

Impact of deforestation in the Amazon basin on cloud climatology

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Shallow clouds are prone to appear over deforested surfaces whereas deep clouds, much less frequent than shallow clouds, favor forested surfaces. Simultaneous atmospheric soundings at forest and pasture sites during the Rondonian Boundary Layer Experiment (RBLE-3) elucidate the physical mechanisms responsible for the observed correlation between clouds and land cover. We demonstrate that the atmospheric boundary layer over the forested areas is more unstable and characterized by larger values of the convective available potential energy (CAPE) due to greater humidity than that which is found over the deforested area. The shallow convection over the deforested areas is relatively more active than the deep convection over the forested areas. This greater activity results from a stronger lifting mechanism caused by mesoscale circulations driven by deforestation-induced heterogeneities in land cover.

climate | land-cover heterogeneity | mesoscale circulations

The deforestation of the Amazon has influenced hydro-meteorological processes in many ways at local (1), regional (2–7), and global scales (8–11). Images from multiple satellites hint at a correspondence between the patterns of clouds and those of land cover over some partially deforested regions (4, 12, 13), in particular over the study domain of this analysis in Rondonia (500 × 500 km² in size centered at 62.5°W and 10.5°S shown in Fig. 1 *Left*). It is known that this type of land cover change causes land breeze that may enhance cloudiness (15–18), leading to the notion that clouds follow deforestation. Past works by the authors (16) and others (17) have shown that these “land breezes” are effective at scales of heterogeneous land cover on the order of 10⁰–10¹ kilometers. These scales are consistent with the “fish bone” deforestation patterns shown in Fig. 1 *Right*. A recent study (14) using visible and infrared images of the NOAA geo-stationary satellites (GOES) found that the enhancement of shallow clouds, measured by the cloud-top height, over the deforested Amazon is statistically significant. Although not reported in that study, there has been evidence showing that deep clouds are prone to develop over forested surfaces over the same study domain (19). The goal of this study is to understand the physical mechanism(s) behind the different behaviors of shallow and deep clouds as a result of deforestation in the Amazon. We will use atmospheric sounding measurements to decipher the meteorological and environmental conditions that lead to the observed patterns of shallow and deep clouds.

Data

The visible and infrared images used for the retrieval of cloud maps over the study domain are provided by 2 NOAA geo-stationary satellites: GOES-7 and GOES-8 at 30-min resolution (freely available at www.class.noaa.gov). A full description of the dataset and the cloud retrieval algorithm can be found in an earlier publications (14, 20, 21). The sounding data used for the retrieval of atmospheric instability conditions come from the



Fig. 1. Study domain. The deforestation map (*Left*, with so-called “fish-bone” pattern highlighted in *Right*) for the study domain [8–13°S, 65–60°W] with the lower-left corner at [13°S, 65°W] and upper-right corner at [8°S, 60°W] in the Rondonia, Brazil (political boundary in red). The light green indicates the deforested pasture surface, and the dark green the forest. Sounding measurements were made at the forest site in Reserva Jaru [10°55′S, 61°55′W] (blue dot), and at the pasture site in Fazenda Nossa [10°45′S, 62°21′W] (orange dot) of the RBLE-3 experiment during 13–26 August 1994. The area with brownish color in the upper-right part of *Left* above the Rondonia boundary is a natural Savannah where an event of deep convection was observed on 25 August (see Fig. 4).

Rondonian Boundary Layer Experiment (RBLE-3) as part of the Anglo-Brazilian Amazonian Climate Observation Study (ABRACOS) (22) during 13–26 August 1994. Sounding profiles were provided by 2 radiosonde balloons simultaneously released at a forest site (the circles in Figs. 3 and 4) and a pasture (deforested) site (the cross in the same figures) 6 times a day at 0300, 0900, 1200, 1500, 1800, and 2100 UTC (local time LT = UTC – 4). The pasture site is surrounded by extensive area with stripes of grass and forest side-by-side. The forest site has upwind fetch of undisturbed forest of several tens of kilometers. Hence the sounding profiles at the 2 sites are considered to be representative of forested and deforested environment.

Statistical Analysis of Shallow and Deep Clouds

Following an earlier study (14), the tendency of shallow or deep clouds developing over deforested (pasture) vs. forest surfaces is characterized by the relative abundance of cloudy pasture/forest pixels over a given domain using a parameter called “cloud density difference” (14), CDD. If the (shallow or deep) clouds have no preference over deforested vs. forest surfaces, CDD is expected to be statistically zero. Deviation of CDD from zero is

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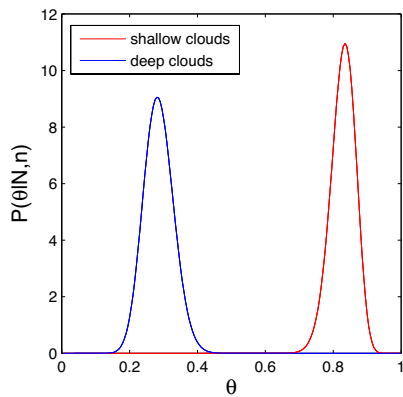


Fig. 2. Statistical analysis. Posterior distributions of θ for shallow clouds (red) and deep clouds (blue)

$$P(\theta|N, n) = \frac{(N+1)!}{n!(N-n)!} \theta^n (1-\theta)^{N-n},$$

where $n = 86$ for shallow clouds and $n = 29$ for deep clouds with $N = 103$ are obtained from the monthly mean CDD data derived from cloud maps using GOES-8 visible and infrared images during 1 September 1994 to 31 March 2003.

an indicator of the effect of land covers on the development of clouds: $CDD > 0$ indicates the tendency of more (shallow or deep) clouds occurring over deforested surfaces than over forested surfaces within the domain. Here, we use the posterior probability of $CDD > 0$ given the long-term observation of cloudiness, θ , to quantify the tendency of shallow/deep clouds occurring over forest vs. deforested surfaces. $\theta = 0.5$ implies that there is no preference for the clouds to appear over one type of land cover (i.e., pasture vs. forest) to the other. The further away of θ from 0.5, the stronger is the indication that convective clouds develop in conjunction with deforestation patterns. Using Bayesian techniques (23), it is possible to show that the posterior distributions of θ follows a beta distribution,

$$P(\theta|N, n) = \frac{(N+1)!}{n!(N-n)!} \theta^n (1-\theta)^{N-n},$$

where n is the number of cloud maps with $CDD > 0$ (shallow or deep) and N the total number of cloud maps.

The estimation of θ reported here is based on the monthly mean CDD according to the cloud maps derived from the GOES-8 visible and infrared imager data over the period of 1 September 1994 to 31 March 2003. The monthly CDDs were calculated from 3-time daily images sampled at 10:45, 13:45 and 16:45 local time (LT) to capture active convection over the study domain. Further details of the cloud retrieval algorithm can be found in an earlier publication (14). Shallow clouds are defined as those with cloud-top brightness temperature (CTBT) > 280 K, and deep clouds with CTBT < 240 K. Out of the 103 months, 86 months had more shallow clouds over deforested surfaces than forest surfaces, and 29 months had more deep clouds over deforested surfaces than forest surfaces. The corresponding 2 probability density functions of θ (one for shallow clouds and one for deep clouds) using these data are shown in Fig. 2. The 2 nonoverlapping posterior distributions of θ for shallow and deep clouds illustrated in Fig. 2 indicate that there is essential zero (cumulative) probability of $\theta < 0.5$ in the case of shallow clouds, and zero probability of $\theta > 0.5$ in the case of deep clouds. This is a strong evidence of the distinct behavior of convective clouds over the deforested Amazon: shallow clouds following deforestation with deep clouds following forest. Note that the distributions of θ shown in Fig. 2 are derived using monthly data of

clouds under all scenarios of synoptic forcing, e.g., large scale subsidence during dry season and strong atmospheric instability during rainy seasons. Even though the development of clouds (shallow or deep) at a certain location sometimes has little to do with land cover and its contrast, e.g., due to synoptic frontal systems, the signal of clouds-landcover coupling represented by the well separated $P(\theta|N, n)$ is unambiguous for both types of clouds. This result confirms the earlier findings (13, 19). The physical mechanisms responsible for the observed surface dependent convection on CDD counts are discussed next.

Physical Mechanisms of Cloud-Deforestation Coupling

The ideal time to study the effect of land cover on convection is during the dry season (May to October for the Amazon) during which frontal systems are less frequent and atmospheric instability is relatively weak. We use data from the RBLE-3 field experiment (13–26 August 1994) together with GOES-7 images over the same period. This 2-week period was in the midst of a severe dry season during which the region was under large-scale high-pressure control and free of frontal systems with no rainfall recorded in gages although the observed deep convection may have led to rainfall in ungaged areas. Under such synoptic conditions, convection tends to be suppressed. Active afternoon shallow clouds (CTBT > 280 K) appeared regularly on 14–19 and 22–23 August, starting to appear at approximately 10:00 LT and continuing throughout the afternoon exclusively over the deforested area. Fig. 3 shows shallow clouds at 15:01 LT on 15 August covering much of the deforested “fish-bone” area, whereas the neighboring forested areas including the natural Savannah in the upper-right part of the study domain were mostly cloud-free. No deep clouds (CTBT < 240 K) occurred within the entire study domain during 14–19 August, 20, 21, and 24 August were quiet days with few shallow clouds over the entire domain. During 20–21 August, smoke from biomass burning was evident as indicated by the smoke trails carried with the predominantly easterly wind with high brightness temperature (≈ 300 K). Again few shallow clouds developed over the entire domain on 25–26 August (Movie S1). Deep clouds were observed over the Savannah and the surrounding forested area in the afternoon on 25 August as indicated by the low CTBT ≈ 220 K (Fig. 4). Movie S1 shows the clouds over the entire period.

The sounding and surface station data from the RBLE-3 experiment have revealed distinct atmospheric instability and boundary layer properties at the pasture and forest sites (see Fig. 3 for their locations). We consider the atmospheric and boundary layer properties at the 2 observation sites to be representative of those over the extended deforested area and its neighboring region covered with dense forest. Fig. 5 shows the time-series of CAPE and CINE (convection inhibition energy) computed from the simultaneous sounding profiles at the 2 sites. It is evident that the atmosphere over the forest surfaces was consistently more (conditionally) unstable than over the deforested surfaces, i.e., a greater CAPE for the forest site than that for the pasture site. Meanwhile the values of CINE at the 2 sites are comparable. The net radiation was at approximately the 500 W m^{-2} level at the forest site, significantly higher than the approximately 350 W m^{-2} at the pasture site. Latent heat flux was at approximately the 150 W m^{-2} level at the pasture site, whereas it was at the approximately 340 W m^{-2} level at the forest site. The measurements from the surface stations (Movie S1) have shown nearly equal surface air temperature at the 2 sites, but substantially higher surface humidity at the forest site. As a result, surface wet-bulb temperature, θ_w , was also significantly higher (≈ 4 K) at the forest site than at the pasture site due to higher humidity. Because the humidity control of θ_w , hence CAPE (24), is a characteristic behavior of an oceanic atmosphere (25), the Amazon may be viewed as a “green ocean” (26).

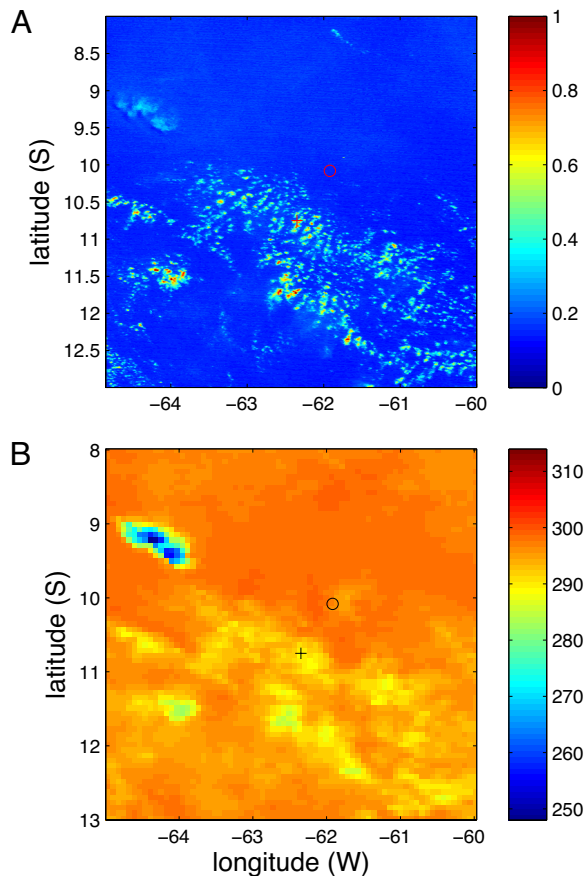


Fig. 3. Cloud map. GOES-7 visible (1-km pixels) and infrared (8-km pixels) (channel 8, 11.17- μm wave length) images at 19:01 UTC (local time = UTC - 4) over the study domain on 15 August 1994. a, albedo; b, brightness temperature (K). o indicates the location of soundings in the forest site; + represents the location of soundings in the pasture site of the RBLE-3 field experiment during 13–26 August 1994. Detection of shallow and deep clouds in this study is based on the combined visible and infrared images (14) as shown here.

We have learned from these observations that relatively active (shallow) convection occurred consistently over the deforested region where the atmosphere was less energized, instead of over the forested area where the atmosphere was more energized. The weak CAPE value may explain why the resulting clouds are shallow in the environment of large scale atmospheric subsidence due to high pressure. Theoretically, the level of neutral buoyancy (LNB) would be the maximum cloud height. The shallow clouds (Fig. 3) did not reach the LNB (Movie S1), which indicates that the large scale atmospheric subsidence during the dry season suppressed the convective activity, leading to the heights of clouds much lower than the LNB. Fig. 5 Upper shows a low level of CAPE at the pasture site during 14–19 and 22–23 August when shallow clouds were observed with patterns similar to those shown in Fig. 3. No CAPE was available at the pasture site on 20, 21 and 24 August when few shallow clouds were showing up. Meanwhile, significant CAPE was present at the forest site throughout the period. Yet there were few shallow clouds over the forest area. Notice that the energy barrier for convection, CINE, was comparable at both sites (Fig. 5 Lower). In addition, the canopy top temperature at both sites was nearly equal (Movie S1) through the entire period of the RBLE-3 experiment. Hence we argue that the (thermal) lifting mechanism is the dominant factor in the development of convection in the dry-season environment. The orographical lifting mechanism is important during wet season (27), but plays a secondary

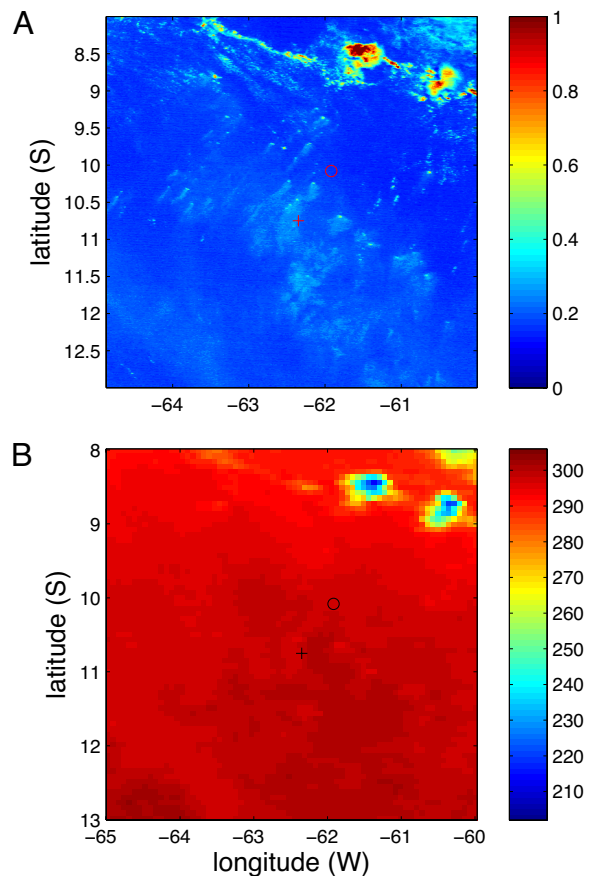


Fig. 4. Cloud map. GOES-7 visible and infrared images over the study domain at 18:31 UTC on 25 August 1994. a, albedo; b, brightness temperature (K). o indicates the forest site; + indicates the pasture site of the RBLE-3 field experiment during 13–26 August 1994.

role in dry season (14). Lack of lifting mechanism over the forested surfaces leads to suppression of convection even though ample potential energy for convection is available. This line of reasoning is consistent with the observations (28) showing significantly weaker sensible heat flux over the forest than over the pasture assuming that the boundary layer turbulence is the dominant lifting mechanism to initiate convection. This argu-

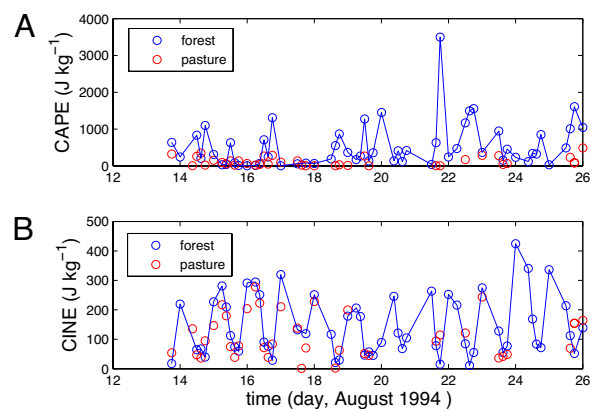


Fig. 5. Sounding data. Atmospheric instability characterized by a CAPE, and b CINE computed from the RBLE-3 radiosonde data simultaneously collected at a native forest site in Reserva Jarú and a deforested pasture site in Fazenda Nossa over the period of 13–26 August 1994.

Table 1. Boundary-layer and cloud heights

LT	Pasture			Forest		
	CBL, m	LCL, m	LFC, m	CBL, m	LCL, m	LFC, m
08:00	60 ± 30	1,000 ± 100	2,200 ± 120	70 ± 30	500 ± 10	2,200 ± 200
11:00	500 ± 240	1,600 ± 100	2,400 ± 560	270 ± 110	1,000 ± 100	2,200 ± 470
14:00	1,500 ± 480	2,200 ± 200	2,600 ± 450	900 ± 300	1,700 ± 340	2,300 ± 220
17:00	1,600 ± 600	2,000 ± 130	2,600 ± 460	1,100 ± 400	1,600 ± 250	1,900 ± 330

Shown are height statistics (mean and standard deviation) of the depth of the convective boundary layer (CBL) [reported by Fisch *et al.* (29)], the lifting condensation level (LCL) (i.e. cloud base), and the level of free convection (LFC) at the pasture and forest sites derived from the RBLE-3 radiosonde data. LT, local time.

ment is reinforced by the observations showing individual (shallow) clouds tending to form over grassy pixels rather than over forested pixels within the partially deforested region (Fig. 1).

Deep clouds, rare events during this 2-week period, occurred only on 25 August. The 2 clusters of deep clouds developing over the natural Savannah and the neighboring forest located in the upper-right corner of the domain (Fig. 4). These deep clouds were associated with relatively large CAPE and small CINE (Fig. 5) compared with those for the earlier times, according to the sounding profiles at the forest site. The point measurements are believed to be representative of the extended forested area as the forest site was surrounded by undisturbed dense forest stretching several tens of kilometers with predominantly easterly wind. Because Savannah is a mixture of trees and grasses, its surface properties in terms of energy balance are expected to be somewhere between the forest and the pasture. Note also that the Savannah is surrounded by undisturbed forest. Therefore, it is reasonable to argue that the atmospheric instability condition over the Savannah was more like that at the forest site than the pasture site. If this is true, large CAPE combined with stronger sensible heat flux (relative to that of the surrounding forest) would provide a favorable environment for the development of deep clouds. Even though the exact surface conditions were unknown at the Savannah, the reality that deep clouds only occurred over this forest-like surface is consistent with the statistical analysis presented earlier. The rarity of deep clouds reflects that there is the lack of lifting mechanism to initiate convection over the forest area, contrary to the lack of sufficient energy to support deep convection over the pasture. The CAPE and the vertical distribution of moisture in the cloud environment determines whether the clouds are shallow or deep once convection is initiated, while the lifting mechanism determines whether clouds occur, shallow or deep, which we discuss below.

Boundary layer turbulence is usually considered the primary lifting mechanism for convection. Sensible heat flux at the pasture site being 2.5 times as large as that at the forest site (28) is indeed consistent with the observation of shallow clouds being active over the pasture surfaces while almost nonexistent over the forested area (except for those eventually developing into deep clouds). Yet there is evidence suggesting that the boundary layer turbulence may not be the only lifting mechanism. The evidence comes from the depth of the convective boundary layer (CBL) versus the height of cloud base, and the time variation of the CBL versus that of cloud development. The depth of CBL is defined as the height at which the gradient of potential temperature changes from zero to positive. The height of the cloud base is the lifting condensation level (LCL, the level at which a parcel of moist air lifted from the surface would become saturated). Both parameters are computed from the RBLE-3 radiosonde data. Table 1 shows the depth of CBL (reported in ref. 29), the cloud base (LCL), and the level of free convection (LFC, the level at which a parcel of moist air lifted from the surface would first become less dense than the surroundings). Deep convection

is possible only when the surface air is lifted beyond the LFC. During 14–19 August when shallow clouds started appearing approximately 11:00 LT each day, the CBL height at 11:00 LT was ≈ 500 m at the pasture site. This is significantly lower than either the LCL of $\approx 1,600$ m level or the LFC of the $\approx 2,100$ -m level at the pasture site. At 14:00 LT during this period, the CBL reached 1,500 m with an uncertainty (i.e., day-to-day variability) of approximately 500 m, whereas the LCL and LFC were $\approx 2,100$ m. Hence the possible role of the boundary layer turbulence in initiating shallow clouds cannot be ruled out at this particular time. At 17:00 LT, the CBL grew further to $>1,600$ m whereas the LCL and the LFC remained more or less the same or slightly lower than those at 14:00 LT. If the boundary layer turbulence were the major lifting mechanism, the shallow clouds would have been more vigorous at 17:00 LT than they were at 14:00 LT. Yet, the GOES-7 images showed that the shallow clouds started declining at 15:00 LT. At the forest site, the LCL were $\approx 1,000$ m at 11:00 LT, 1,800 m at 14:00 LT, and in the range of 1,500–1,900 m at 17:00 LT. They were substantially higher than the CBL at the corresponding times. At both sites, the LFC was consistently higher than the LCL. Note that CINEs were comparable at the 2 sites (Fig. 5B). Although the lack of shallow clouds over the forested area can be explained by the shallow boundary layer relative to the LCL, the boundary layer turbulence alone cannot explain the behavior of the shallow clouds over the deforested area. We need to turn our attention to a second lifting mechanism.

The second lifting mechanism considered here is mesoscale circulations driven by the thermal heterogeneity of the land surface, otherwise known as the land breeze. Souza, *et al.* (28) found that the land surface heterogeneities over the study domain during this study period did cause convective circulation with wind direction toward the pasture from the forest near the surface and with opposite direction above driven by the gradient of nonhydrostatic pressure. Their findings are supported by other earlier studies (16, 30) showing that mesoscale circulations induced by land surface heterogeneities could reach a level significantly higher than the CBL. Although the RBLE-3 data only confirm the existence of convective circulations at the 2 experimental sites, systematic mesoscale circulations are expected to develop between the juxtaposed stripes of tree and pasture over the deforested area. Theoretical analysis (16) has shown that the length scale of the land cover in Rondonia, $\approx 10^1$ km, is effective in driving the mesoscale circulations. A numerical modeling study (18) also predicted that shallow clouds would develop mimicking the “fish-bone” pattern of land cover (see Fig. 1), similar to the observed shallow clouds shown in Fig. 3.

Direct evidence of the mesoscale circulations as an important lifting mechanism also came from the time sequences of shallow clouds (see [Movie S1](#)). The activity of shallow clouds reached its peak at 15:00 LT when the mesoscale circulations also reach peak intensity (16), whereas the boundary layer height reaches its peak a few hours later (28). The GOES-7 images also show that the shallow clouds started to appear at approximately 10:00

LT when the development of mesoscale circulations speeded up. The timing of the shallow clouds was more in phase with that of the mesoscale circulations than that of the boundary layer turbulence. The observational evidence strongly supports the argument that the dominant lifting mechanism was due to the mesoscale circulations instead of the boundary layer turbulence. Lack of lifting mechanism due to mesoscale circulations over the uniform forest is believed to be responsible for few shallow clouds over this study period as the boundary layer turbulence did not initiate convection even though there was plenty of CAPE. We also contend that the deep clouds over the Savannah were due, in part, to its less uniform land cover compared with the neighboring forest. All of the evidence points to the thermally induced mesoscale circulation as a major, if not the only (27), lifting mechanism for convection during dry seasons in the deforested Amazon. Of interest is the absence of shallow clouds on the 25th of August. Significant CAPE was present according to the sounding data and there was no obvious reason for the mesoscale circulation not to develop. It is plausible that clouds were inhibited by biomass burning (31–34) (evidence in the easterly smoke trails in Fig. 4A). Further study is needed to confirm or to refute this idea.

Conclusions

Analysis of satellite cloud maps combined with local sounding measurements has confirmed the findings of earlier theoretical and numerical studies that the land surface heterogeneity with the “fish-bone” pattern has left detectable marks in the regional cloud climatology. The Bayesian analysis has confirmed the patterns of cloudiness over the deforested Amazon: shallow clouds follow the deforestation, but deep clouds do not. Active shallow clouds developed almost exclusively over partially deforested surfaces even though the atmosphere was less unstable (less CAPE) than over the neighboring dense forest where

extensive shallow clouds were absent except for those sporadic ones that eventually developed into deep clouds. The atmosphere over the study domain behaves more like that over oceans with CAPE dominated by the humidity factor. The forested patches in the Amazon may be viewed as “green oceans” surrounded by “continents.” Mesoscale circulations induced by the contrast between forested and deforested surfaces with the existing length scales, have been identified as the likely dominant lifting mechanism for convection based on the existing evidence. Boundary layer turbulence appears to play a secondary role in the situation considered in this study. A lack of lifting mechanism is responsible for suppressed convective activity over extensive homogeneous forest surfaces even though CAPE was abundant during the period of study.

It remains uncertain whether these findings can be used to predict the future climate change in response to the projected deforestation scenarios in the coming decades. An open question is whether the Amazon as a green ocean now will be converted into an area with more continental characteristics as the expanding deforestation makes the land cover more uniform. There must be a limit to the length scale of land cover heterogeneity above which the lifting mechanism is lost and the enhancement of shallow clouds over deforested areas will disappear. An analysis of scales is a subject of future research.

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