# THE EFFECTS OF TROPICAL CYCLONE INDUCED DAMAGE ON THE REGIONAL CLIMATE OF THE U.S. GULF COAST

by

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(Under the Direction of Thomas L. Mote)

### ABSTRACT

This study examines the regional climate change resulting from forest damage along the U.S. Gulf Coast. Weather Research and Forecasting (WRF) model coupled with Noah Land-Surface model was initiated from North American Regional Reanalysis data for a 7-day study of a damage area in southern Mississippi roughly matching the damage pattern from Hurricane Katrina. Three simulations were run with the evergreen needleleaf forest changed to shrubland in the damage path. The second shrubland change returned the evergreen needleleaf forest albedo. The greatest changes were experienced by the first post-Katrina run with the shrubland albedo. The temperatures cool within the study area for the post-Katrina simulation. Ground heat flux decreased, latent heat decreased, winds increased and planetary boundary layer decreased for the post-Katrina run due to high albedo.

INDEX WORDS: hurricanes, deforestation, and climate change

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by

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# **CHAPTER 1**

## INTRODUCTION

## 1.1 Hurricane Katrina

The forested coastal plains of Mississippi and Louisiana are in peril every summer and fall during the Atlantic hurricane season. Tropical storms often form in the Atlantic and propagate into the Gulf of Mexico threatening the coastal regions of the five states bordering the Gulf of Mexico. The coasts of Florida, Alabama, Mississippi, Louisiana and Texas are threatened by tropical activity typically from 1 June to 30 November every year. On 29 August 2005, Hurricane Katrina made landfall in Plaquemines Parish near Buras, LA, as a Category 3 hurricane with a central pressure of 920 hPa around 1110 UTC (0610 CDT) (Knabb et al. 2005). After making landfall in Louisiana, Hurricane Katrina made another landfall near the Louisiana/Mississippi border coastal area around 1445 UTC (0945 CDT) (Knabb et al. 2005) (FIG. 1.1). As Katrina made landfall in Louisiana, wind speeds of 57 m s<sup>-1</sup> (110 kt) were recorded in southeastern Louisiana. During the second landfall on the Louisiana/Mississippi border, wind speeds were approximately 55 m s<sup>-1</sup> (105 kt) (Knabb et al. 2005). Unofficial reports of wind gusts in southern Mississippi were 61 m s<sup>-1</sup> (117 kt) at Poplarville, MS, 56 m s<sup>-1</sup> (108 kt) at Pascagoula, MS, and 55 m s<sup>-1</sup> (106 kt) at Long Beach, MS, while the strongest official gust report of 52 m s<sup>-1</sup> (99 kt) was from the Grand Isle Coastal-Marine Automated Network (C-MAN) station, more than two hours before landfall in southeast Louisiana (Knabb et al. 2005). The range of sustained winds in Mississippi varied from 50-59 m s<sup>-1</sup> (96-113 kt) in the western coastal counties during landfall to sustained winds between  $18-34 \text{ m s}^{-1}$  (34-64 kt) as Katrina

moved northeast into northeastern Mississippi and northwestern Alabama, as shown in FIG. 1.1 and 1.2 (Dewberry 2010). Hurricane Katrina affected people and wildlife alike with destruction of homes and property.

#### **1.2 Effects of hurricane damage**

The Gulf Coast of Louisiana and Mississippi had more than 2.6 million people living along or near the coast before Hurricane Katrina (Buckner 2005). The Gulf coastal regions of Louisiana and Mississippi also contain forested areas of varied kinds from pine plantations to wetland forests. Of the 2 million acres of forested wetlands in Louisiana, more than half are located in the coastal parishes (Chambers et al. 2005). Southern Mississippi has forested reserves such as Desoto National Forest in southeast Mississippi and the Homochitto National Forest in the southwest Mississippi. Considerable tree loss can occur in the forested regions after major wind events such as a hurricane (FIG. 1.3 and 1.4). Hurricane Katrina was no exception; it produced a considerable loss of forest cover. Initial estimates of tree damage from Hurricane Katrina in the De Soto National Forest were 154,590 ha with moderate to heavy damage; about 40% of the trees sustained significant damage (Meeker et al. 2006; Shedd 2005). Roughly 2.023 million ha of forest were considered damaged in an early assessment (USDA Forest Service 2005). About 90% of the forests that were damaged were within roughly 100 km (60 mi) of the Gulf Coast in Alabama, Louisiana, and Mississippi (USDA Forest Service 2005) (FIG. 1.2 and 1.5). FIG. 1.2 shows the magnitude of the forest damage based on Table 3.3, while FIG. 1.5 illustrates the spatial pattern of the forest damage based on Normalized Difference Infrared Index.

#### **1.3 Climate change from hurricane damage**

Forest loss due to natural disasters can modify the local climate, both where the tree loss occurred and in the surrounding areas (e.g., Gandu et al. 2004; Klingaman et al. 2008; Narisma and Pitman 2002). Tree mortality and damage can cause changes in surface albedo, evapotranspiration rate, surface roughness, soil moisture, and diurnal temperature range. When trees are damaged from a high wind event, the damaged trees or fallen limbs do not immediately change color. There is a period after damage when the trees or limbs are still foliated and may have similar albedo as before the damage occurred. Other surface properties, such as roughness length, would change immediately after the damaged occurred. The physical properties of the land surface that are altered due to wind damage potentially affect the local climate of the damaged area as well as the surrounding region.

#### **1.4 Research questions**

Given the significant impact of Hurricane Katrina on Gulf Coast forest cover, and given the previous studies demonstrating a link between land cover change (particularly deforestation) and regional climate, the overarching research question is how the regional climate of the Gulf Coast region was affected by forest damage from Hurricane Katrina. Simulations using the Weather Research and Forecasting (WRF) model with the Noah land surface model were conducted with pre-Katrina land cover and with a simplified post-Katrina land cover. Furthermore, in order to separate the influence of albedo change from the other factors, simulations with pre-Katrina albedo but post-Katrina surface roughness were also conducted.

A majority of previous studies examining the local and regional climate variability from loss of vegetation have focused on deforestation due to human activity, such as logging or clear

cutting. Furthermore, most previous studies of deforestation have examined regions in the tropics, particularly the Amazon Basin (Semazzi and Song 2001; Nobre et al. 1991; Hahmann and Dickinson 1997; Gandu et al. 2004). Studies have found that the drying season has been lengthened (e.g., Nobre et al. 1991). An extended dry season near or within the deforested areas can have an impact on the intensity and frequency of forest fires (Nobre et al. 1991). Additionally, forest fires could be fueled by the damaged trees and the extensive dry season.

This thesis is unique in examining the impact on regional climate from deforestation caused by wind damage rather than human activity. In this thesis, multiple simulations for July were created using WRF to investigate the effects of forest damage on the regional climate, based damage patterns from Hurricane Katrina. The WRF simulations were then compared to determine how the surface energy budget and boundary layer conditions (temperature, moisture, winds) were affected by the deforestation.

A review of the existing literature on the impact of deforestation on climate is provided in Chapter 2. Chapter 3 is a manuscript that outlines the methods and results using three WRF simulations to address the research questions stated above. An extended conclusion is provided in Chapter 4.



**FIG. 1.1.** Hurricane Katrina county/parish designations with maximum sustained wind speeds, with 30-74 mph winds shown in yellow, 75-95 mph in orange, 96-110 mph in brown and 111-130 mph in red (Dewberry 2010).



**FIG. 1.2.** Impact of Hurricane Katrina on forested areas along the hurricane path based on potential down timber from Hurricane Katrina (USDA Forest Service 2005).



**FIG. 1.3.** Image showing an example of tree mortality in a bottomland hardwood forest of the Pearl River basin from Hurricane Katrina (Chambers 2010).



**FIG. 1.4.** An aerial photo of the forest damage in the Pearl River Basin from Hurricane Katrina in 2005 (Earth Observatory 2010).



**FIG. 1.5.** Forest damage caused by Hurricane Katrina at 1km resolution on a scale from 0-1, with red indicating the most severe damage (Wang and Qu 2009).

## **CHAPTER 2**

#### LITERATURE REVIEW

A number of studies have examined the role of deforestation on regional climate, primarily from a modeling perspective. Various weather and climate models have been utilized in the study of climate change due to loss of vegetation, with the findings dependent on the region as well as the spatial and temporal domain. Study areas have included North America, Africa, Australia and the Amazon, among others. While much can be learned by comparing the work in these regions, it must be noted that each region has specific attributes, such as topography, hydrology, forest characteristics, and soils, which may affect the response of the regional climate to loss of forest cover.

Numerous other studies have addressed the type, extent and magnitude of forest damage that occurs from high wind events, including hurricanes. The forest damage pattern may determine how the physical properties of a damaged area are altered. These physical properties, such as albedo and surface roughness, may differ considerably in damaged versus undamaged areas. Topography, meteorology, forest characteristics, and storm frequency influence the type, extent and magnitude of forest damage from high wind events.

#### 2.1 Global/hemispheric climate changes from deforestation

The changes in the surface energy budget induced by deforestation, and resultant changes in temperature and precipitation, have both local and global impacts. For example, Brovkin et al. (1999) and Chase et al. (2000) used model simulations to illustrate how land cover changes can

affect global climate. Brovkin et al. (1999) converted much of the current agricultural land into forested area in a climate system model, CLIMBER-2. The deforestation in the CLIMBER-2 models illustrated the significance of the albedo effects. The output from the model showed deforestation caused a global cooling, mostly in the Northern Hemisphere in the middle and high latitudes and most notably during the spring. Studies that have modeled the effects of anthropogenic modification over time have found global cooling due to deforestation (Brovkin et al. 2006). Chase et al. (2000) simulated the current land use and the natural potential vegetation for the Northern Hemisphere winter using the National Center for Atmospheric Research (NCAR) Community Climate Model, version 3 (CCM3). The resulting simulations from current vegetation back to natural vegetation showed an averaged zonal northward change and a decrease of tropical convection along with an east-west shift in the remaining tropical precipitation (Chase et al. 2000). Through the global modeling of vegetation change, other studies have found the anthropogenic modification of vegetation has minimal global effects on temperature and precipitation but have found a significant impact on a regional scale (Bounoua et al. 2002; Lawrence and Chase 2010; Findell et al. 2007). Bounoua et al. (2002) found cooling in the temperate latitudes and warming in the tropics that averaged globally little or to no change using the Colorado State University general circulation model coupled to a biophysically based land surface model. Brovkin et al (2009) used the Earth System Model of the Max Planck Institute for Meteorology model to create a forest planet, grass planet, and a control run planet. They found that the forest planet increased the temperature and the grass planet decreased the temperature from the control run. Chase et al. (2000) suggest that the teleconnections patterns that are caused by human alteration of the land surface have already affected temperature and precipitation globally.

However, Mahmood et al. (2010) provided an overview of land use/land cover change effects. They stated that to understand the anthropogenic impact on the land cover change, research should have a regional focus as "it is the regional responses, not a global average, that produce drought, floods and other societally important climate impacts." Downwind effects such as an increase in precipitation and lightning from land cover change were also discussed by Mahmood et al (2010).

#### 2.2 Tropics

### 2.2.1 Africa

Semazzi and Song (2001) simulated the deforestation of the tropical rain forests in Africa by replacing the rainforest with savanna grasslands for simulations using CCM3. Over the simulated deforested areas, the annual precipitation decreased, but seasonal precipitation totals had varied responses, such as delayed rainfall season during September through November. The authors suggested that dynamical horizontal convergence of moisture from surrounding areas would decrease due to deforestation (Semazzi and Song 2001). Both surface air temperatures and the ground temperatures increased in the deforested regions. Effects of the cleared rainforest was evident in distant regions during September, October and November (Semazzi and Song 2001). A wave-like rainfall pattern was evident over the near-equatorial region downstream from the deforested region during December through February. Suppressed Rossby wave trains associated with mid-tropospheric latent heat from tropical convection were responsible for the wave-like rainfall pattern. Eastern and western Africa experienced a decrease in precipitation in their simulations. MacKellar et al. (2008) used the Pennsylvania State University-National Center for Atmospheric Research Mesoscale Model (MM5) to show the impact of changing the natural vegetation to present-day vegetation in southern Africa. Cooling occurred over large areas of the continent during September, October, and November. Along with the cooling, there was an increase in large-scale subsidence, decrease in moisture convergence and an increase in geopotential heights. Zeng (2003) discussed the cause of the droughts in the Sahel. One explanation explored was the loss of forest from overgrazing and agriculture.

# 2.2.2 Amazon

Several studies have addressed regional climate change due to deforestation over the Amazon River basin. There is particular concern with this area because it is the largest remaining tropical rain forest and because of the large and rapid loss of forest cover in that region. Sampaio et al. (2007) estimated that 40% of the Brazilian Amazonian rainforest could be converted to agriculture by 2050. Nobre et al. (1991) studied the effects of deforestation in Amazonia on regional and global climate by replacing the Amazonian tropical forests with pasture in model simulations with a global spectral model. They found that the mean surface temperature increased and precipitation, runoff, and evapotranspiration decreased with deforestation. The effects of the land cover change were most evident during the dry season. There were greater diurnal changes in surface temperature and decreased vapor pressure and moisture convergence (Nobre et al. 1991). The authors suggest that the extended dry season would have ecological implications and increase the intensity and frequency of forest fires. Sampaio et al. (2007) used the CPTEC-INPE global atmospheric model by converting rainforest to pasture or soybean cropland in the Amazon and noted that increased albedo and decreased evapotranspiration caused a precipitation change. The reduction of rainfall was stronger during the dry season and when the deforestation exceeded 40% of the original forest cover (Sampaio et al. 2007).

Hahmann and Dickinson (1997) also studied the local and regional effects of deforestation in Amazonia using the NCAR Community Climate Model version 2 (CCM2). The model simulated an annual increase in temperature and a decrease in evaporation and precipitation over the deforested region. The moisture convergence and the precipitation maxima shifted during the wet season but did not decrease overall. The recycling of the precipitation in Amazonia - where rain falling near the coast is recycled inland - was reduced due to the decreased roughness and surface evaporation and the increased albedo of the denuded forest. The disrupted precipitation recycling caused increased precipitation near the coast and decreased precipitation inland in the model simulations. Gandu et al. (2004) found a reduction in the sensible heat flux was more noticeable during the dry months than during the rainy season over the continental areas using the Regional Atmospheric Modeling System (RAMS). Areas of enhanced latent heat flux were located in the uplands north of the equator (Gandu et al. 2004). Temperatures increased from June to August over most of the land within the domain. In their deforested model simulations, areas along the coasts and around the Amazon River showed an annual reduction in precipitation in both the dry and rainy seasons (Gandu et al. 2004). The wind speeds increased along the coast, which decreased the moisture convergence there and increased moisture convergence inland. Bastable et al. (1993) found that temperature and specific humidity did not alter much over the course of the 60-day observation period in the deforested region in the Amazon, but the daily ranges of temperature and humidity in the clearing were twice than that of the forest. Model simulations by Lean and Rowntree (1996) using field studies with the Hadley Centre GCM showed that rainfall and evaporation decreased while temperature and moisture increased as a result of Amazonian deforestation.

D'Almeida et al. (2007) conducted a review of modeling and observational studies and suggested that the size of the area deforested and the resolution of the climate model used can show different results. Most atmospheric general circulation models reviewed have shown weakened water fluxes due to extensive deforestation (D'Almeida et al. 2007). Depending on the resolution and size of deforestation, the precipitation recycling observed in the Amazon may be interrupted which has an effect on the evapotranspiration. The observational studies reviewed by D'Almeida et al. (2007) did not demonstrate an interruption in the hydrological cycle associated with deforestation.

## 2.3 Mid-latitudes

## 2.3.1 Australia

Narisma and Pitman (2002) explored the relation between land cover change and climate change in Australia using MM5. The simulations used land covers that were representative of the vegetation in 1788 and in 1988. Areas mostly in the southwestern region of Australia have been altered from trees to grassland during the last two centuries, while areas in the northeast have been changed from sparse to shrub. Narisma and Pitman (2002) found that the effects of the land cover change in Australia during the austral winter showed that the latent heat flux increased for the northeast and decreased for the southeast and southwest. Narisma and Pitman (2002) also found that in the southwest and the southeast of Australia, the increase in temperature from 1788 to 1988 was more noticeable during summer (January) than during winter (July). A greater decrease in temperature occurred during winter (July) than in summer (January) in northeast Australia, but both changes were statistically significant. They also suggested that the leaf area index and the roughness length had a greater impact than changes in the albedo. For the northeast

Australia study area, the simulated rainfall had increased mostly during winter (July) while the southeast and the southwest regions showed a slight reduction in both summer and winter. The findings are consistent with FIG. 2.1, which shows the impact of changing trees to grass on temperature.

# 2.3.2 North America

Other areas that have experienced land use change for various reasons include the southern U.S. The southern U.S. has lost about 8.5 million ha of forest since 1907 due to clearing for farming and urbanization (Conner and Hartsell 2002). Pielke et al. (1999) studied the effects of land cover change in south Florida using observed land cover from 1900, 1973, and 1993 using RAMS and found that the precipitation decreased from the 1900 natural landscape simulation to the 1993 simulation. Latent heat flux decreased while surface sensible heat flux increase from 1900 to 1993 in southern Florida. Both maximum and minimum land temperatures in south Florida also increased due to the land cover change. Wichansky et al. (2008) changed the modern land cover over New Jersey to the historical land cover from the 1800s using RAMS. The temperatures increased 0.3-0.6°C and dew point temperatures decreased 0.3-0.6°C for the modern land cover. In the Pacific Northwest, O'Neal et al. (2010) used study sites in the Gifford Pinchot National forest on the northwest side of Mount Adams, Washington to determine the affect of land cover change on the climate. O'Neal et al. (2010) found a 0.7°C increase in temperature from late July to late September.

Bonan (1997) studied broader impacts of land use in the U.S. using the NCAR land surface model version 1.0. He created a modern vegetation simulation that had areas in the eastern United States modeled as predominantly crop or a mix of forest and crops, between

100°W and 110°W was grassland and the western United States is comprised of shrubland and semi-desert vegetation. In his natural vegetation simulation, the eastern U.S. consists of mixed forest types while a maximum agriculture simulation was created by replacing some of the forest types in the eastern U.S. with more cropland. Bonan (1997) showed that with modern vegetation there was a cooling over the eastern U.S., a warming over the western U.S., a significant cooling occurred over much of the central U.S., and an increase in moisture in the near-surface atmosphere over much of the U.S. The height of the boundary layer decreased 100 m in the winter and 200-300 m in the summer over the central U.S. in the modern vegetation simulation The decrease in the boundary layer was larger and more wide spread for the maximum agriculture simulation due to changes in surface energy budget. While the precipitation was not significantly altered, the near-surface humidity was altered. Bonan (1999) found that the eastern and central U.S. cooled, maximum temperature decreased and diurnal temperature ranges decreased from the natural vegetation to modern vegetation when using CCM3 and keeping all factors the same except vegetation cover. The cooling is caused from a reduction of net radiation, increased surface albedo, decreased roughness length, and decreased leaf and stem area. Diffenbaugh (2009) studied the modern non-urban land cover distribution over the continental U.S. from potential vegetation and found a cooling of the surface temperatures. Greater moisture was found by Diffenbaugh (2009) in the lower atmosphere and an increase in warm season precipitation using the ICTP Regional Climate Model (RegCM3). Evapotranspiration decreased along with averaged net radiation, sensible heat flux, and radiative surface temperature in a study conducted by Mishra et al. (2010), who converted forest to cropland using the Intergovernmental Panel for Climate Change (IPCC) AR4 GCMs Hadley Centre Coupled Model version 3

(HadCM3), Parallel Climate Model (PCM), and Geophysical Fluid Dynamics Laboratory model (GFDL).

One particularly relevant and recent study was by Klingaman et al. (2008), who modeled the local and regional climate change due to clear-cut logging in the Susquehanna River basin in the northeastern U.S. MM5 coupled with Noah LSM was used to simulate the prehistoric and clear-cut conditions for August and February. In their February simulations, evapotranspiration did not change significantly. They found in August that the increased surface albedo and decreased roughness length altered the surface energy budget, causing a decrease in the latent heat (FIG. 2.2a and b) to decrease net surface shortwave radiation (FIG. 2.2c and d), increase sensible heat flux into the atmosphere (FIG. 2.3a), and a much deeper boundary layer (FIG. 2.3b). Many of the effects of deforestation were more prevalent in their summer simulations than in their winter simulations, as might be expected due to the lack of leaf area and minimal transpiration from forests in winter. One-half of the latent heat flux change from the prehistoric to the clear-cut simulation was explained by the decrease in evapotranspiration (Klingaman et al. 2008). A decrease in net surface shortwave radiation was seen during both the summer and winter, but was greater during the summer. The surface albedo increased due to the tree loss, which had an effect on the net shortwave radiation. The diurnal temperature range was affected because late-morning and afternoon latent heat flux decreased and the sensible heat increased. Klingaman et al. (2008) found that summer (August) temperatures increased more than 1.5°C across the clear-cut region. There was also an increase of the sensible heat for the summer clearcut simulation while winter (February) showed a slight decrease in sensible heat flux. The ground and soil temperatures increased, but the 2 m air temperature during the day increased only slightly due to the increase of mixing of the added heat energy into the lower atmosphere.

There was an increase of soil moisture in the clear-cut August simulation in every soil layer except the near-surface layer (0-10 cm) due to the reduction of root depth of the vegetation. The near-surface layer moisture decreased due to the change in the vegetation root depth from trees to grass, increase in evaporation and reduction of precipitation. The 2 m temperature was mostly affected at night, likely due to reduced mixing in the boundary layer, and a return of a large portion of the heat energy stored in the soil during the day (Klingaman et al. 2008). The mixing ratio for the lower-troposphere in the Susquehanna River basin was lower in the clear-cut simulation. The summer clear-cut precipitation decreased 1.5 - 3.0 cm. They found that some areas downstream of the clear-cut area experienced moisture convergence in the lower levels of the atmosphere, which caused an increase in rainfall downstream of the clear-cut region. The westerlies over the Susquehanna River basin were found to increase due to the decrease in the roughness length in their clear-cut simulation.

#### 2.4 Forest damage from high wind events

Foster et al. (1998) stated that the type of disturbance and the nature of an individual event help determine the extent and distribution of damage. The type and amount of damage to forests from high winds associated with tropical systems depend on a number of factors, including storm meteorology and forest characteristics. A variety of methodologies have been employed to assess the extent of damage, such as aerial photographs of the damaged area and field assessments of the forest plots.

Literature discussing tropical storms impacts in forested regions in the southeast U.S. have been focused along the coasts, and most were case studies of individual hurricanes. Two recent examples are Kupfer et al. (2008), who studied DeSoto National forest in southern

Mississippi, and Ramsey et al. (1997), who studied wetlands in southern Louisiana. Kupfer et al. (2008), Oswalt and Oswalt (2007) and Stanturf et al. (2007) examined damage from Hurricane Katrina. In addition to Hurricane Katrina, Stanturf et al. (2007) also examined Hurricane Rita, which made landfall in southwest Louisiana as a Category 3 on 24 September 2005. Hurricane Andrew reached land on 26 August 1992 as a Category 3 and is included in the Ramsey et al. (1997) study of hurricane damage in the Atchafalaya Basin. Ramsey et al. (1997), Oswalt and Oswalt (2007) and Kupfer et al. (2008) deliberately chose coastal locations to study hurricane damage. Nevertheless, tropical systems can extend inland with hurricane or tropical storm force winds, where inland forests may be affected.

# 2.4.1 Topography

Stanturf et al. (2007) stated that topography has an impact on the amount of exposure to wind. Topographic characteristics such as elevation, slope angle and aspect were used in the study by Kupfer et al. (2008) to find and analyze floodplains and separate the damage in uplands and the bottomlands. Oswalt and Oswalt (2007) also used topography to distinguish between upland and bottomlands and showed that species most likely found in upland areas were among the most damaged. Bottomlands generally consist of hardwood species such as oak and sweetgum while uplands consisted of softwoods such several species of pine. Oswalt and Oswalt (2007) found that in the areas closest to landfall, the upland species were more heavily damaged than the bottomland species, while the hardwoods had the highest percentage of damage across all of the zones. Kupfer et al. (2008) found a difference in the damage between the bottomland hardwoods and the upland softwoods in DeSoto Ranger District of DeSoto National Forest.

### 2.4.1 Meteorology

Kupfer et al. (2008) suggested that the fine-scale wind data allows for a broader analysis of hurricane damage. According to Kupfer et al. (2008), storm meteorology is of secondary importance, less important than stand conditions and site characteristics. Nevertheless, the authors do state that the storm meteorology plays an active role in determining the amount of storm damage. The effect of increasing gust speed over 36.1 m s<sup>-1</sup> on tree damage was dependent on factors such as the species characteristics, soil factors, and storm duration (Kupfer et al. 2008). Rainfall amount along with soil type and topography determines the saturation of the soil which affects the amount and type of damage. Several studies included a description of the storm track in an attempt to determine the period of hurricane-force winds as seen (Oswalt and Oswalt 2007; Kupfer et al. 2008; Batista and Platt 2003; Ramsey et al. 1997).

#### 2.4.3 Forest characteristics

While the location of the forests and the meteorology proved important in understanding the impact of tropical storms, the characteristics of the forest itself, such as species distribution and tree sizes have also been shown to play an important role in the amount of damage caused by a tropical system. A majority of the research has concentrated on the differences in forest damage between hardwoods and softwoods. Ramsey et al. (1997) focused on three sites of cypress-tupelo swamps and bottomland hardwoods in the Atchafalaya Basin after Hurricane Andrew in 1992. The amount of damage varied between the sites due to species composition, topography, and proximity to the hurricane track. Branch damage generally increased with density and height. Lean damage, trees that are leaning but not completely uprooted, deceased with tall trees and trees with a larger diameter, but the results may be affected by other

relationships that also include species group and density. Stanturf et al. (2007) discussed the different species found in various forest structures. Bottomland forests, according to Stanturf et al. (2007), can be easily overturned due to the shallow root systems, but cypress trees in deepwater swamps are not overturned often. Oswalt and Oswalt (2007) studied homogeneous plots consisting of softwoods and hardwoods in various zones extending from Hurricane Katrina landfall on the border of Mississippi and Louisiana. They found that hardwoods experienced more overall wind related damage than softwoods (Oswalt and Oswalt 2008). In the zone closest to landfall, softwoods experienced more damage than the hardwoods. With the subsequent zones, hardwoods experienced more damage with a greater relative difference in the amount of damage between hardwoods and softwoods as the storm moved further inland (Oswalt and Oswalt 2008). Stanturf et al. (2007) estimated potential stem breakage from functions of tree height, tree spacing, and sustained wind speed for four damage areas of Hurricane Katrina. Kupfer et al. (2008) found that stand age was the best predictor of forest damage for the models used in the study with forest type, stand condition, site aspect, and distance to the nearest perennial stream also explained the variation in forest damage. Blowdown was seen after Hurricane Katrina among openings and boundaries where stands of different ages met or stands with different densities met. Stand age as well as proximity to a stream influence the amount of storm damage due to the drainage of the precipitation from the tropical storm. The proximity to a stream as well as the amount of precipitation influences the saturation of the soil. An increase in soil saturation can cause an increase in damage such as an increase in uprooting and windthrow (Foster et al. 1998).

Some severe wind events that are experienced in the southeast U.S. are straight-line winds, tornados, and winds associated with tropical cyclones. Multiple hurricane strikes can

cause significant damage in a given region. Significant damage to timberland can be caused by wind damage and heavy precipitation, such as the 2.23 million ha of timberland in the coastal states of the Gulf of Mexico that were damaged from Hurricane Katina and Hurricane Rita (Stanturf 2007). Damage caused by previous wind events is suggested to affect the amount of damage during a later wind event (Putz and Sharitz 1991).

## 2.4.4 Fire potential

The fire potential after deforestation, insect-induced damage or wind-induced storm damage is greater than before the disturbance occurred. Nepstad et al. (2008) studied the feedback of the Amazon due to forest degradation. When the crowns of the trees were removed, the amount of solar radiation that reached the ground increased, warming the ground. The author stated that land-use activities added to the forest susceptibility to fire by adding ignition sources (Nepstad et al. 2008). A positive feedback occurred with forest clearing; the clearing reduced rainfall, which led to higher vegetation mortality (FIG. 2.4). Laurence (2004) studied the impact of forest fragmentation on atmospheric conditions, fire, physical, and biotic changes. Tropical habitat fragmentation allowed fires to enter up to several kilometers inside the forest while atmospheric circulation variations such as moisture being transported away from the forest can reach 20 km or more (Laurence 2004). Aragão et al (2008) suggested that slash and burn agriculture could enhance the impact of droughts, further increasing the fire risk. Due to deforestation in the Amazon, Congo and Indonesia/New Guinea, the precipitation and relative humidity decreased while wind speed increased, causing the forest fire danger index to increase by 41, 56 and 58% (Hoffmann et al. 2003). The increase in fire frequency was 44, 80, and 123%

in the Amazon, Congo and Indonesia/New Guinea, respectively (Hoffmann et al. 2003). Dyer and Baird (1997) stated that downed trees increase the risk of subsequent fires in Minnesota.

#### 2.5 Summary

Local, regional and global climate change can occur as a result of deforestation, as demonstrated by numerous modeling and observational studies. Various types of climate models have been used to examine the relationship between land cover change and climate in several areas of the world. These studies agree that increased albedo and decreased surface roughness effects due to deforestation both play a role in altering the climate over and near the deforested area. The sign and magnitude of the effects on temperature and moisture may depend on the local geography, type of forest, and spatial scale. Furthermore, several studies have suggested a linkage between deforestation and decreased precipitation / greater drying. This drying potentially could enhance loss of forest cover through effects on stand health and fire frequency.

One particular type of land cover change is a result of the impact of high wind events on forests. Large windstorms, such as hurricanes, may affect large areas of forest cover near and immediately inland from the hurricane landfall. The effects of a hurricane on forests are complex, and have been shown to be a function of storm meteorology, topography, species distribution, tree size, and antecedent precipitation, among other factors. The climate impacts of this type of land cover change on climate have not been examined previously. Chapter 3 of this thesis examines the impact of land cover change from one hurricane – an idealized event based on Hurricane Katrina in 2005 – on the regional climate of the U.S. Gulf Coast.



**FIG. 2.1.** Schematic diagram of the mechanisms behind the impact of the land cover change from trees to grass on temperature (Narisma and Pitman 2002).



**FIG. 2.2.** August (left) and February (right) images of the difference in ensemble means of Clearcut minus the Prehistoric simulations. (a) (b) Latent heat, (c) (d) net surface shortwave radiation, and (e) (f) 2m temperature are shown (Klingaman et al. 2008).


**FIG. 2.3** August difference of the ensemble means between Clear-cut and Prehistoric simulations in (a) sensible heat and (b) height of the boundary layer (Klingaman et al. 2008).



**FIG. 2.4.** Diagram of the process and interactions that could lead to a near-term Amazon forest dieback (Nepstad et al. 2008).

# **CHAPTER 3**

# THE EFFECTS OF TROPICAL CYCLONE INDUCED DAMAGE ON THE REGIONAL CLIMATE OF THE U.S. GULF COAST<sup>1</sup>

<sup>&</sup>lt;sup>1</sup> Becker, L.E., and T.L. Mote. To be submitted to *Journal of Applied Meteorology and Climatology*.

#### ABSTRACT

This study examines the regional climate change resulting from forest damage along the U.S. Gulf Coast. The Weather Research and Forecasting (WRF) model coupled with Noah Land-Surface model were initialized from North American Regional Reanalysis (NARR) data for a 7day study of a damage area in southern Mississippi, roughly matching the damage pattern from Hurricane Katrina. Three simulations were conducted to assess the potential for hurricaneinduced wind damage to alter regional climate. The first simulation used the default USGS land cover information. The second simulation converted evergreen needleleaf forest to shrubland within the damage area, and the third simulation was identical to the second, except the surface albedo for evergreen needleleaf forest was maintained. The greatest changes were experienced by the first post-Katrina run with the shrubland albedo such as the temperatures were reduced an average 0.2°-0.8°C within the study area. Ground heat flux decreased and latent heat decreased, winds increased and changed direction, and the planetary boundary layer decreased for the post-Katrina. The albedo simulation had an increase in 2m mixing ratio, upward ground heat flux increased, and the winds increased comparable to the post run. The changes in albedo affected the PBL height and temperature, while the roughness length affected the winds and 2m mixing ratio. Cross sections showed the effects of the change in the winds and the 2m mixing ratio on the vertical velocities and relative humidity. The vertical velocities shifted south and the relative humidity lowered vertically, suggesting a change in the penetration of the sea breeze front. Diurnal ranges of temperature and mixing ratio in Hattiesburg, MS were affected in both post-Katrina simulations. The changes overall in the albedo run were not as significant as in the post simulation, suggesting the important role of the albedo changes.

# **3.1 Introduction**

Hurricane Katrina struck the Gulf Coast of Louisiana and Mississippi in 2005 within the typical Atlantic hurricane season. On 29 August 2005, it made landfall in Plaquemines Parish near Buras, LA, as a Category 3 hurricane with a central pressure of 920 hPa around 1110 UTC (0610 CDT) (Knabb et al. 2005). After making landfall in Louisiana, Hurricane Katrina made another landfall near the Louisiana/Mississippi border coastal area around 1445 UTC (0945 CDT) (Knabb et al. 2005) (FIG. 3.1). As Katrina made landfall in Louisiana, wind speeds of 57 m s<sup>-1</sup> (110 kt) were recorded in southeastern Louisiana. Hurricane Katrina affected people and wildlife alike with destruction of homes and property.

The Gulf coastal regions of Louisiana and Mississippi also contain forested areas of varied kinds from pine plantations to wetland forests. Southern Mississippi has forested parks such as Desoto National Forest in southeast Mississippi and the Homochitto National Forest in the southwest Mississippi. Considerable tree loss can occur in the forested regions after major wind events such as a hurricane (FIG. 3.2). Initial estimates of tree damage from Hurricane Katrina just in the De Soto National Forest were 154,590 ha with moderate to heavy damage; about 40% of the trees sustained significant damage (Meeker et al. 2006; Shedd 2005). During the early assessments of the damage from Katrina, about 2.023 million ha of forest were considered damaged (USDA Forest Service 2005). About 90% of the forests that were damaged were within roughly 100 km (60 mi) of the Gulf Coast in Alabama, Louisiana, and Mississippi (USDA Forest Service 2005) (FIG. 3.1 and 3.2).

Forest loss due to natural disasters can modify the local climate, both where the tree loss occurred and in the surrounding areas (e.g., Gandu et al. 2004; Klingaman et al. 2008; Narisma and Pitman 2002). Tree mortality and damage can cause changes in surface albedo,

evapotranspiration rate, surface roughness, soil moisture, and diurnal temperature range, causing a positive feedback (FIG. 3.3). When trees are damaged from a high wind event, the damaged trees or fallen limbs do not immediately change color. There is a period after damage when the trees or limbs are still foliated and have similar or the same albedo as before the damage occurred.

Given the significant impact of Hurricane Katrina on Gulf Coast forest cover, and given the previous studies demonstrating a link between land cover change (particularly deforestation) and regional climate, the overarching research question is how the regional climate of the Gulf Coast region was affected by this land cover change. Simulations using a simplified forest damage scenario based on Hurricane Katrina damage estimates were conducted using the WRF model with the Noah land surface model and compared with pre-Katrina land cover. Furthermore, in order to separate the influence of albedo change from the other factors, a simulation with pre-Katrina albedo but post-Katrina surface roughness was also conducted.

A majority of the studies examining the local and regional climate variability from loss of vegetation have focused on deforestation due to human activity, such as logging and clear cutting for crops. Numerous studies of studies of deforestation focused on the tropics , typically in the Amazon (Semazzi and Song 2001; Nobre et al. 1991; Hahmann and Dickinson 1997; Gandu et al. 2004). Many of these studies have found that the drying season has been lengthened by deforestation. An extended dry season near or within the deforested areas can have an impact on the intensity and frequency of forest fires (Nobre et al. 1991). The fires potentially could be stronger due to the fuel provided by the damage and the extensive dry season.

This research is unique in examining the impact on regional climate from deforestation caused by wind damage rather than human activity. In this research, three simulations during

July were created using the WRF to investigate the effects of forest damage on the local and regional climate based on Hurricane Katrina forest damage maps.

## 3.2 Background

A number of studies have examined the role of deforestation on regional climate, primarily from a modeling perspective. The changes in the surface energy budget induced by deforestation, and resultant changes in temperature and precipitation, have both local and global impacts. For example, Brovkin et al. (1999) and Chase et al. (2000) used model simulations to illustrate how land cover changes can affect global climate. Brovkin et al. (1999) converted much of the current agricultural land into forested area in a climate system model, CLIMBER-2. Chase et al. (2000) simulated the current land use and the natural potential vegetation for the Northern Hemisphere winter using the National Center for Atmospheric Research (NCAR) Community Climate Model, version 3 (CCM3). They found that there was a global cooling, and the Northern Hemisphere winter showed an averaged zonal northward change and a decrease of tropical convection along with an east-west shift in the remaining tropical precipitation from current to natural vegetation (Brovkin et al. 1999; Chase et al. 2000). Through the global climate modeling that incorporates vegetation change, other studies have found the anthropogenic modification of vegetation had minimal global effects on temperature and precipitation but have found significant impacts on a regional scale (Bounoua et al. 2002; Lawrence and Chase 2010; Findell et al. 2007). In fact, Mahmood et al. (2010) stated that to understand the anthropogenic impacts, research should have a regional focus.

Several studies of the effect of deforestation on climate have focused on the tropical regions of Africa and South America. For example, using CCM3 Semazzi and Song (2001)

established that over the simulated deforested areas, the annual precipitation decreased and a delayed rainfall season. Both surface air temperatures and the ground temperatures increased in the deforested regions. Effects of the deforestation were also shown in areas not directly over the deforested region. Effects of the cleared rainforest was evident in distant regions during the September, October and November months (Semazzi and Song 2001). Nuñez et al. (2008) showed in an observational study that the cooling experienced and the decrease in the diurnal temperature range in their study in Argentina was due to the increase in soy agriculture. There were greater diurnal changes in surface temperature and decreased vapor pressure and moisture convergence in model studies that incorporated Amazon deforestation (Nobre et al. 1991). Nobre et al. (1991) also found that the mean surface temperature increased and precipitation, runoff and evapotranspiration decreased, with deforestation in a global spectral model. Gandu et al. (2004) using the Regional Atmospheric Modeling System (RAMS) found that the wind speeds increased along the coast of South America, which decreased the moisture convergence there and increased moisture convergence inland, in model scenarios with deforestation in the Amazon. Bastable et al. (1993) found that temperature and specific humidity did not change much over the course of the 60-day observation period in the deforested region in the Amazon, but the daily ranges of temperature and humidity in the clearing were twice than the forest. Most atmospheric general circulation models reviewed have shown weakened water fluxes due to extensive deforestation (D'Almeida et al. 2007).

Other areas that have experienced land use change for various reasons include North America. Pielke et al. (1999) modeled three land cover scenarios using the RAMS. The first was the 1900 landscape, which was closest to the natural vegetation. The second was the 1973 landscape, and the third was the 1993 landscape. Model simulations in Pielke et al. (1999)

resulted in the latent heat flux decreased while surface sensible heat flux increase from 1900 to 1993 in southern Florida. Bonan (1997) studied broader impacts of land use in the U.S. using the NCAR land surface model version 1.0. Bonan (1997) showed that with modern vegetation compared to natural vegetation scenario there was a cooling over the eastern U.S., a warming over the western U.S., a significant cooling occurred over much of the central U.S., and an increase in moisture in the near-surface atmosphere over much of the U.S. The height of the boundary layer decreased over the central United States in the modern vegetation simulation and the decrease was larger and more widespread for the maximum agriculture simulation due to the changes in the surface energy budget. Bonan (1999) found that the eastern and central U.S. cooled, maximum temperature decreased and diurnal temperature range decreased from the natural vegetation to modern vegetation using CCM3.

Changes in albedo, leaf area index, and roughness length have an impact on the near surface temperatures (Strack et al. 2008). Results from Strack et al. (2008) suggest that the increase in temperatures in the eastern U.S. from historical land cover to current land cover is due to the surface roughness and transpiration (i.e., stomatal resistance) changes. Strack et al. (2008) used RAMS coupled with the Land Ecosystem-Atmosphere Feedback (LEAF-2) and changed modern land cover to historical land cover for a June simulation. Fall et al. (2010) stated that the change in distribution of land cover types from 1979 to 2005 affected the moisture availability and temperature in the lower atmosphere, using National Center for Environmental Prediction (NCEP) North American Regional Reanalysis data (NARR), the Advanced Very High Resolution Radiometer (AVHRR) land use/cover classification, the National Land Cover Database (NLCD) 1992-2001 Retrofit Land Cover Change and the Normalized Difference Vegetation Index (NDVI) derived from AVHRR.

Diffenbaugh (2009) used ICTP Regional Climate Model version 3 (RegCM3) to study the modern non-urban land cover distribution over the continental U.S. and found a reduction of the surface temperatures compared to natural vegetation. Greater moisture was found by Diffenbaugh (2009) in the lower atmosphere and an increase in warm season precipitation. Evapotranspiration decreased along with averaged net radiation, sensible heat flux, and radiative surface temperature in a study conducted by Mishra et al. (2010), who simulated the effect of converting forest to cropland using Intergovernmental Panel for Climate Change (IPCC) AR4 GCMs: Hadley Centre Coupled Model version 3, Parallel Climate Model, and Geophysical Fluid Dynamics Laboratory model.

One particularly relevant and recent study was by Klingaman et al. (2008), who modeled the local and regional climate change due to clear-cut logging in the Susquehanna River basin in the northeastern U.S. using the Pennsylvania State University-NCAR Mesoscale model (MM5) coupled with the Noah land surface model (LSM). They found in August that the increased surface albedo and decreased roughness length altered the surface energy budget, causing decreased net surface shortwave radiation, increased sensible heat flux into the atmosphere, and a much deeper boundary layer. Many of the effects of deforestation were more prevalent in their summer simulations than in their winter simulations, as expected due to the lack of leaf area and minimal transpiration from these forests in winter. One-half of the latent heat flux change from the prehistoric to the clear-cut simulation is explained by the decrease in evapotranspiration (Klingaman et al. 2008). The surface albedo increased due to the tree loss, which had an effect on the net shortwave radiation. The diurnal temperature range was affected because late-morning and afternoon latent heat flux decreased and the sensible heat increased. Klingaman et al. (2008) found that summer (August) temperatures increased more than 1.5°C across the clear-cut region.

There was also an increase of the sensible heat for the summer clear-cut simulation. The ground and soil temperatures increased, but the 2 m air temperature during the day increased only slightly due to the increase of mixing of the added sensible heat into the lower atmosphere. The near-surface layer moisture decreased due to the vegetation root depth, increase in evaporation and reduction of precipitation. The 2 m temperature was mostly affected at night, likely due to reduced mixing in the boundary layer, and a return of a large portion of the heat energy stored in the soil during the day (Klingaman et al. 2008). The mixing ratio for the lower-troposphere in the Susquehanna River basin was drier in the clear-cut simulation, and the summer clear-cut area experienced moisture convergence in the lower levels of the atmosphere, which caused an increase in rainfall downstream of the clear-cut region. The westerlies over the Susquehanna River basin were found to increase due to the decrease in the roughness length in their clear-cut simulation.

Global to regional to local climate change can occur as a result of deforestation, as shown by numerous previous studies. Studies agree that both albedo and surface roughness change affect the atmospheric conditions over or near the deforested area. Nearly all of the previous studies use man-made deforestation as a motivation for their research. Large windstorms, such as hurricanes, may affect large areas of forest cover near and immediately inland from the hurricane landfall. The climate impacts of this type of land cover change on climate have not been examined in detail previously. This research examines the impact of land cover change from one hurricane – an idealized event based on Hurricane Katrina in 2005 – on the regional climate of the U.S. Gulf Coast.

## 3.3 Data and methodology

Changes in local and regional climate due to the loss of forest cover in southern Louisiana and Mississippi from Hurricane Katrina is explored through modeling the climate using land cover representative of conditions before and after the storm. Three simulations using the Weather Research and Forecasting model (WRF) in conjunction with the Noah Land Surface Model (LSM) are used to examine the effects of deforestation. The differences in the simulations runs are more extreme than the actual damage and are used to exaggerate possible impacts to highlight those the changes induced by deforestation.

## a. Modeling system

WRF is a numerical weather prediction and atmospheric simulation system that uses fully compressible, Euler nonhyrostatic equations (Skamarock et al. 2008). The applications of WRF are varied and include such applications as parameterized-physics research, regional climate simulations, atmosphere-ocean coupling, and air quality modeling (Skamarock et al. 2008). Within WRF, the Advanced Research WRF (ARW) is a dynamic solver is combined with WRF that was used to study the cases presented in this study. The ARW can be initialized from user defined initial conditions or from interpolated data from real-data (Skamarock et al. 2008). In this study, the initial conditions for ARW were initiated from North American Region Reanalysis (NARR), which is discussed below.

The community Noah LSM is a result of a multi-institutional collaborative effort among NCEP, NCAR, U.S. Air Force Weather Agency, NASA, and the university community to develop a unified land surface model for numerical weather prediction community (Ek et al.

2003). Noah was designed for a number of purposes, including high-resolution real-time weather forecast, air pollution modeling, and local and regional hydrologic applications.

The Noah LSM model (version 3.0) was used to model the land condition changes and was coupled with WRF. Soil moisture, soil temperature, canopy water, root depth, and energy and water flux terms in the surface energy balance and the surface water balance are some of the aspects of the surface and boundary layer that are captured in Noah (Ek et al. 2003).

WRF simulations used three nests, with a grid resolution of approximately 32km in the outermost domain and approximately 3 km grid over southeastern Louisiana and southern Mississippi (FIG. 3.4). The WRF options are shown in Table 3.1. The physics and dynamic options chosen follow those used by Shepherd et al. (2009). The RRTM longwave and the Dudhia shortwave radiation physics options were used because of the atmospheric and cloud interactions. The Kain-Fritsch cumulus parameterization option includes shallow convection, low-level vertical motion in trigger function, and mass flux type with updrafts and downdrafts, entrainment and detrainment (Dudhia 2010). The Monin-Obukhov surface layer option was used due to the exchange coefficients to the surface scheme. The YSU planetary boundary layer (PBL) scheme determines the depth of the PBL from the thermal profile (Dudhia 2010). The Ferrier microphysics were used for the finest resolution domain because Ferrier microphysics option was designed for efficiency (Dudhia 2010). Model simulations were run for 17-day periods in July using identical conditions from NARR. The July 2007 NARR dataset was used because July 2007 was near the 30-year climate normal for the study area. The first 9 days of the run was omitted from the analysis to provide for model spin up.

# b. Model initialization

NOAA's National Center for Environmental Prediction (NCEP) NARR data were used to initialize the WRF simulations. NARR was created for a long-term set of consistent climate data on a regional scale for the North American domain (Mesinger et al. 2006). NARR incorporates a variety of observed and remotely sensed data sources into the Eta Data Assimilation System (EDAS) and Noah LSM. Lateral boundary conditions supplied by National Center for Atmospheric Research (NCAR) and NCEP Global Reanalysis 2. NARR is available at 32km spatial resolution, three-hour temporal resolution with 45 vertical layers from 1979-2003, originally, but is updated to near real time (Mesinger et al. 2006). Some of the variables in NARR data include but are not limited to air temperatures, snow depth, wind, moisture, precipitable water, soil moisture at multiple pressure levels from various sources such as rawinsondes, dropsondes, aircrafts, numerous satellites, surface observations as well as other sources.

# c. Land cover change

Three WRF simulations were run with two modified land cover simulations. The first WRF simulation, the control, was run to simulate the conditions along the U.S. Gulf Coast using the unmodified land cover classification from Noah LSM (FIG. 3.5a). The Noah LSM uses a classification from the United States Geological Survey (USGS) (Table 3.2). The classification has 33 classes from bare soil to various forest types.

The land cover was altered for the two post-Katrina simulations. An area of evergreen needleleaf forest classification in southern Mississippi representative of the most severe and moderate damage based on FIG. 3.1 was changed to shrubland classification for the first modified

run (FIG. 3.5b). FIG. 3.1 was based on Table 3.3 from the potential damage of timberland from Hurricane Katrina. The changes to the land cover are not a realistic representation and were considered a worse case scenario. The land use table used in WRF had an albedo for the evergreen needleleaf forest of 0.12 and the shrubland of 0.22. The evergreen needleleaf forest contained an albedo of 0.10 in the vegetation parameter table while the shrubland was 0.25 (Table 3.4). When forested areas are damaged by high wind events, the damaged trees continue to remain foliated after the damage occurred, but the roughness length along with other properties of the area are altered. Bare soil or brush normally covered by the tree canopy may be exposed when the trees are severely damaged. For the second modified land cover run, the area of shrubland remained the same as the first modified simulation, but the albedo for shrubland was changed to the albedo of the evergreen needleleaf forest.

#### d. Post-processing

Comparisons were made by examining difference maps of 2 m temperature, winds, and energy budget components among the different simulations. Additionally, time series of temperature and energy budget components for locations in or near the affected region were produced. Time series that represent the temperature, etc., of the different simulations were examined. Cross sections were examined, which help demonstrate the local changes in stability and any influence on the sea breeze front.

WRF output files were converted to GEMPAK files using wrf2gem program (Decker 2005). The General Meteorology Package, GEMPAK, was developed by the National Weather Service (NWS) National Severe Storms Laboratory (NSSL) and NASA's Goddard Space Flight Center to analysis, display and diagnosis of geo-referenced data (UCAR Community Programs

2010). The GEMPAK program GDSTAT was used to compute composite meteorological fields for the 7 days. Each averaged grid of the study area was then plotted using GDCNTR. Difference maps and derived fields from the three simulations were created using GDCNTR. The meteorological variables examined included, but were not limited to, ground heat flux, latent heat, planetary boundary layer height, precipitation totals, 2 m temperature, upward moisture flux at the surface, upward heat flux at the surface, and low-level winds. The GEMPAK program GDTSER was used to generate time series of temperature, mixing ratio, and latent heat. GDCROSS was used to make cross sections from Biloxi, MS, (BIX) to Columbus, MS, (CBM) containing the relative humidity, wind vectors, potential temperature and vertical velocity variables.

# 3.4 Results

# a. Composite maps

Difference maps were created for 7-day averages (i.e., composites) of the output from the pre-Katrina simulation (hereafter referred to as the "control" simulation) and each of the two post-Katrina simulations. The first post-Katrina simulation changed the damaged area to shrubland (hereafter referred to as the "post" simulation), while the second simulation retained the forest albedo (hereafter referred to as the "albedo" simulation). Difference maps were created for the post minus control and albedo minus control composite output. Temperatures at 2 m were 0.2-0.8°C lower in the post simulation with a cooling of 0.2-0.6°C extending into southern Alabama to the east of the deforested area. The greatest change in temperature was inland from the Mississippi Gulf Coast in the southeastern area and in the northern portion of the deforested area (FIG. 3.6). This pattern was not evident in the albedo simulation. The differences between

the albedo and post simulations suggest albedo changes were the dominant feature in the surface energy budget.

The ground heat flux was reduced in the post simulation along the Mississippi Gulf Coast. A decrease of at least 2 W m<sup>-2</sup> occurred along the Gulf Coast of Mississippi with decreases as great as 6 W m<sup>-2</sup> in the post simulation (FIG. 3.7a). The albedo simulation had decreases of 2 W m<sup>-2</sup> more uniformly across the deforested area with the greatest reduction along the Mississippi Gulf Coast (FIG. 3.7b). A reduction of latent heat flux at the surface of up to 20 W m<sup>-2</sup> in the southwestern portion of the deforested area occurred in the post simulation. Again, the albedo change appeared to drive these changes as the albedo simulation did not show the same effects (FIG. 3.8a and b). The changes shown over the Gulf of Mexico near the coast of Alabama and Florida were due to increased cloud clover (evident by reduced downwelling shortwave radiation) in the albedo simulation that was not obviously linked to the land cover change in the study area. The upward heat flux at the surface decreased throughout the deforested area in the post simulation. The greatest decrease was in southeastern Mississippi, which experienced a decrease greater than 60 W  $m^{-2}$  (FIG. 3.9a). The albedo simulation did not show the same extent of change as the post simulation (FIG. 3.9b). The changes in the upward heat flux were apparently caused by the albedo differences; the increased albedo, decreased net radiation and resulting decreased temperatures can cause a more stable lower troposphere, which can reduce the height of the mixing layer.

Low-level winds (10 m) in the post and albedo simulations became more westerly than in the control simulation (FIG. 3.10a, b and c). The winds over the deforested area increased by roughly 1 m s<sup>-1</sup> near the Gulf Coast Mississippi for both of the post-Katrina runs. Changes in the winds were apparently due to the decrease in surface roughness, because both post-Katrina

simulations showed a similar change. Winds downwind of the deforested area remained relatively unchanged, except for a small area immediately downwind over Alabama that experienced an increase of about  $1 \text{ m s}^{-1}$ .

Changes in surface energy budget, and resulting changes in temperature and stability, can cause a change in the planetary boundary layer thickness. The planetary boundary layer (PBL) decreased between 300-450 m over the deforested area in the post simulation (FIG. 3.11a). There was generally no change over the deforested area for the albedo simulation PBL (FIG. 3.11b). The decreased roughness length should result in decreased mechanical turbulence, which could be an important factor in PBL height depending on stability, but changes in PBL thickness were not evident in the albedo simulation. The changes in the PBL height apparently were the result of the changes in surface energy budget and boundary layer temperatures.

The changes in the temperature, winds, and latent heat flux can affect low-level moisture. The 2 m mixing ratio increased 0.4-1.2 g kg<sup>-1</sup> over the deforested area (FIG. 3.12a). Reduced vertical mixing due to a reduced PBL height in the post simulation was the most plausible cause of the increase in the 2m mixing ratio shown between 31°N and 32°N. The albedo simulation showed an increased 2 m mixing ratio throughout the deforested area, with the greatest increase of 1.5-2.0 g kg<sup>-1</sup> in areas along the Mississippi Gulf Coast (FIG. 3.12b). Moisture advection (not shown) was examined for each of the three simulations; there was no evidence that the moisture advection significantly differed among the simulations in or near the deforested region. The area of increased mixing ratio closer to the Mississippi coast corresponds to an area of increased cloud cover as shown in the reduction of downward shortwave radiation (FIG. 3.14a and b). The changes in the near-surface humidity do not appear to be driven by the changes in soil moisture between evergreen needleleaf forest and shrubland because the surface soil moisture was actually

decreased (Table 3.4). There was no significant precipitation that occurred during the study period.

Over the Gulf of Mexico, the post simulation showed decreased mixing ratio while the albedo simulation showed increased mixing ratio. The mechanism for these changes is not immediately evident, but it appears to be related to changes in cloud cover over the Gulf and not necessarily directly related to the land cover changes that are of concern here.

## b. Cross sections

Cross sections were constructed from Biloxi, MS, (BIX) to Columbus, MS, (CBM) for 00 UTC 15 July and show the relative humidity, vertical velocities, mixing ratio, and potential temperature (FIG. 3.15a, b, and c). This date was chosen after examination of cross sections from all dates as it appeared to be representative of the conditions during the 7-day period.

The near-surface relative humidity increased in the post and albedo simulations (i.e., lower temperatures and higher mixing ratios) compared to the control simulation (FIG. 3.15a, b, and c). The relative humidity increased near the northern node of upward vertical velocities in the post and albedo simulations, about 200 km inland. The southern node of upward vertical velocity, likely associated with the sea breeze front location, shifted south by approximately 30 km toward BIX in the post and albedo simulations (FIG. 3.15a, b, and c). The stronger and more westerly winds appeared to prevent the sea breeze front from penetrating farther inland. The region of upward vertical velocity in the cross sections near CMB also shifted southerly toward BIX by approximately 10 km and 40 km in the post and albedo simulations. The shifting of the southern node of upward vertical motion, combined with the movement of the downwelling shortwave radiation anomaly in the post and albedo simulations, (FIG. 3.14a and b) suggests that

the preferred region for formation of the sea breeze front moved south due to the change in wind field.

#### c. Times series

Times series of data from Hattiesburg, MS, (PIB) were created to show the effects of the vegetation change on the surface energy budget and near surface conditions. PIB was within the deforested area but sufficiently far from the coast to avoid coastal affects. The temperatures decreased from the control to the post simulation, as shown in the time series (FIG. 3.16a and b). The diurnal temperature range over the course of the 7-day study decreased in the post simulation by about 0.2°C. The albedo simulation temperature and diurnal range changed little from the control simulation (FIG. 3.16c). The temperature difference between the control and the post simulations (<0.1°C).

The latent heat flux at the surface for the post simulation had the lowest maximum values, reducing the daily range from the control simulation by about 13 W m<sup>-2</sup> (FIG. 3.17a and b). The albedo simulation latent heat flux had a slightly higher diurnal range than the control simulation (9.5 W m<sup>-2</sup>).

The simulations had similar diurnal patterns of the upward heat flux at the surface, but the control had the lowest values overall. The albedo simulation had the largest diurnal upward heat flux range ( $364 \text{ W m}^{-2}$ ), which was  $82 \text{ W m}^{-2}$  more than the control simulation. The post simulation upward heat flux was closer to the control simulation, with a difference in the diurnal range of  $18 \text{ W m}^{-2}$ . The 2 m mixing ratio had a decreased diurnal range in both the post and albedo simulations (FIG. 3.18a, b, and c). The daily average mixing ratio for the post and albedo simulations was higher than the control simulation by about 0.5 g kg<sup>-1</sup>.

The diurnal ranges for temperature and latent heat flux at the surface were affected only by the albedo changes in the post simulation, while the mixing ratio was affected by the roughness length change. The diurnal range for temperature, latent heat, and mixing ratio decreased from the control to both the post and albedo simulations, while the average value of the mixing ratio was higher. The change in latent heat flux experienced in the albedo simulation at PIB corresponds to the changes shown across the deforested area.

#### **3.5 Discussion**

Temperatures decreased over the deforested area by 0.2°-0.8°C in the post-Katrina land cover simulation and were consistent with the findings of decreased temperatures due to deforestation by Brovkin et al. (1999), Bounoua et al. (2002), Bonan (1997, 1999), Diffenbaugh (2009). The temperature changes were apparently due to the increase in surface albedo as the simulation that retained the original albedo did not show the same change. The effects of the albedo change in the post simulation were also shown in the PBL height. In the post simulation, the largest decreases in latent heat flux were in the southwest portion of the deforested area. Klingaman et al. (2008), Pielke et al. (1999) and Narisma and Pitman (2002) found a reduction in the latent heat in deforested areas. Klingaman et al (2008) found that evapotranspiration reduction was responsible for half of the decrease in latent heat. The upward heat flux at the surface decreased within the deforested area in the post simulation, mostly in the southeastern section of the deforested area. The containment of the largest changes to the post simulation suggests the latent heat flux and upward heat flux changes within the deforested area were driven by the changes in albedo.

The wind increased in strength and changed to more westerly due to the change in roughness length. Hoffmann et al. (2003) found that the winds increased in their simulation of deforestation, while Gandu et al. (2004) found that the winds increased along the coast with Amazon deforestation. Both post-Katrina simulations experienced an increase in wind speed along the Mississippi coast and within the deforested area. The decrease in the roughness allowed the momentum aloft to mix downward in the deforested area due to the decrease of surface friction.

The PBL was affected by the changes in temperature and wind speeds. The decreased temperature caused the PBL depth to decrease in the northern section of the deforested area in the post simulation. A decrease of 200-300 m in the summer in the PBL was found by Bonan (1997).

The mixing ratio increased across the deforested area in the post and albedo simulations. The increase of the 2 m mixing ratio may be due to moisture convergence near the sea breeze front in the southern part of the deforested area, and/or lack of vertical mixing of moisture due to decreased PBL heights because of the lack of an increased moisture flux. The 2 m mixing ratio increase near the Florida panhandle is likely associated with an increase in cloud cover. Using downward shortwave radiation as a proxy for the location of cloud cover, there was a decrease in the shortwave radiation in the same region for 14, 15 and 16 July. The change in downward shortwave radiation suggests that there was an increase in clouds in the same region as the increase in 2 m mixing ratio. Gibson and Vonder Haar (1990) studied the cloud and convection frequencies over the southeast U.S. as related to geographic and land cover features. They found that cloudiness and deep convection were at a maximum during the nighttime hours over the Gulf of Mexico due to a convergent sea breeze near the shore. The convergence from the sea

breeze causes relative cloud maxima over the Gulf near the shore land areas. Therefore, the modified sea breeze convergence location may be affecting cloud development over the Gulf, and therefore the surface temperature and moisture fields over the Gulf.

The cross sections of 15 July from south (BIX) to north (CBM) showed changes in vertical velocities and relative humidity. The low-level relative humidity increased in the lower atmosphere in the post and albedo simulations and increased inland toward CBM. The more southerly node of upward vertical velocities, which appear to be associated with the sea breeze front location, shifted south 30 km toward BIX. However, the northern node of upward vertical velocity also shifted south by 40 km and 10 km in the post and albedo simulations, which may indicate a change in circulation in this simulation at a scale larger than that of the sea breeze front.

The time series of PIB show a 7-day period of latent heat, temperature, mixing ratio, and upward heat flux at the surface. PIB was chosen because it was within the deforested area and away from the coast. Temperatures decreased from the control to the post and albedo simulations and the diurnal temperature range decreased with the post simulation. The albedo simulation temperatures and diurnal range differed less than 0.1°C from control simulation. The greatest difference in temperatures was between the control and both post-Katrina simulations of about 0.2°C. The daily range for the 2m mixing ratio decreased for the post and albedo simulations, while the diurnal minimums for the post-Katrina simulations were higher by 0.3 and 0.6 g kg<sup>-1</sup> than the control simulation.

# **3.6 Conclusion**

The modeling experiment was designed to examine the effects of severe forest damage on local climate, using Hurricane Katrina as a rough guide. The forest damage was a simplified version of Katrina's damage over southern Mississippi, where evergreen needleleaf forest was changed to shrubland in simulations using WRF coupled with Noah LSM. To understand the relative roles of albedo change versus other possible factors, a simulation was conducted that changed the shrubland albedo within the deforested area to that of the evergreen needleleaf forest. For this study composite difference maps, cross sections of the deforested region, and time series were created to analyze the results.

The WRF simulation examined a 7-day period in July 2007. The post simulation showed the greatest difference from the control simulation. Difference maps from the post simulations showed temperatures reduced, latent heat flux decreased, PBL decreased, and upward heat flux decreased over the deforested area. Some of the results from the control to two post-Katrina simulations generally agreed with previous work (e.g. Klingaman et al. 2008, Pielke et al. 1999, Narisma and Pitman 2002, Bonan 1997, Gandu et al. 2004, and Hoffmann et al. 2003). The albedo simulation did not experience changes as large as the post simulation. The post and albedo simulations had a change in wind strength and direction and an increase in the 2 m mixing ratio. The more westerly winds possibly influenced penetration of the sea breeze front on the Mississippi Gulf Coast. The cross sections showed the vertical velocities and relative humidity profiles changed for both post-Katrina simulations. The times series for the post simulation had the largest differences with albedo simulation between the control and the post simulations.

The changes in the atmospheric conditions such as winds and PBL height can have implications on smoke from forest fires. The changes in the winds could have implications on fire potential and smoke direction in the event of a wildfire. The increased winds can fuel fires that occur along the Mississippi Gulf Coast. The PBL height causes smoke from fires to be trapped closer to the surface and disperse slower. With the increase in fuel for fires from tree debris, the changes in atmospheric conditions are essential to understanding the possible effects on fire and smoke behavior.

Changing evergreen needleleaf forest to shrubland had an effect on the local climate of the Mississippi Gulf Coast. The changes in albedo affected the PBL height and temperature, while the roughness length affected the winds and 2m mixing ratio. To expand upon this work, a longer time frame for the simulations should be chosen to allow for a longer initialization of WRF. A longer duration of the simulations is ideal for allowing WRF initialization more time and a more robust study into the effects of forest damage on the local climate. Incorporating a more realistic representation of the forest damage from a significant hurricane into a forecasting model is also suggested. A higher resolution simulation could be completed to attempt to account for the heterogeneity in damage. Another expansion of this study could be to include other sensitivity studies such as leaf area index, which would consider trees that have been defoliated but have not fallen.

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Options	Domain 1	Domain 2	Domain 3
Resolution	27km	9km	3km
Microphysics	No Microphysics	No Microphysics	Ferrier
Longwave radiation	RRTM	RRTM	RRTM
Shortwave radiation	Dudhia	Dudhia	Dudhia
Surface layer	Monin-Obukhov	Monin-Obukhov	Monin-Obukhov
Surface physics	Noah LSM	Noah LSM	Noah LSM
Boundary layer physics	YSU scheme	YSU scheme	YSU scheme
Cumulus option	Kain-Fritsch	Kain-Fritsch	Explicit

**Table 3.1.** Physics and dynamic options used for the WRF simulations.

Class	Description
1	Urban and Built-Up Land
2	Dryland Cropland and Pasture
3	Irrigated Cropland and Pasture
4	Mixed Dryland/Irrigated Cropland and Pasture
5	Cropland/Grassland Mosaic
6	Cropland/Woodland Mosaic
7	Grassland
8	Scurbland
9	Mixed shrubland/Grassland
10	Savannah
11	Deciduous Broadleaf forest
12	Deciduous needleleaf Forest
13	Evergreen Broadleaf Forest
14	Evergreen Needleleaf Forest
15	Mixed Forest
16	Water Bodies
17	Herbaceous Wetland
18	Wooded Wetland
19	Barren or Sparsely Vegetated
20	Herbaceous Tundra
21	Wooded Tundra
22	Mixed Tundra
23	Bare Ground Tundra
24	Snow or Ice
25	Playa
26	Lava
27	White Sand
28	Unassigned
29	Unassigned
30	Unassigned
31	Low Intensity Residential
32	High Intensity Residential
33	Industrial or Commercial

 Table 3.2. Land cover classes in the Noah LSM.

State and Damage	Total timberland in	Damaged	Percent of
level	affected area	timberiand area	(Porcont)
	(Acres)	(Acres)	(I el cent)
Mississippi			
Severe [8 counties]	2,200,500	1,973,502	90
Moderate [13 counties]	3,908,700	1,191,871	30
Light [11 counties]	2,949,400	206,677	7
Mississippi Total	9,058,600	3,372,050	37
Louisiana			
Severe [1 parish]	21,400	21,400	100
Moderate [6 parishes]	1,155,353	938,863	81
Light [8 parishes]	1,255,065	135,705	11
Louisiana Total	2,431,818	1,095,968	45
Alabama			
Moderate [2 counties]	1,194,349	86,487	7
Light [8 counties]	4,086,139	472,914	12
Alabama Total	5,280,488	559,402	11
Summary			
Severe	2,221,900	1,994,902	90
Moderate	6,258,402	2,217,221	35
Light	8,290,604	815,297	10
Total	16,770,906	5,027,419	30

**Table 3.3.** Potential down timber from Hurricane Katrina (USDA Forest Service).

	Control	Post	Albedo
Albedo	0.12	0.22	0.12
Surface Roughness Length	50	5	5
Surface Moisture	0.30	0.10	0.10

 Table 3.4. Shrubland and evergreen needleleaf forest parameters in LANDUSE.TBL.



**FIG. 3.1.** Impact of Hurricane Katrina on forested areas along the hurricane path based on potential down timber from Hurricane Katrina (USDA Forest Service 2005).



**FIG. 3.2.** Forest damage caused by Hurricane Katrina at 1km resolution on a scale from 0-1 with red being the most severe (Wang and Qu 2009).


**FIG. 3.3.** Schematic diagram of the mechanisms behind the impact of the land cover change from trees to grass on temperature (Narisma and Pitman 2003).



FIG. 3.4. Domains for WRF.



FIG. 3.5. Map of the (a) original land use categories and (b) land use change to shrubland.



**FIG. 3.6.** 2 m temperature (°C) from (a) post minus control and (b) albedo minus control simulations.



**FIG. 3.7.** Ground heat flux (W m<sup>-1</sup>) of (a) post minus control and (b) albedo minus control simulations.



**FIG. 3.8.** Latent heat flux at the surface  $(W m^{-1})$  of (a) post minus control and (b) albedo minus control simulations.



**FIG. 3.9**. Upward heat flux at the surface (W  $m^{-1}$ ) of (a) post minus control and (b) albedo minus control simulations.



**FIG. 3.10.** Winds speed at  $10m (m s^{-1})$  and direction of (a) control, (b) post (c) albedo simulations.



FIG. 3.10 Continued.



**FIG. 3.11.** Planetary boundary layer (m) of (a) post minus control and (b) albedo minus control simulations.



**FIG. 3.12.** Mixing ratio (g kg<sup>-1</sup>) of (a) post minus control and (b) albedo minus control simulations.



**FIG. 3.13.** Upward moisture flux at the surface (kg  $m^{-2} s^{-1}$ ) of the post minus control simulation.



**FIG. 3.14.** Downward shortwave radiation at the surface (W  $m^{-2}$ ) composites of (a) control and (b) post simulations.



Cross section from BIX-CBM of THTA, WND, VV, RH 500 322 320 318 316 314 312 310 308 700 850 -0.3 0.6 0.3 925 -0.3 0.6 0.3 BIX CBM 50 70 90

(b)

**FIG. 3.15.** Cross sections from BIX to CBM for 14 July with (a) control, (b) post, and (c) albedo simulations.



FIG. 3.15. Continued.







FIG. 3.16. Continued.



**FIG. 3.17.** Latent heat flux at the surface  $(W m^{-1})$  of (a) control, (b) post simulations.



**FIG. 3.18.** Mixing Ratio  $(g kg^{-1})$  of (a) control, (b) post (c) albedo simulations.



FIG. 3.18. Continued.

## CHAPTER 4

## CONCLUSIONS

A series of WRF simulations were created to simulate the affects of forest damage on local climate of the U.S. Gulf Coast. A study area in southern Mississippi was chosen, and the evergreen needleleaf forest was converted to shrubland, roughly following the damage pattern due to Hurricane Katrina in 2005. WRF coupled with Noah LSM simulated 7 days in July 2007 using NARR data for initial conditions. Three simulations were created; the first was a control run with no land use changes (control), while the second (post) and third (albedo) had the shrubland changes. In the third simulation, the surface albedo for shrubland was changed to the albedo of the forest. Difference maps, cross sections from Biloxi, MS, (BIX) to Columbus, MS, (CBM), and times series from Hattiesburg, MS (PIB) were created.

Difference maps were created between the control and both post-Katrina simulations. Temperatures decreased 0.2-0.8°C in the post simulation. The cooling extended slightly downwind to the east of the deforested area. The greatest change in temperature was inland from the Mississippi Coast in the southeastern area the northern portion of the deforested area. Decreased temperatures were also observed in previous studies of deforestation by Brovkin et al. (1999), Bounoua et al. (2002), Bonan (1997, 1999), Diffenbaugh (2009) in various locations. Pielke et al. (1999) found the temperatures increased over south Florida after they included the urban changes in land cover in south Florida as well as the vegetation changes. The increase in near-surface temperature experienced by Sampaio et al. (2007) was due to the decrease in evapotranspiration, the lower leaf area, and lower surface roughness length. Leaf area index was not explored in the current study. The temperature increase shown by Klingaman et al. (2008) due to increase in sensible heat and decrease in evapotranspiration. The differences between the type of vegetation that replaced the forested area in Klingaman et al. (2008) and this study could account for the differences in the results shown. The southeastern portion of the deforested area had reduced downwelling shortwave radiation (i.e., increased cloud cover), but the decreased temperatures across the deforested area were clearly a response to increased albedo, which reduces the available net radiation. Temperatures increased over the deforested area in the albedo simulation, suggesting the change in the post simulation was due to the effects from albedo change.

Latent heat flux at the surface decreased throughout the deforested area with the largest decrease of about 20 W m<sup>-2</sup> in the southwestern portion of the deforested area in the post simulation. This was likely due to the reduced available net radiation and lower temperatures in the post simulation, as the albedo simulation did not show the same effects. Klingaman et al. (2008), Pielke et al. (1999), Nobre et al. (1991), and Narisma and Pitman (2002) all observed a decrease in latent heat over their study areas associated with deforestation. Along the Mississippi Coast in both simulations, there was an increase of latent heat flux with some areas more than +30 W m<sup>-2</sup> over the Gulf of Mexico. The upward heat flux at the surface decreased throughout the deforested area in the post simulation with the largest change in the southeastern area of the deforested area, which had a decrease of more than 60 W m<sup>-2</sup>. Again, the albedo simulation did not show the same magnitude of change, suggesting the important role of albedo and available net radiation in driving surface evapotranspiration rates.

Winds were affected by the changes made from forest to shrubland; the average winds of the 7-day study in post and albedo became more westerly than the control simulation. The winds

over the deforested area increased about 1 m s<sup>-1</sup> for the post and albedo simulations. Changes in the winds were likely due to the decrease in surface roughness and therefore greater downward transport of momentum. Winds at 10 m downwind of the deforested area remained relatively unchanged, except for a slight increase in adjacent areas of Alabama. Hoffmann et al. (2003) found that the winds increased in their deforestation model, and Gandu et al. (2004) found that the winds increased along the coast with Amazon deforestation. Klingaman et al. (2008) found the winds in the study area (Pennsylvania) also became more westerly. The changes in the wind speed and direction in the post simulation can have implications for forest fires; the increase in wind speeds can help fuel fires that start in the area.

Changes in 2 m temperature and heat fluxes can cause a change in the planetary boundary layer height. The PBL height decreased between 300-450 m over the deforested area in the post simulation. There was generally no change over the deforested area for the albedo simulation PBL. Bonan (1997) found a decrease of 200-300 m in his simulated summer PBL height over deforested areas. The change in the PBL height apparently was due to the albedo changes, and resulting changes in lower tropospheric temperatures, because the albedo simulation PBL height did not decrease. Roughness length decreases could be important to the changes in the PBL height because of decreased mechanical mixing, but the decrease in PBL height was not evident in the albedo simulation. Changes in the PBL height can be important because they can affect smoke distribution in the case of a forest fire, trapping smoke closer to the surface.

The changes in the winds have an impact on the moisture variables, such as mixing ratio. The 2 m water vapor mixing ratio increased 0.4-1.2 g kg<sup>-1</sup> over the deforested area in the post simulation. There was no evidence of changes in moisture advection or surface moisture fluxes. In fact, the latent heat flux in the post simulation was actually lower than in the control

simulation. The increase in low-level moisture is possibly due to decreased vertical mixing of moisture, due to a lower PBL height. In the southern part of the deforested region, moisture pooling associated with a displaced sea breeze front may have played a role in the additional low-level moisture in that area. The 2 m mixing ratio increase near the Florida panhandle is likely associated with an increase in cloud cover. There was a decrease in the shortwave radiation in the same region for 14, 15 and 16 July suggesting that there was an increase in cloud cover in the same region as the increase in 2 m mixing ratio. Gibson and Vonder Haar (1990) studied the cloud and convection frequencies over the southeast U.S. as related to geographic features. They found that cloudiness and deep convection were at a maximum during the nighttime hours over the Gulf of Mexico due to a convergent sea breeze near the shore. The convergence from the sea breeze causes relative cloud maxima over the Gulf near the shore land areas. Therefore, the modified sea breeze convergence location may be affecting cloud development over the Gulf, and therefore the surface temperature and moisture fields over the Gulf.

The cross sections from BIX to CBM for 15 July show the relative humidity increased in the lower troposphere in the post and albedo simulations. An increase in relative humidity was shown from the northern edge of the deforested area to CBM. A region of upward vertical velocities, likely associated with the sea breeze front, shifted south about 30 km, possibly due to the increase in the westerly winds across the deforested area. The westerly winds may inhibit the penetration of the sea breeze inland. Mahmood et al. (2010) specifically recommended that future research examine the magnitude of the spatial redistribution of moisture convergence (e.g., Pielke and Chase 2003). Changes in moisture convergence can occur not only from the alterations in the patterns of surface sensible and latent heat, but also from changes in surface

albedo and roughness (e.g., Pitman et al. 2004; Nair et al. 2007). This thesis is among the few works that have directly addressed the role of land cover change on processes involving low-level convergence near the coast.

A times series of PIB over the 7-day study period was created to show the effects of the deforestation on the diurnal cycle. PIB was inland but still within the deforested area to avoid potential coastal affects. The temperatures decreased overall from the control to the post simulations. The diurnal temperature range decreased by 0.2°C in the post simulation while the diurnal temperature range for the albedo simulation was near that of the control simulation. The latent heat flux for the post simulation had lower maximum values and higher minimum values, reducing the daily range. The diurnal range of the mixing ratio for the post and albedo simulations decreased by about 0.5 g kg<sup>-1</sup> from that of the control simulation.

Changing the evergreen needleleaf forest to shrubland had an impact on the local climate. Variables such as temperature, surface energy fluxes, and low-level wind were affected by altering the vegetation parameters. The 2 m temperature and PBL height were affected by the changes in albedo, while the changes in the wind and 2 m mixing ratio were evidently results of the changes in surface roughness. The changes to the land cover in this study are more extreme than the actual damage and are used to exaggerate possible impacts to highlight those the changes induced by deforestation.

Adding more realistic forest damage at a higher spatial resolution would allow a more detailed examination of the effects of forest damage on the local climate. By adding more realistic land cover changes from Hurricane Katrina, the higher spatial resolution could more fully incorporate the types of heterogeneity in forest damage discussed in Chapter 2. National Oceanic and Atmospheric Administration (NOAA) Coastal Services Center land cover images

were collected before and after Hurricane Katrina struck the Gulf Coast and could be used to the storm damage along the Gulf Coast (NOAA CSC, 2009). The images from NOAA CSC are from Landsat Thematic Mapper (TM) and Landsat Enhanced Thematic Mapper (ETM+) and focus on the highly impacted areas from Katrina. Another expansion would to include a sensitivity study on the leaf area index. Boundaries created between the different types and amount of damage could have implications on the roughness length, which could have an impact on low-level winds and other variables. A future study could examine the climate changes from heterogeneous damage patterns using a finer resolution model. Other extensions on this study could evaluate the damage from multiple tropical storms, presumably with different wind and damage patterns. The amount and distribution of the damage from another hurricane could be different than Hurricane Katrina damage. Other time periods should also be examined, such as a winter simulation with less overall foliage and reduced Gulf of Mexico temperatures.

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