Fog and rain in the Amazon

Usama Anber^{a,b,1}, Pierre Gentine^{c,1}, Shuguang Wang^d, and Adam H. Sobel^{a,b,d}

^aLamont-Doherty Earth Observatory, Columbia University, Palisades, NY 10964; ^bDepartment of Earth and Environmental Sciences, Columbia University, New York, NY 10027; ^cDepartment of Earth and Environmental Engineering and Earth Institute, Columbia University, New York, NY 10027; and ^dDepartment of Applied Physics and Applied Mathematics, Columbia University, New York, NY 10027

Edited by Kerry A. Emanuel, Massachusetts Institute of Technology, Cambridge, MA, and approved August 12, 2015 (received for review March 12, 2015)

The diurnal and seasonal water cycles in the Amazon remain poorly simulated in general circulation models, exhibiting peak evapotranspiration in the wrong season and rain too early in the day. We show that those biases are not present in cloud-resolving simulations with parameterized large-scale circulation. The difference is attributed to the representation of the morning fog layer, and to more accurate characterization of convection and its coupling with large-scale circulation. The morning fog layer, present in the wet season but absent in the dry season, dramatically increases cloud albedo, which reduces evapotranspiration through its modulation of the surface energy budget. These results highlight the importance of the coupling between the energy and hydrological cycles and the key role of cloud albedo feedback for climates over tropical continents.

land–atmosphere interactions | Amazon | hydrologic cycle | fog | cloud-resolving models

Tropical forests, and the Amazon in particular, are the biggest terrestrial CO₂ sinks on the planet, accounting for about 30% of the total net primary productivity in terrestrial ecosystems. Hence, the climate of the Amazon is of particular importance for the fate of global CO₂ concentration in the atmosphere (1). Besides the difficulty of estimating carbon pools (1–3), our incapacity to correctly predict CO₂ fluxes in the continental tropics largely results from inaccurate simulation of the tropical climate (1, 2, 4, 5). More frequent and more intense droughts in particular are expected to affect the future health of the Amazon and its capacity to act as a major carbon sink (6–8). The land surface is not isolated, however, but interacts with the weather and climate through a series of land–atmosphere feedback loops, which couple the energy, carbon, and water cycles through stomata regulation and boundary layer mediation (9).

Current General Circulation Models (GCMs) fail to correctly represent some of the key features of the Amazon climate. In particular, they (*i*) underestimate the precipitation in the region (10, 11), (*ii*) do not reproduce the seasonality of either precipitation (10, 11) or surface fluxes such as evapotranspiration (12), and (*iii*) produce errors in the diurnal cycle and intensity of precipitation, with a tendency to rain too little and too early in the day (13, 14). In the more humid Western part of the basin, surface incoming radiation, evapotranspiration, and photosynthesis all tend to peak in the dry season (15–17), whereas GCMs simulate peaks of those fluxes in the wet season (10, 11). Those issues might be related to the representation of convection (1, 2, 4, 5, 13, 14) and vegetation water stress (6–8, 15–17) in GCMs.

We here show that we can represent the Amazonian climate using a strategy opposite to GCMs in which we resolve convection and parameterize the large-scale circulation (*Methods*). The simulations lack many of the biases observed in GCMs and more accurately capture the differences between the dry and wet season of the Amazon in surface heat fluxes and precipitation. Besides top-of-the-atmosphere insolation, the simulations require the monthly mean temperature profile as an input. We demonstrate that this profile, whose seasonal cycle itself is a product of the coupled ocean–land–atmosphere dynamics, mediates the seasonality of the Amazonian climate by modulating the vertical structure of the large-scale circulation in such a way that thermal energy is less effectively ventilated in the rainy season.

Results and Discussion

We use the Weather Research and Forecasting (WRF) model at 2-km horizontal grid spacing (see *Methods* for details of the runs). This resolution has been shown to be sufficient to resolve deep convection (no convective parameterization is used) and to correctly represent the sign and magnitude of the land–atmosphere interaction feedback (18), contrary to GCMs, which tend to exhibit soil moisture–precipitation feedbacks of opposite sign to that observed (19). We parameterize the time-dependent large-scale vertical motion as a function of internally resolved convection using the weak temperature gradient (WTG) approximation (*Methods*). The WTG approach has been used in many previous studies of tropical atmospheric dynamics to represent the feedback between locally resolved convection and larger-scale circulation (*Methods*) (10, 11, 20–23). Under WTG, we diagnose the horizontal average large-scale vertical motion (Fig. S1) so as to induce a vertical advective potential temperature tendency, which relaxes the model's domain-averaged potential temperature toward that of the target profile. The same large-scale vertical motion is then also used for vertical advection of moisture (*Methods*).

The target potential temperature profiles we use, representative of the wetter part of the Amazon, are taken from the 2014 Atmospheric Radiation Measurement mobile facility located at Manacapuru, near Manaus, Brazil (3°12'46.70"S, 60°35'53.0"W). The profiles are averaged over the month of February for the wet season, and September for the dry season, as shown in Fig. 1A. At the surface (where WTG is not directly applied; see *Methods*), the dry profile is warmer by about 5 K, reflecting the influence of higher surface heat fluxes (Fig. 1B). In the midtroposphere, the wet profile is warmer by more than 1 K. In the stratosphere, the wet profile is colder by more than 5 K due to the seasonal elevation of the tropopause. All these differences are consequences

Significance

We here demonstrate that we can resolve the seasonality of the hydrologic cycle in the Amazon using an approach, opposite to general circulation models, in which we resolve convection and parameterize large-scale circulation as a function of the resolved convection. The results emphasize the key role of cloud albedo feedback and, in particular, of the morning fog layer in determining the diurnal course of surface heat fluxes and seasonality of the surface and atmospheric heat and water cycles. These results indicate that our understanding of tropical climates over land can be considerably advanced by using coupled land–atmosphere models with explicit convection and parameterized large-scale dynamics.

Author contributions: U.A. and P.G. designed research; U.A. and P.G. performed research; U.A., P.G., and S.W. analyzed data; and U.A., P.G., S.W., and A.H.S. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

Freely available online through the PNAS open access option.

¹To whom correspondence may be addressed. Email: pg2328@columbia.edu or uanber@ldeo.columbia.edu.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1505077112/-DCSupplemental.

Fig. 3. Composite of the WRF simulated 2-d cycle of fractional cloud cover for the (A) wet and (B) dry season. Note the fog layer above the surface in the wet season.

induced in the wet season. However, the shortwave CRF in the wet season is much more negative than in the dry season due to the presence of the fog layer. Because the shortwave CRF dominates in the wet season, and longwave CRF dominates in the dry season, the net CRF is negative in the wet season and positive in the dry. Comparison with CRF obtained from the Clouds and the Earth's Radiant Energy System (CERES) [the CERES SYN1deg daily radiative fluxes (30, 31)] shows a reasonable agreement with our simulations, although some biases exist.

Perhaps surprisingly, the seasonal difference in the top of the atmosphere seasonal mean insolation is not the dominant control that determines the differences in seasonal climate, even though it is ultimately what controls the seasonal cycle in nature. In our simulations, the differences in the target potential temperature profiles are primarily responsible for the seasonal differences described above. We performed sensitivity experiments in which the insolation from the wet season is used with the target potential temperature profile from the dry season and vice versa (see Figs. S5–S7). We also performed sensitivity experiments over Rondonia (10.7°S, 62.7°W), where the seasonal difference in insolation is greater (Figs. S8–S10). When insolation is varied while holding the potential temperature profile fixed, no significant difference is found in terms of the typical pattern of diurnal and seasonal patterns of precipitation. Again, the cloud albedo adjusts so that the surface shortwave radiation is

always higher in the case of the dry season profile, leading to higher evapotranspiration flux (Fig. S9). This behavior differs from convection over oceans, where stronger seasonal insolation leads to higher surface fluxes (and sea surface temperature), and cloud albedo is not so tightly coupled to atmospheric convection because, unlike land, the ocean can both substantially store and transport heat reducing the coupling of evaporation with shortwave incoming radiation.

Methods

Model Configuration. We use the WRF model version 3.3, in three spatial dimensions, with doubly periodic lateral boundary conditions. The experiments are conducted with Coriolis parameter $f = 0$. The horizontal domain size is $192 \times 192 \text{ km}^2$ with a grid spacing of 2 km. There are 50 vertical levels total, with the top level at 22 km, and 10 levels in the lowest 1 km. Gravity waves propagating vertically are absorbed in the top 5 km to prevent unphysical wave reflection off the top boundary by using the implicit damping vertical velocity scheme (32). The 2D Smagorinsky first-order turbulent closure scheme is used to parameterize the horizontal transports by subgrid eddies. The Yonsei University first-order closure scheme is used to parameterize nonlocal boundary layer turbulence and vertical subgrid-scale eddy diffusion (33). The surface fluxes of moisture and heat are parameterized following Monin–Obukhov similarity theory. Microphysics is simulated using the Purdue–Lin bulk scheme (34), which has six species: water vapor, cloud water, cloud ice, rain, snow, and graupel. Radiative fluxes are determined interactively using the National Center for Atmospheric Research Community Atmosphere Model version 3.0 scheme for shortwave and longwave radiation. Both surface and radiative fluxes are fully interactive.

The atmospheric model is coupled to the Noah land surface model (LSM) (35) that has four soil layers at 10, 30, 60, and 100 cm depth. The LSM provides four quantities to the atmospheric model: sensible heat flux, latent

Fig. 4. Diurnal cycle of (A) latent heat flux, and (B) net shortwave at the surface, for WRF modeled (thick) and observed (thin) fluxes. Observed fluxes are taken from the climatology of eddy covariance fluxes observed at K34 station in Reserva Biológica do Cuieiras. We note that surface observations are difficult to obtain in the presence of dew (eddy covariance measurements typically cannot correctly record measurements) so that the observations typically omit fog situations, with an overrepresentation of relatively clear days compared with fog days.

Fig. 5. Cloud radiative forcing, shortwave (SWCRF), longwave (LWCRF), and net (NETCRF) for the wet and dry seasons as simulated (squares) and observed from CERES (circles).

heat flux, upward longwave radiation, and upward shortwave radiation off the ground. The LSM prognostic land states are surface skin temperature, volumetric total (liquid and frozen) soil moisture at each layer, soil temperature at each layer, and canopy water content. Vegetation type is ever-green forest, surface albedo is 0.12, and the wind field is left un nudged.

Parameterized Large-Scale Circulation and Initial Conditions. The large-scale vertical velocity is dynamically parameterized using the WTG method (20, 21). The WTG vertical velocity W_{WTG} is obtained by a Newtonian relaxation with a relaxation time scale τ (over which gravity waves propagate out of the domain) taken here as 2 h (20, 21),

$$W_{WTG}(z) = \frac{1}{\tau} \frac{\bar{\theta} - \theta_0}{\partial \bar{\theta} / \partial z} \quad [1]$$

where $\bar{\theta}$ is the domain mean potential temperature, and θ_0 is the observed potential temperature profile obtained from radiosondes averaged over 1 mo of observations. W_{WTG} is then linearly interpolated in the boundary layer to zero at the surface because gravity waves are not the main mode of buoyancy adjustment in the boundary layer. The impact is negligible in the daytime boundary layer as it is well-mixed so that the vertical gradients are null. Boundary layer height is determined interactively in the WRF model using the bulk Richardson number method and varies diurnally.

Once W_{WTG} is obtained, it is used to define the domain-average large-scale tendencies of potential temperature and specific humidity over the computational domain,

$$\left. \frac{\partial \bar{\theta}}{\partial t} \right|_{\text{Large Scale}} = \frac{\bar{\theta} - \theta_0}{\tau}, \quad [2]$$

$$\left. \frac{\partial \bar{q}}{\partial t} \right|_{\text{Large Scale}} = -W_{WTG} \frac{\partial \bar{q}}{\partial z}, \quad [3]$$

respectively, where $\bar{q}$ is the domain mean water vapor mixing ratio.

Initial conditions are seasonally averaged quantities in the dry and wet seasons using the ERA-Interim data set. The model is run for about 40 d and the analysis conducted on the equilibrium part only, which is the last 30 d. We have performed a sensitivity test on the soil moisture initial conditions, by switching the seasonal magnitudes, and they had no influence on the results. The reference, target temperature profile is time-independent in each season and does not include diurnal variations (21). The modeled diurnal cycles of surface fluxes, clouds, and precipitation are driven solely by the diurnal cycle of radiation at the top of the atmosphere. Daily mean insolation in the dry season is held fixed at $415 \text{ W}\cdot\text{m}^{-2}$ and, in the wet season, at $439 \text{ W}\cdot\text{m}^{-2}$, reflecting values at Manacapuru.

Surface Observations. We used eddy covariance data from the K34 station located in Estação Experimental de Silvicultura Tropical $02^{\circ}37'S$, $60^{\circ}09'W$, located around 60 km from Manaus. We have used data from 2000 to 2006 available at Oak Ridge National Laboratory (36). We used quality-controlled eddy covariance data, based on outliers comparison, wind speed (acceptable variation is two SD units from the linear regression), and unresponsive sensor checks. Eddy covariance measurements typically cannot correctly measure in the presence of dew; thus fog conditions are undersampled, which implies that the latent heat flux in Fig. 4 is an overestimate of the true latent heat flux (an average of fog conditions with little radiation and nonfog conditions with higher radiation).

Conclusion

We have shown that, when given the top of the atmosphere insolation and the monthly mean free-atmospheric temperature profile, the seasonal and diurnal cycles of cloud, precipitation, and surface fluxes can be simulated by a limited domain cloud-resolving model with parameterized large-scale forcing without the biases commonly found in global climate models.

We can view the seasonality in the Amazon as mediated by the atmospheric temperature profile. That profile itself results from the stronger convection in the wet season, but the increased wet season precipitation in the model is still a nontrivial prediction of the model. It can be explained by the reduced ventilation of moist static energy from the column, which is a consequence of the warmer tropospheric temperature profile in the wet season.

The surface fluxes, on the other hand, are strongly controlled by the diurnal cycle of cloud albedo, and especially of wet season fog, which blocks shortwave radiation from reaching the surface in the early morning. This fog is an essential regulator of the Amazon climate.

We demonstrate that a high-resolution cloud-resolving model with parameterized large-scale circulation offers a new window onto the dynamics of climate in the Amazon. In the future, this approach may allow new insights into the Amazon's changes under anthropogenic influence and the capacity of the basin to act as a CO_2 sink in the future.

ACKNOWLEDGMENTS. P.G. thanks Florian Cochard for preliminary radio-sonde and profile analysis. P.G. was supported by Department of Energy Grants GoAmazon DE-SC0011094 and DE-FOA-0000885 on the transition between shallow and deep convection. U.A., S.W., and A.H.S. acknowledge support from the National Science Foundation under Grant AGS-1008847 and the Office of Naval Research under MURI Grant (N00014-12-1-0911). Weather Research and Forecasting experiments were performed on the YETI cluster at Columbia University. Data profiles at the Atmospheric Radiation Measurement site were obtained at www.arm.gov/sites/amf/mao/. Surface flux observations were obtained at dx.doi.org/10.3334/ORNLDAAC/1174.

1. Achard F, Eva HD, Mayaux P, Stibig H-J, Belward A (2004) Improved estimates of net carbon emissions from land cover change in the tropics for the 1990s. *Global Biogeochem Cycles* 18(2):GB2008.
2. Hoffman FM, et al. (2014) Causes and implications of persistent atmospheric carbon dioxide biases in Earth system models. *J Geophys Res* 119(2):141–162.
3. Cai W, et al. (2014) Improved estimations of gross primary production using satellite-derived photosynthetically active radiation. *J Geophys Res* 119(1):110–123.
4. Todd-Brown KEO, et al. (2013) Causes of variation in soil carbon simulations from CMIP5 Earth system models and comparison with observations. *Biogeosciences* 10(3):1717–1736.
5. Cox PM, et al. (2013) Sensitivity of tropical carbon to climate change constrained by carbon dioxide variability. *Nature* 494(7437):341–344.
6. Lee JE, et al. (2013) Forest productivity and water stress in Amazonia: Observations from GOSAT chlorophyll fluorescence. *Proc Biol Sci* 280(1761):20130171.

7. Reichstein M, et al. (2013) Climate extremes and the carbon cycle. *Nature* 500(7462):287–295.
8. Gatti LV, et al. (2014) Drought sensitivity of Amazonian carbon balance revealed by atmospheric measurements. *Nature* 506(7486):76–80.
9. de Arellano JV-G, van Heerwaarden CC, Lelieveld J (2012) Modelled suppression of boundary-layer clouds by plants in a CO_2 -rich atmosphere. *Nat Geosci* 5(10):701–704.
10. Pascale S, Lucarini V, Feng X, Porporato A, Hasson SU (2014) Analysis of rainfall seasonality from observations and climate models. *Clim Dyn* 44(11–12):3281–3301.
11. Martins G, Randow von C, Sampaio G, Dolman AJ (2015) Precipitation in the Amazon and its relationship with moisture transport and tropical Pacific and Atlantic SST from the CMIP5 simulations. *Hydrol Earth Syst Sci Discuss* 12(1):671–704.
12. de Gonçalves LGG, et al. (2013) Overview of the Large-Scale Biosphere–Atmosphere Experiment in Amazonia Data Model Intercomparison Project (LBA-DMIP). *Agric For Meteorol* 182–183:111–127.

- PNAS | September 15, 2015 | vol. 112 | no. 37 | 11477