Reduction of tropical land region precipitation variability via transpiration

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[1] Tropical rainforests are known to exhibit low intraseasonal precipitation variability compared with oceanic areas with similar mean precipitation in observations and models. In the present study, the potential role of transpiration for this difference in precipitation variability is investigated using the National Center for Atmospheric Research (NCAR) atmospheric general circulation model. Comparing model results with and without transpiration shows that in the absence of transpiration, mean precipitation decreases as may be expected. However the incidence of both higher daily total column water and more intense precipitation increases without transpiration; consequently the variability of precipitation increases substantially. These results can be understood in terms of the complex interplay of local near-surface and remote moist dynamical processes with both local positive (boundary-layer drying) and large-scale negative (increased large-scale convergence) feedbacks when transpiration is disabled in the model. It is also shown that surface turbulent fluxes over tropical rainforests are highly correlated with incoming solar energy but only weakly correlated with wind speed, possibly decoupling land precipitation from large-scale disturbances like the Madden-Julian Oscillation. **Citation:** Lee, J.-E., et al. (2012), Reduction of tropical land region precipitation variability via transpiration, *Geophys. Res. Lett.*, *39*, L19704, doi:10.1029/2012GL053417.

1. Introduction

[2] The heavy reliance of many tropical societies on the availability of seasonal rainfall for food, agriculture, and drinking water renders such societies particularly vulnerable to rainfall variability. Recently, *Lintner et al.* [2012] have shown that the distribution of monthly-mean precipitation values over tropical land regions may already be changing in response to anthropogenic warming. In addition, a modeling study by *Lee et al.* [2011] indicates that ongoing changes in vegetation associated with anthropogenic land use and land cover change may contribute to the recent increase in drought occurrence over tropical South America.

[3] Precipitation variability on intraseasonal timescales poses an especially pronounced risk to human systems, given that, the timing and occurrence of wet-season precipitation are critical to agriculture. For example, the Madden-Julian Oscillation (MJO) [*Madden and Julian*, 1994], an intraseasonal mode of eastward propagating planetary scale disturbances originating over the Indian and western Pacific Oceans with a period of 30–90 days, is known to impact regional rainfall over many tropical land regions [*Zhang*, 2005]. An interesting feature of MJO events is the apparent suppression of precipitation variability over tropical rainforests compared with adjacent oceanic regions [*Sobel et al.*, 2008]. More generally, tropical rainforests exhibit lower precipitation variability than nearby oceanic regions with similar mean precipitation.

[4] How the differences in the physical characteristics of land versus ocean impact or modulate climate represents an important issue in interpreting both observed and simulated climate system variability. The finite land surface moisture capacity and the heterogeneity of available surface moisture are thought to play a role in modulating the spatiotemporal variability of land region climate. In this regard, the distribution of vegetation is especially critical. As a consequence of photosynthesis, water leaves plants through open stomata: this process (transpiration) cools the plant and facilitates transport of nutrients from the soil. Moreover, plants may extract soil water that has infiltrated to depths only accessible to roots and thus make such "hidden" subsurface water available to the atmosphere [*Lee et al.*, 2005; *Seneviratne et al.*, 2006; *Teuling et al.*, 2006]. The surface moisture flux from transpiration can modulate the surface energy budget and the atmospheric stability [*Findell and Eltahir*, 1997]. It has also been suggested that transpiration may exert control on the triggering of deep convection [see, e.g., *Findell et al.*, 2011].

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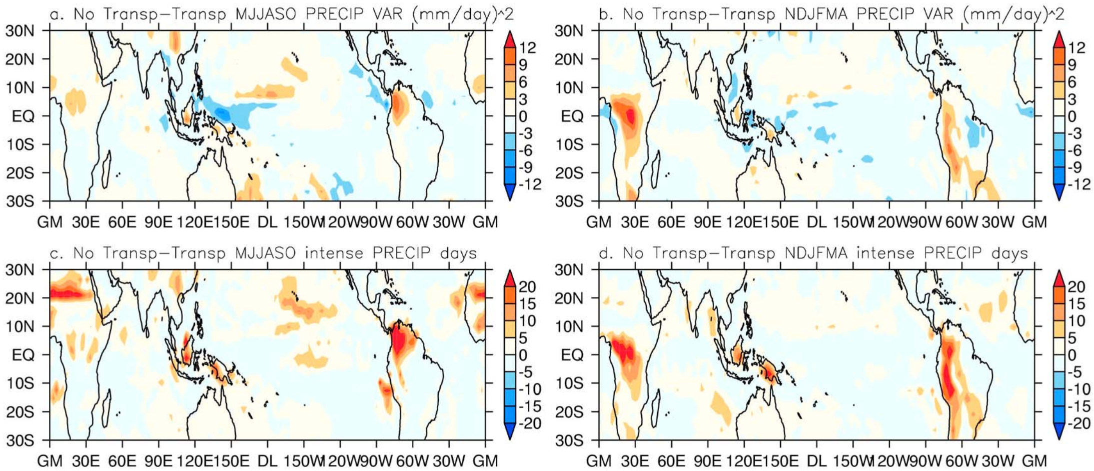

Figure 1. (a and b) Differences between the no-transpiration and transpiration cases in intraseasonal variance of 30–90 day band-pass-filtered daily precipitation and (c and d) the changes in the number of high-intensity precipitation days at each grid point. Figures 1a and 1c are for May through October and Figures 1b and 1d are for November through April. The cutoff in precipitation intensity is determined from the transpiration run as the most intense 3% daily precipitation, and the changes in number of days that exceed the cutoff precipitation in the no transpiration run is calculated. The general pattern does not change when we used different % of precipitation as the cutoff for the intense precipitation.

[5] The role of soil moisture and vegetation on mean precipitation has been extensively studied in the past [e.g., *Shukla and Mintz*, 1982; *D'Odorico and Porporato*, 2004; *Juang et al.*, 2007]. In this study, we evaluate the plausibility of transpiration as a potential explanation of the lower precipitation variability observed over tropical rain forests compared with over ocean. Using a climate model, we examine differences in precipitation statistics between a pair of simulations, a control simulation and a simulation in which transpiration is disabled.

2. Methodology

[6] To assess the role of transpiration on precipitation statistics, we analyze simulations from the National Center for Atmospheric Research Community Atmosphere Model (CAM) version 3 [*Collins et al.*, 2006] coupled to the Community Land Model (CLM) version 3.5 with transpiration (transpiration or control run) and without transpiration (no-transpiration run). In the no-transpiration run, transpiration alone is suppressed, while other characteristics of the land surface, e.g., biomass, roughness and soil type, are identical to the control. In particular, evaporation of water from bare soil and from canopy surfaces (i.e., rainfall interception) still occurs in the no-transpiration case. We note that CLM3.5 also includes a simple groundwater model for determining water table depth. Over ocean regions, the simulations assume a Slab Ocean Model (SOM) with prescribed climatological oceanic q-flux and mixed layer depths, with these quantities calculated using the CAM 3 tool provided by NCAR. Each simulation consists of 40 years of output, although we restrict our analysis below to the last 10 years to avoid spin-up effects. The simulation is performed at T42 resolution (2.8125° × 2.8125°) with 26 atmospheric layers and 10 soil layers up to ~3.5 m.

[7] Like other models, NCAR CAM underestimates precipitation variability [e.g., *Dai*, 2006]. The model convection parameterization is based on quasi-equilibrium theory [*Zhang and McFarlane*, 1995]. Schemes based on quasi-equilibrium often fail to exhibit the entire temporal spectrum of deviations from equilibrium [*Neelin et al.*, 2008]; in particular, intraseasonal variability is often weaker than in the observations [*Zhang et al.*, 2006]. Moreover, because the runs are performed at relatively coarse resolution, potentially important impacts of terrain or small-scale heterogeneity are not resolved.

[8] Although CAM precipitation amounts do not match the observed amounts precisely in all regions, e.g., too much precipitation is simulated over the Indian Ocean, the broad features, such as the relative partitioning of precipitation between land and ocean, are captured (Figure S1 in the auxiliary material).[1] For our purposes, we note that CAM does simulate the key feature of interest here, namely, the intraseasonal variance over tropical land regions is typically smaller than over oceanic regions with comparable mean precipitation. Although consistent with observations, the simulated precipitation variance is smaller than observed because convection is triggered too often in the model [*Lee et al.*, 2009]. This deficiency may influence the magnitude of the precipitation response to transpiration.

3. Results and Discussion

[9] Removal of transpiration obviously reduces tropical latent heat flux over land regions (Figure S2). Total evapotranspiration decreases in all seasons when transpiration is shut down, but the percent decrease is largest late in the local dry season (e.g., September–October–November for Amazonian forest in Figure S2). In terms of mean precipitation, the reduced surface moisture flux in the absence of transpiration is associated with reduced rainfall, as may be expected [*Shukla and Mintz*, 1982]. The reduction of mean precipitation over the continents in the absence of transpiration can

[1] Auxiliary materials are available in the HTML. doi:10.1029/2012GL053417.

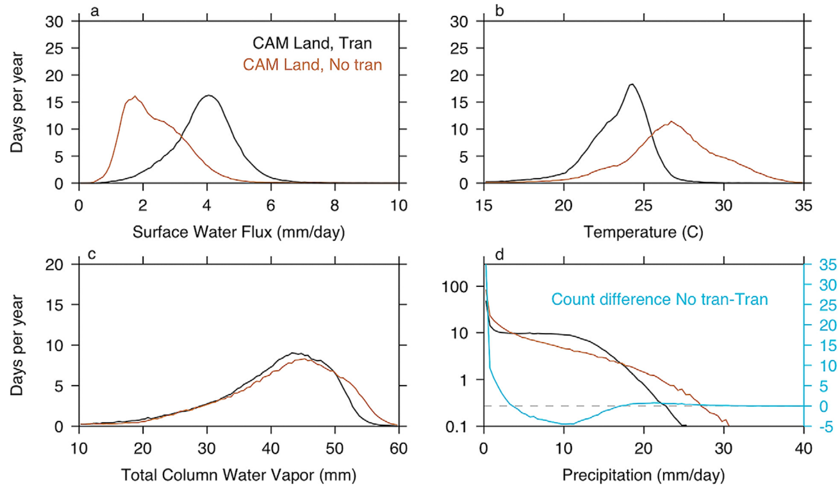

Figure 2. The distribution of daily (a) evaporation, (b) surface air temperature, (c) total column water vapor and (d) precipitation (left axis) precipitation count difference (right axis) between no-transpiration and control runs from model simulations for all land grid points with precipitation greater than 2000 mm/year.

be viewed in terms of positive land-atmosphere coupling [*Seneviratne et al.*, 2010], with water captured from earlier rain events recycled into subsequent precipitation.

[10] In contrast to the mean precipitation changes, the statistics of daily precipitation change in a more complicated way with transpiration disabled. Indeed, the incidence of the most intense daily precipitation rates actually increases in the no-transpiration case (Figures 1c and 1d). While the frequency of precipitation rates in the range of 3–18 mm day^{-1} drops when transpiration is removed, the occurrence of driest days (rainfall < 3 mm day^{-1}) increases. Thus, the removal of transpiration in the NCAR model is seen to amplify the extremes of the simulated daily precipitation distribution.

[11] To place these results in some context, we note that the onset of the rainy season has been both observed and simulated to occur earlier with high surface latent heat flux, as water vapor supplied by the surface makes convection more favorable around the onset of the wet season [*Fu and Li*, 2004; *Boyce and Lee*, 2010; *Lee and Boyce*, 2010]. In other words, without transpiration, the dry season is lengthened; indeed, Figure 2d indicates a substantial increase in the number of days with little precipitation in the no-transpiration case. Thus, days without precipitation and days with intense precipitation are less numerous in the presence of transpiration because of the buffering of atmospheric moisture content by transpiration.

[12] In the absence of transpiration and the associated decrease in latent heat, the near-surface atmosphere warms and dries (Figure S3). The near-surface warming propagates into the upper atmosphere because convection centers are located over tropical rainforests, and the increasing near-surface temperatures over rainforests warm the whole tropical troposphere through efficient tropical wave dynamics that propagate the localized heating anomaly throughout the tropical belt [*Chiang and Sobel*, 2002]. Even as the total local surface water flux and near-surface moisture content are decreased, total column moisture may actually attain higher daily values (Figures 2c) in the no-transpiration run because of increased temperature [*Neelin et al.*, 2008] and increased moisture convergence [*Lintner and Neelin*, 2009]. Concurrently more intense precipitation is observed in the no-transpiration case, corresponding to a build up of convection available potential energy (CAPE) and increased convective inhibition (CIN). A negative land-atmosphere feedback is thus created through large-scale atmospheric modifications.

[13] Over tropical oceans, precipitation intensity exhibits a power-law dependence on total column water vapor [*Bretherton et al.*, 2004; *Peters and Neelin*, 2006], with a temperature-dependent critical moisture threshold that must be overcome for deep convection to occur [*Neelin et al.*, 2008]. To the extent that a similar relationship holds over land, it is plausible that increasing temperature in the no-transpiration simulation raises the critical amount of atmospheric water vapor required for land region deep convection to occur. Plotting daily-mean land region total column water vapor against mean precipitation intensity (Figure S4) indicates lower precipitation intensity at a given water vapor for the no-transpiration case compared with the control case, indicating that a similar moisture-precipitation relationship holds for land regions in NCAR CAM.

[14] Moisture budget analyses for tropical ocean regions suggest that much of the precipitation is balanced by large-scale moisture convergence [*Bretherton and Sobel*, 1996]. During wetter periods, when large-scale conditions favor low-level moisture convergence, higher temperatures in the no-transpiration case promote moister conditions and more precipitation, which in turn induce more convergence through convection-convergence feedbacks (Figure 3). Figures 1a and 1b and Figure 3 (bottom) clearly show that the intraseasonal signal is attenuated in the control simulation relative to the no-transpiration simulation. Such behavior is broadly compatible with observational studies showing that the most intense thunderstorms occur over dry forests of Africa or the Midwest of the US [*Zipser et al.*, 2006], where transpiration is expected to be low compared to everwet tropical rainforests.

[15] During drier periods, with weakened large-scale convergence, temperatures in the no-transpiration case are

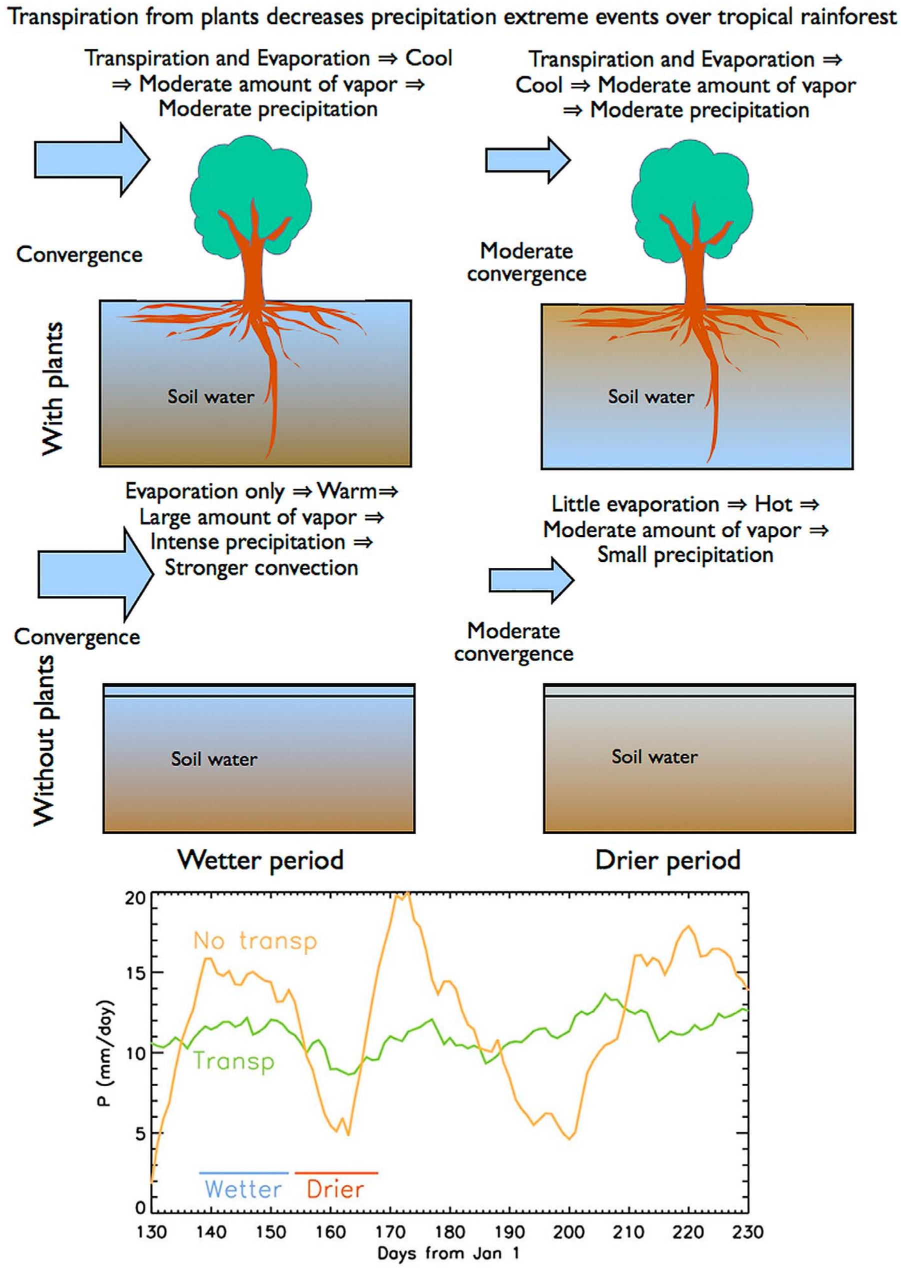

Figure 3. The role of transpiration from plants on decreasing precipitation variability over tropical rainforests. Plants can extract available soil moisture, making a larger reservoir of subsurface water available to the atmospheric vapor. During wetter periods, higher temperatures in the no-transpiration case promote more moisture and precipitation, which induces higher convergence. During drier periods, much higher temperatures increase the threshold of deep convection, so there is less precipitation and a slower recovery from drier to wetter conditions when transpiration is absent. Bottom panel shows the 10-day running average of precipitation over Borneo (latitude 1.4°S; longitude 113°E) from model simulations as an ideal example. The transpiration case (control) shows weak intraseasonal variations relative to the run without transpiration.

even higher because the surface dries out, so turbulent surface flux partitioning favors more sensible heating, which in turn favors surface warming. The increase in temperatures raises the threshold of deep convection, so during drier periods with less convectively favorable large-scale conditions, the likelihood of overcoming the convective threshold diminishes without transpiration [*Neelin et al.*, 2008; *Muller et al.*, 2009]. This points to the operation of a positive land-atmosphere feedback through boundary-layer modulation [*Findell and Eltahir*, 1997].

4. Summary and Conclusion

[16] Over tropical rainforests, observations from TRMM indicate that intraseasonal precipitation variability is lower than over ocean regions with similar climatological mean

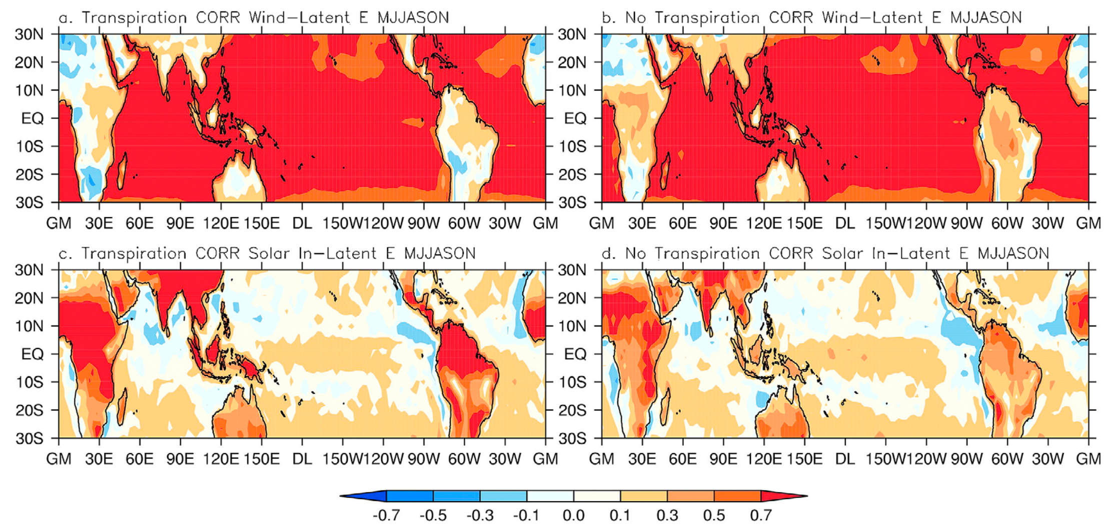

Figure 4. Correlation between surface latent heat flux and wind speed (a) for the control run and (b) for the no transpiration run and between surface latent heat flux and incident solar energy at the surface (c) for the control run and (d) for the no transpiration run. All variables are 30–90 day band-pass filtered daily values.

precipitation [*Sobel et al.*, 2008]. Hypothesizing that consistently high evapotranspiration over tropical rainforests is related to low precipitation variability, we compare precipitation statistics from a pair of NCAR climate model simulations with and without transpiration. In the absence of transpiration, mean precipitation decreases while simulated daily precipitation variability rises substantially, with increasing incidence of both dry and wet extremes of the daily precipitation distribution. Thus, it appears plausible that transpiration dampens the impact of propagating, large-scale disturbances such as those associated with active MJO periods by modulating temperature and moisture content in the planetary boundary layer [e.g., *Findell and Eltahir*, 1997]. These model-based indications of the role of transpiration in modulating tropical intraseasonal precipitation variability raise intriguing questions that could serve as potential targets for observational assessment and evaluation in other models.

[17] It is worth mentioning that other differences between land and ocean may contribute to the contrasting MJO behavior between tropical rainforests and oceans. For example, *Sobel et al.* [2008] suggest that the lower land surface heat capacity reduces the impact of wind induced surface heat exchange (WISHE) over land because of finite land surface moisture holding capacity. Indeed, land region surface heat fluxes tend to be highly correlated with incoming solar energy but only weakly correlated with wind speed (Figure 4) [see also *Araligidad and Maloney*, 2008]. As a consequence the surface heat fluxes over land are not strongly coupled to the large-scale dynamics on intraseasonal timescales. In the absence of transpiration, the simulated surface latent heat flux dependence on incoming solar energy decreases while its dependence on wind increases (Figures 1b and 1d), making land areas more coupled to the MJO-like disturbances (e.g., Figure 3).

[18] In a broader sense, the buffering of rainfall extremes via transpiration could have substantial implications for land surface and ecosystem changes since erosion rates are thought to be higher where rainfall is more variable [*Molnar*, 2001]. Vegetation reduces land surface erodibility by supplying root cohesion [*Schmidt et al.*, 2001], promoting infiltration [*Viles*, 1990], adding roughness that slows overland flow, and providing a canopy that intercepts and attenuates rainfall reaching the surface. Thus, regional reductions of vegetation cover could have a compounding impact on landscapes, accelerating erosion both by promoting more intense rainfall and by making the land surface more vulnerable. Moreover, since plant productivity increases when variations in precipitation and temperature decrease [*Medvigy et al.*, 2010], the suppression of precipitation variability by transpiration may augment the effects of transpiration capacity on assimilation capacity [*Boyce et al.*, 2009], in turn leading to increased biomass production.

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