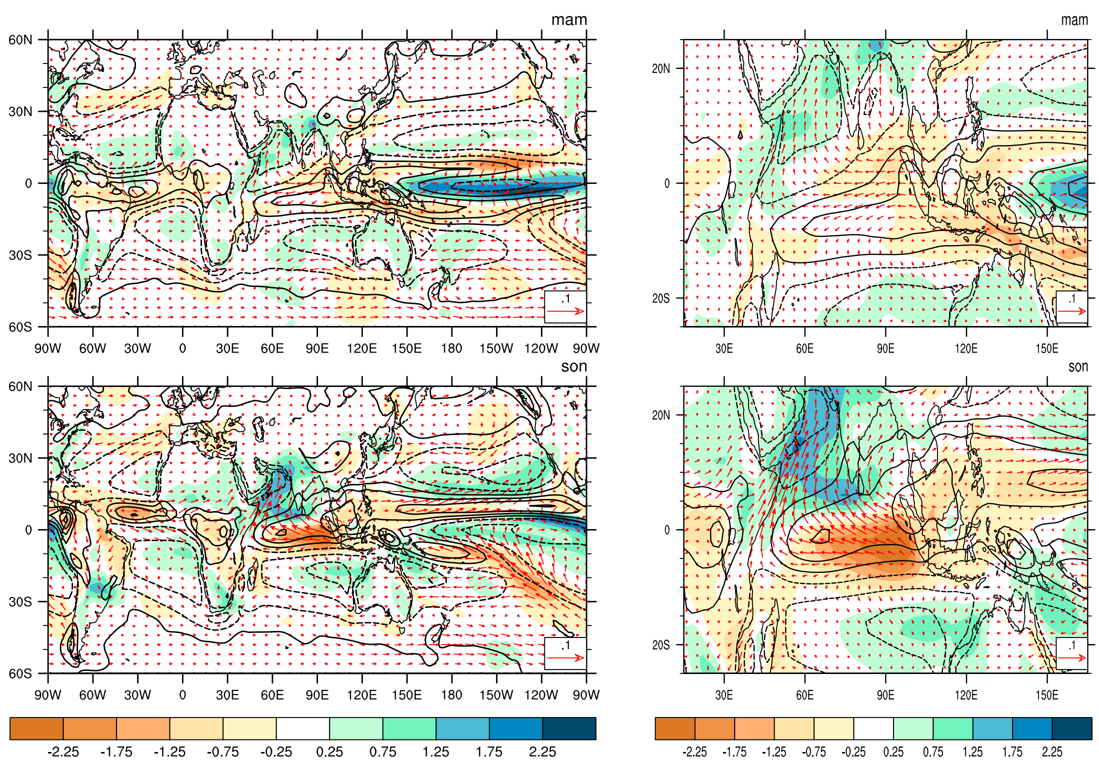

Figure 4. The change in the dynamical term in the moisture budget between the end of the 21st and end of the 20th centuries. Contour represents the $P - E$ climatology, with contours as in Figure 1. Vectors represent the dynamical change in moisture flux, computed as the vertical integral of climatological specific humidity multiplying the change in horizontal components of wind.

explain the positive change in ΔMCD, which is due primarily to anomalous moisture advection (not shown, but in actuality reduced advective drying) from the moist core to the relatively drier margin.

However, there are important differences between seasons. In MAM, the change in circulation and associated moisture flux over equatorial East Africa appears as a regional manifestation of an El Niño-like response to increased radiative forcing. Figure 4 shows enhanced convection and a convergent, anomalous moisture flux over the central and eastern equatorial Pacific, with associated drying over the Maritime Continent. Anomalous easterly moisture flux over the equatorial Indian Ocean toward the east African coast is part of the larger, divergent circulation from the Maritime Continent region. It follows from the multimodel mean projected warming in the Pacific Ocean (Figure S5 of supporting information) being greater in the eastern than the western equatorial Pacific, thus decreasing the climatological zonal SST gradient. It should be noted that in the current climate, El Niño–Southern Oscillation (ENSO) does not show a consistent rainfall teleconnection to eastern Africa in MAM (Lyon, 2014). However, recent studies (Liebmann et al., 2017; Lyon & Vigaud, 2017) provide observational evidence that recent drying in East Africa during MAM was associated with an anomalous Walker circulation over the Indian Ocean, with enhanced convection in the western equatorial Pacific and subsidence over East Africa, suggesting that a similar (and opposite-signed) link to the Pacific is at least a plausible mechanism in the CMIP5 models.

The projected wetting in equatorial East Africa is greater in SON than in MAM, again with the dynamical term contributing most to the increase. In SON, the precipitation change in the equatorial central and eastern Pacific is muted compared to MAM, although there is clear moisture divergence and associated drying over the Maritime Continent consistent with a more general tropical circulation slowdown (Figure 4). Changes in circulation and precipitation affecting equatorial East Africa in SON are more pronounced over the equatorial Indian Ocean and likely affected by climatological warm biases in SST off the East African coast, which appear to become amplified in projections (Lyon & Vigaud, 2017; Yang et al., 2015b).

5. Discussion and Conclusions

CMIP5 projections of a wetting of equatorial East Africa in both MAM and SON are explained by circulation changes that cause anomalous moisture advection from the core toward the margin, consistent with the slowdown in the overturning circulation expected from warming and a shift in SON to more southerly flow. These are, however, model projections and caveats must be discussed.

First, the wetting of equatorial East Africa depends in part on anomalous moisture advection from the Congo Basin. This leaves room for concerns that the complex topography of the region may not be represented with sufficient accuracy in global models to trust the results. Detailed analyses of moisture transport across the East African mountains in available observations, reanalyses, and simulations with regional climate models, for example, those run under the CORDEX framework (http://www.csag.uct.ac.za/cordex-africa/), and comparison with CMIP5 models, would seem a logical next step.

A second concern is uncertainty associated with the El Niño-like change in SST, particularly in MAM. It is true that the multimodel mean projects an El Niño-like state (Collins et al., 2010; Tierney et al., 2015), with increased precipitation in the central and eastern equatorial Pacific in all seasons. However, competing feedback processes control intensity, duration, and variability of ENSO events (Ferrett & Collins, 2016). Discrepancies in the strength of these competing feedbacks could result in an erroneous shift of climate toward an El Niño-like base state in response to rising greenhouse gases (Cane et al., 1997; Clement et al., 1996; Coats & Karnauskas, 2017; Kohyama et al., 2017; Kohyama & Hartmann, 2017). At present, we do not know whether the current cooling phase of the tropical Pacific is a result of internal variability alone or is partly attributable to the emergence of a La Niña-like response to rising greenhouse gases. An observed warming trend in tropical West Pacific SSTs, however, likely has an anthropogenic contribution and, when combined with cooler conditions in the East Pacific (via natural variability or forced change), serves to enhance the zonal equatorial SST gradient, conditions tied to decreased long rains in MAM (Funk & Hoell, 2015; Vigaud et al., 2017). Overall, the CMIP5 models may thus be more realistically capturing the anthropogenically forced change in western versus eastern Pacific SSTs.

Third, in the case of SON, changes in the wind field appear somewhat consistent with a delayed cessation of the Northern Hemisphere summer monsoon (i.e., early in the SON season). However, long-term projections of monsoonal precipitation are particularly sensitive to differences in model formulation, especially in convection (Hawkins & Sutton, 2009). In addition, coupled models generally fail to properly capture the observed annual cycle of SSTs in the western equatorial Indian Ocean (Yang et al., 2015a), particularly from boreal summer into the fall. This result is associated with model rainfall in SON being greater than in MAM, the reverse of what is found in observations and a result that appears to become amplified in climate model projections (Lyon & Vigaud, 2017). In sum, in both seasons there are reasons to be cautious about model realism.

The apparent paradox between the recent decline in East African rainfall and the model-projected wetting points to how research in climate science can respond to user needs for an explanation of underlying causes. In-depth analyses of long-term projections of climate change at regional scale, by clarifying the processes implicated in change, can guide efforts to identify the emergence of these changes via monitoring current trends, raising or lowering confidence in model projections accordingly. Such mechanism-based investigations can provide important caveats/warnings regarding the reliability of model behavior in specific regions. The contrast of recent drying with model-projected wetting makes clear the need for climate scientists to be an integral part in adaptation projects, to guide interpretation of the observational record and the multimodel projections made available by IPCC in preparation for its Assessment Reports (Meehl et al., 2007; Taylor et al., 2012). While observations indicate that there has been a slight increase in the SON short rains (Liebmann et al., 2014), the MAM long rains remain anomalously low. And while differences between recent observed SST conditions in the eastern equatorial Pacific and CMIP5 SST trends appear to largely be a result of internal decadal variability, this does not necessarily exonerate the models from improperly projecting future conditions there. Thus, in elucidating the plausible dynamics of anthropogenically forced climate change, we argue for an iterative decision-making process that synthesizes understanding of current observed trends, including contribution of internal/decadal variability, and future model-projected change. The dynamical interpretation of model-projected change provided here is an attempt to place consideration of future climate change on a sound mechanistic basis. The identified uncertainties, however, lead us to conclude that it is not clear that the climate of East Africa will indeed become wetter as a result of increasing greenhouse forcing despite model consensus and that a drier future should not be disregarded. Only improved model representation of the complex East African climate and its connections to the larger global climate system will enable less uncertain projections for the future.

Acknowledgments
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