Is "rich-get-richer" valid for Indian Ocean and Atlantic ITCZ?

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[1] Climate models often project an increase of rainfall under global warming over the climatologic wet regions from the global zonal-mean perspective. However, this "rich-get-richer" mechanism is not valid on a basin scale. In this study by analyzing climate change experiment outputs from an idealized atmospheric general circulation model with uniform sea surface warming and the Coupled Model Intercomparison Project Phase 5 (CMIP5) models, we note that the intertropical convergence zones along the equatorial Indian Ocean and the equatorial Atlantic Ocean exhibit a very different response to anthropogenic forcing. In the present-day climate in boreal summer (winter), the tropical Indian (Atlantic) Ocean exhibits two pronounced rainbands, with one branch located over the Indian monsoon (Amazon) region and the other located near the equator. In future warmer climate, the two rainbands compete through a local Hadley circulation; as a result, only the stronger branch becomes wetter while the weaker one affected by anomalous descending motion and moisture divergence becomes drier. Thus, on a basin scale, the wet does not always get wetter.
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1. Introduction

[2] The most pronounced feature from long-term average of satellite images over the tropical Indian Ocean (IO) in northern summer is occurrence of two zonally oriented rain bands (see *Li and Wang* [2005] and *Li* [2010] for a review). The northern branch lies at 15°N and is associated with the South Asian summer monsoon. The southern branch lies slightly south of the equator and is often referred to as the equatorial IO intertropical convergence zone (ITCZ). A similar double rain band pattern appears in northern winter over the tropical Atlantic section. The southern rain band appears mostly over Amazon land and is closely related to the South American monsoon. The northern rain band is mostly confined over the equatorial Atlantic Ocean, and is often termed as the Atlantic ITCZ. An interesting question related to future climate projection is how the double rain band structure in the IO and Atlantic will change by the end of 21st century under global warming.

[3] One of the major mechanisms regarding future precipitation change is "rich-get-richer", which emphasizes the thermodynamic effect of moisture change acting upon little changed circulation [*Chou and Neelin*, 2004; *Held and Soden*, 2006]. Under a constant relative humidity constraint, increases in water vapor due to warmer temperature favor precipitation over the climatologic wet regions (such as the tropics and mid-latitude storm track regions), as low-level flows bring the enhanced moisture into the regions. Precipitation tends to decrease over the dry subtropical regions where descending motions dominate. By analyzing projected rainfall changes from the IPCC AR4 models, *Held and Soden* [2006] illustrated that the zonal-mean precipitation change follows closely the "rich-get-richer" rule.

[4] Does the "rich-get-richer" rule also fit for a zonally asymmetric rainfall pattern? *Xie et al.* [2010] found that the spatial distribution of tropical precipitation change is to a large extent determined by the relative warming pattern of sea surface temperature (SST), that is, increased (decreased) precipitation appears in the regions where SST warming is greater (smaller) than the tropical average. They suggested that the "rich-get-richer" rule is only valid when a model is forced by a uniform warming SST pattern. *Chou et al.* [2009] separated positive and negative rainfall changes over the climatologic wet and dry regions from the IPCC AR4 models and found that rainfall increase or decrease can happen in both the climatologic wet and dry regions, implying the invalidity of the "rich-get-richer" rule on regional scales. The reductions of rainfall in a wet region could be linked to a so-called upped-ante mechanism [*Neelin et al.*, 2003; *Chou and Neelin*, 2004]. Under this mechanism, the warmer troposphere engenders a higher threshold for convection to occur. For a given rate of precipitation, more moisture must be present. Thus only the convective branch with greater moisture supply can meet the new "convection upped" (i.e., higher threshold for convection to occur) under global warming. The enhanced convection further induces a dry moisture advection from subsidence region, leading to drought in the margins of convection center.

[5] In this study, we focus on future precipitation changes in the tropical IO and Atlantic sectors where the monsoon is pronounced. A special feature in both the regions is the dynamic connection between monsoon rain band over land and ITCZ over the ocean. For example, it has been shown that the monsoon rain band over India is negatively correlated with the rain band over the equatorial IO on intraseasonal [*Gyoswami and Shukla*, 1984; *Jiang and Li*, 2005; *Qi et al.*, 2008] and interannual [*Li et al.*, 2003] timescales. The physical process that connects the two convective branches is through a local Hadley circulation – a strengthened monsoon trough at 15°N may induce anomalous subsidence near the equator, which suppresses the equatorial ITCZ. Does the opposing effect happen under global warming? The "rich-get-richer" rule would imply that in future warming climate state precipitation in both the monsoon zone and the equatorial ITCZ will strengthen. The dynamic effect of local Hadley circulation would imply an opposite rainfall

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change between the two climatologic wet zones. Will the dynamic effect dominate the thermodynamic effect, or vise versa? What will projected rainfall patterns look like over the IO and Atlantic sectors when forced by a spatially varying or a spatially uniform SST warming pattern? If the "rich-get-richer" rule does not apply over the monsoon ocean, what are the mechanisms responsible for regional precipitation change? We intend to address the aforementioned questions based on the analysis of the Coupled Model Intercomparison Project Phase 5 (CMIP5) model outputs and time-sliced atmospheric general circulation model (AGCM) experiments.

2. Model and Experiment Description

[6] Thirteen CMIP5 model outputs from both historical and RCP4.5 scenario simulations are used to analyze the rainfall change from the present-day (1979–2003) to future (2075–2099) climate state. To seek robust signals and reduce uncertainty among models, we took a multi-model ensemble (MME) approach so that only multi-model composite rainfall patterns are shown. For multi-model ensemble average, the global model outputs with resolutions ranging from T42 ($\sim$2.8°) to T106 ($\sim$1.125°) are interpolated into a 1 degree latitude/longitude grid using a bilinear interpolation technique. Because precipitation changes are quite similar among the same model families, only one sample that shows the best performance of rainfall climatology from each model family is included in MME. Considering data available for a moisture budget diagnosis, we used 13 CMIP5 models for the ensemble analysis. These models are bcc-csm1-1, CanESM2, CSIRO-Mk3-6-0, FGOALS-s2, GFDL-CM3, GISS-E2-R, HadGEM2-ES, inmcm4, IPSL-CM5A-MR, MIROC5, MPI-ESM-LR, MRI-CGCM3, and NorESM1-M. For detailed description of individual CMIP5 models and their present-day and global warming experiment designs, readers are referred to the web site (http://cmip-pcmdi.llnl.gov/cmip5/).

[7] All CMIP5 models projected a spatially varying future SST warming pattern. To fully understand the sensitivity of rainfall change to the SST pattern, it is desirable to compare the CMIP5 results with an idealized simulation with a uniform warming pattern. This was done by applying a time-sliced method [*Bengtsson et al.*, 1996; *Li et al.*, 2010], using the Max Planck Institute (MPI) ECHAM5 [*Roeckner et al.*, 2003] AGCM at T106 ($\sim$1.125°) resolution. The present-day run with ECHAM5 T106 (referred to as T106_pd) is an AMIP-type simulation using observed monthly SST over the period of 1978–1999. A constant warming of 2.24 K is added to the present-day climatology for the future day simulation in which greenhouse gas concentration is specified at the level of 2080–2100 in the A1B scenario. The value of 2.24 K was derived from the global average of projected future SST warming pattern simulated from the coupled ECHAM5/MPI-OM model [*Jungclaus et al.*, 2006] that participated in the IPCC AR4. The uniform warming ECHAM5 experiment is referred to as T106_mw.

3. Results

[8] First we examine present-day and future global zonal-mean rainfall distributions from the ECHAM5 T106 (Figures 1a and 1e) and CMIP5 composite (Figures 1b and 1f). The black curves are present-day rainfall distributions, which show two wet zones over the tropics and mid-latitudes respectively and a dry zone in the subtropics. The tropical convective zone coincides with the ascending branch of the Hadley circulation, whereas the rain band between 30°N and 60°N (30°S and 60°S) is associated with the mid-latitude storm tracks. The dry zone is primarily related to the subtropical high. The rainfall peaks shift northward as season progresses from boreal winter to summer. The simulated zonal mean rainfall patterns from both the ECHAM5 and CMIP5 MME are quite realistic compared to observations.

[9] The projected changes of zonal-mean rainfall distributions in both JJA and DJF agree well with the "rich-get-richer" rule, that is, precipitation increases over the climatologic wet regions and decreases in the subtropical dry zones. The change appears robust not only in the uniform warming experiment (Figures 1a and 1e), but also in the CMIP5 composite with spatially varying warming patterns (Figures 1b and 1f).

[10] The "rich-get-richer" rule, however, does not apply to the equatorial ITCZ in both the IO and Atlantic. In the tropical IO sector, the rain band over the Indian monsoon region (around 10°–15°N) is strengthened in boreal summer under global warming, whereas the rain band south of the equator is suppressed (Figures 1c, 1d, 2a, and 2b). As a result, the projected precipitation change shows a striking meridional dipole pattern under global warming. Such a dipole structure appears in both the T106 uniform warming experiment (Figures 1c and 2a) and the CMIP5 MME with spatially varying SST warming (Figures 1d and 2b). A similar dipole pattern is found in austral summer over the tropical Atlantic sector. While the rain band over the South American monsoon region is strengthened under global warming, the rain band at the equatorial ITCZ decreases (Figures 1g, 1h, 2d, and 2e).

[11] To quantitatively measure the consistence of future rainfall projection among 13 CMIP5 simulations, we define 85% (70%) robustness when the signs of future rainfall projection at a given grid are same among 11 (9) out 13 simulations, represented by dark (light) shadings in Figures 2c and 2f. It is noted that the CMIP5 outputs show a highly consistent projection on the rainfall dipole structure in the IO and Atlantic ITCZ regions. The result indicates that the dipole rainfall pattern is a robust global warming signal, even though the amplitude and detailed structure of the projected rainfall field from individual models (see auxiliary material) are diverse. In addition to robustness information, the intra-ensemble standard deviation is also given in Figures 2c and 2f (presented by contours) to illustrate the ensemble spread.[1] It is found that the intra-ensemble spread is of the similar amplitude to the projected mean rainfall change.

[12] The numerical results above suggest that in the region where large-scale convective zones are dynamically linked (through either a local Hadley cell or a Walker cell), only the strongest convective branch can be strengthened under global warming; weaker branches may become wetter or drier, depending on relative strength of the circulation-induced dynamic effect and the moisture-induced thermodynamic effect. Thus, on a regional scale the rich does not always get richer, and only the richest within the region gets richer.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2012GL052399.

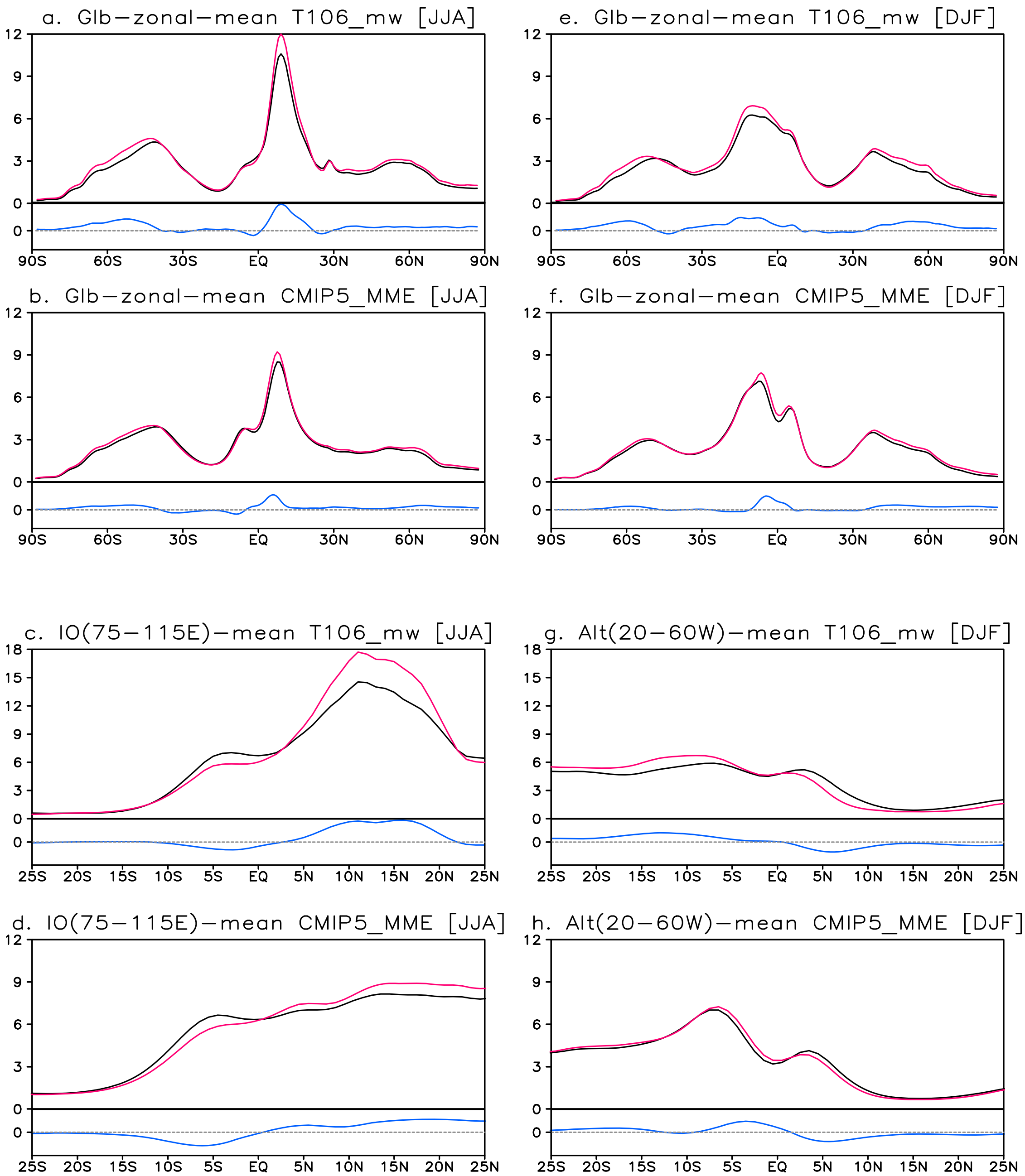

Figure 1. Global zonal-mean precipitation (unit: mm day^{-1}) in present-day (black line) and future (red line) climate and their difference (blue line) in boreal summer (June–August) based on (a) ECHAM5 T106 experiment and (b) CMIP5 MME simulations. (c, d) Same as Figures 1a and 1b but for zonal-averaged precipitation along 75°E–115ºE. Same as left panel, right panel shows the results of global zonal-mean precipitation (e and f) and regional zonal-averaged precipitation along 20°W–60°W (g and h) during austral summer (December–February).

[13] The "richest-get-richer" feature appears to be a robust signal over the monsoon dominated basins. To examine what specific processes are responsible for the opposite rainfall change pattern over the climatologic wet zones in the IO and Atlantic, we examine a vertically integrated moisture budget equation shown below:

$$\Delta P = -\Delta\langle \mathbf{V} \cdot \nabla q \rangle - \Delta\langle q \nabla \cdot \mathbf{V} \rangle + \Delta E \qquad (1)$$

where $\Delta(\ )$ represents the difference between the future and present-day climate simulations (future minus present-day), P is precipitation, $\langle\ \rangle$ indicates vertical integration from 1000 to 100 hPa, ∇ is the horizontal gradient operator, q is the specific humidity, $\mathbf{V}$ is the horizontal vector wind, and E is surface evaporation. According to equation (1), the rainfall changes are caused by the sum of changes in horizontal moisture advection, moisture convergence associated with mass convergence (or vertical motion) and surface evaporation.

[14] The diagnosis of the moisture budget for the rain band over the Indian monsoon region (75°–115°E, 10°–15°N) shows that the increase of precipitation in future climate

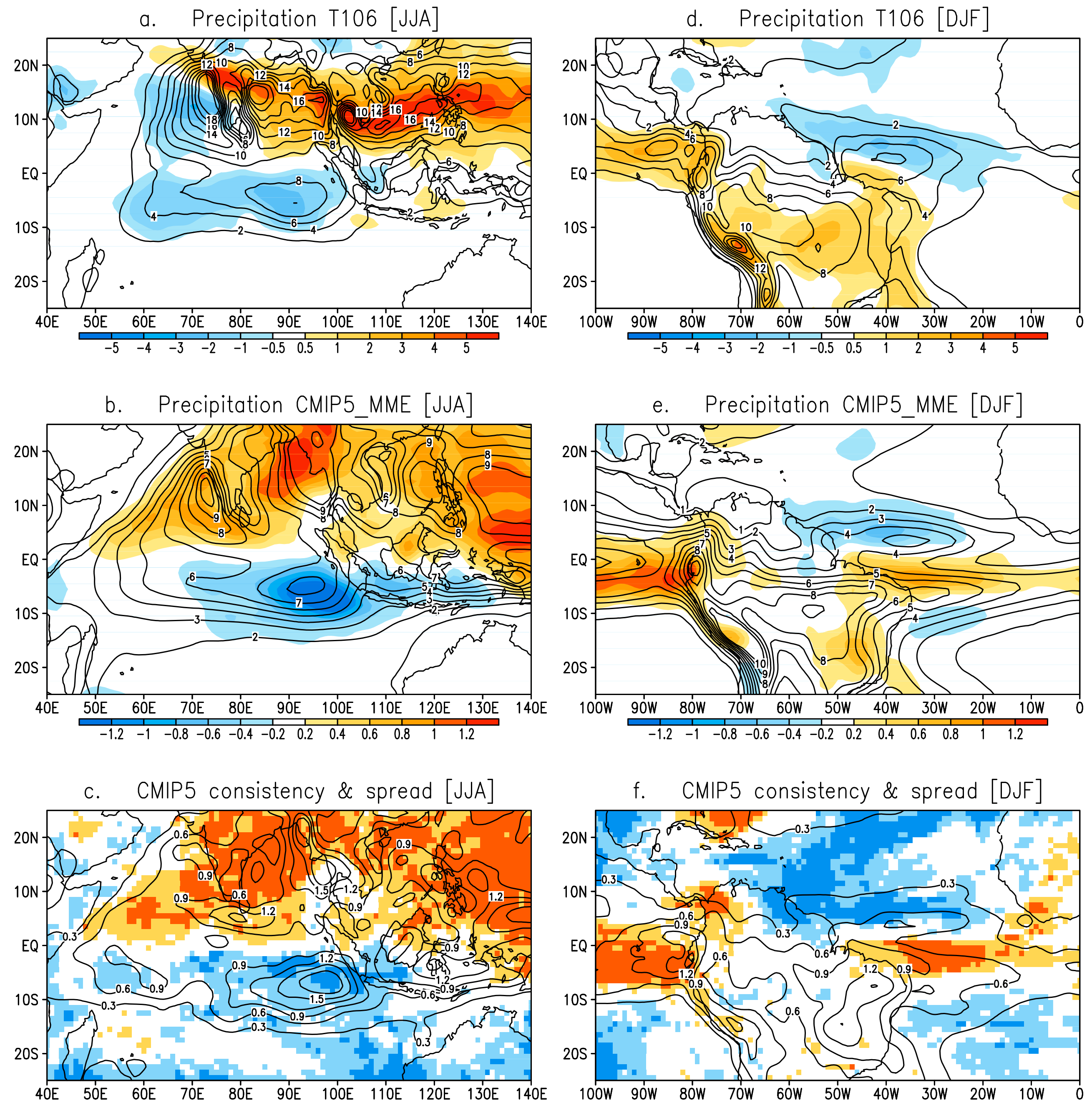

Figure 2. Patterns of precipitation change (shadings, mm day^{-1}) during boreal summer from (a) ECHAM5 T106 and (b) CMIP5 MME simulations. Contours represent the present-day precipitation climatology (mm day^{-1}). (c) Consistency and spread of CMIP5 simulations. The dark (light) shadings indicate that 11 (9) out of 13 simulations project the same signs of rainfall change at a given location. Orange and blue shadings represent rainfall increase and decrease respectively. Contours indicate the intra-ensemble standard deviation of projected rainfall change (unit: mm day^{-1}). (d–f) Same as Figures 2a–2c except for austral summer.

state is mainly attributed to the strengthening of moisture convergence in the T106_mw. The evaporation change also contributes positively to the rainfall increase but its amplitude is much smaller than the moisture convergence term. The horizontal moisture advection, on the other hand, plays a negative role (Figure 3a). It is not surprising because the convergent low-level flow brings relatively dry air into the convective region [*Chou et al.*, 2009]. In contrast, over the equatorial ITCZ (75°–115°E, 2.5°–7.5°S), the negative rainfall change is primarily attributed to anomalous moisture divergence, which opposes the effects of the evaporation and horizontal advection (Figure 3a). Note that in both the regions, the sum of the three terms in the right hand side of equation (1) is close to the simulated precipitation changes, indicating that the moisture budget diagnosis is reliable. The diagnosis of the moisture budget in the CMIP5 MME shows a consistent result that the moisture convergence dominates the precipitation changes in both the regions (Figure 3b).

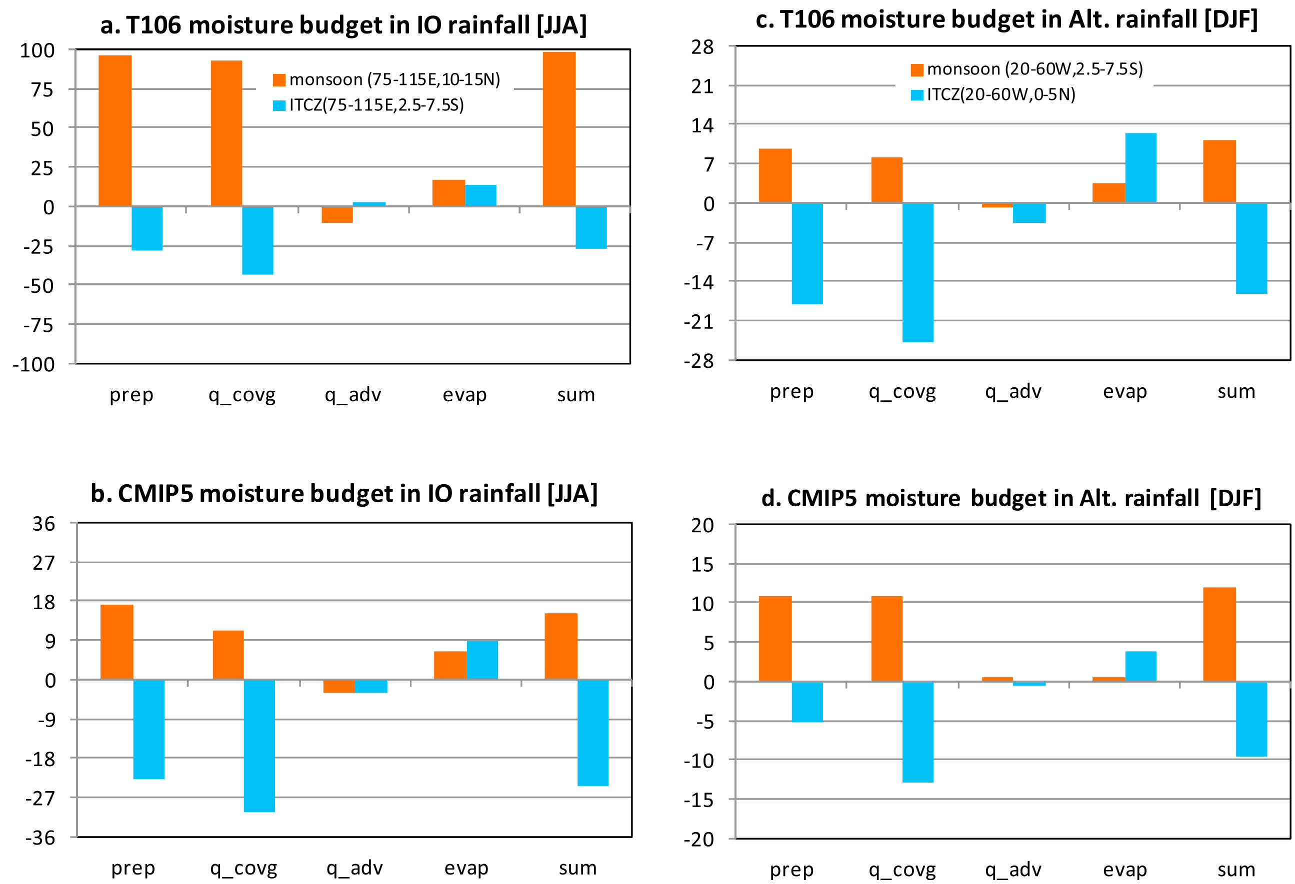

Figure 3. (left) Precipitation changes and moisture budget terms averaged over the Indian monsoon rainband (75°–115°E, 10°–15°N, orange bars) and the equatorial ITCZ (75°–115°E, 2.5°–7.5°S, blue bars) during boreal summer from (a) T106 experiment and (b) CMIP5 MME simulations. From left to right: Simulated precipitation change, moisture convergence, horizontal advection, evaporation and sum of the three moisture budget terms. (c and d) Same as Figures 3a and 3b except for moisture budget terms over the South American monsoon rainband (20°–60°W, 2.5°–7.5°S) and the Atlantic ITCZ (20°–60°W, 0°–5°N) during austral summer. Unit is W m^{-2}.

[15] The same result was derived for the Atlantic sector in northern winter. It was found that the dipole rainfall change pattern (i.e., precipitation decrease in equatorial ITCZ and increase over Amazon) is mainly attributed to the difference in the moisture convergence term in both the ECHAM5 uniform warming simulation (Figure 3c) and the CMIP5 MME (Figure 3d).

[16] The results above indicate that moisture convergence plays a key role in determining the dipole rainfall pattern. A strengthened (weakened) moisture convergence increases (decreases) rainfall over the monsoon (oceanic ITCZ) area, even though the enhanced surface evaporation associated with warmer surface temperature occurs in both bands. Because the moisture convergence is the leading contributor to the rainfall dipole pattern, we further decompose this term into the following three components, namely, anomalous moisture convergence due to the change in moisture (i.e., a thermodynamic effect), due to circulation change (i.e., a dynamic effect), and due to nonlinear contribution of both moisture and circulation changes, that is,

$$-\Delta\langle q{*}D\rangle = -\langle \Delta\ q{*}D_{pd}\rangle - \langle q_{pd}{*}\Delta\ D\rangle - \langle \Delta\ q{*}\Delta\ D\rangle \quad (2)$$

where the asterisk denotes the multiplication sign, D denotes the divergence and subscript 'pd' denotes the present-day climate.

[17] The calculation of each budget term in equation (2) shows that the major cause of the rainfall dipole in the monsoon oceans lies in the dynamic effect. Although the thermodynamic effect (i.e., first term in the right hand side of equation (2)) is positive over both the monsoon rain band and oceanic ITCZ, its amplitude is greater in the former, due to stronger climatologic mean convergence (or ascending motion) there. A greater value of $-\langle\Delta\ q\ *\ D_{pd}\rangle$ in the monsoon rain band may strengthen local Hadley circulation through enhanced diabatic heating, leading to low-level convergence (divergence) anomalies over the monsoon (oceanic ITCZ) region. The so-induced circulation change (through term $-\langle q_{pd}\ *\ \Delta D\rangle$) further impacts the rainfall contrast between the two wet zones. As a result, the rainfall dipole pattern is formed. The nonlinear term is generally small and negligible.

[18] Along the oceanic ITCZs, the dynamic effect (term $-\langle q_{pd}\ *\ \Delta D\rangle$) dominates the thermodynamic effect (term $-\langle\Delta\ q\ *\ D_{pd}\rangle$). As a consequence, a negative moisture convergence anomaly results. The result is consistent among

the ECHAM5 T106 and the CMIP5 MME. Therefore, the failure of the "rich-get-richer" in the equatorial IO and Atlantic ITCZs is attributed to the dynamic constraint of the Hadley circulation. Due to competition of moisture source among dynamically connected convective systems, only the strongest branch gets wetter while the weaker ones may become drier.

4. Summary and Discussion

[19] The conventional wisdom is that higher global temperature will inevitably increase atmospheric moisture (and rainfall) as a result of the Clausius-Clapeyron equation applied at the atmosphere-ocean interface, which highlights the role of thermodynamic effect. However, the response of the real atmosphere, notably in regard to precipitation, is more complex than conventional thermodynamic thinking. This is especially so in the tropics where multi-scale, nonlinearly interactive moist dynamics can have unconventional and important effects on the dynamical organization of large-scale precipitation patterns.

[20] In this study we examined precipitation changes under global warming over the tropical IO and Atlantic sectors, based on simulations of 13 CMIP5 models and a time-sliced AGCM experiment with a uniform SST warming pattern. Whereas the global zonal mean rainfall displays a well-known "rich-get-richer" pattern with increased (decreased) precipitation over the wet (dry) region, precipitation changes along the oceanic ITCZs in the IO and Atlantic basins illustrate a very different characteristic. It is found that precipitation increases in the monsoon rain branch while it decreases in the oceanic ITCZ, forming a meridional dipole pattern. Both the CMIP5 model composite and the idealized AGCM experiment forced by uniform SST warming reveal a similar rainfall dipole pattern, suggesting that in a region with dynamically connected convective systems co-existing, the rich does not always get richer, and only the richest in the region gets richer. The result implies that the "rich-get-richer" rule is no longer valid when two or more rain bands compete against each other. As those models have different model physics and future warming patterns, the rainfall dipole pattern appears robust regardless of model physics and future SST warming patterns.

[21] A diagnosis of vertically integrated moisture budget reveals that the dynamic effect associated with circulation change dominates the thermodynamic effect associated with moisture change. A strengthened heating over the monsoon rain band enhances local Hadley circulation and leads to anomalous low-level divergence or anomalous descending motion over the equatorial ITCZ. The anomalous moisture divergence dominates rainfall change along the IO and Atlantic ITCZs. Thus, on a regional scale, the "rich-get-richer" is no longer valid.

[22] The projected dipole rainfall pattern might relate to the upped-ante mechanism in the sense that only the strongest convection region with a sufficient moisture supply can maintain convection under global warming, while less strongly convective region may not. As a result, the wet regions do not always get wetter. Similar to the upped-ante mechanism, we also emphasize the importance of dynamic control to the future regional rainfall change. The major difference lies in that the upped-ante mechanism focused on dry moisture advection in the margins of individual convection, whereas the present study emphasizes the dynamic connection of two (or more) convective branches via the Hadley (or Walker) circulation. Due to such connection, enhanced diabatic heating in one branch due to global warming may induce anomalous descending motion and moisture divergence over the other branch. Consequently, a dipole pattern of rainfall change is formed in the IO and Atlantic ITCZ regions.

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