54 Meso-scale climate change due to lowland deforestation in the maritime tropics

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ABSTRACT

Annual precipitation on the Caribbean island of Puerto Rico has decreased steadily during the twentieth century, on average by 16%. The reduced rainfall manifested itself in the form of regular water rationings for millions of inhabitants during the 1990s. This chapter examines the link between the reduction in precipitation and the land-cover change using a combination of energy balance measurements and meso-scale atmospheric modeling. The explanation of the reduction in precipitation proved to be different than expected. Based on measurements made earlier over rain forest and pasture in Amazonia, a forest-covered island was expected to be cooler because of the higher transpiration of forest compared to grassland. The opposite proved to be the case: transpiration by a coastal wetland forest was less than that of an adjacent, well-watered grassland. In addition, the forest's albedo was 8% lower than that for the grassland. Together, these two factors caused the sensible heat flux over the forest to be twice that over the grassland. The surface energy balance observations over forest and grassland were used in a meso-scale atmospheric circulation model (RAMS) to simulate the meteorological effects of island-wide deforestation. The simulations indicated that the development of a sea breeze during the day dominates the climate on the island. In model runs in which the island was assumed to be completely covered with forest, the sea breeze was considerably stronger than when the vegetation had been transformed to grassland. Along the sea breeze front, convergence caused upward air motions. As sea breeze convergence was stronger over a forested island, more clouds were formed, albeit at a higher elevation, and there was an estimated 10–20% enhancement of precipitation compared to a deforested island. In the deforested scenario, the cloud base was typically lowered by 200 m. Refinement of the model is required to obtain more accurate estimates of the changes in precipitation, although most likely the relevant processes have been included.

INTRODUCTION

Evidence that land cover influences cloud formation and precipitation is increasing (Cutrim *et al.*, 1985; Lawton *et al.*, 2001; Ray *et al.*, 2006; Makareva and Gorshkov, 2007; Pielke *et al.*, 2007; cf. Meesters *et al.*, 2009; Nair *et al.*, this volume). Precipitation decreases exponentially with distance from the ocean over extensive non-forested areas, whereas no such decline is observed where there are extensive tracts of natural forest (Makareva and Gorshkov, 2007). In continental Amazonia, 30–50% of the

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precipitation is estimated to originate from locally evaporated moisture, the remainder being supplied by the ocean (Eltahir and Bras, 1994; Costa and Foley, 1999). Hence, an effect of large-scale forest conversion on precipitation in the region is to be expected and many modeling studies (reviewed by Lean *et al.*, 1996; Costa, 2005) have predicted a reduction in the amount of precipitation after complete conversion of Amazonian forest to pasture. Increases in surface albedo, reductions in transpiration as a consequence of the shallower root zone of the replacing grassland vegetation, and reduced interception evaporation are considered to be the major causes for these reductions (Nobre *et al.*, 1991).

It is of interest to explore to what extent such effects also apply under maritime conditions where the climatic influence of the nearby ocean can be expected to be much more pronounced (Malkus, 1955) and land-cover change typically extends over much smaller scales. The Caribbean island of Puerto Rico (180 × 60 km) provides a case in point. After the passage of Hurricane Hugo over the island in September 1989 – which caused widespread defoliation – the cloud base was observed to rise by a few hundred meters to well above the island's highest peaks (>1050 m.a.s.l.) (Scatena and Larsen, 1991). The phenomenon disappeared after several months as the forest canopy regererated. Changes in the Puerto Rican climate are also evident in long-term precipitation records. Bisselink (2003) found summer precipitation totals (May–October) for the majority of 24 stations between 1931 and 1996 to be decreasing significantly (by 0.6–2.3 mm year^{-1}), although winter precipitation increased by 0.3–1.7 mm year^{-1}. The eight stations with the longest period of record (~100 years) all had negative trends in annual precipitation (−1.6 to −4.9 mm year^{-1}). Furthermore, 1997, 1994, and 1991 were the second, third, and sixth driest years in the twentieth century (Larsen, 2000). Mandatory water rationings were imposed six times in the 1990s for periods up to 6 months, with strong societal and ecological impacts and an estimated economic loss of US$165 million in 1994 alone (Lugo and García-Martinó, 1996). The negative precipitation trends roughly coincide with the deforestation of the island from the coastal plains toward the interior mountains, reaching 80% in 1899 and 94% in the 1940s. The cleared land was used primarily for agricultural purposes – pasture and sugar cane in the coastal plain, and coffee and subsistence farms in the uplands. After World War II, many degraded farmlands were abandoned, while government policy caused the island's economy to shift from agriculture to industry. Consequently, secondary forest cover gradually increased, along with urbanization and industrial development in the lowlands (Dietz, 1986; Aide *et al.*, 1995; Franco *et al.*, 1997). By 2000, urban and developed land covered 15.4% of the island while non-wetland forests covered 44.8% (Kennaway and Helmer, 2007). The total pasture area on the island remained constant from 1951 to 2000, covering about one-third of the island.

The objective of this chapter is to determine whether land-cover transformation in the coastal plains may have caused the observed reduction in precipitation totals on Puerto Rico. A micrometeorological field campaign was carried out to quantify the water and energy budgets associated with the original lowland forest and a nearby pasture considered representative of post-forest conditions. Next, the observations were used in a meso-scale atmospheric circulation model to assess the effects of island-wide land-cover change on climate. Given that the frequency, height, density, and spatial distribution of clouds constitute important boundary conditions for the occurrence and functioning of montane cloud forests (cf. Jarvis and Mulligan, this volume), the chapter pays special attention to the effect of lowland land-cover change on cloud occurrence in the adjacent Luquillo Mountains. Here, forests above *c.* 800 m.a.s.l. (Weaver, 1995) are frequently enshrouded in fog and low cloud (cf. Holwerda *et al.*, this volume #28 and 29).

MATERIALS AND METHODS

Field experiment

Two sites were selected near Sabana Seca (18° 27′ 34″ N, 66° 12′ 30″ W), some 15 km west of the capital of San Juan and about 1000 m from the coast line. Here, old-growth *Pterocarpus officinalis* forest (14 m canopy height) and grassland (up to 2 m tall) were found within a kilometer from each other and subject to an unobstructed flow of air from the ocean in the mean direction of the trade winds (NE). Prior to the arrival of the Europeans in Puerto Rico, *P. officinalis* forest constituted the main freshwater wetland ecosystem on the northern coastal plains. *Pterocarpus* was also (one of) the most abundant tree species in mixed forests along rivers on the floodplains (Holdridge, 1940). In addition, *P. officinalis* is an important tree species all along the Atlantic coast from Brazil to Mexico, along the Pacific coast from Costa Rica to Ecuador, and on most Caribbean islands except Cuba (Janzen, 1978; Cintrón, 1983). According to a land survey in 1990, pasture is the most common post-deforestation land-cover type in Puerto Rico (52% of the deforested area). Croplands (sugar cane, coffee and banana) account for another 14%, with the remaining land used for urban and industrial areas, roads, and water (Franco *et al.*, 1997). As such the selected sites are considered representative of the general pre- and post-deforestation land-cover types in the island's lowlands.

Temperature, relative humidity, and wind speeds at the two sites exhibit clear diurnal and seasonal patterns. Temperatures range between 25 and 30 °C in summer and between 22 and 28 °C in winter. Atmospheric humidity is close to saturation at night but drops to 75% and 70% at midday in summer and winter, respectively. Wind speeds are low at night (~1 m s^{-1}) but increase to 6–8 m s^{-1} during the day under the influence of the sea breeze. Mean annual precipitation in the area is about 1700 mm, with monthly totals being somewhat lower in February and March (Van der Molen, 2002).

Micrometeorological instrumentation for the determination of surface energy budgets and the fluxes of sensible heat, latent heat (evaporation), and momentum according to the Euroflux methodology (Aubinet *et al.*, 2000) were installed on a scaffolding tower at the forest site and on masts at the pasture site. Measurements were conducted from May 1997 until May 1998. Closure of the energy balance was very good at 103 ± 11% for the forest site vs. 105 ± 5% for the pasture (Giambelluca *et al.*, 2009). Full instrumental and methodological details can be found in Van der Molen (2002).

Modeling the effect of land-surface type on atmospheric circulation

To analyze the influence of the changes in energy partition and surface fluxes after forest conversion on atmospheric circulation, the meso-scale RAMS (Regional Atmospheric Modeling System) version 4.2 model (Pielke *et al.*, 1992) was used. The effect of the conversion was determined by comparing the atmospheric fields from a model run in which all vegetation up to 300 m elevation was parameterized as lowland forest ("forest run"), and another model run with pasture as the vegetation ("pasture run"), under otherwise identical conditions. The vegetation above 300 m.a.s.l. ("upland forest", comprising 30% of the land surface) was kept constant in the two runs and had its own parameterization based on measurements made over montane palm forest in the Luquillo Mountains. Because the exact parameterization of the upland forest is not essential in the present context, the reader is referred to Van der Molen (2002) for details.

The upper-air model results were verified with rawinsonde data, paying particular attention to the trade winds and atmospheric stability, to ensure a realistic reference case. Simulating the effect of (changes in) surface fluxes on atmospheric circulation at this level of scale requires that the largest of turbulent motions are resolved explicitly – in this case thunderstorms, convective cells, and meso-scale circulations such as sea breezes and mountain-valley winds – which typically have a horizontal extent of kilometers. Therefore, the finest horizontal grid resolution used in the model was 1 km, with a domain stretching 40 km out over the ocean from the north and south coasts. This fine, inner grid was nested within coarser grids (4 and 20 km spacing) with a larger domain, the coarsest of which covered 300 km of ocean on all sides of the island, thereby effectively removing the lateral boundaries from the area of interest. The finest grid had a relatively small extent of 21 km in an east–west direction to reduce computing time. Turbulent mixing was parameterized using the Smagorinsky-type local deformation scheme (Smagorinsky, 1963) and short- and long-wave radiation according to the Chen and Cotton scheme (1983, 1987) in which long-wave emissivities are tuned to match observed long-wave radiation at the surface. Cloud- and rain-water mixing ratios were parameterized using the cloud micro-physics scheme (with other particles disabled) of Walko *et al.* (1995). Initialization and forcing of the lateral boundaries of the coarsest grid were performed using National Center for Environmental Prediction reanalysis data.

The parameterization of the vegetation part of the model was given particular attention. The model frame, LEAF-2 (Walko *et al.*, 2000) has been constructed around the concept that the surface consists of vegetation (represented by a single "big leaf") and soil. All fluxes between vegetation, soil, and atmosphere are transferred through the canopy air, with the fluxes described as a function of gradients and resistances. Three types of fluxes and associated resistances are distinguished: (i) from vegetation to canopy air, (ii) from soil to canopy air, and (iii) from atmosphere to canopy air. The most important resistances are the aerodynamic (r_a) and surface resistance (r_s) because these determine the rate of transfer from the leaf surface to canopy air, and through the plant's stomata, respectively. In the present study, r_a was related to wind speed and r_s to global radiation, rendering the parameterization empirical rather than physical. However, successful tests of the parameterization ensured accurate representation of the respective fluxes and of vegetation/canopy–air temperatures and water-vapor mixing ratios by the model (see Van der Molen, 2002 for details).

The performance of the model in general and the vegetation module in particular was successfully verified for a relatively clear day (5 September 1997), considered typical for Puerto Rican summertime conditions in terms of strength and direction of the trade winds and the partitioning of net radiant energy into sensible and latent heat fluxes. In addition to the "forest" and "pasture" model runs, additional simulations were carried out to test the influence of (i) the presence of the ocean, (ii) the island's topography, and (iii) synoptic-scale weather conditions on atmospheric circulation and cloud formation.

RESULTS

Energy budgets over lowland forest and pasture

The most prominent changes in the surface energy balance as a result of forest conversion to pasture were: (i) an increase in albedo from 13–15% for forest to 18–23% for pasture (Figure 54.1), (ii) a reduction of *c.* 9% in net radiation R_n, and (iii) a reduction in sensible heat flux H and a concomitant increase in latent heat flux LE_v (Figures 54.2 and 54.3). The seasonal variations in albedo shown in Figure 54.1 are related to grazing and cutting of the grass

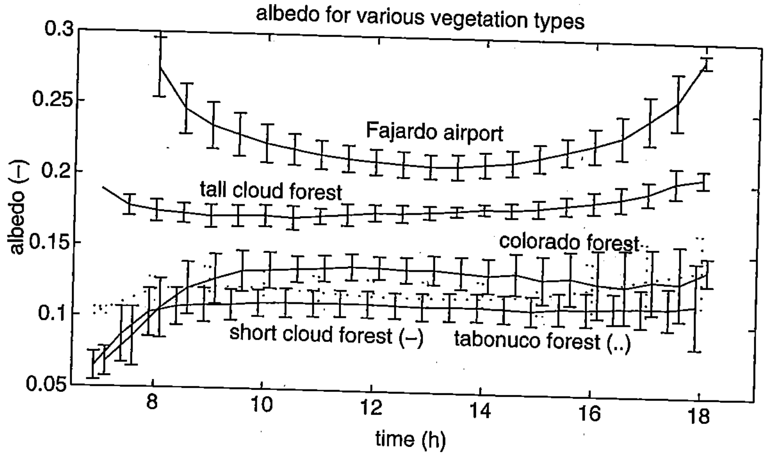

Figure 54.1. Seasonal course of daily albedo for wetland forest and pasture near Sabana Seca, northern Puerto Rico between May 1997 and May 1998.

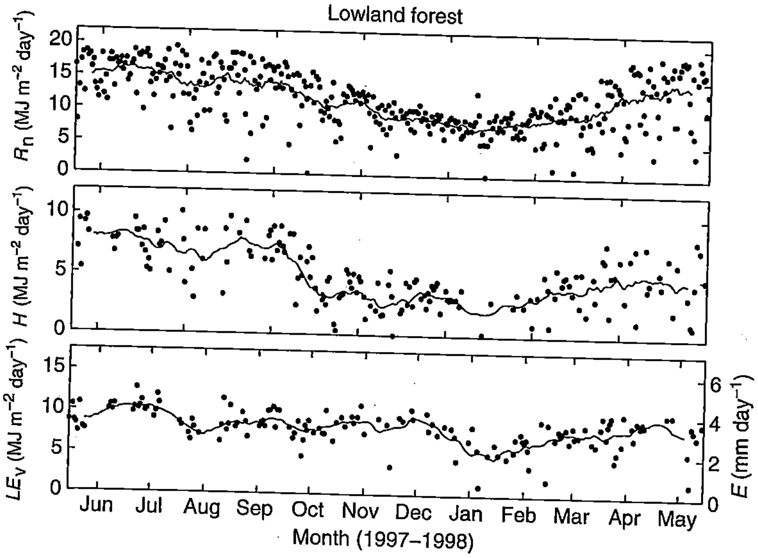

Figure 54.2. Seasonal course of daily totals of net radiation, and sensible and latent heat fluxes above a wetland forest near Sabana Seca, northern Puerto Rico between May 1997 and May 1998.

at the pasture site, and flowering and canopy closure after storm damage at the forest site.

The fluxes of sensible and latent heat constitute two important links between the land surface and the overlying atmosphere. The momentum flux (influenced by the aerodynamic roughness of the surface) is another link but this proved to be less important (Van der Molen, 2002). The seasonal changes in R_n, H, and LE_v for forest and pasture are shown in Figures 54.2 and 54.3, respectively. The 9% difference in R_n is clearly borne out but the most impressive change after forest conversion is the reduction in H from 4–10 MJ m^{-2} day^{-1} over forest to 2–3 MJ m^{-2} day^{-1} over pasture, whereas LE_v shows an opposite pattern (albeit to a lesser extent because of the reduction in R_n). The mean daily evapotranspiration rates (based on LE_v) determined for the forest and pasture were 3.3 and 3.8 mm day^{-1} or 69 and 81% of R_n, respectively.

The changes in energy budget after land-cover transformation were even more distinct on a diurnal basis. As shown in Figures 54.4 (forest) and 54.5 (pasture) the energy storage terms G (net soil heat flux), S (heat storage in vegetation), and J (idem in the air column below the top of the vegetation) were small compared to the radiant (R_n) and turbulent (H, LE_v) fluxes. Apart from the apparent difference in Bowen ratio (i.e. H/LE_v), the rates at which H and LE_v increased in the early morning differed as well: at the forest site they increased simultaneously, whereas in the pasture H started to increase *c.* 1.5 hours later than LE_v.

Model results

The agreement between modeled and observed vegetation and canopy air temperatures and water vapor mixing ratios, wind speeds, and momentum fluxes, as well as net long-wave and

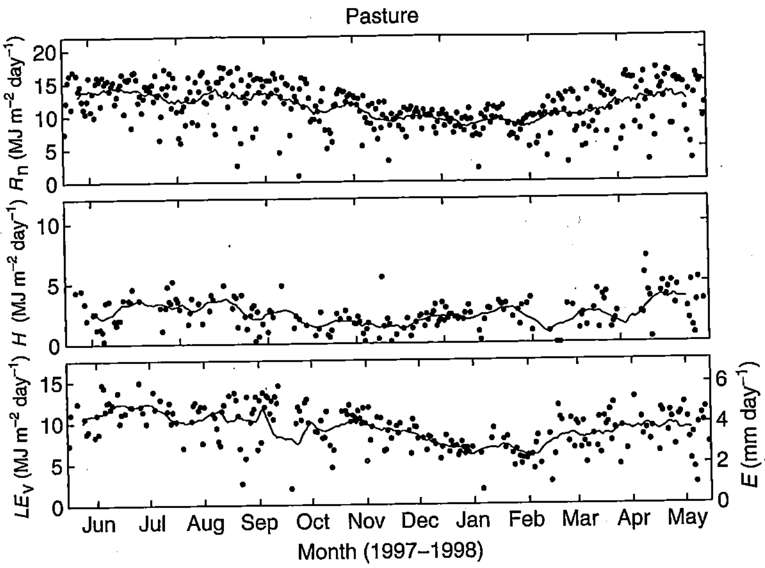

Figure 54.3. Seasonal course of daily totals of net radiation, and sensible and latent heat fluxes above a pasture near Sabana Seca, northern Puerto Rico between May 1997 and May 1998.

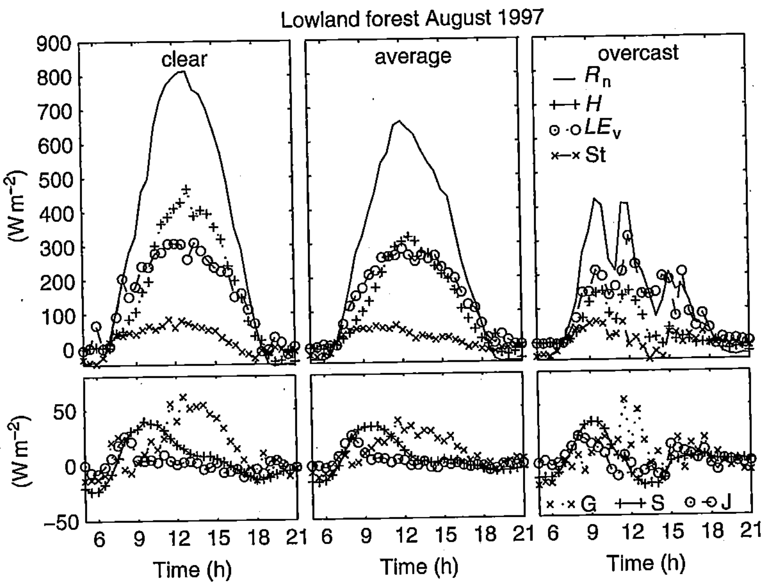

Figure 54.4. Monthly mean diurnal course of net radiation partitioning at the Sebana Seca wetland forest in August 1997 for clear, average, and cloudy days.

short-wave radiation totals was good, with deviations being much smaller than the respective diurnal variations (Van der Molen, 2002). Whilst the latter are not shown here for reasons of space, the strong agreement between the observed and modeled diurnal fluxes presented in Figure 54.6 is the result of the good matches obtained for the respective variables.

The results of the respective model runs are presented below in the form of averaged cross sections of atmospheric fields in a north–south direction over the island near the location of the experimental sites. A number of neighboring cross-sections were averaged to give a general impression of the atmospheric circulation over the island. Considering that both "forest" and "pasture" runs were initialized with identical atmospheric conditions, the model results are best compared for the early afternoon situation. By that time of the day the cumulative differences in atmospheric heat and moisture content between the two land covers have become sufficiently pronounced, whilst turbulence is still active, for instance at 15.00 h local time (Figure 54.7).

In the "forest" run, the potential temperature (top panel in Figure 54.7) near the land surface and above the island is about

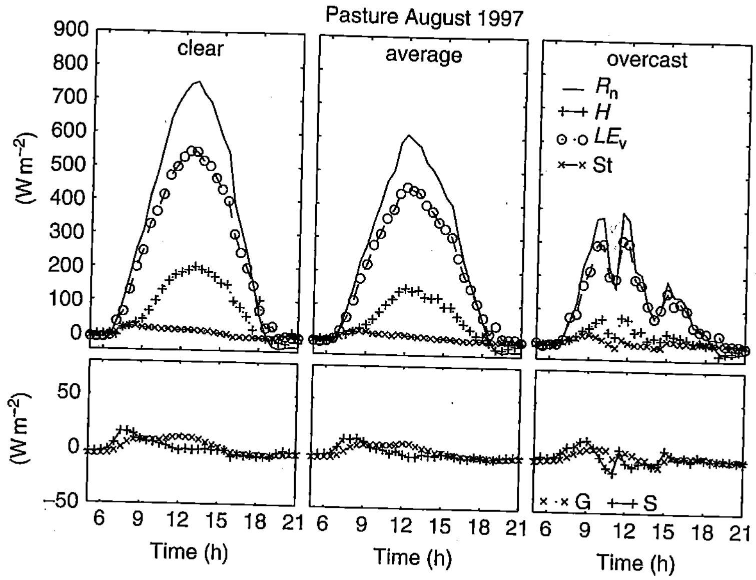

Figure 54.5. Monthly mean diurnal course of net radiation partitioning at the Sebana Seca pasture in August 1997 for clear, average, and cloudy days.

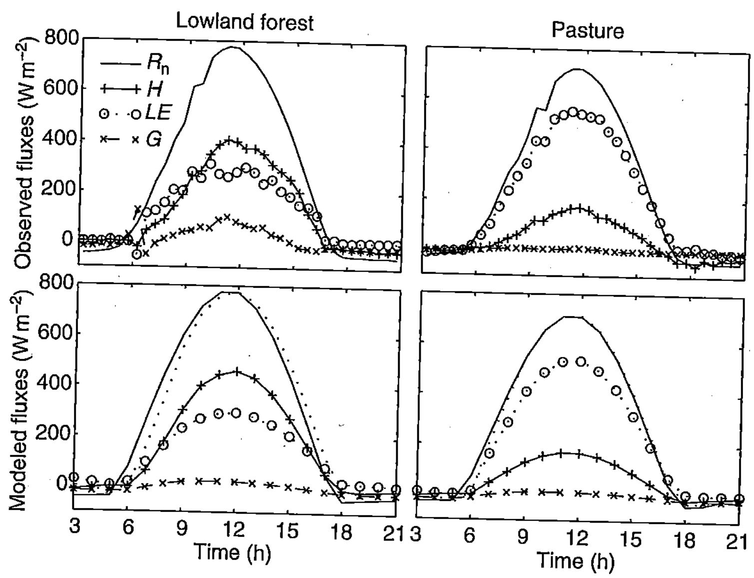

Figure 54.6. Observed (top panel) vs. simulated (bottom panel) surface energy budgets for lowland forest and pasture at Sebana Seca. The dotted line in the lower panel indicates the sum of sensible heat H, latent heat LE_v, and net soil heat flux G.

2 °C higher than in the "pasture" run. This renders the atmosphere above the island more unstable and well mixed to a higher elevation for the forested situation, as is also apparent from the distortion of the temperature contour lines at higher levels. The stronger convection associated with forest is also reflected in the number, size, and strength of convective cells above the island, indicated by the contour lines of positive vertical velocity (Figure 54.7, center of bottom panel). Directly related to this increased upward movement of air above the island, is the convergence of moist air from the ocean to the island from both sides (Figure 54.7, center of top panel) through the formation of a sea breeze. This sea breeze convergence determines the amount of moisture transported upward to levels where condensation (and therefore cloud formation) occurs (cf. Foster, this volume). Indeed, the bottom panel of Figure 54.7 indicates that more moisture is transported to higher levels in the "forest" run, creating denser clouds, albeit at a higher lifting condensation level (LCL) because of the higher temperatures (Figure 54.8).

Amounts of liquid water in the atmosphere as a function of time and height above the surface for the "forest" and "pasture" runs are shown in Figure 54.8. The amount of cloud condensate proves to be several times larger over an island with forested lowlands than with pasture. Moreover, the LCL is several hundred meters higher in the "forest" run than in the "pasture" run.

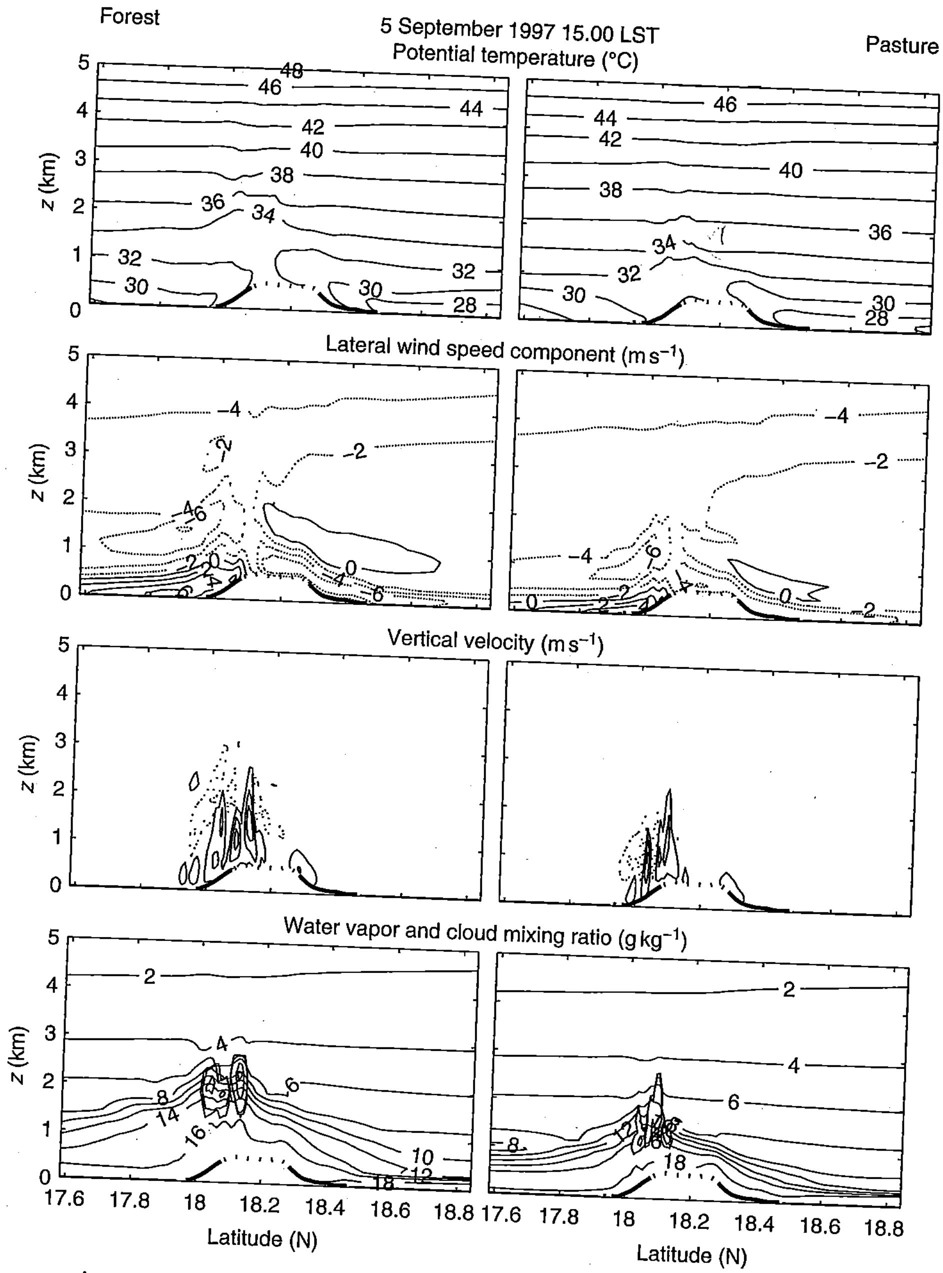

Figure 54.7. Averaged cross-sections of the atmospheric fields of potential temperature (top panel), lateral (S–N) wind speed (center top), vertical velocity (center bottom), and water vapor and cloud mixing ratio (bottom panel) in the model runs with lowland forest vegetation (left) and pasture vegetation (right). Negative contours are dotted, vertical velocity contours drawn every 0.25 m s^{-1} starting from 0.125 m s^{-1}, cloud water contours drawn at 0.001, 0.01, 0.1, 0.2, 0.3, . . . g kg^{-1}. The thick solid line indicates the location of the island with either lowland forest or pasture vegetation; where the line becomes dashed the vegetation is replaced by upland forest. Cloud water mixing ratio contours indicate values averaged over the longitudinal dimensions of the grid.

For all model runs, a fairly linear relationship was found between the liquid water mass in the model domain and the precipitation rate.

Proof of the earlier statement that the sea breeze is the main driver of the atmospheric circulation above Puerto Rico may be obtained by performing a simulation in which the ocean is replaced by extensive and identical lowland forest, thereby essentially removing the cause for the development of a sea breeze. Replacing the surrounding ocean by lowland forest showed the development of numerous small convective cells at regular intervals of about 10 km and reaching a height of 1–2 km. These cells quite effectively mixed water vapor and heat throughout the boundary layer, but failed to reach the LCL. In the case of "pasture" vegetation, the convective cells were less numerous and considerably weaker. However, in one of the cells some condensation occurred, which did not happen in the

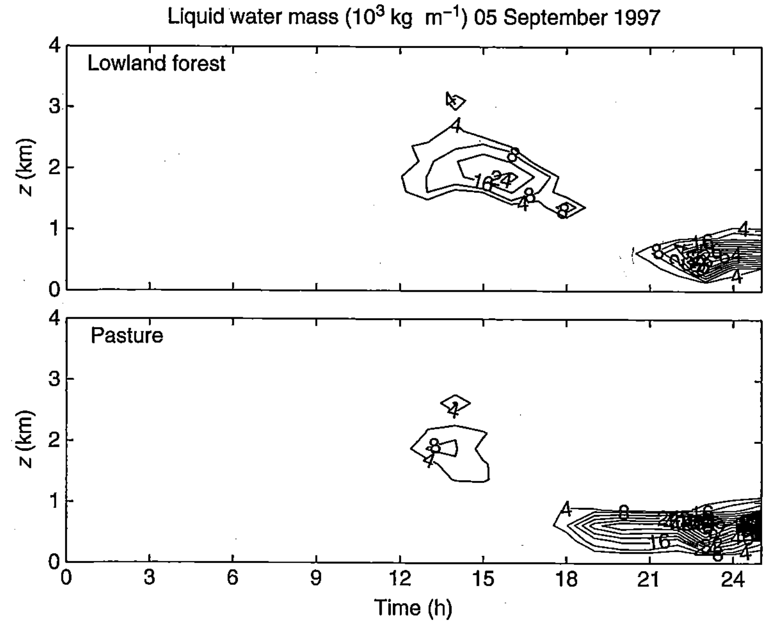

Figure 54.8. Liquid water mass over land in the finest grid as a function of time and height in thousands of kg per vertical meter. The land area over which the cloud mass is summed is 1452 km^2.

corresponding "forest" run. This may be attributed directly to the higher relative humidity of the air in the convective cells over "pasture," which resulted in a lower LCL (Van der Molen, 2002). This experiment indicates that the sea breeze acts to organize the convective cells into fewer but stronger cells and as such it may indeed be regarded as the driver of the local circulation (cf. Malkus, 1955).

Similarly, a model simulation was performed with the topographic height of the island set to zero so as to test whether or not mountain winds played a role in cloud formation. Removing the topography (but retaining the ocean) produced only minor differences compared to the original simulations with topography in place, indicating that: (i) the Luquillo mountains do not limit the inward penetration of the sea breeze front, (ii) orographic lifting does not have much effect on the meso-scale circulation, and (iii) mountain-valley winds play a minor role compared to the sea breeze circulation.

Simulations carried out under varying synoptic conditions indicated that the liquid water content of clouds was higher above an island with forested coastal plains, as long as the sea breeze dominated the circulation. In conditions with strong wind, a highly stable free atmosphere, or heavy cloud cover, the sea breeze did not develop. Under conditions of strong winds or overcast skies, turbulence is driven mainly by wind shear, resulting in smaller differences between "forest" and "pasture" runs. Conversely, when the boundary layer was topped by a highly stable free atmosphere, the convective cells simply were not able to penetrate high enough to reach the LCL and again the difference between "forest" and "pasture" simulations remained small.

DISCUSSION

Observational results

The present results for the change in albedo upon conversion to pasture are in agreement with other studies. Albedo values of 0.10–0.14 have been reported for various lowland tropical forests (Roberts *et al.*, 2005) vs. 0.17–0.20 for tropical pastures (Monteny and Gosse, 1976; Wright *et al.*, 1992; Culf *et al.*, 1995; Waterloo *et al.*, 1999). However, the presently obtained results for the associated changes in heat fluxes differ substantially from other studies, where midday latent heat fluxes over tropical rain forests are typically 400–500 W m^{-2} (Shuttleworth *et al.*, 1984; Tani *et al.*, 2003; Kumagai *et al.*, 2004), with associated Bowen ratios <1. For pastures in Amazonia, Bowen ratios of 0.43 have been reported under moist conditions, increasing to 0.96 after 20 days without precipitation (Wright *et al.*, 1992). Typical evapotranspiration rates (*ET*) for Amazonian forest and pasture are *c.* 4 and 2 mm day^{-1}, respectively (Shuttleworth *et al.*, 1984; Wright *et al.*, 1992; Gash *et al.*, 1996).

At mean *ET* rates of 3.3 and 3.8 mm day^{-1}, respectively, the water use of the lowland forest and pasture in Puerto Rico are at odds with the findings cited above for Amazonian forests and pastures. This has several reasons. First of all, due to frequent precipitation and high groundwater levels, water supply to the Puerto Rican pasture was never limiting, whereas in Amazonia moisture stress occurs during the dry season (Wright *et al.*, 1992). Furthermore, the *Pterocarpus* wetland forest at Sabana Seca grade into mangrove forests and frequently experienced brackish water at the surface, which may have caused physiological water stress. Also, the forest was relatively short-statured (14 m) compared to most other lowland tropical forests (typically 30–50 m high; Roberts *et al.*, 2005), whereas the Sebana Seca pasture had relatively tall grass, reaching maximum heights of 1.5–2 m in the absence of grazing (compared to <0.3 m in Amazonian pasture; Wright *et al.*, 1992). Such factors tend to reduce the normally found contrasts in evaporation between tropical grasslands and forest. Nevertheless, the similarity in average daily *ET* for the *Pterocarpus* forest and pasture is striking, given that the midday latent heat flux LE_v above the forest is almost half that above the pasture (300 vs. 550 W m^{-2} on clear days). This is because the maximum of LE_v at the forest site decreased much less going from clear to cloudy conditions, whereas at the pasture site this was associated with a decrease of almost 50% (Figures 54.4 and 54.5). This is yet another indication that the transpiration rate at the forest site was indeed limited by factors other than available energy.

Meso-scale modeling

The modeled sensitivity of the strength of the sea breeze to land-cover change is the logical consequence of the associated changes in surface fluxes and appears to be rather robust. The predicted changes in strength of the circulation and in the degree of cloud condensation are significant and in line with the observed trends in decreasing precipitation (Bisselink, 2003). However, the present modeling results cannot be translated directly to quantitative changes in amounts of cloud condensation or precipitation, because: (i) these have not been verified with observations, and (ii) the sea breeze circulation does not depend on the magnitude of H and LE_v alone, but also on atmospheric stability, strength of the trade winds, and other synoptic-scale weather conditions (Malkus, 1955).

In a similar modeling study of the effects of forest conversion to pasture in northern Costa Rica and adjacent Nicaragua, Lawton *et al.* (2001) derived higher cloud bases over pasture than over forested areas, a finding that at first sight would seem contradictory to the present results. However, in the latter study, H was higher for pasture and LE_v lower than for forest. As such, the underlying processes causing the predicted atmospheric changes appear to agree in the two studies. Nair *et al.* (2003) and Nair *et al.* (this volume) present further evidence in the form of satellite observations showing reduced cloud development over deforested areas in Costa Rica.

In the model run where ocean was replaced by lowland forest, the sea breeze did not develop; instead, numerous convective cells were formed that proved less than effective in transporting moisture upward to a level required for condensation. Some cloud condensation occurred in the associated "pasture" run, mainly because relative humidity was high enough for the convective cells to reach the lifting condensation level despite the fact that convection was relatively weak. This result is quite similar to modeling results obtained for Amazonia (Nobre *et al.*, 1991; Lean *et al.*, 1996), where, as in northern lowland Puerto Rico, higher cloud condensation and precipitation are associated with the vegetation having the highest *ET*, i.e. lowland rain forest in Amazonia and tall grassland in Puerto Rico. Thus, comparing continental and maritime tropical conditions, the main driver behind convection and cloud condensation appears to shift from LE_v to H. For the maritime case, this stands to reason because the moisture-laden trade winds blowing from the ocean bring in abundant moisture regardless of land-cover type.

The present study has focused mainly on dry canopy conditions. Indeed, including rainfall interception and subsequent recycling of re-evaporated water introduces so many new processes that the model used would not be applicable without a full verification and parameterization of the interception process (cf. Holwerda *et al.*, 2006). However, it is important to note that the sea breeze circulation depends on the presence of a significant sensible heat flux, a condition that may not be met under conditions with wet canopies where advected energy from the ocean seems to be the main driver of wet-canopy evaporation (Schellekens *et al.*, 2000; Holwerda *et al.*, 2006; Wallace and McJannet, 2006). Furthermore, the differences between "forest" and "pasture" runs were smaller under conditions of heavy cloud cover (Figures 54.4 and 54.5).

The model simulations further indicated that the conversion of wetland forest to pasture in Puerto Rico is associated with a lowering of the cloud base by up to several hundred meters, because the air feeding the convective cells is cooler and contains more water vapor. Whilst in reality clouds are frequently observed at altitudes of 600–1000 m.a.s.l., in the model simulations this was 1400–2000 m.a.s.l. Although actual cloud base observations are not available for the specific day for which the modeling was performed, the difference may reflect some combination of the prevailing weather conditions and inaccuracies of the model. Furthermore, it should be realized that the vertical grid spacing used in the model was about 100 m, i.e. a comparable order of magnitude as the differences in predicted LCL between the "forest" and "pasture" runs. Therefore, conclusions on the sensitivity of the cloud base to changes in vegetation cover are mainly qualitative at this stage.

The presence of the ocean appeared to be of crucial importance in this study, because of the dominant role of the sea breeze circulation which caused much stronger upward air movements than there would have been under continental conditions. An extension of the Puerto Rican work has demonstrated that the effects of meso-scale land-cover transformations on atmospheric circulation under maritime conditions across the tropics are much more pronounced than under more continental conditions (Van der Molen *et al.*, 2006).

CONCLUSIONS

The surface fluxes of radiation, sensible heat (H) and latent heat (LE_v) were measured above a wetland forest and a pasture considered representative of the pre- and post-deforestation situation in the coastal plain of northern Puerto Rico. Forest conversion to pasture increased the albedo from 13–15% to 18–23%. In combination with changes in net long-wave radiation, net radiation decreased on average by 9%. Average daily evapotranspiration (ET) amounted to 3.3 and 3.8 mm day^{-1} for the forest and pasture, respectively, whereas H decreased drastically from 4–10 MJ m^{-2} day^{-1} to 2–3 MJ m^{-2} day^{-1}. The change was also manifest in the diurnal course of surface energy fluxes: on a clear summer day in August, H and LE_v reached maxima of 420 and 300 W m^{-2}, respectively, above forest, vs. 200 and 550 W m^{-2} above pasture. The occurrence of frequent showers, a high groundwater table, and high foliar biomass provided optimum evaporation conditions in the pasture, in contrast to the wetland forest site which carried relatively short and open vegetation that was regularly inundated with brackish water as well.

The sea breeze proved to play a major role in the atmospheric circulation on the island. In a simulation with the lowland parts of the island forested, more sensible heat was predicted to be transferred from the surface to the atmosphere, resulting in stronger convection and consequently a stronger sea breeze than with lowlands under pasture. Also, the warmer and drier air above the forest (compared to that above pasture) led to a higher lifting condensation level (LCL). Because the first effect dominates, significantly more cloud condensation, and consequently precipitation, was predicted in simulations over a forested island. These results appear typical for clear days without a pronounced temperature inversion or strong winds, i.e. when a sea breeze circulation develops. Under cloudier or windier conditions, the contrasts between "forest" and "pasture" runs were less pronounced and even became reversed when atmospheric stability was too strong for convective cells to reach the LCL in the case of "forest", although not for "pasture."

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