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Impact of Deforestation on the Sustainability of Biodiversity in the Mesoamerican Biological Corridor

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1. Introduction

Tropical rain forests play an essential role in housing global biodiversity, and they accommodate more than 50% of all species in the world while occupying only ~10% of the surface land of the Earth [*Myers*, 1992; *Pimm*, 2001]. However, during the last 10,000 years humans have significantly influenced land surface characteristics by altering the vegetation to include plant species more suitable for their consumption, a process that includes converting forests to agricultural lands, livestock grazing, and building settlements [*DeFries et al*., 2004]. Current rates of deforestation are extremely high and are known to have significant impact on regional and global atmospheric and climate changes [*Laurence et al*., 2004] in addition to the direct local effects of deforestation. The scale and speed of global habitat loss and fragmentation is alarming, with only about half of the pre-industrial forest areas remaining as forests. These forest fragments are becoming the only refuge for most of the global tropical wildlife, but as these habitats fragment into smaller and smaller pieces and become more isolated, local extinction rates accelerate [*Bennett*, 1999].

Central America or Mesoamerica, which occupies only 0.5% of the global land area, provides habitat for more than 7% of the world's species [*Mittermeier et al*., 2000]. This region has a population growth rate of > 2% per year with high levels of poverty, unsustainable exploitation of natural resources, soil erosion and one of the world's highest rates of deforestation, losing 2.1% of forests/year [*FAO*, 1999]. This scale and speed of habitat loss and forest fragmentation in one of the earth's biologically richest regions has led conservationists to propose the Mesoamerican Biological Corridor (MBC) project, an integrated regional initiative intended to conserve biological and ecosystem diversity in a manner that also provides sustainable economic development [*Carr et al*., 1994; *Miller et al*., 2001].

The MBC is an ambitious effort intended to connect large existing isolated parks, forest fragments and reserves with new protected areas through an extensive network of biological corridors within the five southern states of Mexico and the Central American countries (Guatemala, Belize, El Salvador, Honduras, Nicaragua, Costa Rica and Panama). The intent is to establish an environment that provides better prospects for the long-term survival of the native species, provides migratory pathways for the others, and addresses the region's socioeconomic needs. This would stem and reverse the erosion of biodiversity in the existing forest fragments in Mesoamerica. Ideally these proposed connecting corridors would contain the biological communities that were originally present. However, most of the current and proposed connecting corridors do not contain their original forest, but are instead occupied by agricultural landscapes containing croplands, grassland and various forms of degraded woodlands. Additionally, these regions have a varied topography of altitudes ranging between sea level and 3000 m. The topography and land characteristics of the corridors vary widely, from lowlands to high mountain peaks and dense-forest regions to croplands and woodlands respectively. The establishment of fully functional corridors will depend upon the regrowth of forests in many areas. However, the extent of deforestation within Central America may already have had climatic consequences that affect the stability and sustainability of currently protected areas and the proposed corridor regions [*Laurence et al*., 2004].

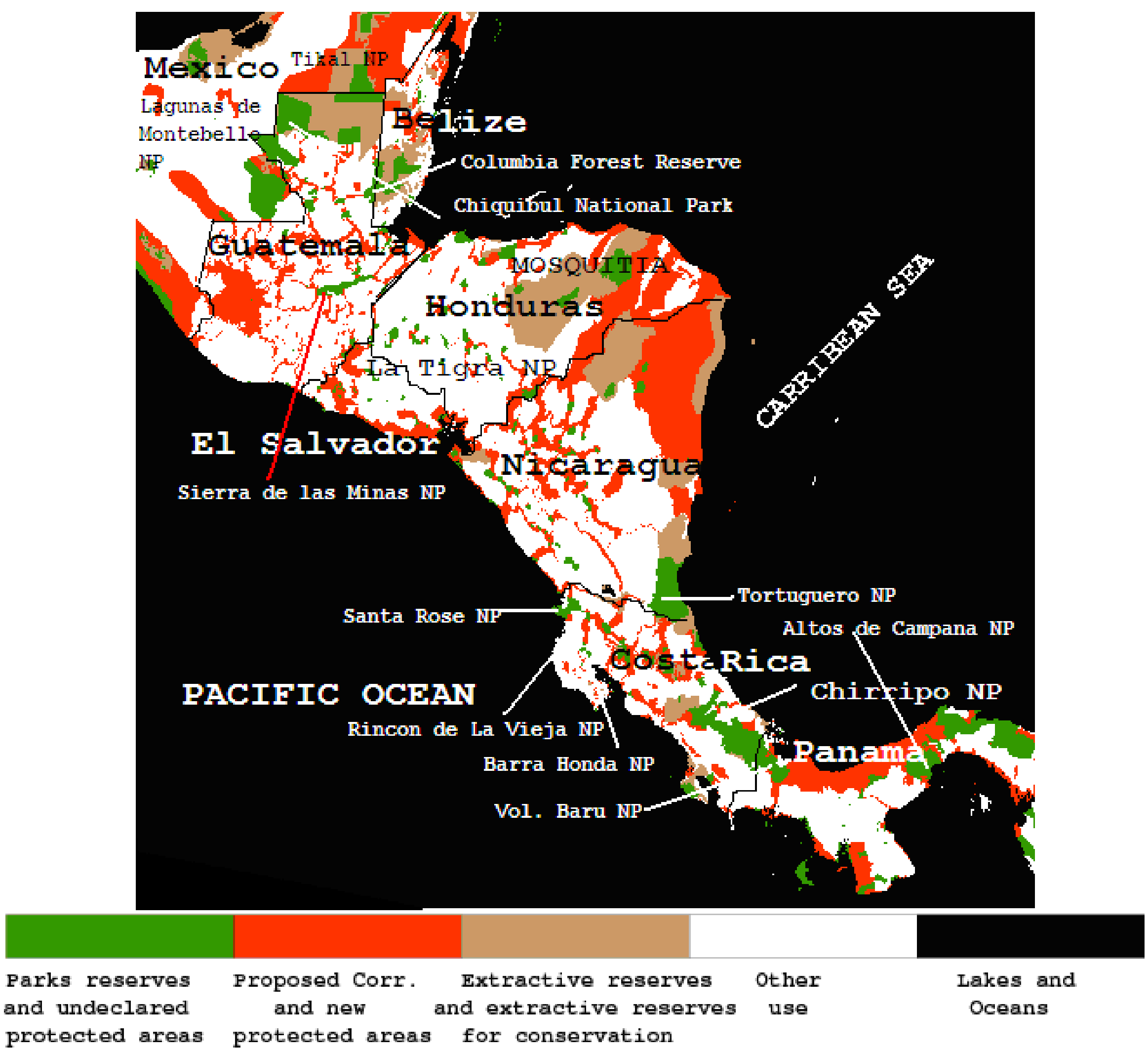

Fig. 1. The map of the Mesoamerican Biological Corridor.

According to the Intergovernmental Panel for Climate Change (IPCC) 3rd Assessment report [*IPCC*, 2001], there are high chances of adverse impacts on the existing natural global ecosystems, biodiversity and food supply due to the projected climate changes in the future.

Observations show that there have been decreases in frog population and other small mammals that may be related to climate change [*IPCC*, 2001].

Previous studies show that changes in land use impact regional climate which in turn may enhance and sustain these changes [*Hansen et al*., 2001; *Hansen and Rotella*, 2002; *DeFries et al*., 2002]. Deforestation changes the surface energy budgets and generally decreases latent heat (LH) fluxes from surface to the atmospheric boundary layer and increases the sensible heat (SH) fluxes [*Lawton et al*., 2001; *Nair et al*., 2003; *Ray et al*., 2006]. The net result is hotter and drier air over the deforested and forested regions leading to increased dryness. However due to the continuous deforestation throughout Central America, there is concern about the long-term stability and even the sustainability of the MBC. This chapter is built upon studies to understand the environmental stability of forests in the corridors and their surroundings.

The map of the proposed MBC is shown in Figure 1. The regions in red color in the map are the proposed corridor regions. National parks and protected areas are shown in green color. The extractive reserves shown in brown color are proposed for conservation. Some hunting and logging are permitted in these reserves. However, loggings in the extractive reserves are followed by reforestation. The guiding rules for the extractive reserves vary from country to country, but the basic requirement of reforestation is the same.

There are 600 protected areas as a part of the MBC network [*Herrera*, 2003]. The number and percent of territory covered by these protected areas are given in Table 1.

Country	Number of protected areas	% of territory covered by the protected areas
Southern Mexico	33	18.8%
Belize	59	44.8%
Guatemala	104	26.3%
El Salvador	3	1.6%
Honduras	106	19.0%
Nicaragua	76	21.7%
Costa Rica	151	24.6%
Panama	69	29.5%

Table 1. The number of protected areas in each territory and the percentage of area covered by them.

According to Central American Protected Areas System (SICAP), 29 percent of the protected areas which had been legally designated by 1998 cover less than 1,000 hectares and 67 percent of protected areas cover less than 10,000 hectares. Only 22 are larger than 100,000 hectares and only four of these cover more than 500,000 hectares.

2. Impact of deforestation on regional hydrometeorology

The clearing of forest results in an immediate reduction of intercepted water storage capacity followed by a decrease in interception and transpirational loss of water to the atmosphere [*Swift et al*., 1975; *Eshleman*, 2004]. This is in turn followed by increase in runoff and/or overall decrease in water yield capacity [*Whitehead and Robinson*, 1993]. Further, deforestation leads to decrease in the water storage capacity of the soil [*Shukla et al*., 1990] as well as the fraction of available soil moisture [*Ray et al*., 2003; *Manoharan et al*., 2009]. Additionally, the deforestation reduces the overall roughness of the surface [*Gash and Nobre*, 1997] and increases the albedo above the region [*Costa et al.*, 2007]. These factors have high impact on the aridity of these places. Moreover, deforestation leads to warming in the Tropics and cooling in the temperate regions [*Bonan*, 2004]. The changes in temperature can range from a couple of degrees to tens of degrees Celsius [*Gash and Nobre*, 1997; *Ray et al.*, 2003; *Manoharan et al.*, 2009]. Thus, deforestation changes land cover. Thus influencing the albedo, surface temperature, soil fertility, surface roughness, soil moisture and changes in the magnitude of thermal energy (LH and SH) fluxes. The above changes, in turn, influence the regional boundary layer depth, cloudiness, cloud optical properties and local rainfall [*Nair et al.*, 2003; *Ray et al.*, 2003; *Pielke*, 2001]. In a stable atmosphere the clouds tend to form earlier over the moist surfaces, whereas in a less stable environment, the clouds tend to form earlier over the drier surfaces [*Wetzel et al.*, 1996]. In a forested region the boundary layer air tends to be moister than in a deforested region. An average difference of 1g kg^{-1} difference in specific humidity has been observed between the forested and deforested forests in the Amazon [*Bastable et al.*, 1993]. *Pielke* [2001] provides a detailed review of the influence of vegetation and soil characteristics on cumulus cloud formation and precipitation, and notes in particular that the alteration in heat fluxes as a result of deforestation modifies the convective activity by modifying the environment for thunderstorms, which are an effective conduit of heat, moisture, and momentum to higher latitudes and exerts major impacts on global weather and climate.

MBCs are regions of contrasting vegetation types such as forests adjacent to deforested regions. There are several observational and modeling studies [*Segal et al.*, 1988; *Avissar and Liu*, 1996; *Weaver and Avissar*, 2001] that have shown that such contrasting vegetation types lead to differential heating which in turn results in sea-breeze-like mesoscale circulations that increase cloudiness. *Avissar and Liu* [1996] noted that the updrafts created by surface heterogeneity are much stronger than those created as a result of mechanical turbulence. Climatic feedbacks from deforestation can also alter rainfall patterns, initially increasing [*Avissar et al.*, 2002] then followed by drastic decreases in precipitation [*Avissar et al.*, 2004]. For example, *Lyons et al.* [1993] showed that in southwest Australia a substantial clearing of native vegetation led to a 20% decrease in local winter rainfall. Also *Ray et al.* [2003] in their study over western Australia along the bunny fence (a rabbit proof fence running 750 km separating the native vegetation from the farmland) area observed a higher frequency of low level cumulus cloud cover over the native vegetation side than over the farmland. The land use changes led to differences in soil moisture availability and hence the surface energy fluxes which in turn enhanced the cumulus cloudiness over the native vegetation than the agricultural land. However other studies by *Otterman* [1990], *Sud et al.* [1993], *Pielke et al.* [1998] show that deforestation leads to decreases in rainfall. Since the mid 1970s, tropical forest regions have experienced declines in precipitation at a rate of 1.0±0.8 % per decade with sharp declines in northern Africa (3 % to 4 %/decade), marginal declines over Asia, and no significant trend in Amazonia.

Forest clearing tends to increase SH fluxes and reduce LH fluxes. This, in turn, causes the development of deeper turbulent convective boundary layers, with widespread cumulus clouds more likely to occur over the deforested regions than over the pristine forests (e.g., *Avissar et al.*, [2002]). Tendencies of increased convective available potential energy (CAPE), increased updraft widths and increased cloud base heights also have been reported (e.g., *Negri et al.*, [2004]). CAPE is a measure of the energy available for convection. It is directly related to the vertical speed of the updrafts and thus higher values of CAPE indicate greater potential for severe weather. In tropical soundings, parcel temperatures of 1 to 2 K excesses may occur at a depth of 10 - 12 km. A typical value of CAPE is then 500 Jkg^{-1}. However, for a mid-latitude thunderstorm environment, the value of CAPE often may exceed 1000 Jkg^{-1}, and in severe weather cases it may exceed 5000 Jkg^{-1}. This small value of CAPE in the tropical environment is the major reason that the updraft velocities in tropical cumulonimbus are observed to be much smaller than those in mid-latitude thunderstorms [*Holton*, 2004].

Convective activity is strongly influenced by surface characteristics, with changes in land cover producing changes in local surface temperatures and precipitation rates. From satellite observations *Rabin et al*. [1990] and *Cutrim et al*. [1995] reported increased cloudiness over deforested areas in Amazonia and attributed this to land surface heterogeneity. Using GOES (Geostationary Operational Environmental Satellite), TRMM (Tropical Rainfall Measuring Mission) and Special Sensor Microwave Imager (SSM/I) satellite data, *Negri et al*. [2004] found that enhanced dry season surface heating created a thermal circulation which increased shallow cumulus clouds, and the precipitation resulting from deep convection over deforested relative to those over forested regions in Amazonia. However, observations are not entirely consistent. Based upon ten years of 3-hourly infrared window channel observations taken during the International Satellite Cloud Climatology Project (ISCCP) over a 2.5^{o}x2.5^{o} grid, *Durieux et al*. [2003] reported no significant differences in dry season cloud cover between forested and deforested regions of Amazonia.

Modeling studies likewise are inconsistent. *Eltahir* [1996] reported that large-scale deforestation could weaken large-scale circulation patterns which would lead to reduced rainfall. At the mesoscale, *Eltahir and Bras* [1994] reported that deforestation will lead to a reduction in precipitation, but would have no effect on large-scale circulations. However, at small scales on the order of 10-100 km, *Wang et al*. [2000] reported that the organization of rainfall reflects land cover patterns and that there is enhanced cumulus cloud cover and enhanced deep convection over deforested patches. As expected they found no relationship between shallow clouds and land cover patterns in the wet season. During the period between the dry and wet seasons, they suggested that deforestation may enhance afternoon cloudiness while contributing nothing to precipitation. However, during the dry season they found that the organization of rainfall does reflect land cover patterns, with enhanced shallow cumulus over deforested patches leading to enhanced deep convection. In contrast recent modeling studies by *Costa et al*. [2007] and *Sampaio et al*. [2007] came to divergent results. In these studies Amazonian forest was replaced by pasture and soybeans. *Costa et al*. [2007] used the Community Climate Model coupled to the Integrated Biosphere Simulator (CCM3-IBIS) climate model on a 2.81^{o} grid and *Sampaio et al*. [2007] used the Centro de Previsao do Tempoe Estudos Climaticos do Instituto Nacional de Pesquisas Espaciais (CPTEC-INPE) global model at 2^{o} spatial resolution. Both results showed that replacement of forest by pasture leads to higher values of albedo, SH flux, and surface temperature with decreased values of roughness, turbulence, Leaf Area Index (LAI), root depth, LH flux, evapotranspiration, cloud cover and precipitation. Intriguingly, precipitation was decreased even further as pasture was replaced by soybeans. This was attributed to the albedo of soybean plantation being higher than that of the pasture. *Sampaio et al*. [2007] found that cloud cover was significantly decreased by about 12% over deforested areas converted to pastures and by about 16% for soybean croplands, while precipitation decreased by 18% over pastures and 25% over soybeans. However, these studies utilized synoptic-scale grids that may not be representative of smaller-scale processes. Indeed, *Sampaio et al*. [2007] suggested that fragmented forest patches may create local circulations which in turn may enhance precipitation over the deforested regions. Table 2 summarizes the above discussed literature survey.

S.N.	Reference	Data & Study Area	Key conclusions/Remarks
1	*Otterman, 1990*	Landsat, Israel	Afforestation leads to reduced surface albedo and reduced soil heat flux and hence increases in precipitation.
2	*Rabin et al., 1990*	AVHRR from NOAA-7, Oklahoma	Clouds form earliest over regions of high SH and high albedo and are suppressed over regions of high LH fluxes. Convection enhancement at mesoscale results due to land surface heterogeneity.
3	*Lyons et al., 1993*	Field experiments, AVHRR, Southwestern Australia	Substantial clearing of native vegetation lead to a 20% decrease in local winter rainfall. Cumulus cloud frequency is thus high over areas with high LH fluxes and high CAPE.
4	*Eltahir and Bras, 1994*	Amazonia	Small scale deforestation (~250 km) may lead to reduction in precipitation, but would have no effect on large-scale circulations.
5	*Cutrim et al., 1995*	GOES, Amazonia	Enhanced dry season cumulus clouds frequency over forest cleared regions.
6	*Avissar and Liu, 1996*	RAMS	Contrasting vegetation types lead to differential heating which in turn results in sea-breeze-like mesoscale circulations that increase cloudiness. Updrafts created by surface heterogeneity are much stronger than those created as a result of turbulence.
7	*Eltahir, 1996*	Amazonia	Large-scale deforestation (~2500 km) could weaken large-scale circulation patterns which would lead to reduced rainfall.
8	*Rabin and Martin, 1996*	GOES, Central United States	Slightest change in elevation can modulate the cumulus cloud frequency. And cumulus frequency is inversely associated with plant cover and available soil moisture.
9	*Pielke et al., 1998*	RAMS, South Florida	During the past 100 years 11% decrease in summer deep cumulus rainfall due to land cover change and this climate change is irreversible due to permanent land cover change.
10	*Wang et al., 2000*	MM5V2, Rondônia, Amazonia	At scales of 10 km observed enhanced cloud cover and enhanced and enhanced deep convection over deforested patches during dry season.
11	*Weaver and Avissar 2001*	RAMS, ARM-CART, US Central Plains	Enhancement in mesoscale convection arising due to land cover heterogeneity.

S.N.	Reference	Data & Study Area	Key conclusions/Remarks
12	*Avissar et al., 2002*	Satellite observations and Model simulations, Amazonia	Climatic feedbacks from deforestation can also alter the rainfall patterns, initially increasing followed by drastic decrease in precipitation.
13	*Ray et al., 2003*	ASTER, MODIS, GMS5, Southwestern Australia	High frequency of cumulus cloud cover over regions of high LH heat flux and high available energy.
14	*Durieux et al., 2003*	ISCCP, GPCP, TRFIC, Amazonia	More wet season rainfall in deforested regions and less dry season rainfall than the forested regions.
15	*Nair et al., 2003*	GOES 8, Landsat MSS, RAMS, Costa Rica	Deforestation leads to warmer, drier air upwind of the mountain and increasing the cloud base heights.
16	*Malhi and Phillips, 2004*	Tropics	Since mid 1970s, significant decline in precipitation at a rate of 1.0±0.8 % per decade with sharp decline in northern Africa (3 to 4 %/decade), marginal declines over Asia, and no significant trend in Amazonia.
17	*Negri et al., 2004*	TRMM & SSMI, Southwest Brazil	During dry season there is enhanced shallow cumulus cloudiness and deep convection over deforested areas than dense forests.
18	*Ray et al., 2006*	MODIS, GOES, RAMS, Guatemala	High frequency of cumulus cloud cover, high rainfall rate over drier deforested areas than pristine forests.
19	*Costa et al., 2007*	CCM3-IBIS climate model (2.8^o), Amazonia	Forests to pasture lead to reduced cloud cover and rainfall; forest to soybean lead to increase in albedo and further decrease in cloud cover and precipitation.
20	*Sampaio et al., 2007*	CPTEC-INPE (2^o), Amazonia	Observed similar to *Costa et al*. [2007].
21	*Nepstad et al., 2002*	Brazil's Tapajo´s National Forest, in east-central Amazonia	The forest leaves were quite tolerant to the soil moisture reduction provoked by throughfall exclusion. Instead of a pulse of leaf shedding, the exclusion treatment have inhibited the formation of new leaves, leading to a decline in fine litter production and, eventually, a thinning of the leaf canopy.

Table 2. Literature survey on satellite remote sensing and modeling studies of impact on land cover change on regional cumulus cloud cover and precipitation.

Other significant and indirect impacts of land use changes include loss of spiritual and cultural benefits from ecosystems, both for the indigenous people and others enjoying recreational opportunities [*Ramakrishnan*, 2001]. Deforestation could also result in disease emergence [*Patz et al*., 2000; *Patz et al*., 2004] such as dengue and malaria [*Tauil*, 2001], diarrhea [*De Souza et al*., 2001] and other respiratory diseases [*D'Amato et al.,* 2001].

3. Impact of deforestation on flora and fauna due to hydrometeorological disturbances

Temperature, precipitation, wind/storms, solar radiation, long-wave radiation, atmospheric concentration of carbon dioxide and ozone influence biogeochemical cycles, greenhouse gas fluxes and surface energy balance, which in turn impact the biodiversity of ecosystems. Species tend to be attracted to their optimum climate. Therefore, if temperature and precipitation changes, species would be expected to either expand or contract their range depending on favored conditions [*Peters and Darling*, 1985; *Ford*, 1982].

Forests that are undisturbed tend to be dark under the canopy, humid, with stable temperature, and light wind [*Laurence et al*., 2002]. Deforestation creates forest edges with increased temperatures, reduced humidity and increased sunlight. This "edge effect" can penetrate 40 to 60 m deep in the forest [*Kapos*, 1989; *Didham and Lawton*, 1999]. These changes in the hydrometeorology parameters impact the flora and fauna found in the forest fragments. Many tropical animals require large areas of native vegetation for their survival, and isolation of forest fragments impacts their survival due to lack of water and food. Studies by *Dale et al*. [1994] over the tropical forests show that some species in small and isolated patches of forests do not cross even relatively small deforested areas. The survival of species in isolated forest patches strongly depends on suitable habitats of sufficient spatial extent to support their population. Decreases in the movement of animals across an ecosystem can limit/reduce the nutrient exchange between forest patches [*Saunders*, 1991].

For plants, hydrometeorological changes are impacted by decreased evapotranspiration, and soil moisture depletion. Fragmented forests are more vulnerable to lateral shear force exerted by increased wind speed, turbulence and vorticity [*Bergen*, 1985; *Miller et al*., 2001]. This increases the mortality rate of trees and damage within 100 to 300 m of the edges of forest fragments [*Ferreira and Laurence*, 1997; *Laurence et al*., 1998]. *Laurence et al*. [2000] found that in Amazonia trees die three times faster near the edges than those at the interior. Some trees simply drop leaves and die at the forest edges due to sudden changes in temperature, moisture and sunlight [*Lovejoy et al*., 1986; *Sizer and Tanner*, 1999]. Tree mortality impacts canopy dynamics [*Ferreira and Laurance*, 1997], which in turn alters forest structure, composition and diversity. New trees growing near the edges adapt to the new environment, but these are dissimilar to the forest-interior trees [*Viana et al*., 1997]. Thus, rare and localized species whose range becomes unsuitable tend to be threatened to extinction unless dispersion and colonization is possible.

4. Outline of this study

Although there are many studies as discussed above [Table 2], from both observations and models [*Negri et al*., 2004; *Wang et al*., 2000; *Costa et al*., 2007; *Sampaio et al*., 2007] to quantify the impact of deforestation on regional weather and climate, many of these studies exclusively focus on large homogeneous, pristine forests of Amazonia that were replaced by farmlands and pastures. The results presented in the literature are not only inconsistent, but in many cases are opposing in their conclusions. Furthermore, it is unknown to what degree results reached for large, relatively homogeneous regions such as Amazonia are applicable to small regions with strong oceanic contributions to weather and climate.

Ray et al. [2006] utilized satellite observations and regional atmospheric model simulations in Guatemala and adjacent areas and reported that deforestation locally intensifies the dry season, increasing the risk of fire along the long corridor regions connecting the protected areas. They showed that the deforested habitats in dry season have higher day-time temperatures, less cloud cover, less soil moisture and low values of Normalized Difference Vegetation Index (NDVI) than the forests in the same life zone.

A detailed analysis of the climate parameters, such as change in land cover, surface temperature, NDVI, soil moisture, albedo, cloud formation, and precipitation over the protected reserves and the corridors connecting these reserves for different seasons, is required to determine the regions in the MBC that are potentially "*stable*" and "*unstable.*" This research work examines these issues in detail over samples of forested and deforested regions in Guatemala and the stability and sustainability of the MBCs in the region. analyzes whether relatively small-scale forested regions adjacent to deforested regions in Guatemala create meaningful differences in convective initiation and precipitation, which would be of importance to the sustenance of the proposed MBC.

5. Study area

Figure 1 shows the parks, reserves and protected regions within the study area along with the narrow corridors proposed to connect patches of similar habitat. The largest protected region is the Maya Biosphere Reserve in the northern Petén region which contains more than a million hectares of tropical forest. *Cochrane* [2003] showed that long corridors with long perimeters relative to their area may be particularly threatened by fire because forest edges usually are drier and more vulnerable. *Ray et al*. [2006] suggested that deforestation may be lengthening and locally intensifying the dry season which would adversely impact second-growth forest regeneration.

Guatemala is composed of the mountainous highlands, the Pacific coast region south of the highlands and the hot, humid tropical and relatively flat Petén lowlands to the north. Approximately one-third of Guatemala is forested with about half of that total is composed of primary forests. The choice of this site is dictated in part because *Ray et al*. [2006] showed that at the height of the dry season (March), many of the forests in the Petén region have estimated rainfall deficits of up to 25mm which would have potentially serious consequences for the corridor regions. The *Ray et al*. [2006] results were generated from cloud cover rainfall regression statistics, and a more extensive analysis of the region is necessary to estimate the potential vulnerability of the proposed MBC corridors.

6. Model

The GEMRAMS atmosphere-vegetation coupled model [*Eastman et al*., 2001; *Beltrán* 2005; *Beltrán et al*., 2008] was used for the modeling experiments. It is comprised of the Colorado State University Regional Atmospheric Modeling System (RAMS) 4.3 [*Pielke et al*., 1992; *Cotton et al*., 2003] and the General Energy and Mass Transport Model [GEMTM, *Chen and Coughenour*, 1994]. RAMS is a general-purpose, atmospheric simulation model that includes the equations of motion, heat, moisture and continuity in a terrain-following coordinate system. It is a fully three-dimensional and non-hydrostatic model. RAMS also includes a soil-vegetation-atmosphere transfer scheme, the Land Ecosystem-Atmosphere Feedback model, version 2 (LEAF-2) [*Walko et al.*, 2000] that represents the storage and exchange of heat and moisture associated with the vegetation and canopy air and soil.

GEMTM is an ecophysiological process-based model that can be used to simulate the dynamic interactions between the atmosphere and the growing canopy [*Chen and Coughenour*, 1994]. Several of the GEMTM components were coupled to RAMS: canopy radiation transfer, plant and root growth, soil water dynamics, biomass production and soil respiration submodels. These components require an additional set of parameters, mostly vegetation dependent, to characterize these biological processes.

In GEMRAMS the near-surface atmosphere and biosphere are allowed to dynamically interact through the surface and canopy energy balance. Precipitation, canopy air and soil temperature, humidity, winds and surface LH and SH fluxes are computed by RAMS. Photosynthesis at the leaf-level is calculated for sunlit and shaded leaves as a function of photosynthetic active radiation (PAR) and temperature. Water stress effect on the assimilation rate also is considered. At the canopy level, photosynthesis and conductance are calculated by scaling-up from the corresponding sunlit and shaded leaves using sunlit and shaded LAI using light extinction coefficients from a multi-level canopy radiation model [*Goudriaan*, 1977]. The available photosynthate is allocated to leaves, stems, roots and reproductive organs with variable partition coefficients which are functions of soil water conditions. As water stress increases, the fraction allocated to root growth increases. The root profile is updated daily through the processes of branching, extension and death [*Chen and Lieth*, 1993].

Cumulus parameterization in the model is accomplished using the Kain-Fritsch scheme [*Kain and Fritsch*, 1993]. GEMRAMS is a state-of-the-art soil-vegetation-atmospheric simulation approach which offers much increased realism in modeling complex forest-deforestation circulation patterns. The original GEMRAMS model was built based on RAMS v4.3. The RAMS model has evolved to the latest version v6.0, and one of the major improvements includes the use of independent satellite observations of vegetation greenness represented by the Normalized Difference Vegetation Index (NDVI).

6.1 Model configuration

Two nested domains are used. The outer domain, with a horizontal grid of 40 km x 40 km and covering an area about 2000 km on a side, is centered at the point of 16.0N and -90.0W in Guatemala. This domain is used mainly to incorporate as much real-time weather as possible within the chosen regional scale domain. Real-time weather data are obtained from National Centers for Environmental Prediction Final gridded analysis datasets (NCEP FNL), which is global at 1 x 1 degree, 6-hourly. The inner domain in this study has a horizontal grid of 10 km x 10 km and covers an area of 620 km x 620 km, centered at the same point. The inner and outer domains are shown overlaid onto the map of vegetation types compiled from MODIS data by the University of Maryland in Figure 2a. Figure 2b shows the topography of the study region. The Petén study area is characterized by relatively low relief (< 300 m) and is bounded roughly from 16N to 18N and 89W to 91.5W.

Thirty-five vertical levels are used in the model, with the lowest level 20 m from ground, increasing with a ratio 1.15 up to a maximum of 1200 m near the model top at 18.7 km. The fine vertical grid limited the model time step to 30 seconds for the outer and 10 seconds for the inner domain. It is noted that the model was run with the "full" dynamic features (topography, various landscape features, etc.) over the two nested domains.

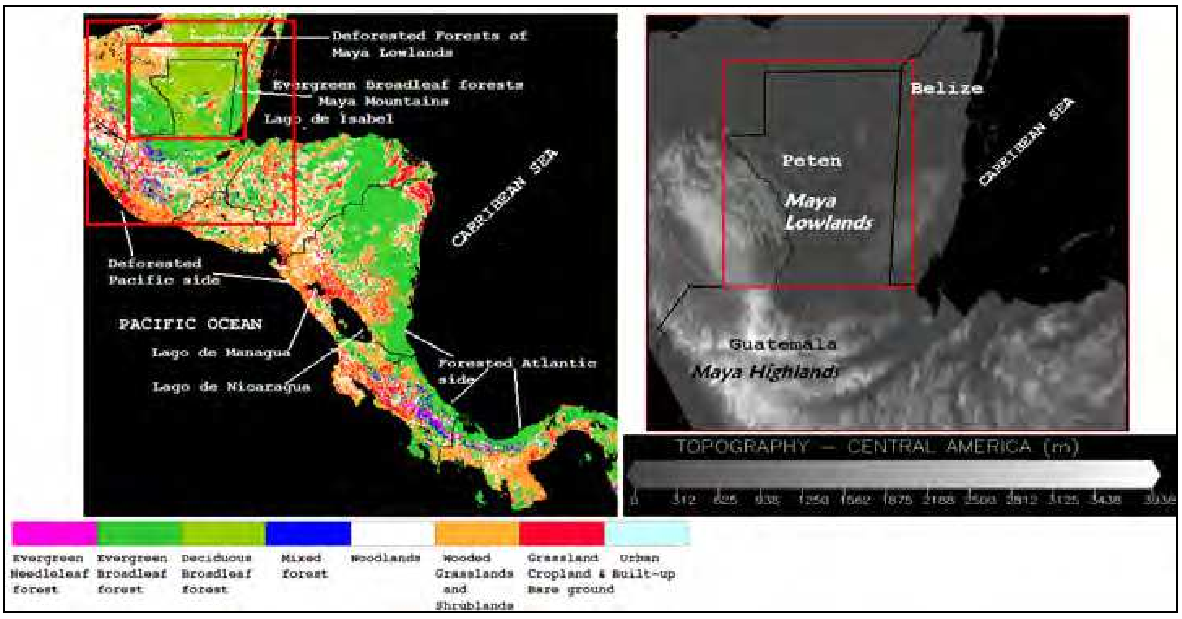

Fig. 2. (a) The University of Maryland ecosystem map of Central America with outer and inner domains overlaid (red boxes), (b) The two nested domains used for model simulation shown over the topography map of Guatemala. The outer domain has a horizontal grid of 40 km x 40 km and covering an area about 2000 km on a side and is centered at the point of 16.0N and -90.0W in Guatemala. The inner domain has a horizontal grid of 10 km x 10 km and covers an area of 620 km x 620 km, centered at the same point. The major vegetation is the Evergreen Broadleaf Trees, which shows indeed a quite "smoothed" distribution. However, there are small-scale patchy, heterogeneous land covers which represent partial- or non-forested land covers.

The northern half of the Petén region tends to be characterized by protected regions and tropical forests, while the southern and western regions are heavily deforested. LAI in these dense tropical rainforests are ~ 6 while values in the range of ~2 are associated with the small-scale, patchy, heterogeneous land surface conditions in the non-forested areas. Roughness heights are approximately 2 m in the forests and a few centimeters in the pastures. Albedo values of about 14% are taken for the forests and approximately 16.5% for the deforested regions.

6.2 Soil initialization

The model soil parameters are more difficult to initialize, due to the lack of satisfactory data in most regions. *Reichle et al*. [2004] discussed a three-way comparison regarding soil modeling (in-situ measurement, remote satellite observation, and numerical modeling) and pointed out that there is as yet no "consensus" among the three. In the current study, soil moisture is initialized using the NCEP FNL 2-layer soil data, in which vertical variation is incorporated into the model. Horizontally, the data over Guatemala is averaged. Soil temperature is initialized with "zero-offset" from the NCEP FNL lowest air temperature. Also, soil (3D) texture is initialized following the same procedure of LAI and vegetation fraction as provided by RAMS v6.0.

7. Model results

The objective of this study is to determine environmental and climatic differences in forested and deforested regions in the lowland Petén region of Guatemala as well as circulation patterns both within these regions and along the borders. Large differences between the forested and deforested areas would support the hypothesis of *Ray et al*. [2006] who proposed that the proposed MBC corridors are potentially unstable.

A 30-day simulation of the dry season is performed in the Petén region with the northern half forested and the southern half deforested. This is in rough agreement with the primarily forested conditions found in the northern Petén today and the largely deforested conditions found in the southern region.

Figure 3 shows the model configuration of vegetation assumed in this study. The vertical north-south line (AB) through the center of the region at 90.25W shows the location at which most of the results are described. The horizontal east-west line through the center of the region at 17N divides the primarily evergreen broadleaf forested region to the north from the primarily deforested pasture region to the south.

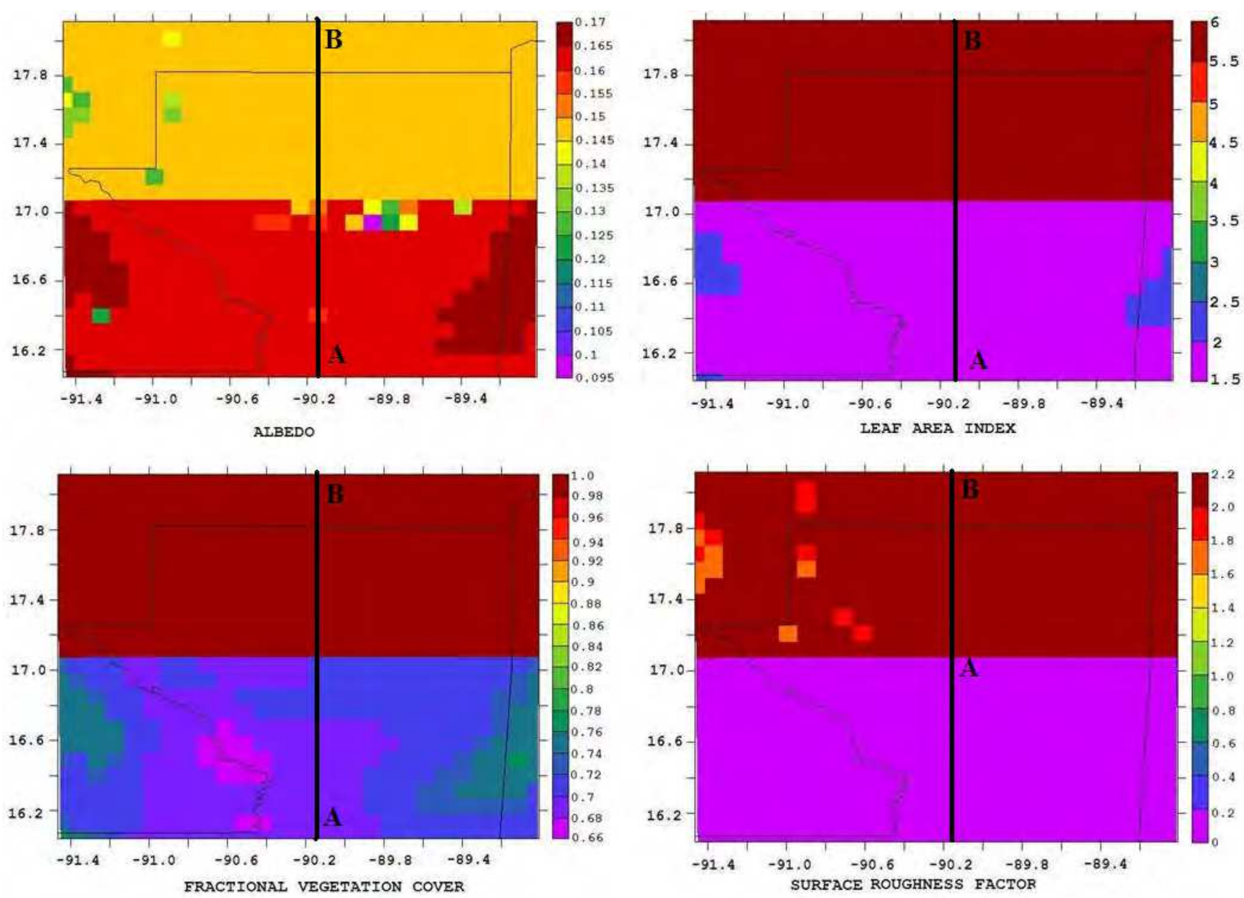

Fig. 3. Model Configuration: (a) Albedo of the Petén. (b) LAI field over the Petén on March 8th, 2003 (dry day) at 12 noon local time (1800 UTC). (c) and (d) Similar to (b) but for fractional vegetation cover and surface roughness factor respectively.

Based upon satellite images of the Petén region, it is assumed that fractional vegetation cover is about 98% in the forested regions and about 70-75% in the deforested regions. As seen in Figures 3 a, b, c and d the LAI is ~6 for the Evergreen Broadleaf Forests, surface roughness length is about 2m and surface albedo is about 14%. Note that once the vegetation type is chosen, the GEMRAMS model initializes the surface parameters. The value of 14% for the forests is consistent with satellite remote sensing estimates and the literature (e.g., *Pielke*, 1984, Table 11-8). Note that coniferous forests have much lower albedo on the order of ~10% and LAI values of 2-4, but these are not prevalent in the study region.

In general, forests may have albedo values ranging from about 10% to 20%, depending upon forest type and season. Whereas, the LAI values for the deforested regions range from 1.5 - 2.5 with very small roughness lengths (nearly zero) appropriate for pastures and with albedo ~ 16.5%.It is important to note that the GEMRAMS model is fully dynamic. Therefore, the surface parameters of albedo, LAI, fractional vegetation cover and roughness factor change over time in response to environmental conditions such as surface temperature, humidity and precipitation. However, for the short term study conducted here over a one month period, the surface parameters varied little.

Within a typical dry season, there may be some days which are hot, dry and cloudless, others that have fair-weather cumulus and others that experience unstable atmospheric conditions, deep convection and heavy precipitation. Figure 4 shows daily precipitation averaged over the forested and deforested regions for March 2003. Note that there was no precipitation in first half of the month over both the regions. About a third of the days experienced small precipitation events such as showers, and about six of the days experienced unstable conditions with deep convection and heavy precipitation. The environmental conditions necessary for the formation of deep convection are destabilization of the air parcels and lifting the destabilized air to the level of free convection [*Wallace and Hobbs*, 2006]. The destabilization is associated with the lifting of the air parcel and the low level convergence influenced from large-scale forcings such as an extratropical cyclone, which are generally anticipated a day or more before. In this decade, 2003 was year of many extratropical cyclones. Central America was highly influenced by the troughs associated with the cold fronts coming from north [*IPCC*, 2007].And the lifting of air parcels that initiates the deep convection is associated with localized, short-lived and less predictable forcings such as the sea-breeze or outflow of any pre-existing convective storms [*Wallace and Hobbs*, 2006].

Figure 5a shows SH fluxes peak values tend to occur at 1400LT, which is the time of maximum convection on days in which it occurs. SH fluxes range in value from about 400-500 Wm^{-2} for about the first two weeks of March and then again on the dry days of 21-22 March. SH flux decreased to about 300 Wm^{-2} on 16 March the day convective rains. Then slowly increasedas the ground dried out. The day of 23 March had strongly unstable conditions and heavy precipitation and SH fluxes < 200 Wm^{-2} with similar low values at the end of the month. Note that SH fluxes are within 10% of each other in the forested and deforested regions throughout this dry season on dry and convective days.

Figure 5b shows the corresponding LH fluxes during this month at the same time of the day. LH fluxes range from < 200 Wm^{-2} on the very dry days to > 600 Wm^{-2} on the very convective days during the later half of March. High LH release associated with warm surface temperatures acts to maintain the horizontal temperature gradient thereby increasing the supply of potential energy to build up the deep convection [*Wallace and Hobbs*, 2006]. Note in particular that the LH fluxes are up to twice as large in the forested regions during the “dry” days.Differences in LH fluxes between the forested and deforested regions are much smaller during the convective days.

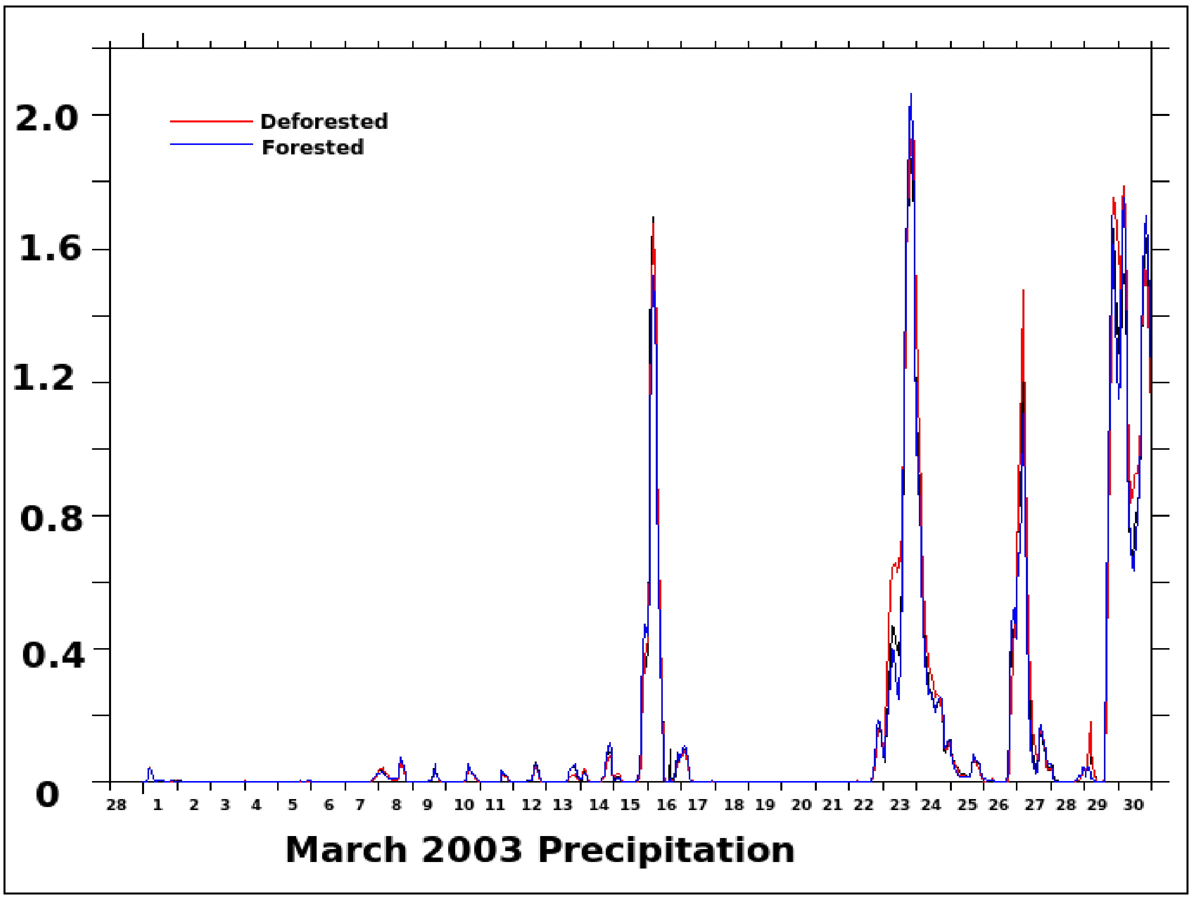

Fig. 4. Diurnal (hourly) precipitations for March 2003 averaged over forested and deforested regions.

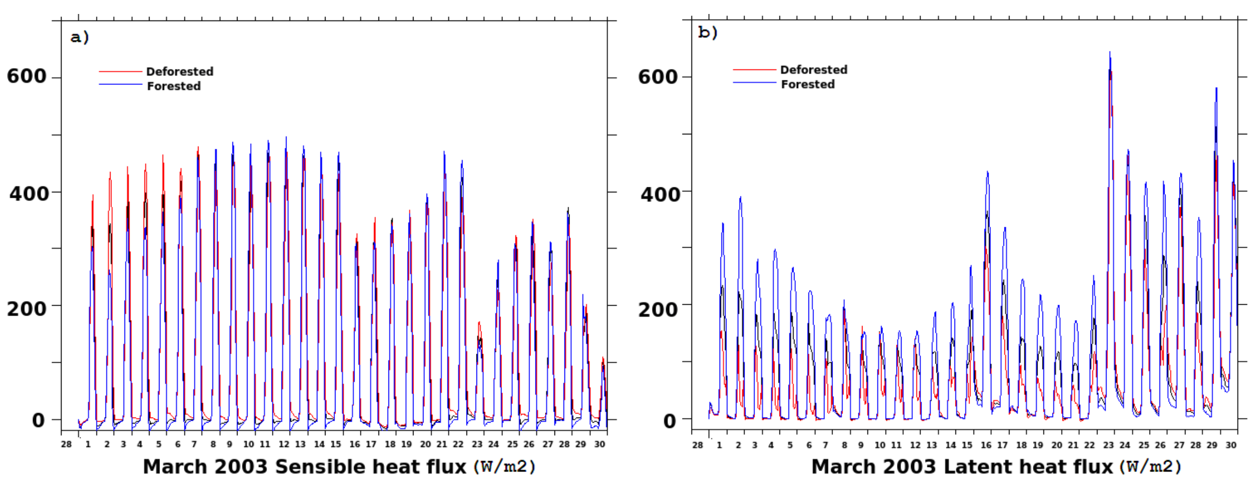

Fig. 5. (a) Diurnal (hourly) SH flux for March 2003 averaged over forested and deforested regions, (b) same as (a) but for LH flux.

It might be expected that the forests with their larger LH fluxes would produce greater cloud cover on the drier days, but this is not found to be the case during this study period. The following case studies examine representative dry, showery and convective days, comparing conditions in the forested and deforested regions in each case.

7.1 Dry day

Table 3a,b shows temperature, LH, SH, PBL height, precipitation and cloud cover for the south (pasture) and north (forest) sides for both a representative dry day (March 8) and a representative convective day (March 23) as a function of time (0600, 1000, 1200, 1400 and 1800 LT). These are values averaged over each of the two sides, forest to the north and pasture to the south.

a)	Dry day						Convective day					
Time	Temperature (K)		LH (Wm^{-2})		SH (Wm^{-2})		Temperature (K)		LH (Wm^{-2})		SH (Wm^{-2})	
	Pasture	Forest	Pasture	Forest	Pasture	Forest	Pasture	Forest	Pasture	Forest	Pasture	Forest
6am	296.18	293.69	12	8.23	12.47	15.31	299.11	297.57	100.95	31.87	14.44	49.56
10am	305.92	303.56	163.96	54.02	309.58	439.61	302.12	299.42	618.114	719.05	87.52	47.08
noon	310.49	306.44	37.61	149.31	471.17	485.66	302.73	300.89	670.557	476.62	122.63	82.4
2pm	310.79	306.66	28.03	138.75	373.34	333.41	302.83	299.08	574.53	482.88	117.29	32.73
6pm	303.73	300.45	0.5044	0.7795	7.12	-26.14	298.42	295.94	128.29	60.37	-5.57	-10.197

b)	Dry day						Convective day					
Time	Planetary Boundary layer (m)		Precipitation (mm)		Cloud Cover (%)		Planetary Boundary layer (m)		Precipitation (mm)		Cloud Cover (%)	
	Pasture	Forest	Pasture	Forest	Pasture	Forest	Pasture	Forest	Pasture	Forest	Pasture	Forest
6am	164.38	491.38	0.32	0.77	13.95	13.76	465.27	293.49	37.62	11.91	21.24	16.46
10am	1104.23	1267.63	0.59	0.87	16.72	13.8	927.65	1199.39	44.97	15.58	34.17	22.68
noon	1658.03	1811.46	0.59	0.87	13.85	13.76	1193.71	1456.6	50.73	18.12	33.08	22.49
2pm	2017.77	2065.17	0.6	0.88	12.62	12.62	1272.75	1727.46	55.29	22.82	37.57	21.72
6pm	1442.22	1088.76	0.6	0.88	10.88	12.14	834.66	994.18	61.39	25.52	20.67	18.85

Table 3. Temperature (K), LH flux (Wm^{-2}), SH flux (Wm^{-2}), PBL height (m), precipitation (mm) and cloud cover (%) for the pasture (south) and forest (north) sides for dry day (March 8th, 2003) and convective day (March 23rd, 2003) at 6 am, 10 am, 12 noon, 2 pm and 6 pm.

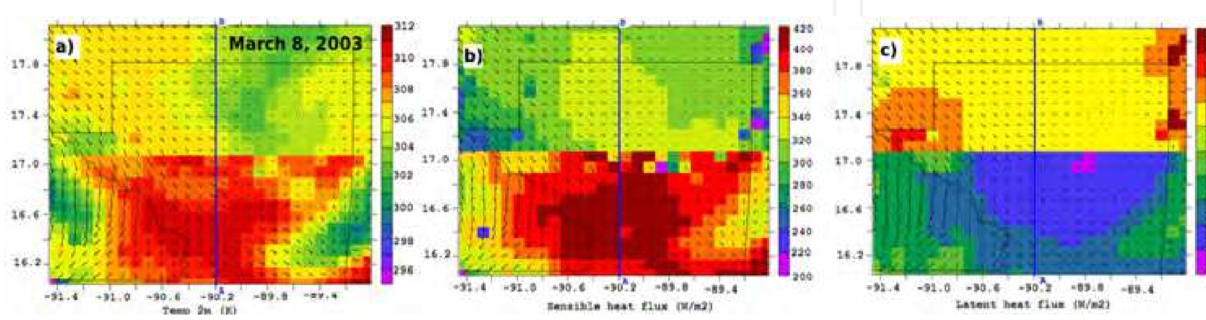

Fig. 6. Spatial distribution of temperature at 2 m (K), SH flux and LH flux on the dry day (March 8th, 2003) at 1400 LT

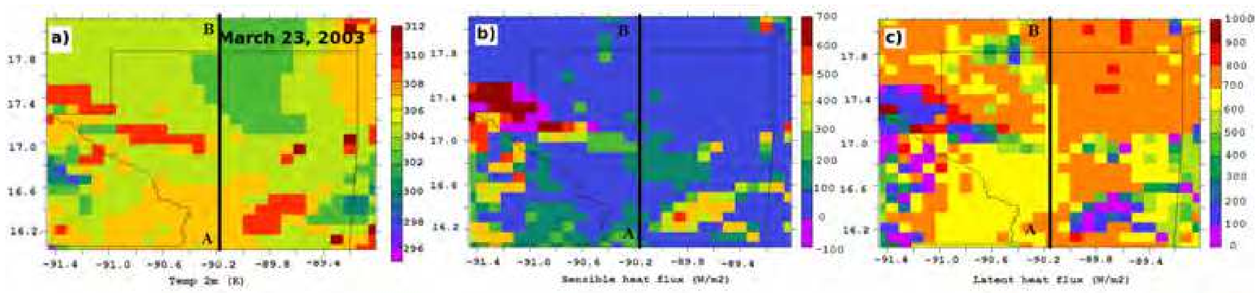

Fig. 7. Spatial distribution of temperature at 2 m (K), SH flux and LH flux at 1400 LT on the convective day (March 23rd, 2003)

For the dry day, Table 3a shows that temperature in the pasture is about 2K warmer than the forest in the early morning, increasing to about 4K warmer during mid-day. Indeed, the literature and the satellite observation studies discussed in Chapter 3 show that during dry season deforested regions tend to be hotter than forested ones in virtually all regions worldwide. Also we see that the values of LH and SH fluxes were very small in the early morning, with SH values approaching 500 Wm^{-2} in both pastures and forests by mid-day and then decreasing again by evening. Sensible heat values were relatively similar in both pastures and forests.

Under these very dry conditions, values of LH from the pastures spiked to values of about 160 Wm^{-2} in mid-morning (10am LT) due to "burnoff of early morning dew while forests had values only a third as large. By mid-day (noon LT) LH fluxes decreased to about 30 Wm^{-2} in the deforested regions while values in forests increased to about 140 – 150 Wm^{-2}. Note that during mid-day SH fluxes were about three times larger than the LH fluxes in both pastures and forests.

Cloud cover ranged from about 12% to 14% over both regions during this dry day, and precipitation was minimal, averaging less than 1 mm in both regions. The PBL height was <200 m over the pastures in the early morning and about three times that height (about 500 m) over the forests.

The boundary layer height grew rapidly during the morning to about 1800 m over the forests and about 1650 m over the pastures by noon and then to about 2000 m by 1400 LT. The PBL remained slightly higher over the forests for most of the day, except during the evening hours.

Figures 7a, b, c show the spatial distribution of surface temperature, SH and LH fluxes, respectively, for the study area at 1400 LT for this dry day. On the dry day there is clear distinction between the forests and deforested regions. 2m surface temperatures over the southern deforested regions are 4 to 8 K warmer than forests in the north. Similar differences are seen in the SH and LH fluxes spatial plots.

7.2 Convective day

Very different conditions prevailed during the convective day of 23 March. In the more humid conditions, Table 3a shows that temperatures were several degrees higher in both pastures and forests in the early morning hours of 23 March than found during the dry day. This is due to higher radiative cooling during the nighttime hours over the dry areas. On the convective day, temperatures were relatively constant during the day, ranging from about 298-299 K in the morning to only about 302-303 K during the early afternoon hours, a variation of about 4 K. Note that on the dry day temperatures increased by 12-14 K from morning to early afternoon.

Under the relatively wet conditions of the convective day, a reversal in the behavior of the LH and SH fluxes is found, as compared to the dry day. On the convective day the SH fluxes are relatively small, in the range from 50 – 125 Wm^{-2} in both pastures and forests, while LH fluxes reached 600-700 Wm^{-2} in the late morning hours before decreasing somewhat during mid-day. Note that LH fluxes were significantly larger over pastures during mid-day than over forests and that SH fluxes were somewhat higher over pastures than forests.
Cloud cover is significantly higher over pastures than over forests on the convective day, with values of about 23% over forests and up to 38% over pastures during the early afternoon. These differences in cloud cover also are reflected in differences in precipitation. The precipitation increased from about 12 mm in the early morning hours to about 25 mm by evening over the forests, an increase of about 13 mm during the day. However, precipitation increased from about 38 mm in the early morning over the pastures to about 61 mm by late afternoon, an increase of 23 mm during the day. Overall, precipitation was more than double over the pastures. On an average the rain rate of the forested region was 0.114 mm/hour and deforested region was 0.151 mm/hour. The results suggest that under sufficiently convective conditions, pastures generate significantly higher precipitation rates than do forests

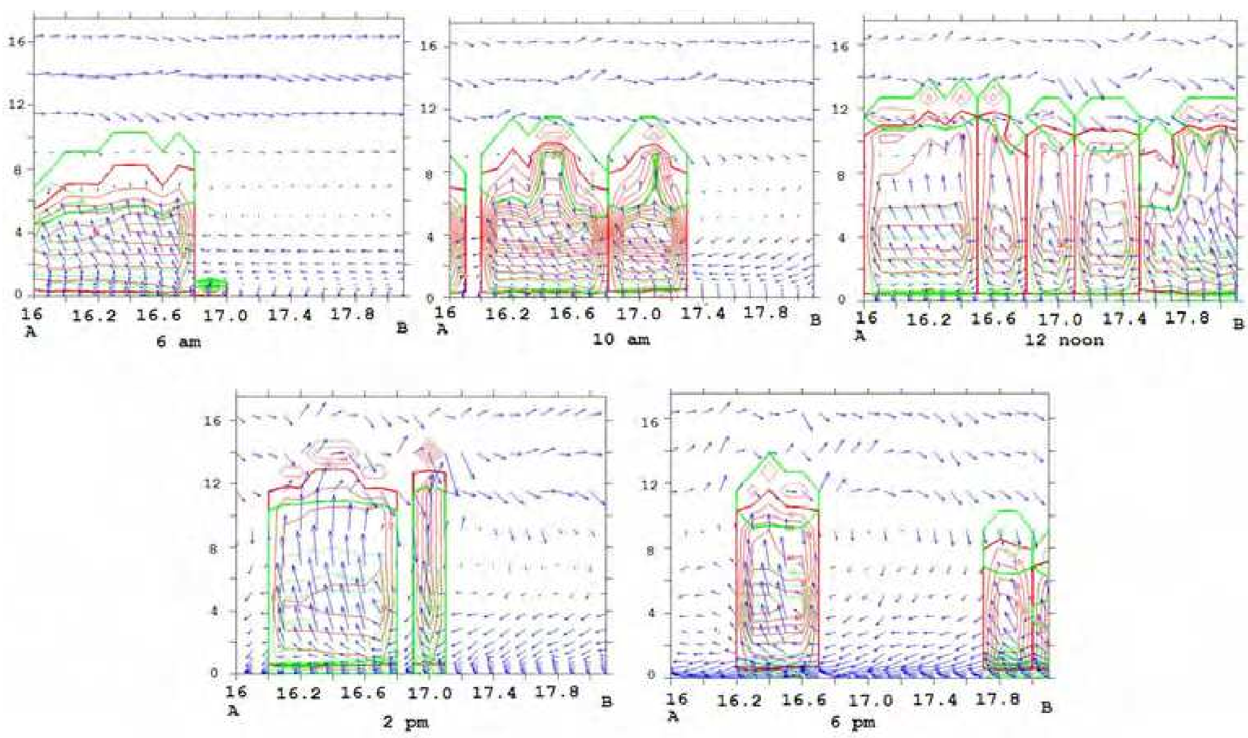

Fig. 8. Development of circulation patterns along the AB line shown in Figure 7 from early morning (6 am) to late afternoon (6 pm) on March 23rd, 2003 (convective day). The horizontal axis shows the latitude (in degrees) and the vertical axis is the height from the ground (in km). The red lines represent convective heating (^oC day^{-1}) (solid line – heating and dashed line – cooling) and the green lines represent convective moistening (g $kg^{-1}day^{-1}$) (solid line – moistening and dashed line – drying).

The height of the PBL was higher over the pastures (~450 m) than over the forests (~300 m) in the early morning hours. By 1400 LT the PBL grew to about 1300 m over the pastures and to about 1700 m over the forests, a value only slightly smaller than during the dry

conditions. The height of the PBL over forested regions is not highly sensitive to wet and dry conditions. However, note that the height of the PBL over pastures is very sensitive to wet and dry conditions, reaching only 1275 m during the convective day.
Figures 8a, b, c show the spatial pattern of surface temperature, SH and LH fluxes, respectively, at 1400 LT over the study region. On convective day we don't clearly see the difference between the forest and the deforested regions spatial plots as seen on a dry day (Figure 7).

7.3 Circulation patterns

Figure 8 shows the development of circulation patterns along the line AB in Figure 7 from early morning to late afternoon on 23rd March, the convective day. In the morning hours, there is early convective activity over the pastures, with cloud tops reaching about 9 km. Note that convection is found only over pastures and not over the forests in the early morning. By 1000 LT strong updraft regions are developing in the convective regions and cloud tops reach about 12 km in height. At this time convective activity is initiated over the forests near the forest-pasture boundary. By local noon convective activity is found over the entire region, both over pastures and forests, with cloud tops reaching 13-14 km. Note the regions of strong updraft. By 1400LT the forest regions have ceased convection along this AB line, although very strong convection with very large updrafts is found over the pastures. By late afternoon, convective activity is ceasing, but with isolated cells over both pastures and forests.
Note that the cloud top heights are approximately the same over both pastures and forests. To examine the realism of these results, GOES infrared imagery was obtained for 23 March 2003. Cloud top heights were examined over both forested and deforested regions, and there were no significant differences in the results (not shown). Once generated the convective clouds in all situations modeled have sufficient CAPE to reach the tropopause level.

8. Discussion and conclusions

High surface temperatures together with the troughs associated with the cold fronts coming from the north tend to destabilize the air. This together with the local sea-breeze increases the potential energy required for increasing convection. And as we see from the results, convective activity with precipitation starts from the mid of March 2003. This together with the prevailing high surface temperature destabilizes the air leading to more convective storms during the latter days of March 2003.
During dry conditions LH fluxes are very low over both pastures and forests, and SH fluxes are a factor of three to ten times larger. PBL heights reach 2000 m during the heat of the day and there is minimal cloud cover on the order of 13% and virtually no precipitation for these dry conditions.
A very different scenario occurs during wet convective conditions. Under these conditions convection is initiated early in the morning hours over the pastures and not over the forests. By mid-day convection is found over both pastures and forests, and by late afternoon convection decreases over both regions, but much more so over the forested regions. LH fluxes become very large (~700 Wm^{-2}) and are five to ten times larger than the SH fluxes. Cloud cover over the forests increases to about 22% during mid-day but up to about 38% over the pastures. Overall, substantial precipitation rates of 61 mm were found over the

pastures compared to less than half this amount (~25 mm) for the forests. PBL heights are much lower over pastures than over forests.

These results are consistent with *Negri et al*. [2004] who utilized GOES data for their Amazonia study, a wet region. Higher cloud covers and precipitation rates are found over deforested regions. *Manoharan et al*. [2010] also used GOES data and found higher cloud cover over deforested regions in Guatemala. However, note that such conditions of higher cloud cover and precipitation are found only under wet, convective conditions and are not found under dry conditions. Furthermore, the results are consistent with *Wang et al*. [2000] who reported deforestation can create mesoscale circulations with rising motions that trigger dry season moist convection. The present results clearly demonstrate that much strong convective circulations are created over pastures (deforested) regions than over forests.

In terms of the sustainability of the lowland corridor regions in the proposed MBC, the results strongly suggest that forested corridors will experience warmer conditions due to higher temperatures in surrounding deforested areas. Also from the observational study by *Manoharan et al*. [2010], we see severe dryness and drought prevailing in the region during 2003. However, by far the most important factor is precipitation. During the first half of the month, there is little or no rainfall, whereas, during the latter days of the month (March 2003) we see significant convective activity over the region. This is the result of the increase in energy that initiates convection by increased SH release during the initial days of March and associated local-sea breeze. Thus, the forested corridors will receive higher than normal precipitation rates due to the fact that surrounding warmer deforested regions generate higher convective activity. The above scenario implies a "climate tipping point" will not occur in the proposed corridor regions within the lowland regions of Guatemala in the study area which would threaten their stability and sustainability.

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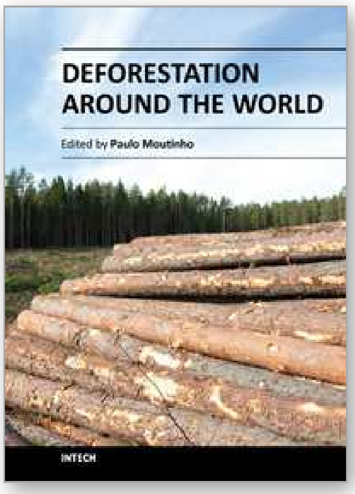

Deforestation Around the World

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Deforestation and forest degradation represent a significant fraction of the annual worldwide human-induced emission of greenhouse gases to the atmosphere, the main source of biodiversity losses and the destruction of millions of people's homes. Despite local/regional causes, its consequences are global. This book provides a general view about deforestation dynamics around the world, incorporating analyses of its causes, impacts and actions to prevent it. Its 17 Chapters, organized in three sections, refer to deforestation impacts on climate, soil, biodiversity and human population, but also describe several initiatives to prevent it. A special emphasis is given to different remote-sensing and mapping techniques that could be used as a source for decision-makers and society to promote forest conservation and control deforestation.

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