Mesoscale Climate Change due to Lowland Deforestation in the Maritime Tropics

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Abstract

Annual precipitation on the Caribbean island of Puerto Rico decreased steadily during the 20th century, on average by 16 %. The reduced rainfall manifested itself in the form of regular water rationings during the 1990s which hit millions of inhabitants. Simultaneous with the reduction in rainfall there was widespread deforestation, notably in the coastal lowlands. This paper examines the link between the reduction in precipitation and the land cover change using a combination of energy balance measurements and mesoscale atmospheric modelling.

The explanation of the reduction in precipitation appears to be quite different than expected. Based on measurements made earlier over rainforest and pasture in the Amazon, a forest covered island would be expected to be cooler because the higher transpiration -of the forest compared to grassland- tends to cool the surface. During an intensive measurement campaign on Puerto Rico, the opposite appeared to be the case: transpiration by a coastal wetland forest proved to be less than that for a grassland. In addition, the

forest albedo was 8 % lower than that for grassland. Together, these two factors caused the sensible heat flux over the forest to be twice as high as that over the grassland, whereas forest evaporation was lower.

The surface energy balance observations over forest and grassland were used to derive proper land surface parameterizations, which were implemented in a mesoscale atmospheric circulation model (RAMS) to simulate the meteorological effects of island wide deforestation. The model simulations indicated that the development of a sea breeze during the day dominates climate on the island. Sea breezes develop when the land surface is warmer than the surrounding ocean. In model runs, where the island was assumed to be completely covered with forest, the sea breeze was considerably stronger than in model runs where the vegetation had been transformed to grassland. Along the sea breeze front, convergence caused upward air motions. As this happens more strongly over a forested island, more clouds are formed but at a higher elevation, with 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 determined. This project has offered new insights into the effects of climate change and may contribute to improved land use and water resources policies on Puerto Rico.

1.Introduction

Is land cover connected to cloud formation and precipitation? Such a relationship has indeed become evident in model studies for the Amazon basin, where forest has been cut on a very large scale, leading to a reduction in simulated amount of precipitation (Shukla et al., 1990, Lean and Rowntree, 1993, Dolman et al., 1999). The major causes for the change are identified as the increase in albedo, the reduction in transpiration as a consequence of the shallower root zone of the replacing grassland vegetation, as well as the reduced interception evaporation. Under the continental conditions of the Amazon, 30-50 % of the precipitation originates from local evaporation and transpiration (Lean and Warrilow, 1989, Eltahir and Bras, 1994, Costa and Foley, 1999), thus the direct impact on precipitation is clear. However, would these effects of land use change still apply to the much smaller scale of the Caribbean islands such as Puerto Rico (180 x 60 km)? One of the first direct observations of such an effect was the rise of the cloud base by a few hundred meters to well above the island's highest peaks (> 1000 m) after the passage of hurricane Hugo in September 1989 over the island, whereas these peaks are normally covered in clouds (Scatena, personal communication): Hugo caused islandwide defoliation, with apparent climatic consequences.

Changes in climate also appear in precipitation records. In a detailed trend study, Bisselink (2003) found precipitation totals in Puerto Rico decreasing significantly by -0.6 to -2.3 mm yr^{-1} in the summer half year (May - October) for the majority of 24 stations between 1931and 1996, although winter precipitation increased by 0.3 to 1.7 mm yr^{-1}. The eight stations with the longest period of record (± 100 years) all have negative trends in annual total precipitation between -1.59 to -4.90 mm yr^{-1}. Furthermore, 1997, 1994 and 1991 were the 2nd, 3rd and 6th driest years in the 20th century (Larsen, 2000). Societal significance is clear considering the mandatory water rationings, which occurred 6 times in the 1990's for periods up to six months, with strong impact on the human population, industry, agriculture and ecology and an estimated economic loss of $165 million in 1994 (Lugo and García-Martinó, 1996). An increase in the height of the clouds may also affect the biotope of the tropical montane cloud forest, which depends strongly on water supply from fog and low clouds (Pounds et al., 1999, Bruijnzeel and Hamilton, 2000).

These negative precipitation trends roughly coincide with the deforestation of the island, which started in the 16th century from the coastal plains towards the interior mountains, reaching levels of 65% in 1828, 80% in 1899, 91% in 1931 and 94% in the 1940's, the cleared land being used for agricultural purposes. After then, hill sides were abandoned due to erosion and land degradation, while government policy caused the island's economy to shift from agriculture to industry, so that the secondary forest cover gradually increased from the mountainside to 32 % in 1990, although urbanisations and industrial areas continue to take up more space in the lowlands (Wadsworth, 1950, Durland 1929, Gill, 1931, Koenig, 1953, Aide et al., 1995, Dietz, 1986, Birdsey and Weaver, 1982, 1987, Franco et al., 1997).

The objective of this paper is to determine whether land cover transformation in the coastal plains may cause the observed reduction in precipitation totals on Puerto Rico. As the effect of land cover change on the atmosphere is via the fluxes of energy, moisture and momentum, a year-long micro-meteorological field campaign was carried out to quantify these fluxes above typical original lowland forest and a nearby pasture, model for the deforested conditions. Next, the observations were used in a mesoscale atmospheric circulation model in order to assess the effects on climate. As a result, some of the following sections are made up of an observational and a modeling part, while both perspectives are converging near the end. Special attention is paid to the maritime conditions on Puerto Rico, in contrast with the continental conditions in the Amazon basin.

Clouds, their frequency, height, density and spatial distribution, form important conditions for the occurrence of Tropical Montane Cloud Forests ecosystems. This study shows that anthropogenic land cover changes have important implications for the regional climate through the formation of convective clouds.

2.Methods

2.1 The measuring campaign

Two experimental sites were selected with land cover representative for the era before and after the conversion of rain forest to agricultural lands. A particularly suitable location was found near the town of Sabana Seca (18°27'34"N, 66°12'30"W), some 15 km west of the outskirts of the capital of San Juan and about 1000 m inland from the coast line, with a stretch of virgin *Pterocarpus officinalis* forest and an area converted to pasture, within a kilometer from each other and with an unobstructed flow of air from the ocean in the mean wind direction. Prior to the arrival of the Europeans in Puerto Rico, *Pterocarpus officinalis* forests were the major freshwater wetland ecosystem, occurring on the northern coastal plains just behind the mangrove belts along the coasts, where the salinity dropped. *Pterocarpus* was also (one of) the most abundant tree species in mixed forests along the river floodplains (Holdridge, 1940, Woodburry, 1978, Eusse and Aide, 1999). Moreover, *Pterocarpus officinalis* is an important tree species all along the Atlantic coast from Brazil to Mexico and along the Pacific coast from Costa Rica to Ecuador and on the Caribbean islands except Cuba (Cintron, 1983, Janzen, 1978). A land survey in 1990 indicates pasture to be the most common post-deforestation land cover type, accounting for 52 % of the deforested area. Croplands (sugar cane, coffee and banana plantations) account for another 14 %, with the remaining land being used for urban and industrial areas, roads and water (Franco et al., 1997). As such the selected observation sites are representative of the general pre- and post-deforestation land cover types. Chapter 4 (Discussion) goes into more detail about the representativeness of the field sites.

At the forest site a scaffolding tower was erected and on the pasture site several masts were installed, which were equipped with micro-meteorological instrumentation, including long- and shortwave radiometers and eddy covariance equipment. The measurements were conducted from May 1997 until May 1998.

The fluxes of sensible heat, latent heat and momentum were calculated according to the Euroflux methodology (Aubinet et al., 2000), resulting in a closure of the energy balance of 103 ± 11% at the lowland forest site and 105 % ± 5% at the pasture site after applying the EUROFLUX method (Aubinet et al, 2000).

2.2 Modelling the effect of the land surface on the atmospheric circulation

With the effect of land cover transformation on the surface fluxes determined in the experimental campaign, the next step is to use that information to analyse the influence of the surface fluxes on the atmospheric circulation using a meso-scale atmospheric circulation model, for which RAMS (Regional Atmospheric Modeling System) version 4.2 was used. Using a numerical simulation model is a suitable method to analyze the effect of a relatively small distortion from a reference situation, in this case the change in surface flux related to the conversion lowland of forest into pasture. The effect of the conversion was determined by comparing the atmospheric fields from a model run in which the vegetation was parameterised as lowland forest and another model run with the vegetation as pasture, but otherwise identical conditions. In this study the upper air model results were verified with rawinsonde data, paying particular attention to the tradewinds and atmospheric stability, giving confidence that the reference case is realistic. Simulating the effect of surface fluxes on the atmospheric circulation on a medium large scale (smaller than continental) typically requires that the largest of turbulent motions are resolved explicitly, in this case thunderstorms, convective cells and mesoscale circulations such as sea breezes and mountain-valley winds, which are of an horizontal scale of kilometers. Therefore the finest horizontal grid resolution used in the model is 1 km, with a domain stretching 40 km out over ocean on the North and South coasts, while this fine grid is nested in coarser grids (4 and 20 km spacing) with a larger domain, with the coarsest domain covering 300 m of ocean on all sides of the island, thus effectively removing the lateral boundaries from the area of interest. The finest grid has a relatively small extent of 21 km in the East-West direction to conserve computing time. Turbulent mixing is parameterised using the Smagorinsky-type local deformation scheme (Smagorinsky, 1963) and short- and longwave radiation with the Chen and Cotton (1983,1987) scheme with the longwave emissivities tuned to match the observed longwave radiation at the surface, and cloud and rain water mixing ratios with the cloud microphysics scheme (other particles disabled) (Walko et al., 1995). Initialisation and forcing of the lateral boundaries of the coarsest grid is performed using NCEP re-analysis data.

The vegetation part of the model is given particular attention. The original model frame, LEAF-2 (Walko et al., 2000) is constructed with the concept that the surface consists of vegetation (a 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 a resistances. Thus four compartiments are distinguished, vegetation, soil, canopy air and (the lowest level of the) atmosphere and each is assigned a temperature and a water vapor mixing ratio. Correspondingly, there are three types of fluxes and resistances: from vegetation to canopy air, from soil to canopy air and from atmosphere to canopy air, consequently modelling the surface fluxes comes down to designing proper parameterisations for the resistances. The derivation of such parameterisations from observations is described in further detail in section 3.2. The difference between so-called ‘forest runs’ and ‘pasture runs’ is that in the lowland areas the parameters for forest are replaced by those of pasture. This change is applied only in the lowlands with an elevation below 300 m, while in both the forest and pasture runs the higher areas are covered by so-called upland forest, with its own parameterisation, resulting in fluxes somewhat in between pasture and lowland forest. In this configuration, 30 % of the land surface is attributed to upland area, which is realistic for the current situation. The upland forest parameterisation is derived from meteorological measurements in an area of palm forest in El Yunque in the North-East of the island. For space saving reasons and because the exact parameterisation of the upland forest is not essential in this study, this subject is not given more attention in this study, but the key parameters of upland forest are given in table 3.1.

The performance of the model in general and the vegetation module in particular was succesfully verified for a relatively clear day, 5 September 1997, typical for Puerto Rican summertime conditions with reference to the strength and the east/northeasterly direction of the tradewinds and the partitioning of net radiative energy into sensible and latent heat fluxes. The main conclusions are drawn from these simulations, whereas additional simulations are carried out to test the influence of the presence of the ocean, of the topography and of the synoptic scale wheather conditions.

3. Results

3.1. Observational results -- Comparing the energy budgets over lowland forest and pasture

The most prominent changes in the surface energy balance as a result of land cover changes are in the albedo and net radiation as well as in its partitioning into sensible and latent heat fluxes. Fig. 3.1 shows the annual course of albedo (reflection coefficient) of lowland forest and pasture, indicating that the forest reflects 13-15 % and the pasture 18-23 % of the global radiation. Variations of the albedo are related to grazing and cutting of the grass and flowering and closing of the forest canopy after storm damage. When taking the difference in longwave radiation in account as well, on average the net radiation appears to be 9 % larger over forest than on pasture.

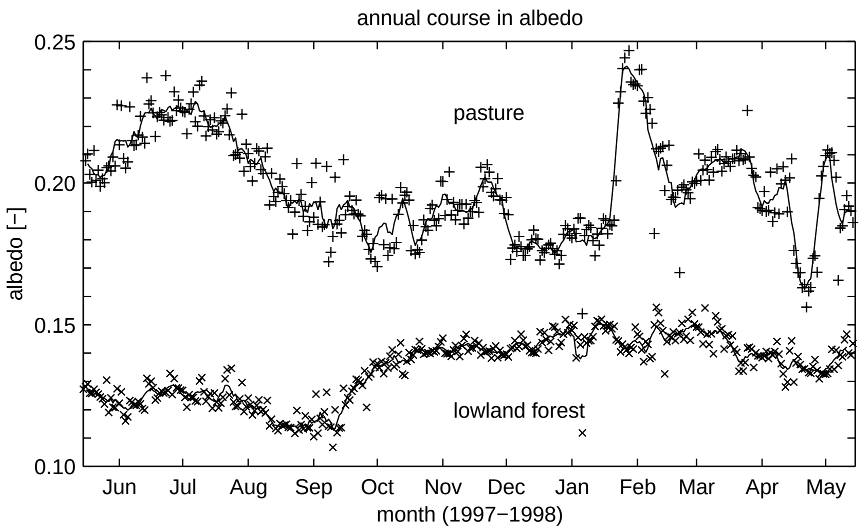

Figure 3.1. Annual course of albedo on lowland forest and pasture.

The fluxes of sensible and latent heat flux form one of the connections between the land surface and the atmosphere above. The momentum flux influenced by the surface roughness is another connection, which appears to be of less importance in this study. The seasonal courses of the net radiation and the sensible and latent heat fluxes, are shown in the Figs. 3.2 and 3.3.

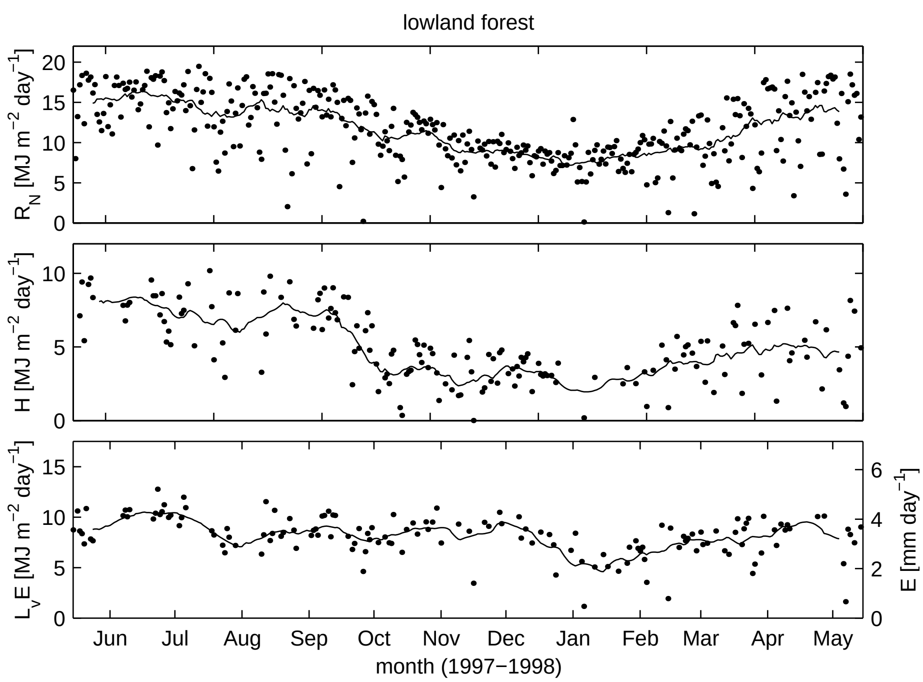

Figure 3.2. Seasonal courses of daily totals of net radiation, sensible and latent heat flux above lowland forest.

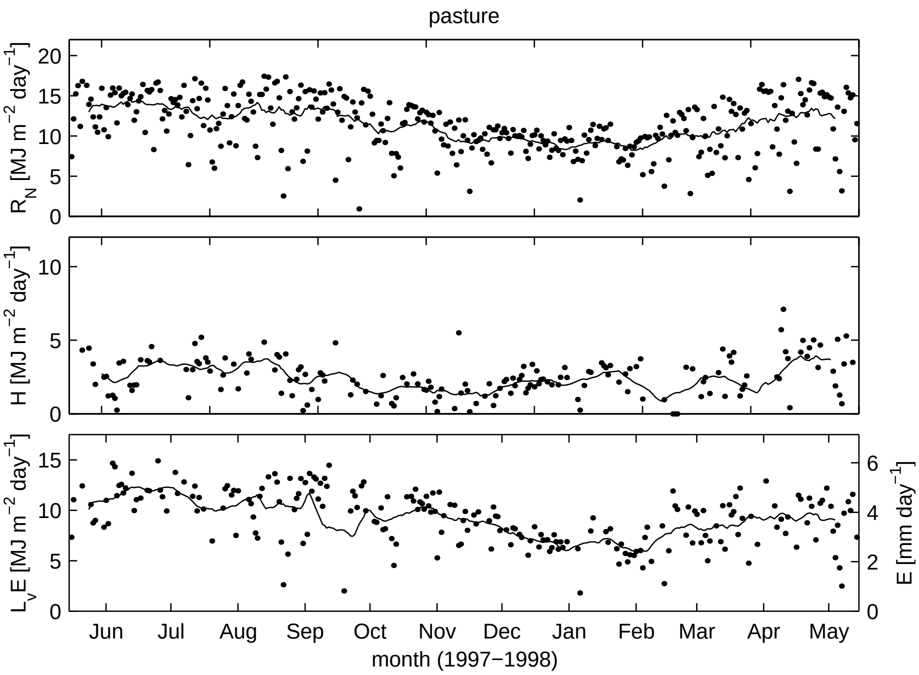

Figure 3.3. Seasonal courses of daily totals of net radiation, sensible and latent heat flux above pasture.

The 9 % difference in net radiation is clearly seen in Figs 3.2 and 3.3, but the most impressive change with land cover is the reduction in sensible heat flux from 4-10 MJ m^{-2} day^{-1} over forest to 2-3 MJ m^{-2} day^{-1} over pasture, whereas the latent heat flux (evapo-transpiration) shows the opposite pattern, but to a lesser extent: the annual mean evaporation plus transpiration rates on forest and pasture are 3.3 and 3.8 mm day^{-1} or 69 vs. 81 % of the net radiation, respectively. The changes in the energy budgets with land cover transformation become even more distinct in the Figs. 3.4 and 3.5, where the diurnal cycles are shown of the partitioning of the energy balance for the month August. Both graphs show that the storage terms G, S and J are small compared to the radiative and turbulent fluxes. Apart from the apparent difference in Bowen ratio, an interesting phenomenon is the difference in the rates at which the fluxes increase in the early morning: on the lowland forest H and L_vE increase simultaneously, whereas on the pasture the sensible heat flux starts 1.5 hour later than the latent heat flux.

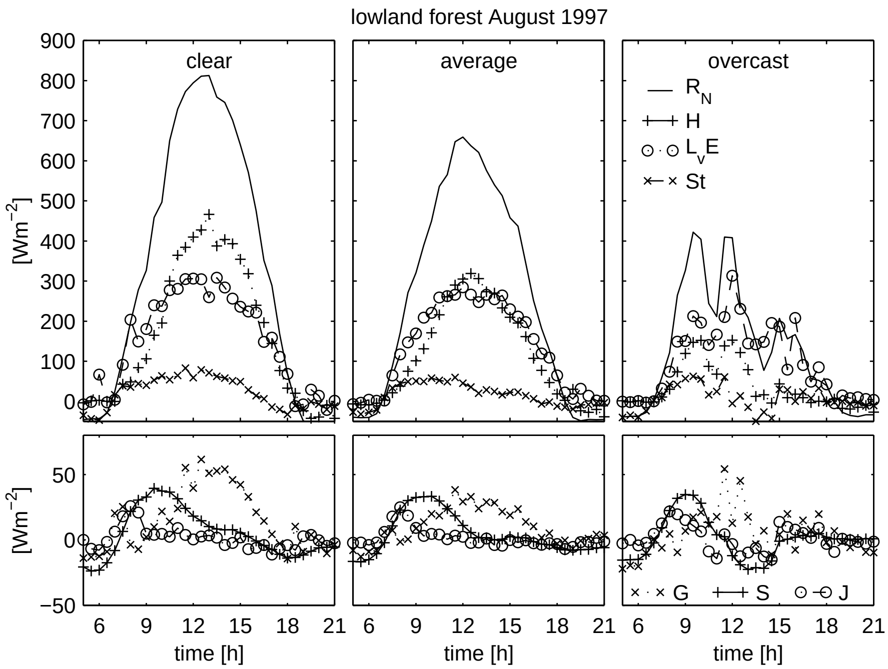

Figure 3.4. Monthly mean diurnal course of the partitioning of net radiation on the lowland forest in August 1997 for clear, average and cloudy days.

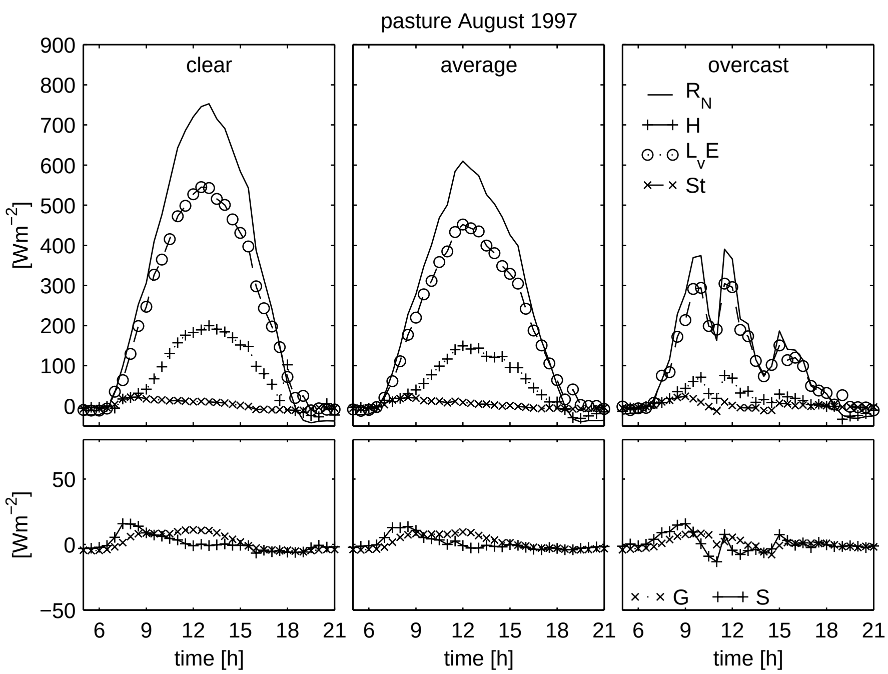

Figure 3.5. Monthly mean diurnal course of the partitioning of net radiation on the pasture in August 1997 for clear, average and cloudy days.

3.2. Vegetation parameterisation

Modelling the micro-meteorological effect of land use change consists for a large part of developing parameterisations for the net radiation and its partitioning, consistent with the representation of processes as a gradient-resistance model (section 2.2). The most important are the aerodynamical and surface resistance, which determine the rate of transfer from the leaf surface to canopy air and through the plant's stomata, respectively. In our approach, the aerodynamical resistance was related to wind speed and the surface resistance to global radiation, making the parameterization empirical rather than physical, however succesful tests of the parameterization in RAMS ensure an accurate representation of the fluxes and vegetation/canopy air temperatures and water vapour mixing ratios in the model (see section 3.3).

3.3. Modelling results

We have shown how observational micro-meteorological data were used to derive a proper parameterisation of lowland forest and pasture vegetation in the model. In this section we will show that with these parameterisations the surface processes are indeed accurately simulated. Not shown (to save space) is the agreement between observed and modeled vegetation and canopy air temperature and water vapor mixing ratio, wind speed and momentum fluxes, as well as longwave and shortwave radiation. All of these variables show good agreement, deviations are much smaller than the diurnal variations. A comparison of the diurnal cycle of observed and modeled fluxes is presented in Fig. 3.6, showing good agreement between both, as a result of the good match of the aforementioned variables.

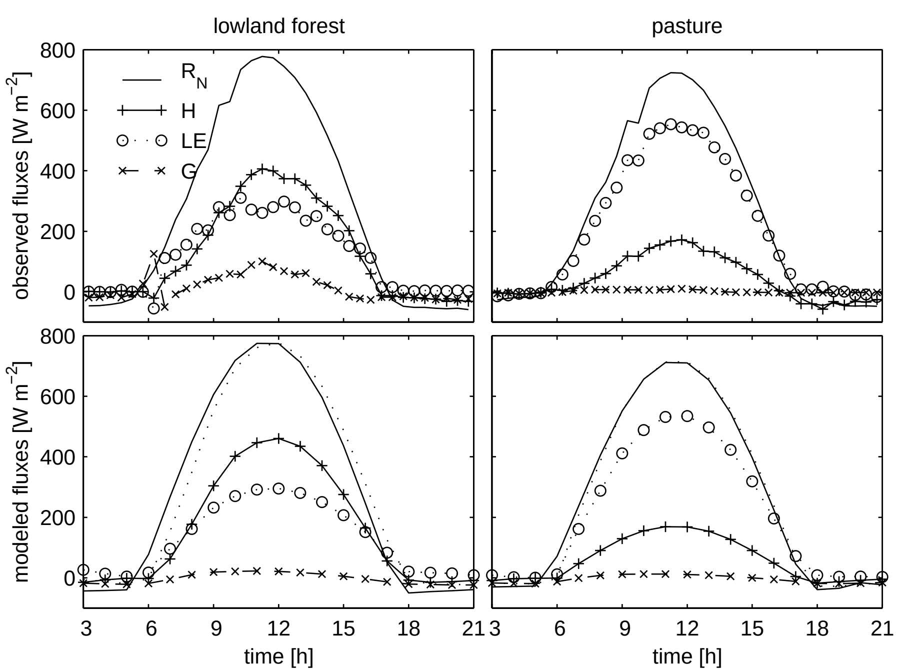

Figure 3.6 Observed (top) and simulated (bottom) surface energy budgets in the lowland forest and pasture model runs. The dotted line in the lower panels indicates the sum of H, LvE and G.

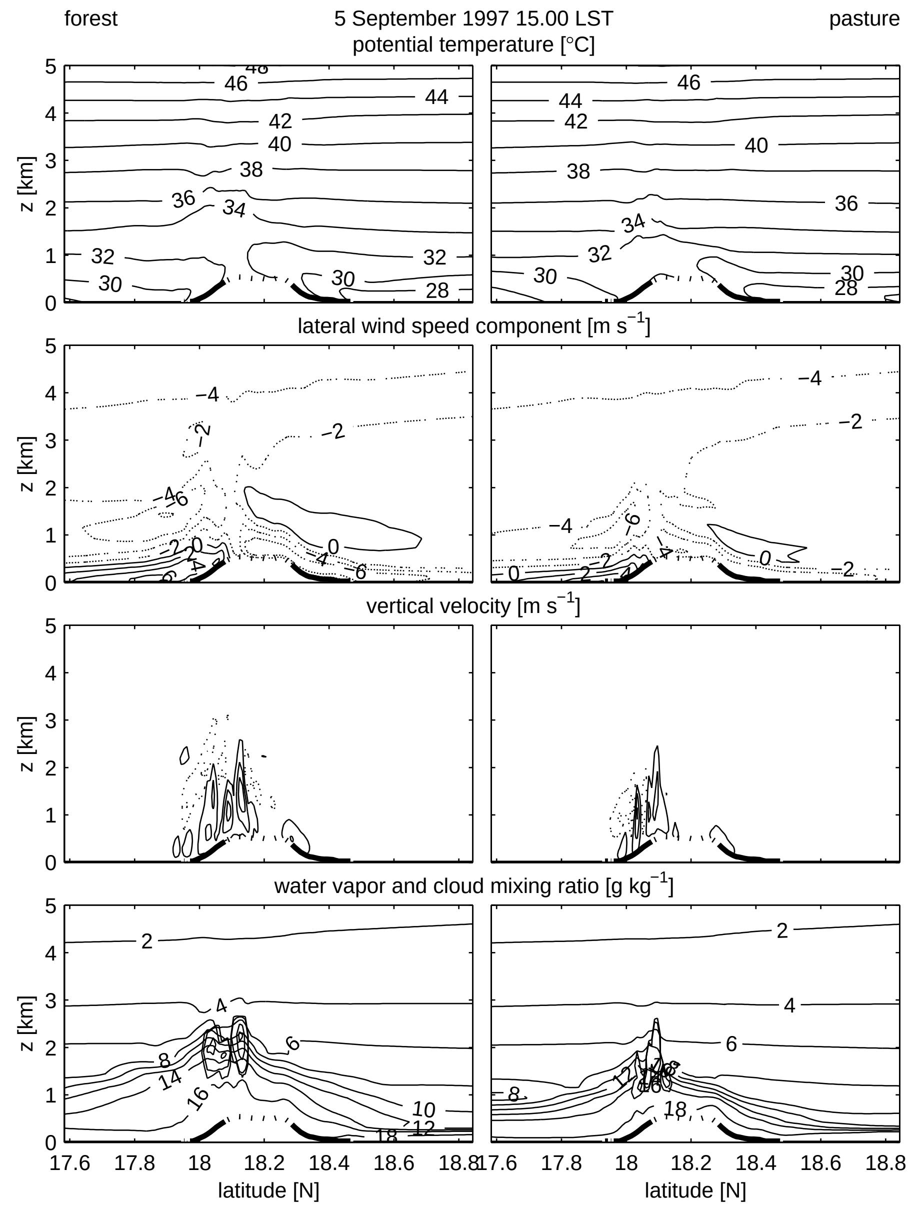

Figure 3.7. Average cross sections of the atmospheric fields of potential temperature (top), lateral wind speed (center top), vertical velocity (center bottom) and water vapour and cloud mixing ratio (bottom) in the model run with lowland forest vegetation (left) and pasture vegetation (right). Negative contours are dotted, vertical velocity contours are drawn every 0.25 m s^{-1} starting from 0.125 m s^{-1}, cloud water contours are 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 lowland forest and pasture vegetation, where the line is dashed the vegetation is replaced by upland forest. It is important to realise that the cloud water mixing ratio contours indicate values averaged over the longitudinal dimensions of the grid.

With a correct representation of modelled fluxes, forming the connection between the vegetation and the atmosphere, the effect of changing the vegetation on the atmosphere may be simulated as described in section 2.3. The results of the model runs are analysed in the form of averaged cross sections of atmospheric fields. The cross section is in the North-South direction over the island of Puerto Rico near the location of the experimental sites. A number of neighboring cross sections are averaged to give a general impression of the atmospheric circulation over the island. Considering that both model runs with lowland forest and pasture vegetation are initialized with identical atmospheric conditions, the model results are best analysed in the early afternoon, when the differences in fluxes have accumulated, but turbulence is still active, for instance at 15.00h local time (Fig. 3.7).

In the model run with lowland forest vegetation, the potential temperature (top) near the land surface and above the island is about 2 ^{o}C higher than in the pasture run, making the atmosphere above the island more unstable or well mixed to a higher elevation, as becomes apparent from the distortion of the temperature contour lines at higher levels as well. The latter is also reflected in the number, size and strength of convective cells above the island, indicated by the contour lines of positive vertical velocity (Fig. 3.7, center bottom): convection is stronger in the run with lowland forest vegetation. Directly interrelated with the upward movement of air above the island is the transport of air from the ocean to the island from both sides (Fig. 3.7 center top, lateral =South to North), thus forming a sea breeze circulation above the island. It is the convergence of this sea breeze circulation over the island which determines the amount of moisture that is transported upward to levels where condensation occurs, i.e. the cloud density. Indeed, Fig. 3.7 (bottom) indicates that more humidity is transported to higher levels in the model run with lowland forest vegetation, creating denser clouds with a higher cloudbase.

The mass of liquid water as a function of time and height for the forest and pasture runs are shown in Fig. 3.8. It clearly shows that the difference in the amount of cloud condensate is a few times larger over an island with forested lowlands than with pasture. Moreover, the lowest level at which clouds occur is up to a few hundred meters higher in the forest run than in the pasture run. The cloud formation in the evening seems to be erroneous, because it is the result of the model producing too much stability without mixing after sunset with related fog development. For all model runs, a fairly linear relationship was found between the liquid water mass in the model domain and the precipitation rate.

Previously in this section it has been stated that the sea breeze is the main driver of the atmospheric circulation above Puerto Rico, although without clear proof. This proof may be obtained by performing a simulation where the ocean is replaced with lowland vegetation, thus removing the causes for the development of a sea breeze. Similarly, a model simulation was performed with the topography height set to zero (but leaving the upland vegetation in place), so as to test whether or not mountain winds play a role. The simulations with the ocean replaced by lowland forest show the development of many small convective cells at regular intervals of about 10 km reaching a height of 1 to 2 km. These cells quite effectively mix water vapour and heat troughout the boundary layer, but fail to reach the cloud condensation level. In the case of pasture vegetation, the convective cells are less numerous and considerably weaker. However, in one of the few cells some condensation occurs, which does not happen in the corresponding forest run. This cloud condensation may directly be attributed to the higher relative humidity of the air in the convective cells, resulting in a lower cloud condensation level.

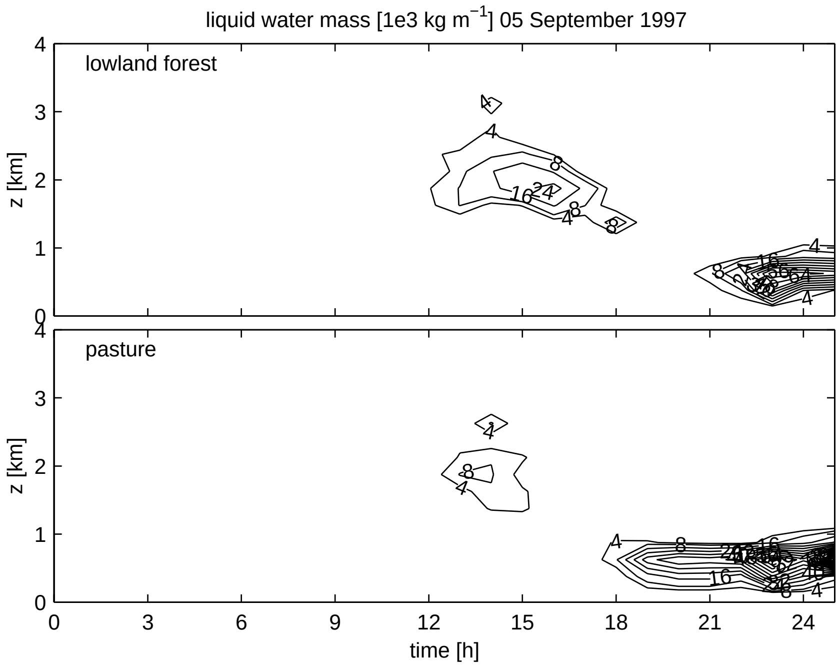

Figure 3.8. Liquid water mass over land in the finest grid as a function of time and height in thousans of kg per vertical meter. The land area over which the cloud mass is summed is 1452 km^2.

This experiment indicates that the sea breeze acts to organise the convective cells to fewer but stronger cells and as such the sea breeze may indeed be regarded as the driver of the circulation.
In the simulation with the topography removed (but with ocean), only minor differences were found compared to the original simulations, indicating that the mountains do not limit the inward penetration of the sea breeze front, that orographic lifting does not have much effect on the mesoscale circulation and that mountain-valley winds play a minor role compared to the sea breeze circulation.

Simulations carried out under varying synoptic conditions indicate that the liquid water content of clouds is higher above an island with forested coastal plains than when the plains are converted to pasture, when the sea breeze dominates the atmospheric circulation. In conditions with strong wind or a very stable free atmosphere or a heavy cloud cover, the sea breeze does not develop. In cases with strong wind or cloud cover, turbulence is mainly driven by wind shear, resulting in smaller differences between the forest and pasture runs, but in cases where the boundary layer is topped by a very stable free atmosphere, the convective cells are not able to penetrate high enough to reach the cloud condensation level. In these conditions, the difference between the pasture and forest simulations is small.

4. Discussion

4.1 Observations

The results of the measuring campaign are quite in agreement with other studies of land use change if we consider the effects of albedo change. A range of albedo of 0.08 to 0.14 is reported for a wide range of forest types and for pastures values of 0.17 to 0.20 (Jarvis et al.,1976, Monteney and Gosse, 1976, McCaughy, 1985, Culf et al., 1995, McCaughy, 1985, Waterloo, 1994). However, the flux results are quite different from other studies, where midday latent heat fluxes are typically 400 W m^{-2} over tropical rain forests (Shuttleworth et al., 1984, Wright et al, 1992), with consequently Bowen ratios smaller than 1. For pastures and ranchland in Amazonia, Bowen ratios of 0.43 are reported under moist conditions, increasing to 0.96 after 20 days without precipitation (Wright et al., 1992), corresponding to evapo-transpiration rates of 3.8 and 1.7 mm day^{-1}. The typical dry season evapo-transpiration rate for Amazonian ranchland appears to be 2.1 mm day^{-1}. It is clear that the annual mean evapo-transpiration rates of 3.3 and 3.8 mm day^{-1} at the Puertorican experimental sites of lowland forest and pasture form an effect of deforestation opposite to the Amazonian case. However, a few reasons may be mentioned for these differences with other studies: 1) due to frequent precipitation and high ground water levels, water supply for the pasture is never limiting, while in the lowland forest, being a coastal wetland, the water level is frequently above the surface, which may actually cause bio-physiological stress factors due to oxygen shortage and salinity, 2) the lowland forest has quite a different stature than typical tropical rain forests, being relatively short (14 m) and open (10 % estimated gap fraction), whereas the pasture has relatively tall vegetation reaching maximum heights of 1.5 to 2 m in absence of cattle. Still the experimental sites are considered representative for the conditions before and after land use change, while similar wetland pastures occur in Central America, for example, and are not unique for Puerto Rico. The location of the observation sites close to the coastline ensures a high ground water table during the majority of the year, whereas the groundwater table may drop along a transect towards the islands interior. If this would mean that pasture would transpire less due to water stress, while *Pterocarpus* forest may actually transpire at a faster rate because the bio-physiological stress factors are lessened, the contrast in Bowen ratio between pasture and forest would be reduced along the transect. However, there are a few facts that seem to suggests contrary to this argument: i) measurements of the Bowen ratio performed in February 1997 on a field near Fajardo Airport, a few kilometers from the coast at an elevation of 30 m were very similar to those taken at Sabana Seca in the same period (Van der Molen, 2002); ii) considering that Pterocapus is one of the most resilient tree species to wetland growing conditions, thus outcompeting other species in these areas, the occurrence of *Pterocarpus officinalis* prior to deforestation in the entire stretch of the coastal plains of Puerto Rico suggests the general presence of harsh wetland growing conditions in the coastal plains at that time; iii) the development of a weaker sea breeze after deforestation of the coastal plains of the island is identified as the main mechanism causing the changes in cloud regime. The development of the sea breeze as a result of the differential heating over land and sea would suggest that land cover changes closer to the coast line would have a stronger effect on the sea breeze than do changes further away, so that land cover changes in the elevated parts of the coastal plains may not be so relevant to climate change. While these arguments may not be conclusive and may be subject to experimentation, they do support the choice of the location of the measurement sites as representative for and relevant to the changes studied.

It is striking that the average daily evapo-transpiration at lowland forest and pasture sites are not very different (3.3 and 3.8 mm day^{-1}, Figs. 3.2 and 3.3), while the diurnal cycles show that during midday the latent heat flux above lowland forest is almost half of that over pasture (300 vs. 550 W m^{-2} on clear days, Figs. 3.4 and 3.5). This is because for the lowland forest the maximum latent heat flux decreases much less going from clear to average and cloudy days, whereas at the pasture site this is associated with a decrease of almost 50 %. This is yet another indication that the transpiration rate at the lowland forest is limited by factors other than available energy.

The current study is mainly focussing on the effect of land use change on the surface fluxes under dry conditions. While the flux measurements were continued during precipitation, and interception evaporation was usually observed to increase the latent heat flux under wet conditions, the accuracy of the results may be a matter of debate. However, evaporation of intercepted rainfall has been reported to be 8 – 11 percent for lower montane cloud forest in the Luquillo Mountains in the North East of the island (Frangi and Lugo, 1985, Krelinger and Krijgsman, 2001). Schellekens et al. (2000) suggests interception rates of over 50 % on an annual basis for that site. However, due to the location of these sites in the lower part of the mountains the frequency of showers is much higher than at the current experimental sites in the coastal plains.

4.2 Modelling

The result of the sensitivity of the sea breeze appears rather robust, as it is the logical consequence of the change in surface flux with land use change. The differences in strength of the circulation and in the amount of cloud condensation are significant and confirm the observations of decreasing precipitation trends. However, the modelling results cannot be directly translated into quantitative changes in amount of cloud condensation or precipitation, i) because these have not been verified with observations, ii) and because the sea breeze circulation does not only depend on the surface fluxes, but also on atmospheric stability, strength of the (trade-) winds, and other synoptic scale weather conditions.

In a model study of the effects of land cover change in Central America (Costa Rica), Lawton et al., (2001) found that cloud bases are higher over pasture than over forested areas, as opposite to our results. However, in their model study the sensible (latent) heat flux was higher (lower) for pasture than for forest, which is opposite to our results as well. As such, the processes causing the atmospheric changes appear to agree in both studies. Nair et al. (2003) present satellite observations showing that the cloud development over deforested areas in Costa Rica was reduced with respect to forested areas

that he model simulations agree well with satellite observations of cloud distributions
found
In the model run with ocean replaced by lowland vegetation, the sea breeze did not develop, instead numerous convection cells formed, which were less effective in transporting moisure to condensation levels. In that case, cloud condensation occurred in the pasture run, but not in the forest run. Although convection was relatively weak above the pasture, the relative humidity was high enough for the convective cells to reach the lifting condensation level. This result is quite similar to modeling results obtained above Amazonia, where more cloud condensation and precipitation occurs over the vegetation with the highest evapo-transpiration rate, even if this vegetation is rain forest in Amazonia, and not pasture. Thus, comparing continental and maritime conditions, the role of the main driver behind convection and cloud condensation is switched from the latent heat flux to the sensible heat flux. And in the maritime case, this is quite comprehensible, because water vapor is abundant in the tradewinds.

As mentioned in section 4.1, this study is mainly focussing on dry conditions, when rainfall interception plays no role. The effect of rainfall interception and recycling of cloud water introduces so many new processes not addressed in this study, that the used model would not be applicable without re-verification and parameterisation of interception. However, it is important to note that the sea breeze circulation depends on the presence of significant sensible heat fluxes, a condition that may not be met under conditions with precipitation. In section 3.3 we observed that the difference between the forest and pasture runs were smaller under conditions of heavy cloud cover.

The model simulations indicate that the conversion of vegetation to pasture is associated with a lowering of the cloud base with up to a few hundred meters, because the air feeding the convective cells is cooler and contains more water vapour. The question how this result should be interpretted. In reality clouds are frequently observed at altitudes of 600 to 1000 m, but in the model simulations this is 1400 to 2000 m, while cloud base observations are not available for this specific day, the difference may be related to the specific weather conditions on the testing day, but it could as well be a modelling inaccurracy. Furthermore it must be realised that the vertical grid spacing is about 100 m, which is of the same order of magnitude as the differences between the runs. Therefore conclusions on the sensitivity of the cloud base to changes in vegetation cover should be mainly qualitative in this stage.

The presence of the ocean appears of crucial importance in this study, because of the dominating role of the sea breeze circulation, causing upward air movements to be much stronger than they would have been under continental conditions. This study has shown that under maritime conditions meso-scale land cover transformations are able to cause significant changes in the local atmospheric circulation, with consequences for the occurrence of clouds and precipitation.

5. Conclusions

5.1 Observations

The surface fluxes of radiation, sensible and latent heat were measured above a lowland forest and a pasture in the coastal plains of Puerto Rico, representative of the pre- and post deforestation situation. Change of the land cover from lowland forest to pasture is associated with an increase of albedo from 13-15 % to 18-23 %. In combination with changes in the net longwave radiation, the net radiation decreases by an average 9 %. The average daily evapo-transpiration amounts to 3.3 and 3.8 mm day^{-1} for lowland forest and pasture, while the sensible heat flux decreases drastically from 4-10 MJ m^{-2} day^{-1} to 2-3 MJ m^{-2} day^{-1}. This change also becomes apparent in the diurnal courses: on a clear summer day in August, the sensible and latent heat fluxes reach a maximum of 420 vs. 300 W m^{-2} above lowland forest and 200 vs. 550 W m^{-2} over pasture.

The reason why conversion of lowland forest to pasture results in an increase in evapo-transpiration rate, which is not generally found in other land use change studies (e.g, in Amazonia), is the occurrence of frequent showers and a high ground water level, supplying sufficient water in combination with the relatively short and open character of the lowland forest and the tall stature of the pasture vegetation. Although the Puertorican situation is thus different from tropical continental studies, these vegetation types are representative for Puerto Rico and other Central American countries before and after land conversion.

5.2 Simulations

The sea breeze appears as the driver of circulation above the island of Puerto Rico. In a simulation of the circulation above an island with a forested lowland, more sensible heat is transferred from the surface to the atmosphere, resulting in a convection above the lowlands and consequently a stronger sea breeze. Due to convergence of the sea breeze above the island, upward air motions become stronger and a circulation develops. In the circulation, air is transported upward from near the surface, and above lowland forest this air is warmer and drier than above pasture, having two effects: 1) the sea breeze circulation is stronger above lowland forest and 2) the cloud condensation level is higher. Because the first effect dominates, significantly more cloud condensation with consequent precipitation occurs in simulations over a forested island. This results appears typical for clear calm days without a strong capping inversion and without strong winds, i.e. typical for days when a sea breeze circulation develops. On other days, the differences between the forest and pasture runs are less pronounced and may be reversed in the case when the atmospheric stability is too strong for convective cells to reach the cloud condensation level above lowland forest, but not above pasture.

The cloud base, the lowest level at which cloud condensation occurs, is determined by the relative humidity of the air feeding the circulation and because in the forest run the air is warmer and contains less moisture, the cloud base is higher than in the pasture run. The simulated increase of the cloud condensation level is in the order of 100 m, although this result is probably better used in a qualitative way because of related uncertainties.

6.References

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