Meteorological Impacts of Land Use Change in the Maritime Tropics

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door

Michiel Kors van der Molen

geboren te Gouda

promotor : prof.dr. H.F. Vugts
copromotoren : dr. L.A. Bruijnzeel
dr. F.N. Scatena

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Acknowledgements

It all began with the fieldwork in Puerto Rico, that lasted for over a year. Hans Vugts, my promotor, two technicians, Niek van Harlingen and Ron Lootens and I flew to Puerto Rico. It took us four full weeks to build all the towers, on steep slopes, in a mangrove swamp and in the burning sun, and install the equipment; and then they left. I found myself with all these instruments and some hastily written instructions for what to do in case of a hurricane. At the time, I couldn't really say I quite understood what we had done, but it did work. I am glad to present the results in this thesis.

Here I want to give full credit to all who have contributed to the preparation and carrying out of the fieldwork. After almost 5 years I am still impressed by the thoroughness of the preparations, not a single screw, wire, datalogger program, support arm, battery charger or instrument was missing. I have already mentioned Niekie and Ron, who came to Puerto Rico, but there are many more people who contributed to the success of the field work, who stayed in Amsterdam: Hans Bakker, Theo Hamer, Jan Vink, Cees Groen, Peter Ploeger (†), zeg maar de jongens van de werkplaats and at the electronics department: Johan de Lange, Koos de Bruine and Wim van der Plas. Dank jullie wel voor alle inzet!

Fortunately, my professor Hans Vugts, came back after a while. With him, we performed several intensive measuring campaigns, which were sometimes hard, but always enjoyable. I remember Hans working, seemingly for hours at the time, surrounded by mosquitos, wasps and ants, on a datalogger program's execution interval (whether or not those two dots would appear on the display) or on the grounding of the sonic anemometer, trying to figure out why $\overline{w}$ (the average vertical wind speed) would not be zero. But always with the reward of a cold beer on the beach, where we had to go daily to measure the sea surface temperature, or a large Margarita and the famous Super Burrito Wet at Lolita's. Hans, thanks very much for your dedication to the fieldwork, that provided my with excellent quality data, and for directing me afterward through the data and the modeling to writing my thesis.

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After a period of data-analysis came a time to start modeling. I got to work closely together with Antoon Meesters. I started out using Antoon's atmospheric circulation model and together we built a cloud condensation scheme into the model. Later we found that incorporating radiation effects of clouds would be *een lastige zaak* (not an easy job) and I had to use a different model. At this moment however, you have managed to build many new features in your model, including the cloud-radiation interaction. I have appreciated the many discussions we had about modeling, data analysis and the efforts you have made to improve my work. I enjoyed the times we went to the mensa to eat our best-value 'mensamaaltijd' and we talked about all kinds of things. Thanks, Anthony!

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After a period of trying to get the model to work, I decided to contact prof.dr. Roger Pielke at the Atmospheric Science Department of the Colorado State Univer-

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At last my thesis neared completion. As my second co-promotor, Sampurno Bruijnzeel thoroughly read my thesis and made a lot of comments and suggestions. Off course, I did not look forward to working up to *21, but it improved my work considerably. I appreciate you finding the time to do it.

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1

General introduction

1.1 Land use history of Puerto Rico

The island Puerto Rico is the smallest of the Greater Antilles. Measuring roughly 180 x 60 km, it is situated in the eastern Caribbean at 18°15′N and 66°30′W (figure 1.1). Apart from the coastal plains on the north and south coast, the island is mountainous, with the highest peaks in the central and north-eastern part of the island rising to elevations of 1000-1300 m a.s.l. (figure 1.2).

In pre-Colombian times, the island was largely covered by forest, although archeological discoveries have revealed that the inhabitants of that time, the Taínos Indians, cleared forest areas for agricultural purposes (*Gomez and Ballesteros*, 1980). With the arrival of the Spanish in the early 16th century a major phase in the forest clearing began. Timber production was one reason, but clearing was also done for agricultural pursuits including annual cropping, sugar cane, pasture, coffee and banana plantations. By 1828, 65 percent of the island had been cleared (*Wadsworth*, 1950). In 1899, forest cover was only 20 percent, while 55 percent had been transformed into pasture and 9 percent into coffee plantations. The forest area was further reduced to 9 percent in 1931 (*Durland*, 1929; *Gill*, 1931) and as little as 6 percent in the late 1940's (*Koenig*, 1953). As the hill sides were subject to erosion and plantations were frequently damaged by hurricanes, cropland and pasture were abandoned in the uplands, and the forest gradually recovered (*Aide et al.*, 1995). Furthermore, U.S. and Puertorican government policies intended to shift the focus of the island's economy from agriculture toward industrial activities (*Dietz*, 1986). In 1980, reforestation had taken place to the point that 28 percent of the formerly deforested areas had recovered, making Puerto Rico one of the few tropical sites where reforestation is taking place at a higher rate than deforestation (*Birdsey and Weaver*, 1982, 1987), while at the same time, urbanizations and industrial areas continued to use more space. In 1990, 32 percent of the land was forested (*Franco et al.*, 1997), mostly regenerative secondary forest.

Figure 1.1: Map of Central America and the Caribbean. The arrow indicates the island Puerto Rico.

1.2 Evidence of climate change on Puerto Rico

There are indications that the climate on Puerto Rico is changing. For example, trend analysis of annual precipitation totals at the eight stations with the longest periods of record on the island, shows that precipitation totals have decreased significantly during the last century, for 6 out of these 8 stations (figure 1.3, see also appendix A for details, figure 1.2 for the location of the stations). Although the 10 driest years are distributed fairly even over the century, *Larsen* (2000) found that 1997, 1994 and 1991 were the 2nd, 3rd and 6th driest years of the 20th century.

Furthermore, the observation that, after widespread defoliation due to the passage of hurricane Hugo over Puerto Rico in September 1989, the cloud base was well above the highest peaks ($>$1000 m) in the Luquillo Experimental Forest in the north-eastern part of the island for a number of months, whereas the peaks are normally enveloped in clouds *F.N. Scatena* (personal communication), suggests a link between the development of clouds and the vegetation cover (see also *Bruijnzeel and Hamilton* (2000)).

The probability that deforestation of the island may induce a reduction of precipitation totals, is relevant, because during prolonged drought periods, the fresh-

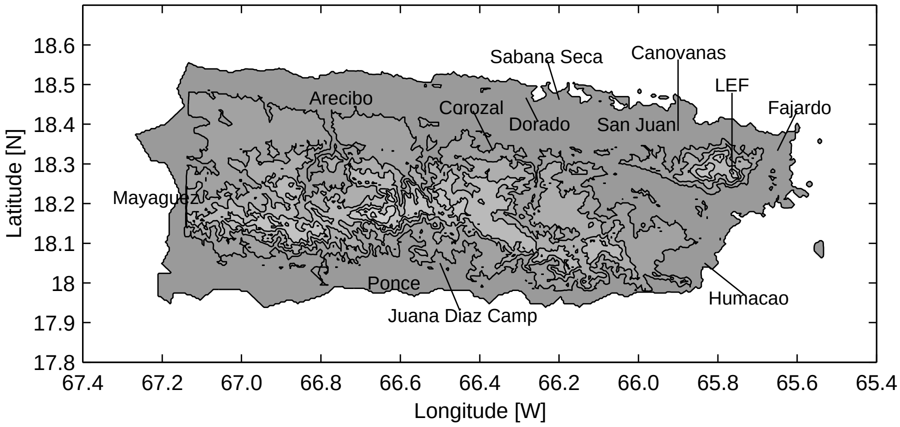

Figure 1.2: Topographical map of Puerto Rico. The contour interval is 200 m.

water storage capacity on the island may not be sufficient to meet demands for domestic, agricultural, industrial and ecological purposes. In fact, the mandatory water rationings, which were implemented six times during the 1990's for periods of up to six months (*Larsen*, 2000), had a strong impact on the population, as well as on agriculture, with an estimated economic loss of $165 million in 1994 (*Lugo and García-Martinó*, 1996).

From an ecological point of view, a change in the lifting condensation level may affect the biotope of the already endangered ecosystem known as the tropical montane cloud forest (*Pounds et al.*, 1999; *Bruijnzeel and Hamilton*, 2000). The often stunted, epiphyte-loaded trees in these forests receive a considerable amount of their water supply through the process of cloud stripping, i.e. filtering of wind-driven mist and low clouds by the vegetation, a process that is also referred to as horizontal precipitation (*Bruijnzeel and Procter*, 1995; *Bruijnzeel*, 2000). The existence of this vulnerable forest type, that is still widespread in the uplands of Central America and the Caribbean (*LaBastille and Pool*, 1978; *Vazquez-Garcia*, 1995), is especially sensitive to a lifting of the cloud base, because this would raise the lower boundary of occurrence (*Still et al.*, 1999; *Foster*, Submitted).

The island of Puerto Rico provides a particularly suitable location to study the impacts of land cover transformation, because detailed long-term climatic, hydrologic and land use records are available. The results of such a study will, at least partially, be applicable to other maritime tropical areas, such as other Caribbean islands, Central America and also parts of South-east Asia and the Pacific.

1.3 Review of model studies of climate impact of land cover change

Many researchers have investigated the effects of deforestation on regional climate, making use of general circulation models. Most attention has been paid to large-

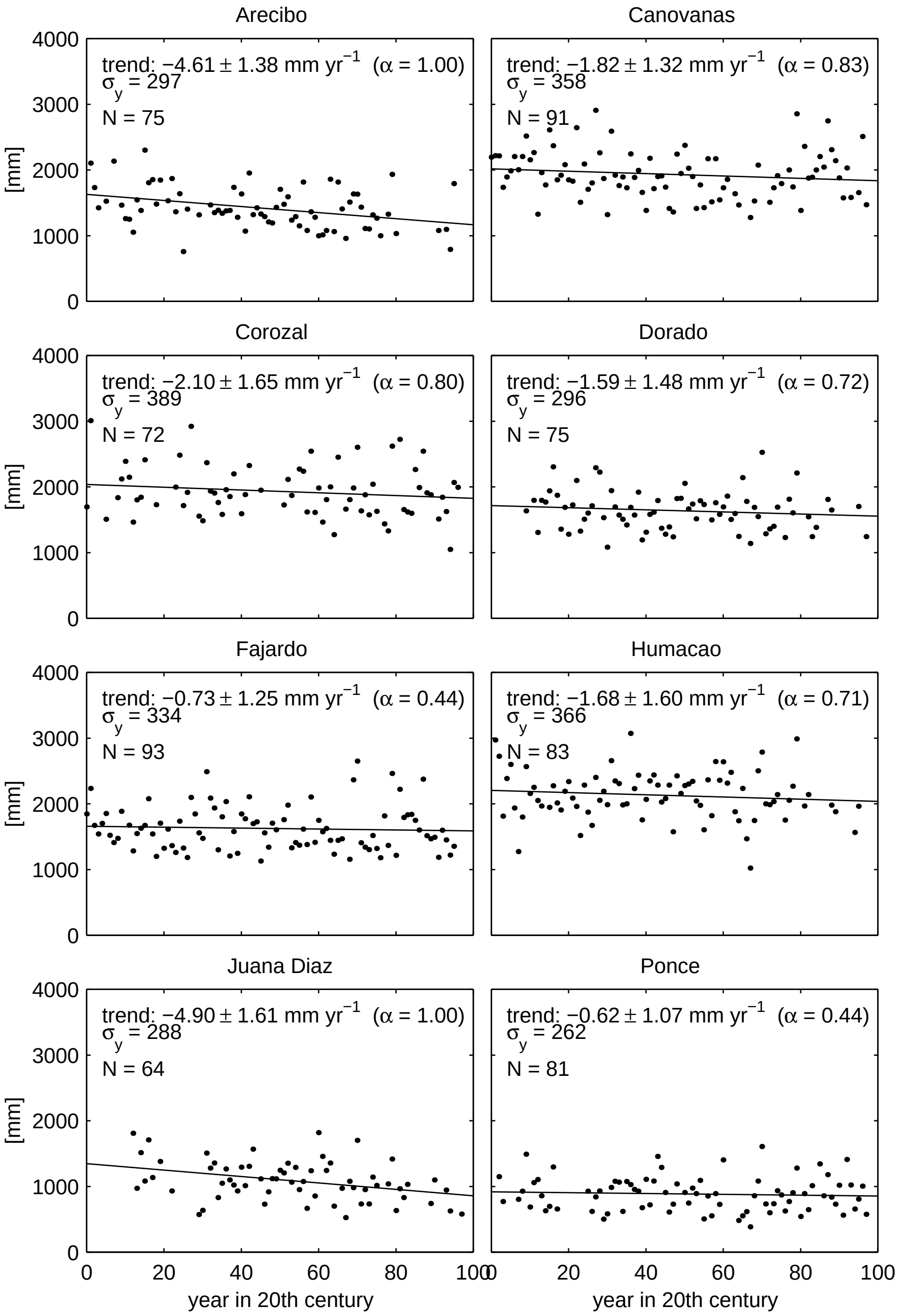

Figure 1.3: Trends in annual precipitation in the 20th century for eight selected stations on Puerto Rico. α represents the confidence level. Data source: *National Climatic Data Center* (1999).

scale deforestation under continental tropical conditions, notably the conversion to pasture of the Amazonian rain forest block (*Costa*, in press). The least complex models only take the associated increase in albedo (i.e. the fraction of sunlight reflected at the surface) into account (*Mylne and Rowntree*, 1992; *Dirmeyer and Shukla*, 1994; *Polcher and Laval*, 1994a; *Yukuan et al.*, 1994). In such cases, the first direct effect of forest conversion is the reduction of absorbed sunlight, which means that less energy becomes available to warm up the air near the surface (sensible heat) and to evaporate water from the surface or from the vegetation (latent heat). Considering that 30-50 percent of the precipitation is thought to originate from local evaporation in the Amazon region (*Lean and Warrilow*, 1989; *Eltahir and Bras*, 1994; *Costa and Foley*, 1999), the reduction in evaporation will also reduce precipitation. *Polcher* (1995) stresses that a reduced sensible heat flux lowers the frequency of convective events, thereby also diminishing regional precipitation. The net effect of decreased precipitation (P) and evaporation (E) is usually called moisture convergence (P-E), which may thus increase or decrease, depending on the respective changes in P and E predicted by the models (*Costa*, in press).

Model studies with advanced vegetation schemes are able to incorporate the response of the plants to changes in soil moisture (*Shukla et al.*, 1990; *Lean and Rowntree*, 1993; *Ashby*, 1999). When precipitation becomes less, the soil moisture content decreases. The vegetation usually responds by reducing its transpiration rate. It depends on the specific situation, such as the sensitivity of the vegetation or the rainfall distribution in time, whether the change in transpiration is greater or less than the change in precipitation. In most model studies the predicted moisture convergence has become smaller after tropical deforestation (*Lean and Warrilow*, 1989; *Shukla et al.*, 1990; *Lean and Rowntree*, 1993; *Dolman et al.*, 1999), but this is not necessarily so, as shows the work of *Dirmeyer and Shukla* (1994). Similarly, *Polcher and Laval* (1994b) obtained a reduction in moisture convergence for south-east Asia and Amazonia after a simulated change from rain forest to grassland, but not for Africa.

It may be clear that the potential for climatic change due to land cover transformation is greater when the transformation is taking place on a larger scale, implying that atmospheric feedback mechanisms could then become stronger as well. For example, an increase in albedo associated with deforestation will reduce the potential for convection, which can modify the large-scale atmospheric circulation when occurring on a large scale (*Eltahir*, 1996; *Costa and Foley*, 2000).

There are numerous other processes and feedback mechanisms that complicate the simplified impression above. For example, if the vegetation responds to a reduction in soil moisture by strongly reducing the transpiration rate, more energy will become available to heat the surface and the air above it, thereby increasing the potential for convection and related precipitation (*Shukla et al.*, 1990). Another feedback mechanism exists in shading of the ground surface by clouds: as mentioned before, deforestation increases the albedo, resulting in less absorbed solar radiation at the surface. However, if this results in less clouds, the first effect may partly be compensated because more solar radiation will reach the surface when the cloud cover has decreased (*Polcher and Laval*, 1994b).

Other factors of importance are the reduction of the rainfall interception storage, the smaller roughness length and the shallower root zone associated with deforestation. The small interception storage of grassland areas compared to most forest types, leads to a smaller part of the total precipitation being intercepted and evaporated directly back into the atmosphere. On the one hand, the vegetation benefits from the increased soil moisture content resulting from the reduced interception, while on the other hand, more water is removed from the atmosphere this way. The reduction in surface roughness results in less turbulence mixing, therefore allowing larger gradients of temperature and moisture to exist near the surface. It depends on the situation whether the sensible heat or the moisture flux benefits more from the larger gradients. In the case of interception evaporation (when the surface resistance to evaporation is zero), a reduced aerodynamical roughness directly means slower evaporation (*Lean and Warrilow*, 1989).

As forests usually root deeper than other vegetation types, deforestation generally means that a shallower part of the soil is rooted, thereby directly decreasing the total amount of soil moisture available to the plants (*Nepstad et al.*, 1994). However, *Polcher and Laval* (1994a) point out, that soil moisture content is only important under conditions that it would be limiting plant growth. For example, the change in soil moisture predicted after forest conversion for south-east Asia was considered unimportant, because water is abundant anyway.

Giambelluca (1996); *Giambelluca et al.* (1999, 2000) stress the need to distinguish between the post-deforestation vegetation of pasture and secondary forest, as the latter may in many places cover considerable portions of previously cleared land and resembles the original forest more than pasture vegetation, which is often assumed as post-deforestation land cover in climate change studies using global circulation models.

Studies of climatic impact of smaller scale tropical deforestation are scarce. *Nair et al.* (Submitted) and *Lawton et al.* (Submitted) have investigated the effect of deforestation in the Atlantic lowlands of Costa Rica on the formation of clouds. By analysis of satellite imagery, they found that clouds became less abundant over deforested areas, whereas in meso-scale atmospheric model simulations, they showed that the lifting condensation level increased after deforestation due to an assumed reduction of the evapo-transpiration rate and an enhanced sensible heat flux. However, these changes in the surface energy balance were not checked against observations.

The studies cited above give an indication of the meteorological and ecological processes that relate land cover to precipitation. However, the results cannot be merely copied and applied to the situation in Puerto Rico, or other maritime tropical areas, because deforestation on Puerto Rico has taken place under quite different conditions than those prevailing in the continental settings of tropical Amazonia or Africa (*Shuttleworth*, 1989; *Bonell and Balek*, 1993).

In the first place, the island of Puerto Rico is much smaller than the equatorial continental tropical areas that most studies are focused on. Secondly, the island is surrounded by warm seas and is located away from the equator and in the trade wind belt. The trade winds constantly supply warm and moist air to the island. As a result, the recycling of precipitated water through (local) evaporation is no longer essential to prevent the air from gradually drying out after forest conversion, as supposedly occurs in Amazonia (*Polcher and Laval*, 1994b). Thus the atmosphere is modified on a smaller spatial and therefore temporal scale in Puerto Rico.

Furthermore, and again in contrast to Amazonia, the presence of fairly high mountains on Puerto Rico induces orographic rain and clouds. Additionally, during daytime the island becomes warmer than the surrounding ocean, with the development of a sea breeze as a result. This sea breeze brings cool air from the ocean to the warmer land and moves inland over a typical distance of several tens of kilometers (*Xian and Pielke*, 1991). Given Puerto Rico's relatively small size of 180 km x 60 km, the sea breeze has the capability to strongly influence the atmospheric circulation (*Malkus*, 1955).

A final contrast with more equatorial continental situations relates to the degree of rainfall interception by tall forests under wet tropical maritime conditions such as found on Puerto Rico. There is increasing evidence that the amount of rainfall intercepted by forest in and around the Caribbean is much higher than observed in Amazonia (typically 30-50 percent vs. 5-15 percent of incident rainfall, respectively). The underlying mechanisms are not fully understood as yet but must include a combination of low rainfall intensity, high surface roughness of forests, due to irregular regrowth after frequent hurricane damage and, especially, advection of heat from the surrounding ocean (*Schellekens et al.*, 2000).

1.4 Objectives and general approach

The specific conditions under which deforestation occurred on Puerto Rico, as compared to continental tropical areas, and the potentially strong impacts on the island's population and economy, call for a separate study of the impacts of deforestation on the atmospheric circulation over Puerto Rico. This thesis delivers the results of an investigation that addresses this subject and that meets the objectives specified below.

The smaller scale at which deforestation took place, the presence of mountains and the occurrence of a sea breeze all make the application of atmospheric general circulation models inappropriate in the Puertorican case. The island would be represented by no more than a few grid points in such a model, so that it could not resolve the smaller scale circulations, that characterize the Puertorican situation. Instead, the use of a mesoscale circulation model, with its higher horizontal resolution, is desirable. Because the time scale of the modifications of the atmospheric flow, inflicted by the island of Puerto Rico, is typically in the order of an hour to one day, there is no need to simulate the flow longer than this, provided that longer-term feedbacks to atmospheric changes, e.g. through soil moisture content, are either unimportant or known and dealt with.

Vegetation is connected to the atmosphere through the surface fluxes of radiation, heat, moisture and momentum. In order to correctly simulate the effect of deforestation on the atmospheric flow, these fluxes need to be quantified for the corresponding vegetation types occurring before and after forest conversion. As this could not be done with existing data, a micro-meteorological field campaign was organized to collect the necessary data. This field campaign took place from May 1997 until May 1998, so that an entire annual cycle was covered. Appropriate micro-meteorological observations were performed at a forested and a deforested (pasture) site in the northern coastal plains of Puerto Rico. In addition, measurements were made at a number of locations in the eastern Luquillo mountains in order to characterize the climatic conditions and surface energy budgets associated with a series of natural forest types along an elevational gradient.

The results from the field campaign have been upscaled from the micro-scale to the meso-scale by the use of a numerical meso-scale atmospheric circulation model, *RAMS* (*Walko et al.*, 2000). This model was configured in such a way that it simulated the air flow over Puerto Rico and the surrounding ocean for two contrasting scenarios, i.e. with the coastal plains fully forested or entirely converted to pasture. The characteristics of the forest and post-forest vegetation, required in the computer model, were derived from the results of the field campaign. The upland vegetation was not changed, but always represented by the appropriate forest type. The model simulations were usually started at midnight and were run for 24 hours. The model solutions are analyzed in terms of changes in cloud cover, cloud base height, total liquid water content and precipitation, due to land cover transformation.

1.5 Departmental context

The department of Environmental GeoSciences at the Faculty of Earth Sciences of the Vrije Universiteit Amsterdam has a history of studying the water (and nutrient) dynamics of forests and the effects of land cover transformations under tropical maritime conditions (`http://www.geo.vu.nl/~geomil`). For example, *Waterloo* (1994) studied the effect of reforesting fire-climax grasslands in south-west Viti Levu, Fiji with *Pinus caribaea*, as well as the hydrological impacts of hurricane disturbance and forest felling and burning. *Hafkenscheid* (2000) investigated the hydrology and biochemistry of montane cloud forests of contrasting stature in the Blue Mountains in Jamaica, elsewhere in the Caribbean, whereas *Schellekens* (2000) studied hydro-meteorological processes in the sub-montane tabonuco forest in the Luquillo Experimental Forest (LEF) in Puerto Rico, including the determination of the water budgets at the catchment scale. Recently, a third investigation has been started in the LEF to ascertain the physical causes of the high wet canopy evaporation rates in the study area cited earlier. Performing detailed surface energy budget observations over various types of terrain is a specialism of the department as well, as shown by *Smeets* (2000) and *Vermeulen* (2001), who carried out measurements over melting glaciers in Austria and Iceland and over heterogeneous terrains in the Netherlands, respectively. Experience of modeling meso-scale circulations, specifically the sea breeze circulation at the Dutch Wadden islands off the north coast, has been acquired by *Meesters* (1991). The present study, as well as those of *Schellekens* (2000) and the follow-up research in the LEF by F. Holwerda M.Sc. are carried out in close cooperation with the International Institute of Tropical Forestry (IITF), USDA Forest Service, Rio Piedras, Puerto Rico (Dr F.N. Scatena).

1.6 Outline of the thesis

This thesis continues in chapter 2 with an introduction to the physiography of Puerto Rico including the climatology of the trade winds and the set-up of the measurement campaign, the selection of the field sites, instrumentation and the collection of additional data.

Chapter 3 describes the procedures that were followed to analyze the raw data. More specifically, chapter 3 discusses the methods used to calculate the turbulence fluxes of sensible and latent heat and the other terms in the surface energy balance. The degree of closure of the obtained surface energy balance is used as a means to validate the observations.

The resulting observations are presented in chapter 4. Particular attention is paid to a micro-meteorological comparison of the lowland forest and pasture sites. The results obtained for the natural forest sites in the mountains are given as well.

The surface observations presented in chapter 4 are intended to serve in the derivation of appropriate vegetation parameterizations to be used in a meso-scale atmospheric circulation model (*RAMS*), capable of linking processes and mechanisms at the surface, in the atmospheric boundary layer and at the circulation at the synoptic scale. Chapter 5 treats the model's dynamics and the modifications that were made. It is not intended to give a detailed description of all the parameterizations in the model, as they are widely available, e.g. *Tripoli and Cotton* (1982); *Pielke et al.* (1992); *Walko et al.* (1995b, 2000). However, arguments for the use of specific model options are presented, along with a detailed description of the vegetation parameterization.

The results of the simulations are presented in chapter 6. At first the model is validated using the surface observations and existing rawinsonde data. Next, model simulations with pasture and lowland forest vegetation are compared. This comparison leads to a first understanding of the impact of land use change on the meso-scale atmospheric circulation. Subsequently, a number of model runs are performed to investigate the relative importance of several factors that affect the circulation, such as the topography, the speed and direction of the trade winds and the strength and height of the temperature inversion.

Finally, the conclusions of the present investigation are drawn in chapter 7 and various suggestions made for future research.