LETTER

Enhanced spring convective barrier for monsoons in a warmer world?
A letter

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Abstract Twenty-first century climate model projections show an amplification of the annual cycle in tropical precipitation with increased strength in both wet and dry seasons, but uncertainty is large and few studies have examined transition seasons. Here we analyze coupled climate model projections of global land monsoons and show a redistribution of precipitation from spring to summer in northern (North America, West Africa and Southeast Asia) and southern (South America, Southern Africa) regions. The annual cycle changes are global in scale. Two mechanisms, remote (based on tropospheric stability) and local (based on low level and surface moisture), are evaluated through the annual cycle. Increases in tropospheric stability persist from winter into spring and are reinforced by a reduction in surface moisture conditions, suggesting that in spring both remote and local mechanisms act to inhibit convection. This enhanced spring convective barrier leads to reduced early season rainfall; however, once sufficient increases in moisture (by transport) are achieved, decreases in tropospheric stability result in increased precipitation during the late rainy season. Further examination of this mechanism is needed in observations and models, as the projected changes would have substantial implications for agriculture, water management, and disaster preparedness.

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1 Introduction

In this article we study 21st century projections of the annual cycle of precipitation in global land monsoon regions (e.g. Wang and Ding 2006). Seasonally wet/dry monsoons result from directional shifts in winds and moisture transport due to the longer response time of oceans versus land to the annual cycle of solar heating (Chao and Chen 2001; Webster et al. 1998). Under anthropogenic warming scenarios, land-sea thermal contrasts are expected to increase in part due to differences in thermal inertia between land and ocean, but largely because oceans divert more of the anomalous incoming energy into latent heat rather than increasing surface temperature (Sutton et al. 2007). Where moisture is abundant (i.e., over oceans) warmer surface temperatures lead to increased evaporation due to the nonlinear Clausius-Clapeyron relationship, and robust increases in atmospheric water vapor, which are associated with weakening of the tropical (Hadley, Walker and monsoon) circulations (Held and Soden 2006). Despite this weakening of tropical circulations, multi-model climate projections indicate a tendency towards increased monsoon precipitation due to increased low-level moisture convergence (Christensen et al. 2007). Evidence for future precipitation increases has been documented for Australia (Meehl et al. 2007a) and South Asia (Douville et al. 2000), where a 5–25% increase in precipitation was found in the models that best represent the interannual variability and teleconnections associated with the monsoon (Annamalai et al. 2007). However, the North American monsoon region is expected to become drier in the annual mean (Seager et al. 2007), and much uncertainty exists for the future of the West African monsoon and tropical South America (e.g. Giannini et al. 2008; Vera et al. 2006). The response of global monsoons to greenhouse warming is complicated by a number of factors, including the expected dynamical weakening of the tropical circulation (Tanaka et al. 2005; Vecchi and Soden 2007), related changes in the tropical tropospheric stability (Chou et al. 2001; Neelin et al. 2003), and the regional effects of aerosols and black carbon (Lau et al. 2006; Meehl et al. 2008).

The monsoon response to greenhouse gas forcing has been examined using a framework based on moist static energy (MSE), which exploits the role of evaporation in both energy and water budgets (Neelin and Held 1987). Neelin and collaborators (Neelin et al. 2003; Chou and Neelin 2004; Chou et al. 2009) use the MSE framework to evaluate changes in horizontal gradients in humidity, whereby core regions of tropical deep convection demonstrate increases in low-level moisture and moisture convergence, leading to decreased gross moist stability, and are thus projected to become wetter in a warmer world ("rich get richer"). The margins of deep convecting regions, which do not have access to the same levels of increased low-level moisture due to advection from nearby nonconvecting regions, show decreased precipitation ("upped ante"). Giannini (2010) has used this MSE framework to explore two competing mechanisms involved in the divergent responses of climate models to greenhouse gas forcing in the Sahel region: *remote* (or top down) and *local* (or bottom up). First, in the *remote* mechanism, large scale tropospheric warming controls vertical stability in the global tropics (Sobel et al. 2002; Chiang and Sobel 2002), and reduces continental precipitation in those regions that cannot meet the increasing demand for near-surface moist static energy (Chou et al. 2001; Neelin et al. 2003). In this case, the precipitation reduction is reinforced by a consequent reduction in evaporation due to decreased precipitation recycling.

In the second, *local* mechanism, the land surface response to anthropogenically enhanced terrestrial radiative forcing dominates. Where surface moisture is sufficient, increased evaporation leads to near-surface increases in moist static energy, instability, and precipitation. The increase in precipitation is then reinforced by enhanced moisture convergence. Where moisture is insufficient, increased terrestrial radiation is balanced by increased sensible heat flux. In the models that project drying in the Sahel, the *remote* mechanism dominates, while in models projecting a wetter Sahel the *local* mechanism is at work (Giannini 2010).

These studies have focused on the fully established wet and dry seasons (Dec–Feb, Jun–Aug). However, studies that examine the complete annual cycle indicate a redistribution of precipitation within the annual cycle. For example, the South American and West African monsoons both exhibit drying in spring and increased precipitation during summer in projections (Seth et al. 2010; Biasutti and Sobel 2009; Biasutti et al. 2009).

In the present analysis, we examine global land monsoon regions using the *MSE* framework as described by Giannini (2010), which acknowledges the potential importance of the surface energy budget in understanding precipitation in land monsoon regions. The analysis is performed through the annual cycle, thus permitting a view of the transition seasons. We will show that, despite model uncertainties in annual precipitation, a shift in the annual cycle is discernable and appears to be part of a global response to greenhouse forcing. We argue that the transition from dry to wet season is likely to be important in order to understand changes in the monsoon regions.

2 Spring drying in continental monsoons

Despite the disagreement among climate models regarding projections of annual or seasonal mean Sahel precipitation in the 21st century (e.g. Giannini et al. 2008), there is consensus regarding a weakening of early and strengthening of late season rainfall (Biasutti and Sobel 2009). Models indicate a similar reduction in spring and an increase in summer precipitation in the core region of the South American monsoon, which is associated with insufficient low level moisture convergence in spring and a substantial increase in convergence during summer (Seth et al. 2010). Multi-model projected changes in the annual cycles of precipitation, shown averaged over longitude for each monsoon region in Fig. 1 (c–i, see Section 4 for region definitions), demonstrate drying during spring, Mar–May at 15–25°N (Sep–Nov at 10–20°S) in the northern (southern) hemisphere. In addition to South America and West Africa, a shift from spring to summer precipitation is present in North America, Southern Africa, and Southeast Asia. Only South Asia and Australia exhibit mixed results during spring. The shift is visible in averages of the four northern and three southern monsoon regions (Fig. 1a and b).

A robust large-scale response to greenhouse gas forcing has been shown in tropical precipitation wherein summer hemisphere monsoons and winter hemisphere dry seasons are simultaneously strengthened, creating an asymmetric inter-hemispheric signal (Tan et al. 2008). The shift in the annual cycle of precipitation in the monsoon regions (Fig. 1) appears to be part of this global response. The reduction of spring and increase in summer can be seen in the global annual cycle of precipitation averaged
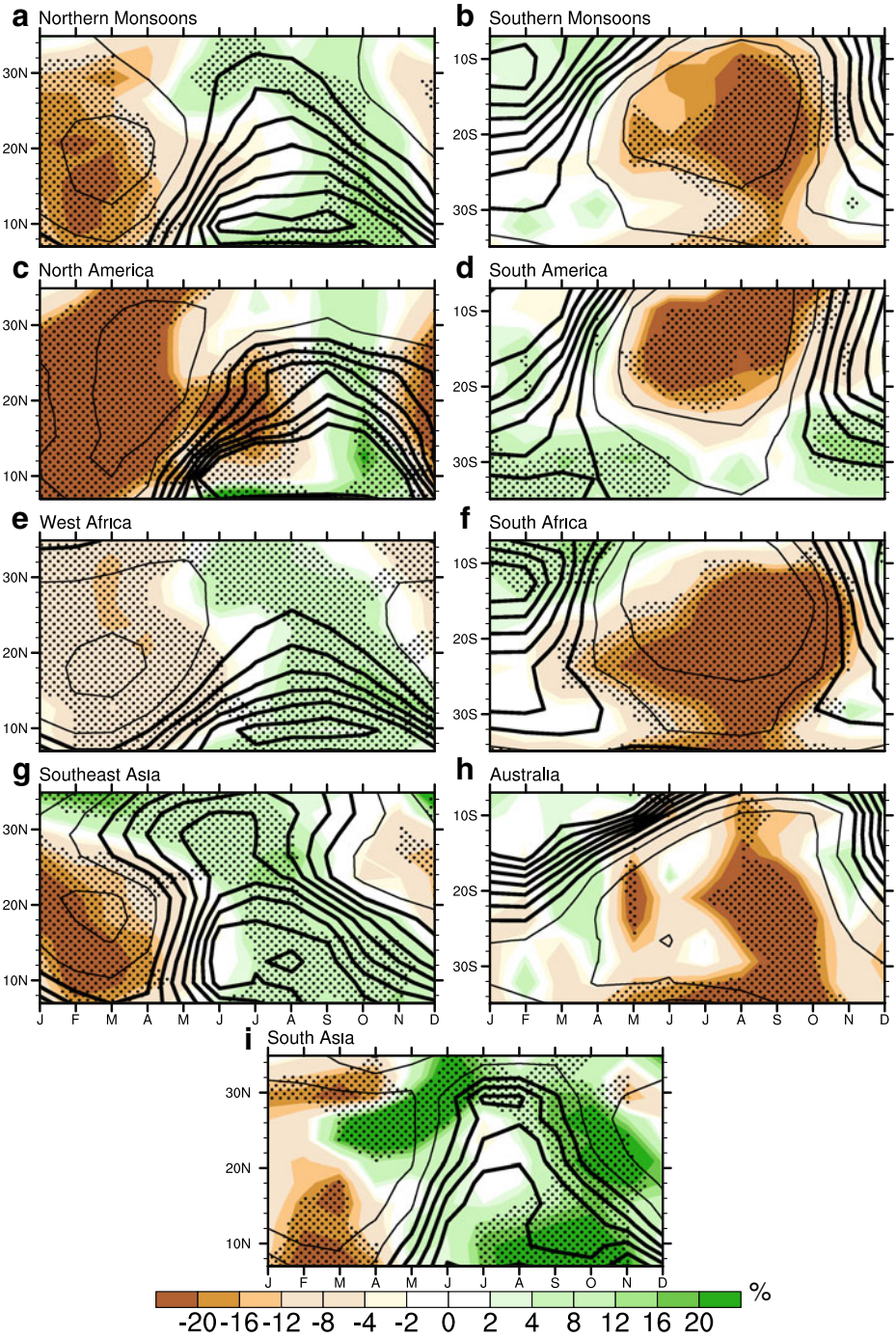
Fig. 1 Multi-model average precipitation % differences (*colors*) for periods 2070–2099 (*A2*) minus 1970–1999 (*20C*) averaged over longitude for the monsoon regions, shown month versus latitude. *Black contours* represent climatological precipitation for each region (interval 1 mm/day, from 1–12, with *heavy lines* for precipitation greater than 2 mm/day). Areas of significant change are stippled

over longitude (Fig. 2a). The precipitation reduction is stronger and extends deeper into the rainy season over land (Fig. 2b), while the late rainy seasons (Feb–Mar, Aug–Oct) show clear strengthening of summer hemisphere rainfall.

Can this global-scale shift in the timing of tropical precipitation be understood in terms of the *remote* and *local* mechanisms outlined above? Recall the remote mechanism is related to increased stability that results from a warmer tropical troposphere. Gross stability of the tropical tropospheric is the difference between MSE in the poleward flow at upper levels and the low-level equatorward flow (Held 2001). The moist static energy includes the effects of temperature and moisture and is defined $MSE = DSE + Lq$, where the dry static energy is defined $DSE = c_p T + gZ$, and c_p is the specific heat at constant pressure, T is the layer temperature, g is gravity, Z is geopotential height, L is the latent heat of evaporation, and q is specific humidity. Because there is little water vapor in the flow aloft, the MSE in
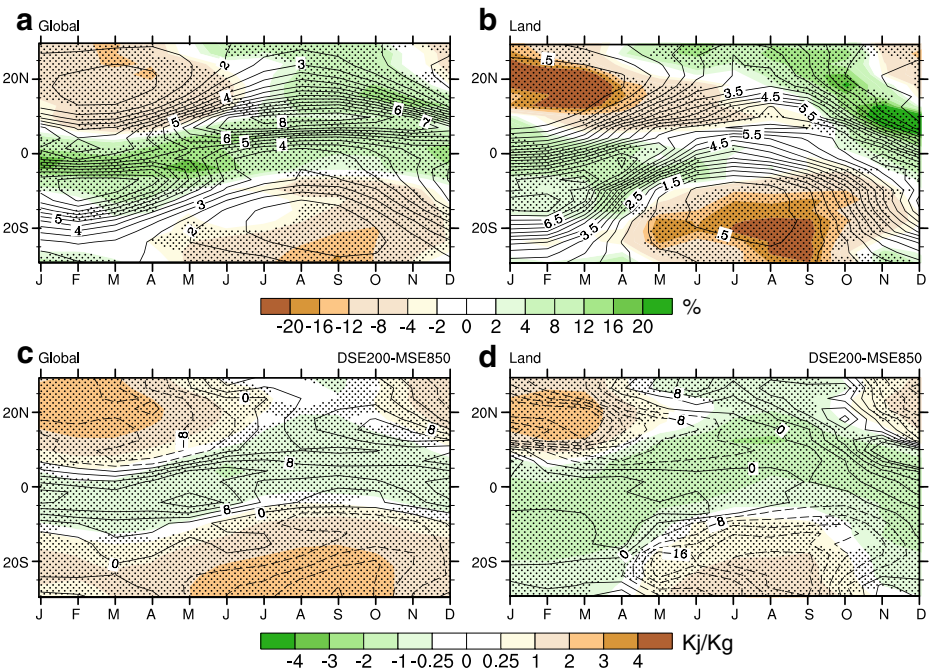

Fig. 2 Multi-model differences for periods 2070–2099 (*A2*) minus 1970–1999 (*20C*) averaged over longitude globally (*left*) and for land only (*right*), shown month versus latitude for % precipitation (*colors*) and precipitation climatology for period 1970–1999 (*black contours*, interval 1 mm/day, from 1–12) (**a**, **b**), and *vertical gradient* of moist static energy (200–850 hPa MSE, Kj/Kg), where positive differences indicate increased tropospheric stability (*brown*) and with *black contours* showing % precipitation changes (**c**, **d**). Areas of significant change are stippled

the upper troposphere is equivalent to DSE (e.g. Held 2001). Thus, as a measure of free tropospheric stability, we examine changes in the vertical gradient of moist static energy, $vMSE$, which is defined $vMSE = DSE_{200} - MSE_{850}$.

Figure 2c and d present the annual cycle of $vMSE$ averaged over longitude globally (c) and for land only (d), where positive (negative) changes in vMSE indicate greater stability (instability), which would tend to inhibit (enhance) precipitation in future scenarios. Precipitation % differences are also shown in Fig. 2c and d as black contours. Despite increases in surface temperatures and humidity, changes in tropospheric stability are not consistent throughout the year in the subtropics. In winter, the $vMSE$ increases, indicating greater stability to convection, and in summer it becomes more negative (less stable), as expected from previous results. Figure 2d also shows that during the spring transition to the wet season (Aug–Oct and Mar–May), the positive $vMSE$ changes from the dry season persist, indicating increased stability to convection over land. This result suggests that springtime drying is controlled at least in part by the *remote* (top down) mechanism.

If we examine Fig. 2d closely, the precipitation reductions continue into Nov (SH) and Jun (NH), even after $vMSE$ indicates a switch from a more stable to less stable troposphere. In order to explore this extension of the drying into early summer, we examine (Fig. 3) the terms which comprise $vMSE$, which include the temperature terms, or DSE at 200 hPa, and at 850 hPa the MSE and its components (DSE and the moisture term, Lq). The reversal of color scales (Fig. 3) between upper (a and b) and lower (c–h) levels is designed to visualize that positive changes in DSE at upper levels act to stabilize while positive changes in the MSE terms at lower levels act to destabilize the troposphere. This will also aid in understanding why globally, free tropospheric stability increases much of the year in the subtropics (Fig. 2c).

At upper levels, DSE_{200} increases year-round in the tropics and subtropics, with the largest increases between 20°N–20°S which are relatively constant through the year as shown in Fig. 3a and b. Note that statistical significance has been omitted from Fig. 3 for clarity, but is similar to that seen in Fig. 2c and d. Lower level MSE_{850} also increases everywhere, but shows seasonality with the largest increases migrating poleward into the summer hemisphere (Fig. 3c and d). Thus the increased free tropospheric stability during winter and early spring results from a larger increase in DSE_{200} than in MSE_{850}, consistent with the *remote* mechanism. However, this still does not explain the continued reduction in precipitation after tropospheric stability decreases (Fig. 2d, Nov in SH and Jun in NH) and MSE_{850} has increased to warm season values. We further decompose MSE_{850} into its moisture term Lq (Fig. 3e and f) and temperature terms (DSE) (Fig. 3g and h). The tropics and summer hemisphere rainy seasons are dominated by the moisture term, while the subtropics and dry seasons are controlled by the temperature terms. During the spring transition, increases in DSE continue to be larger than Lq, which suggests that tropospheric destabilization initially results from increased temperatures. However, until sufficient moisture is imported, decreased stability cannot produce increased precipitation. Is this the *local* mechanism at work?

Previous work suggests there are three primary phases in the transition from the dry to the wet season in monsoon regions: a local build-up of available potential energy due to increasing latent heat fluxes (initiation), the transition of the large scale circulation which leads to net moisture convergence in the region (development), and once onset is established (mature) an upper-tropospheric anticyclonic circulation
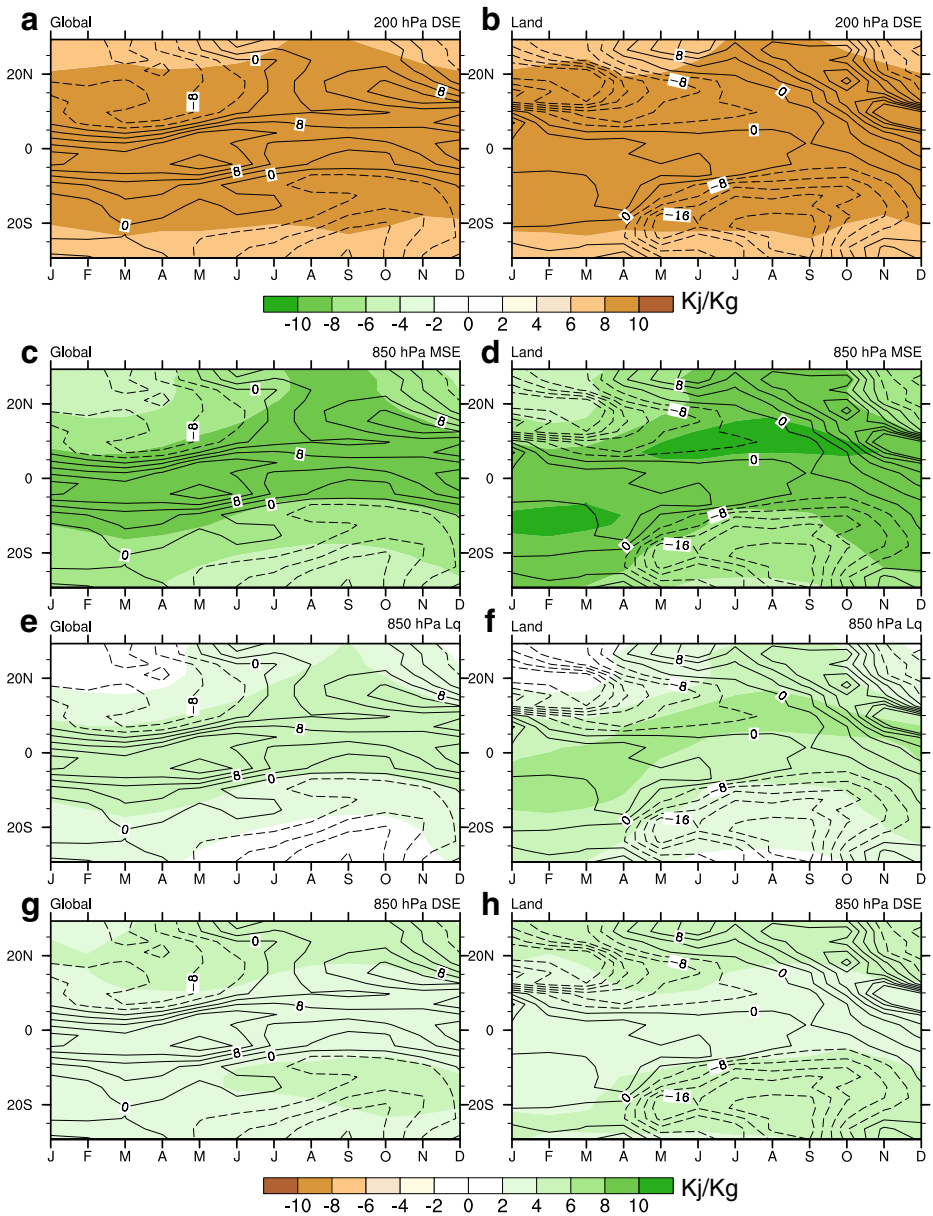
Fig. 3 Multi-model differences for *A2* minus *20C* averaged over longitude globally (*left*) and for land only (*right*), shown month versus latitude for 200 hPa DSE, where positive differences indicate increased stability (*brown*) (**a**, **b**), 850 hPa MSE (**c**, **d**), 850 hPa Lq, moisture term only (**e**, **f**) and 850 hPa DSE, temperature terms only (**g**, **h**) in Kj/Kg, where positive differences indicate decreased stability (*green*). *Black contours* represent % precipitation changes

continues to spin up until it reaches its full strength (Li and Fu 2004). The initiation phase is thus sensitive to local latent heat fluxes that have the potential to delay the timing of the large-scale transition. Further, springtime soil moisture anomalies are known to result in a positive feedback to early season precipitation (Collini et al. 2008). The local land surface influence becomes less important once convection has been initiated (Li and Fu 2004), although land wetness anomalies can also influence rainfall within the monsoon season (Taylor et al. 2010; Grimm et al. 2007).

In the present case, anomalous terrestrial radiation affects the surface energy balance, and as previously mentioned, over oceans and moist land this excess energy
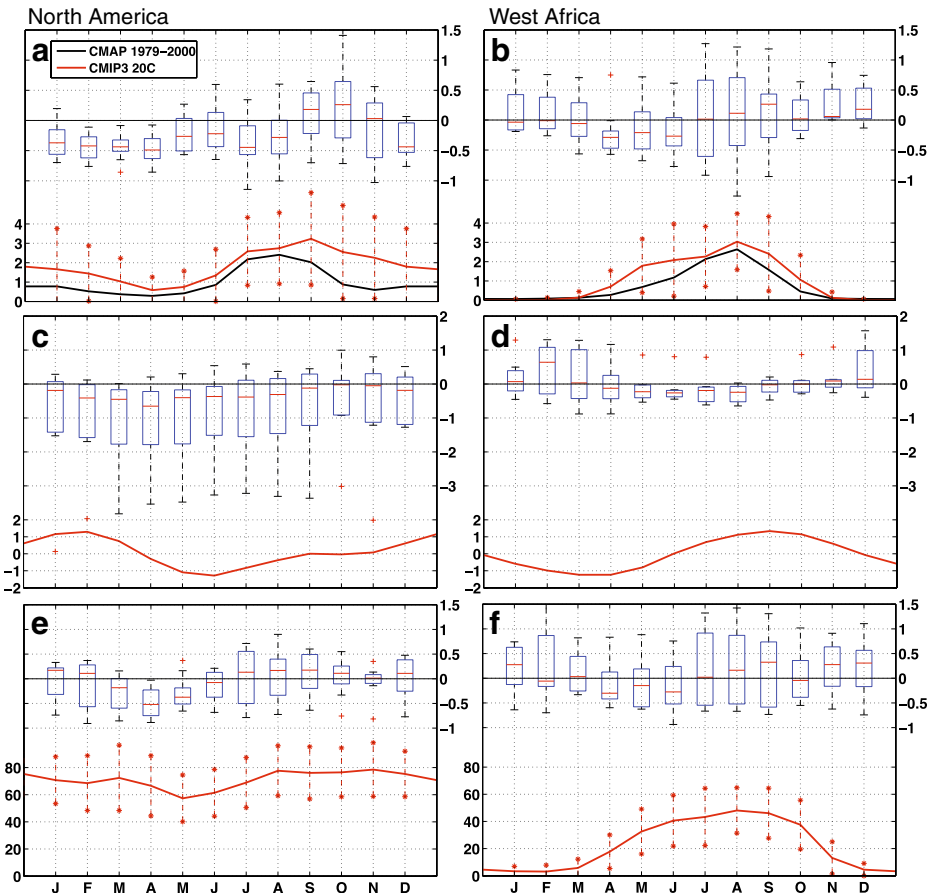

Fig. 4 North America (*left*) and West Africa (*right*) monthly climatological observed estimate (*black*) and model mean (*red*) precipitation (mm/day) for *20C* where *asterisks* represent the maximum standard deviation from the multi-model ensemble, and with *A2–20C* differences presented as box plots (**a**, **b**). Same for soil moisture except that climatology has been standardized (**c**, **d**) and latent heat flux (W/m^2) (**e**, **f**). Differences are standardized by the monthly standard deviation for *20C* for each model. Upper and lower bounds of boxes represent 75th and 25th percentiles, respectively, with whiskers corresponding to ±1.5 times the inter-quartile range and outliers shown as *red crosses*

is expended in the form of latent heat flux. In subtropical land monsoon regions, where the dry (winter) season is expected to become drier, one might expect a consequent reduction in locally available surface moisture during spring. Therefore, we evaluate the simulated annual cycles of soil moisture and latent heat flux (LHF) as measures of the *local* mechanism in the projected precipitation changes for the American and African monsoon regions, which display the strongest spring/summer precipitation changes. On this monthly time scale in the four regions (Figs. 4 and 5), LHF (e and f) increases tend to be concurrent with precipitation (a and b) in the climatological annual cycle, while soil moisture (c and d) slightly lags the precipitation increases. In the projections, LHF deficits occur during the dry season and do not show positive values until precipitation increases. The LHF increases appear to be coincident with precipitation, and the drier surface conditions in winter persist into the spring. This suggests that the *local* mechanism, which requires sufficient local moisture, is unable to activate in these monsoon regions until moisture is supplied by atmospheric transport.
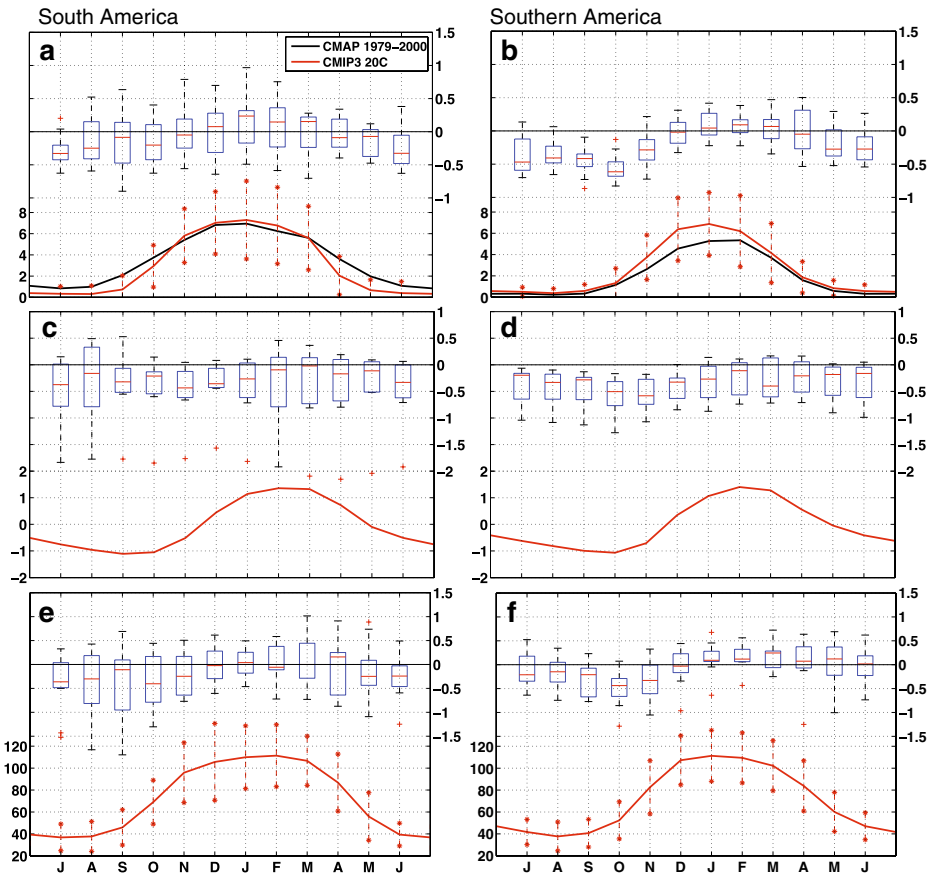

Fig. 5 Same as Fig 4, but for South America and Southern Africa

3 Discussion

While projected total precipitation changes in monsoon regions are uncertain, the results presented here indicate reductions in spring and increases in summer precipitation in multi-model ensemble 21st century climate projections. Competing mechanisms which have been previously identified as being important in precipitation changes, *local* (enhanced evaporation, decreased stability, and increased precipitation) and *remote* (warmer troposphere, increased stability, and decreased precipitation) are evaluated in time through the annual cycle, with an emphasis on the transition from dry to wet seasons. The *remote* (top down) mechanism controls the projected changes during winter and the *local* (bottom up) mechanism controls during summer. However, during spring, both appear to inhibit convection.

It is well established that the dry season in subtropical regions is enhanced due to increased moisture divergence associated with the descending branch of the Hadley circulation (Meehl et al. 2007a). The measure of tropospheric stability (remote mechanism) presented here shows wintertime increases in stability in the subtropics that are strongest over land. We also find that the increased stability persists into spring and can explain much of the projected precipitation reductions. Even after tropospheric stability decreases, precipitation reductions continue for a short period. Analysis suggests that surface moisture, which is essential for the local mechanism to engage, is lacking at the end of a warmer and drier dry season. Thus both remote and local mechanisms act to create an "enhanced spring convective barrier" leading to reduced early season rainfall; however, once sufficient moisture is imported, decreases in tropospheric stability result in precipitation increases.

Our results suggest that the spring transition may be important in characterizing precipitation changes in monsoon regions, and perhaps in other subtropical regions (e.g., Meso-America) which also show a delayed onset of the rainy season (Rauscher et al. 2008). It must be noted that these model results do not apply to the South Asian or Australian monsoon regions, which may be influenced by additional factors. The South Asian region, for example, has shown increases in pre-season rainfall associated with absorbing aerosols and black carbon (Lau et al. 2006; Meehl et al. 2008). The mechanisms presented here will require further testing with daily data from both observations and improved, higher-resolution climate models to determine if the seasonal changes are due to timing (onset) or character (intensity) of rainfall. In particular, while there is some observed evidence of a weakening of global land monsoon rainfall over the past 50 years (Wang and Ding 2006; Zhou et al. 2008), the weakening is due mostly to Africa and South Asia. Precipitation trends show substantial decadal variability and robust changes in the annual cycle have not been established for most regions (Christensen et al. 2007). A reduction of spring and increase in summer rainfall would have substantial implications for agriculture, water management, and disaster preparedness in monsoon regions.

4 Methods

Simulations from ten Coupled Model Intercomparison Project (CMIP3) global climate models (Meehl et al. 2007b) are analyzed with emphasis on the following continental monsoon regions: North America (NAM, 115–102.5W, 20–35N), South

America (SAM, 60–40W, 10–25S), West Africa (WAf, 10W–20E, 10–25N), South Africa (SAf, 20–40E, 10–25S), South Asia (SAsia, 65–85E, 10–25N), Southeast Asia (SEA, 100–120E, 10–25N), and Australia (Aus, 120–140E, 10–25S). Monthly data from the 20th century historical simulations (20C, for the period 1970–1999) and 21st century SRES A2 (A2, 2070–2099) emissions scenarios are examined.

The 20th Century (20C) simulated precipitation is evaluated using the monthly Climate Prediction Center Merged Analysis of Precipitation (CMAP) (Xie and Arkin 1996). Statistical significance is computed for the difference between the means using a Student's t-test and stippled regions in figures show regions of significance above the 90% confidence level.

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