Reduction of tropical land region precipitation variability via transpiration

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Abstract

It is well known that tropical rainforests exhibit low intraseasonal precipitation variability despite high annual-mean precipitation. Analyzing simulations of the NCAR atmospheric model coupled to the Community Land Model with and without transpiration, it is shown that transpiration over tropical land regions effectively dampens temperature and precipitation variability over rainforests, thereby reducing the influence of large-scale disturbances. Since transpiration supplies more than 50% of the simulated total surface water flux over tropical rainforests, transpiration acts as a strong buffer on atmospheric moisture content. In the absence of transpiration, mean precipitation decreases while simulated precipitation variability rises substantially, with increasing incidence of both dry and wet extremes. The mechanisms that account for these changes in the mean precipitation and its distribution reflect a complex interplay of local, near-surface and remote moist dynamical processes. Coupled with anticipated hydrologic cycle impacts on global warming, it is argued that reduced transpiration associated with on-going large-scale land use change like deforestation is likely to increase the future occurrence of extreme precipitation and temperature events. Moreover, since plant productivity is higher under less variable hydroclimatic conditions, these results point to the intriguing possibility of a positive ecohydrological feedback between vegetation growth and reduced variability over rainforests.

1. Introduction

The heavy reliance of many tropical societies on the availability of seasonal rain for food and economic security renders such societies vulnerable to rainfall variability. Precipitation variability on intraseasonal timescales poses an especially pronounced risk, given that the timing and occurrence of wet-season precipitation is critical to agriculture. The Madden-Julian Oscillation (MJO) (Madden and Julian, 1994), an intraseasonal amplification of eastward propagation of planetary scale disturbances over the Indian and western Pacific 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 is the low precipitation variability over tropical rainforests despite its high climatological mean precipitation. This is regarded as one key to a better understanding of the MJO (Sobel et al., 2008). Some factors that may account for the contrasting MJO behavior between tropical ocean regions and rainforests include smaller heat capacity over land versus ocean, which lowers the impact of wind induced surface heat exchange (WISHE) over land versus ocean (Sobel et al., 2008), and a stronger diurnal cycle over land versus ocean (Salby and Hendon, 1994).

Because of the large heat capacity of the ocean surface layer, intraseasonal variations in surface heat flux over oceans are not strongly coupled to incoming solar radiation, but rather are dominated by latent heating and are thus highly correlated with wind speed (Figure 1; also see Araligidad and Maloney, 2008). In contrast, given that lateral and vertical transport of energy below the land surface is minimal, surface latent heat flux over tropical land regions tends to be highly correlated with incoming solar energy on intraseasonal timescales, especially since a large portion (> 50%) of total latent heat flux over tropical land regions comes from transpiration from plants (Figure S1a), most of which occurs when solar energy is available for photosynthesis. The land surface latent heat flux is also not strongly correlated with wind speed on intraseasonal timescales, implying that the surface moisture flux over land is not strongly coupled to the large-scale dynamics on intraseasonal timescales. Because plants can extract soil water that is otherwise hidden from the atmosphere on short timescales, i.e., water from earlier rainfall that has infiltrated to depths only accessible to plant roots, plants make subsurface water available to the atmosphere. Transpiration thus represents a potential control of precipitation distribution over land.

We assess the influence of transpiration on precipitation and temperature variability using climate model simulations, focusing on intraseasonal timescales. The role of evapotranspiration on the mean precipitation has been studied in the past (e.g., Shukla and Mintz, 1982), but as far as we are aware, the present study is the first to discuss its possible implications for intraseasonal variability. In particular, we demonstrate how transpiration may effectively dampen precipitation and temperature variability over tropical land regions. Theses model-based indications on the role of transpiration in modulating tropical intraseasonal precipitation variability raise intriguing questions that could serve as potential targets for observational assessment and evaluation on other models.

2. Model

We performed simulations using the National Center for Atmospheric Research Community Atmosphere Model version 3 (Collins et al., 2006) coupled to the Community Land Model version 3.5 (Oleson et al., 2008) with transpiration (transpiration or control run) and without transpiration (no-transpiration run). Apart from transpiration, other characteristics of the land surface, e.g. biomass and soil type, are identical for both runs; in particular, evaporation of water from bare soil and from a canopy surface (intercepted after rainfall) still occurs in the no-transpiration case.

The model is run at T42 resolution (2.8125°x2.8125°) with 26 atmospheric layers and 10 soil layers up to ~3.5 m. The model was coupled to a Slab Ocean Model (SOM) with prescribed climatological oceanic q-flux and mixed layer depths. The depth of the mixed layer and q-flux in the ocean are calculated using the CAM 3 tool provided by NCAR (Collins et al., 2004). The runs were performed for 40 years, with the last 10 years analyzed below to avoid spin-up effects.

In general, NCAR CAM underestimates precipitation variability because convective parameterization schemes based on quasi-equilibrium tend not to capture the entire spectrum of the departure state from the equilibrium state (Neelin et al., 2008). In particular, intraseasonal variation is much weaker than observations (Zhang et al., 2006). Moreover, because the runs are performed at relatively coarse resolution, potentially important impacts of terrain on precipitation are not resolved. However, we believe that the mechanisms we present below are robust because NCAR CAM reproduces the gross features of tropical convection, and the process hypothesized to increase precipitation variability in the no-transpiration case are physically consistent with the observed characteristics of tropical convection.

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 precipitation (Figures S2) are reasonable. For our purposes, we note that the model captures the key feature of interest here, namely, the intraseasonal variance over tropical land regions is typically smaller than over oceanic regions receiving comparable precipitation, consistent with observations, although the simulated variance is smaller than observed (Figure S3; see Figures 1 and 2 from Sobel et al., 2008).

3. Results and discussion

Since transpiration is a large component of total land region latent heat flux (Figure S1), removal of transpiration diminishes mean precipitation over most tropical land regions (c.f., Shukla and Mintz, 1982). However, despite the decrease in mean precipitation, intraseasonal precipitation variance greatly *increases* over tropical land when transpiration is removed (Figures 2 and S3). In the absence of transpiration from vegetation, the simulated surface latent heat flux dependence on incoming solar energy decreases while its dependence on wind increases (Figure 1b and d).

Near-surface atmospheric temperatures over tropical land regions are much higher in the absence of transpiration (Figure S4) because of the decrease in latent heat flux and the increase in sensible heat flux (Lee et al., 2005; Lee et al., 2011). The near-surface warming propagates into the upper atmosphere because convection centers are located near tropical rainforests (Figure S2a), 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 (Figure S4) (Chiang et al., 2002). Total column moisture increases over most rainforest regions, consistent with thermodynamic considerations based on the Clausius-Clapeyron relationship and increased moisture convergence (Figures 3 and S4), even while the total local surface water fluxes decrease. In addition, less frequent precipitation implies a smaller sink for tropospheric water vapor. Overall land region relative humidity is lower in the absence of transpiration.

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). While it remains to be seen whether a similar moisture-precipitation relationship holds for land regions, it is plausible that increased temperature raises the critical amount of atmospheric water vapor required for land region deep convection. At a given location, one might expect this increased barrier to lower mean precipitation, but what about the underlying land area convection statistics? Histograms of daily transpiration, temperature, moisture content, and precipitation for grid points over the Amazon and Borneo (Figure 3) show that the overall variability of all these quantities increases without transpiration (cf. Koster and Suarez, 1996). In particular, for precipitation, the incidence of both very low and *very high* precipitation values increases in the absence of transpiration. How do we interpret such statistical changes?

Over tropical oceans, moisture budget analyses imply 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 4). Such behavior is broadly compatible with observational studies showing the most intense thunderstorms to occur over dry forests of Africa or the Midwest of the US (Zipser et al., 2006), where transpiration is expected to be low rather than over everwet tropical rainforest. During drier periods, with weakened large-scale convergence, temperatures in the no-transpiration case are even higher because the surface dries out, so turbulent surface flux partitioning favors more sensible heat loss, which in turn favors surface warming. The increase in temperatures raises the threshold of deep convection, so during drier periods with the less convectively favorable large-scale conditions, the likelihood of overcoming the convective threshold is diminished without transpiration. Also, the onset of the rainy season has both been observed and simulated to occur sooner with high water fluxes from the surface because water vapor supplied by the surface makes convection more favorable around the onset of the wet season (Fu and Li, 2004; Lee and Boyce, 2010). Without transpiration, the characteristic return time for deep convection is lengthened, and the system spends more time in the dry phase; indeed, Figure 3 indicates a substantial increase in the number of days with little precipitation in the no-transpiration case. Thus, both the 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.

4. Summary and conclusion

Plants can access and transpire water that has infiltrated deep below the land surface that would otherwise not return to the atmosphere, at least not locally. The results presented here suggest that transpiration may account for decreasing precipitation variability, consistent with previous work (Boyce and Lee, 2010; Lee and Boyce, 2011; Findell et al., 2011), by dampening 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 (Findell and Eltahir, 1997). Transpiration could further shorten the dry season because the transpiration-induced surface moisture supply is crucial near the onset of the wet season (Fu and Li, 2004), when large-scale conditions switch from disfavoring to favoring deep convection. For plants to shorten the dry season, they require access to sufficiently deep soil moisture reservoirs to overcome the evaporative demand during the dry season, and thus trees with deep roots are more important than grasses with shallow roots. Our results futher imply that extreme hydroclimatic conditions (floods and droughts) would become more frequent following a regional reduction in forest coverage due to deforestation or climate change, compounding the increase in precipitation extremes that are projected to occur under global warming (O'Gorman and Schneider, 2009; Lintner et al., 2012).

In a broader sense, the buffering of rainfall extremes via transpiration could have substantial implications for land surface and ecosystem changes. It has been proposed that erosion rates are highest where rainfall is most variable (Monlar, 2001), because sediment transport in rivers scales nonlinearly with water discharge. Vegetation can reduce 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. Thus, the regional reduction 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. In addition to the effects on erosion rates, a combined reduction of vegetation cover and intensification of precipitation extremes would likely alter the distribution of processes shaping the landscape; thus, the style of erosion may be a widespread signature of life on Earth's surface (Dietrich and Perron, 2006). Moreover, since plant productivity increases when precipitation and temperature vary over a small range (Medvigy et al., 2010), the suppression of precipitation variability by transpiration may have augmented the effects of transpiration capacity on assimilation capacity (Boyce et al., 2009), leading to increased biomass production as larger transpiration capacities evolved with the advent of flowering plants.

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Figure captions:

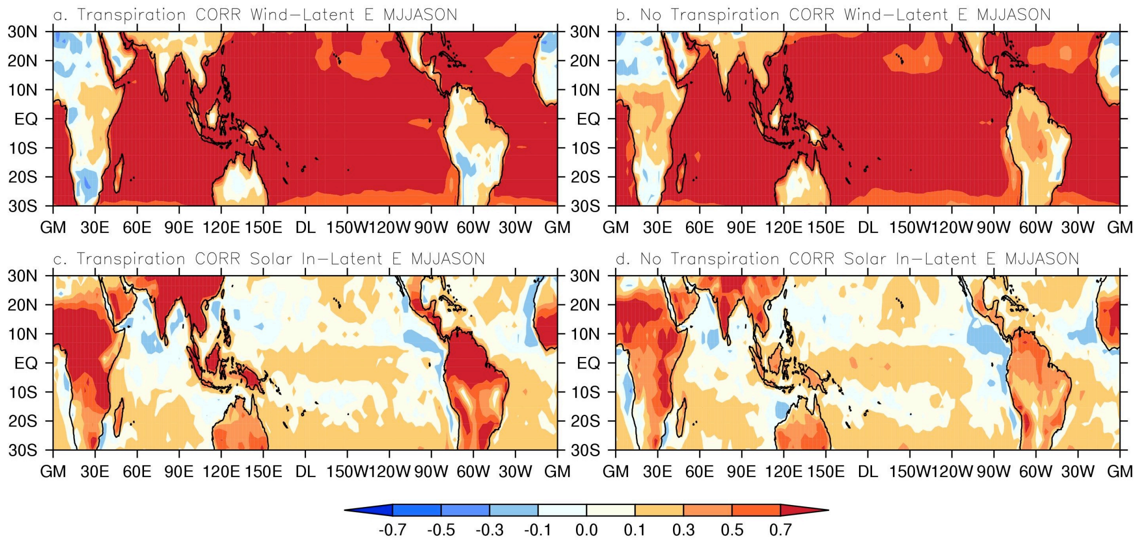
Figure 1. Correlation between surface latent heat flux and wind speed (a for the control run and b for the no transpiration run) and between surface latent heat flux and incident solar energy at the surface (c for the control run and d for the no transpiration run). All variables are 30-90 day band-pass filtered daily values.

Figure 2. Differences between the no-transpiration and transpiration cases in intraseasonal variance of 30-90 day band-pass-filtered daily precipitation (a and b) and the changes in the number of high-intensity precipitation days (c and d) at each grid point. a and c are for May through October and b and d 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.

Figure 3. The distribution of daily precipitation, evaporation, surface air temperature, and total column water vapor over Borneo (1.4°S, 113°E) and over Amazonia (1.4°N, 115.3°E) for the control (green) and no-transpiration (orange). Precipitation variability increases without transpiration.

Figure 4. 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.



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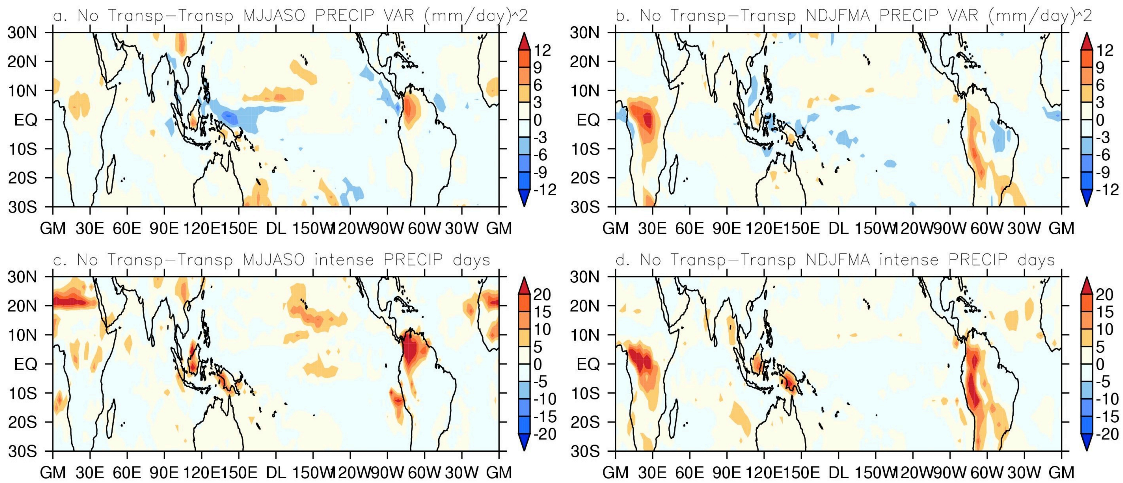

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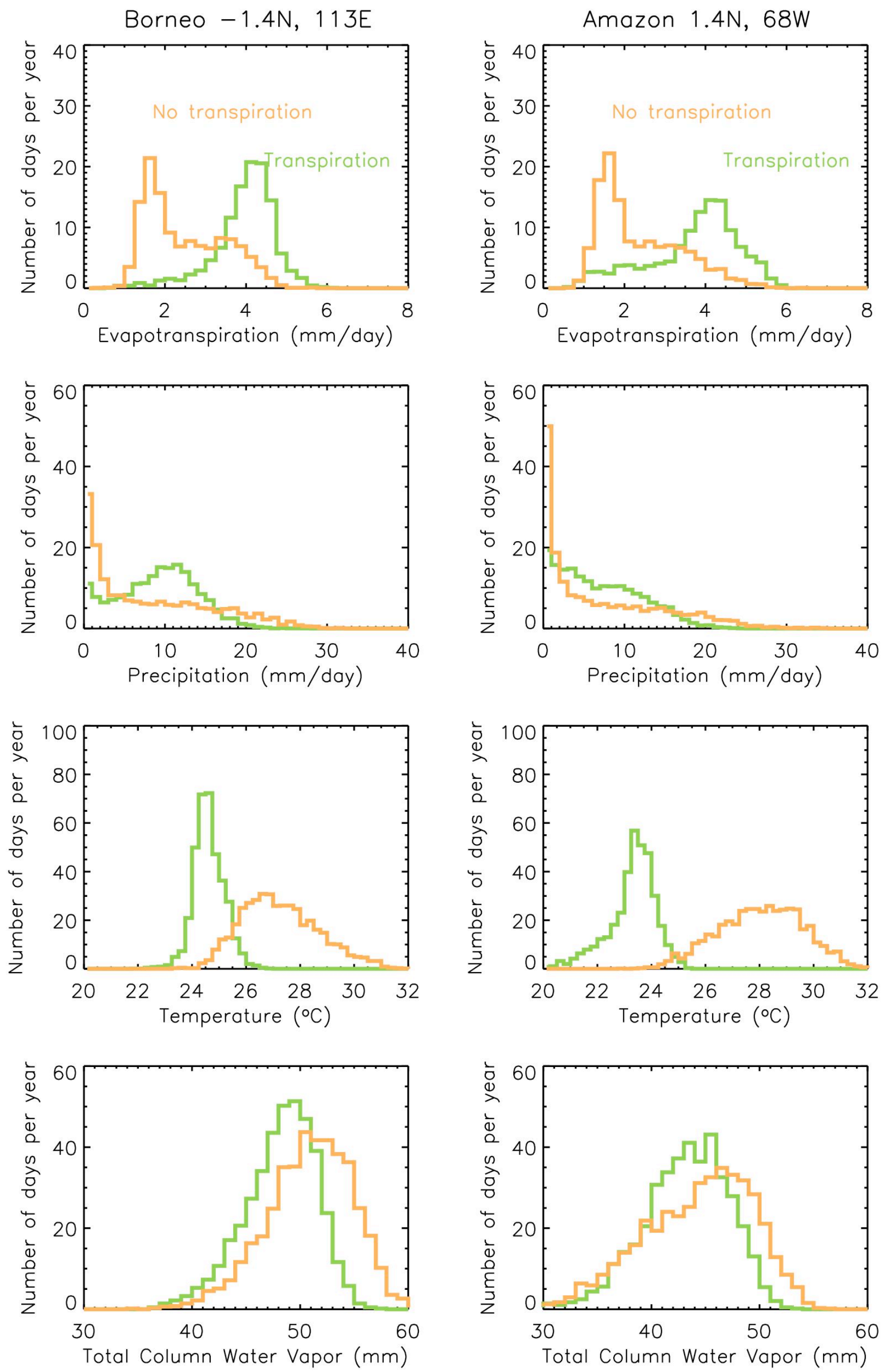

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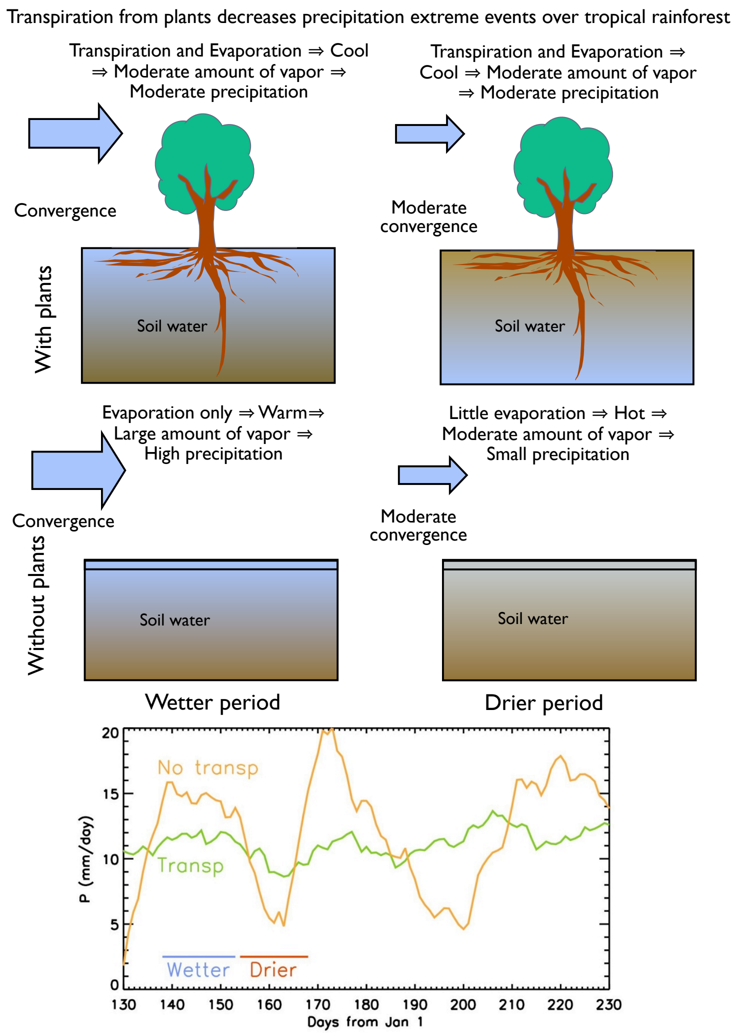

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