Hydrometeorological Responses to Abrupt Land Surface Change Following Hurricane Michael

Shannon Alexis Nelson

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HYDROMETEOROLOGICAL RESPONSES TO ABRUPT LAND SURFACE CHANGE FOLLOWING HURRICANE MICHAEL

A Thesis

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements of the degree of Master of Science

in

The Department of Oceanography and Coastal Sciences

by

Shannon Alexis Nelson
B.S., University of West Florida, 2019
August 2021
Acknowledgments

I am glad to acknowledge the backing of several people during my time at LSU. First and foremost, I am sincerely grateful for my advisor Dr. Paul Miller. His insight, good sense of the best path forward, and gracious support made an indelible impression on me. I also express great thanks to my committee members Dr. Robert Rohli and Dr. Chunyan Li. Their wisdom expanded my understanding and encouraged me to see the beauty in the mathematics that describes the atmosphere and ocean around me. I want to also acknowledge Dr. Phillip Schmutz, my undergraduate advisor at the University of West Florida, for giving me my first opportunity to perform basic empirical research.

Many thanks are sent to my fellow graduate students Ally Kristan, Jill Tupitza, and Zoë Shribman. Their support and friendship made my time in Baton Rouge that much more enjoyable. I also thank COMET lab members Cade Reesman and Robert Forney for being my sounding board and always having thought-provoking questions for me. Finally, I could never give enough credit to my mother, father, and brother. I am truly fortunate to have continual inspiration and encouragement from my loved ones. I dedicate my thesis to them.
# Table of Contents

Acknowledgments .................................................................................................................... ii

List of Tables ............................................................................................................................ iv

List of Figures ............................................................................................................................ v

Abstract .................................................................................................................................... viii

Chapter 1. Introduction ................................................................................................................. 1

Chapter 2. Literature Review ...................................................................................................... 5
  2.1. Tropical Cyclones .............................................................................................................. 5
  2.2. Land-Atmosphere Processes ............................................................................................ 7
  2.3. The Local Water Cycle .................................................................................................... 10

Chapter 3. Research Design ....................................................................................................... 14
  3.1. Study Area and Event Summary .................................................................................... 14
  3.2. Model Initialization ......................................................................................................... 17
  3.3. Data Analysis Methods ................................................................................................. 21
  3.4. Flash Flood Analysis Methods ...................................................................................... 24
  3.5. Limitations ..................................................................................................................... 26

Chapter 4. Results and Discussion ............................................................................................ 27
  4.1. Model Validation ............................................................................................................ 27
  4.2. Response of Surface Energy Fluxes ............................................................................. 32
  4.3. Response of Temperature ............................................................................................. 38
  4.4. Response of Humidity ................................................................................................... 42
  4.5. Impact on Cloud Fraction and Precipitation ................................................................. 43
  4.6. Preliminary Flash Flood Results .................................................................................... 52

Chapter 5. Conclusions .............................................................................................................. 56

References ................................................................................................................................. 59

Vita ............................................................................................................................................ 64
List of Tables

3.1. WRF configuration and parameterization schemes. ................................................................. 20

4.1. Correlation of post-Michael relative humidity for one month using $R^2$ values from the linear relationship between the defoliated scenario and observations. ......................... 29

4.2. Differences in mean latent and sensible heat flux within areal extents of Zone 1 and 2 over the one-month period including their respective confidence intervals. ................. 33

4.3. Differences in mean two-meter air temperature within areal extents of Zone 1 and 2 over the one-month period with their confidence intervals. ...........................................39

4.4. Average humidity differences within areal extents of Zone 1 and 2 over the one-month period plus confidence intervals. .......................................................... 42

4.5. Mean low- and mid-cloud fraction and accumulated precipitation differences and CIs. .... 46

4.6. Flash flood report counts for ten Florida counties 20 years prior to Hurricane Michael....... 53
List of Figures

2.1. Net radiation is the sum of net shortwave and net longwave radiation (Modified from the COMET Program’s Introduction to Tropical Meteorology Ch 6.3.1.1) ........................................ 8

2.2. Atmosphere-surface processes involving energy and moisture on a vegetated land surface, focusing on radiative transfer, evaporation, transpiration, interception, precipitation, and flood flow (The COMET Program’s Introduction to Tropical Meteorology Ch 6.2.2) ........................................................................................................ 9

3.1. Study area in central northwest Florida to southwest Georgia, USA. Hurricane Michael’s track is represented by the black solid line and the direction of movement is northeastward through the area of study. ............................................................................ 14

3.2. Monthly tornado and thunderstorm wind frequency obtained from Storm Reports for Bay County, Florida: 1998-2018 ................................................................................................................... 15

3.3. Aqua and Terra MODIS imagery a day before and after Hurricane Michael made landfall, showing defoliation and surface browning corresponding with Michael’s track (Modified from The Weather Channel 2018) ................................................................. 17

3.4. Spatial pattern of reduction applied to LAI and VEGFRA variables, showing a decreasing reduction proportion with distance from the center track and coastal landfall site .......................................................................................................................... 19

3.5. Example of reduction applied to VEGFRA variable, which shows the most severe reduction in vegetation at the landfall site, tapering to a 50 percent reduction proportion at the edge of the hurricane track .............................................................. 19

3.6. WRF domain centered over Hurricane Michael landfall site with a horizontal grid of 483 x 344 and 3-km grid spacing .................................................................................................................. 21

3.7. Five airport validation stations: (1) Tallahassee, Florida, (2) Albany, Georgia, (3) Apalachicola, Florida, (4) Bonifay, Florida, and (5) Dothan, Alabama .................................................. 22

3.8. Two data analysis zone boxes for model output analysis. Zone 1 includes parts of Florida, Georgia, and Alabama (map extent), while Zone 2 consists of an area over the landfall track (red box) ........................................................................................................ 23

3.9. Ten Florida counties (red circle) used for Storm Data search of flash flood reports and of the two USGS river gages (blue circle) (Modified from U.S. Census Bureau, Census 2000) .................................................................................................................. 26

4.1. Correlation coefficients of the defoliated simulation and observed post-Michael two-meter temperature. The first pane shows a map of station locations (numbered 1–5) around Michael’s center path (black line). The remaining five panes show linear regressions used to establish $R^2$ for each of the five stations from 12 October to 10 November 2018 ........................................................................... 28
4.2. Station locations (numbered 1-5) around Michael’s center path (first pane, black line), and time series of 3-hr defoliated simulation (dash-dotted) and observed (solid) relative humidity (%) over a one-week period for each of the five stations from 18–25 October 2018. ................................................................. 30

4.3. Accumulated precipitation (mm) over a one-month period following Hurricane Michael.  
(A) Observed precipitation from Stage IV. (B) Defoliated scenario precipitation, with the track of Hurricane Michael (black line). ................................................................. 32

4.4. Sensible heat flux difference (W m$^{-2}$) (defoliated minus control) map over the one-month period following Hurricane Michael. ................................................................. 34

4.5. Latent heat flux difference (W m$^{-2}$) (defoliated minus control) map over the one-month period following Hurricane Michael. ................................................................. 34

4.6. Box plot of sensible (dotted) and latent (solid) heat flux differences (W m$^{-2}$) within Zone 2 versus each 3-hr Z simulation output time for the one month following Michael. ....... 35

4.7. Sensible (dotted) and latent (solid) heat flux (W m$^{-2}$) for the defoliated (blue) and control (red) scenarios on 21 October 2018. ................................................................. 36

4.8. Upward ground heat flux (W m$^{-2}$) for 21 October 2018 at 18 Z for (A) the control scenario and (B) the defoliated scenario. ................................................................. 37

4.9. Box plot of temperature differences (C°) within Zone 2 at respective Z times over the one-month period. ................................................................. 39

4.10. Mean temperature difference (C°) map over the one-month period following Hurricane Michael. ................................................................. 40

4.11. Temperature difference map (C°) for 22 October 2018 00 Z. ................................................................. 40

4.12. Upward ground heat flux (W m$^{-2}$) for the defoliated scenario on 21 October 2018 at 09 Z. ................................................................. 41

4.13. Mean relative humidity (%) difference map over the one-month period following Hurricane Michael. ................................................................. 42

4.14. Low- and mid-cloud fraction difference maps versus a nearby sounding. (A) Sounding from Tallahassee for 18 October 2018 at 00 Z. Green curved gridlines denote dry adiabats (°C), blue curved gridlines indicate saturation adiabats (°C), and purple slanted gridlines indicate saturation mixing ratio lines (g kg$^{-1}$) (B) Change in low-cloud fraction (defoliated minus control) and (C) the change in mid-cloud fraction for 17 October 2018 21 Z. ................................................................. 44

4.15. Differences in low (purple), mid (orange), and high (green) cloud fraction (%) over Zone 1 (solid) and Zone 2 (dotted) averaged over one month for 21 Z. .......... 45
4.16. Accumulated precipitation (mm) over one month after Hurricane Michael. (A) Control scenario precipitation and (B) defoliated scenario precipitation, with a black line representing the track of Hurricane Michael. ................................................................. 48

4.17. Percent difference of the (A) control simulation and (B) defoliated simulation from Stage IV observed data (i.e., \(\frac{\text{Precip}_{\text{Obs}} - \text{Precip}_{\text{Sim}}}{\text{Precip}_{\text{Sim}}}\)) for the one-month period following Hurricane Michael (black line). ................................................................. 49

4.18. Enhancement of precipitation downwind of a modeled hurricane defoliation on the Georgia coast. The red area indicates the zone of strong convection where convection initiates, denoted by an “A.” The light blue area represents where enhanced precipitation would fall, also indicated by “B.” The gray-toned grid squares represent the green vegetation fraction (Modified from Miller et al. 2019b). ................................................................. 51

4.19. Illustration showing altered momentum and flow over a defoliated landscape (Modified from Miller et al. 2019b). ................................................................................................................................. 51

4.20. Comparison of accumulated rainfall and nearby river gages for 1 September to 30 November 2018. (A) Time series of area-averaged accumulated precipitation (mm) from IMERG. Time series of gage heights for (B) Econfina Creek near Bennett, Florida, and (C) Chipola River near Altha, Florida. The blue line represents gage height level (ft), the green baseline denotes the period of approved USGS data, the red line indicates flood stage, and the red line indicates measured gage height. ......................... 54

4.21. Modeled surface runoff (mm) for 2 November at 00 Z for (A) the control simulation and (B) the defoliated simulation. ................................................................................................................................. 55
Abstract

While many of the destructive environmental conditions associated with tropical cyclones are well recognized, tropical cyclone-induced defoliation, a reduction in green leaves and mature vegetation, has been largely overlooked as a source of environmental stress following tropical cyclone passage. The land surface change associated with defoliation reduces evapotranspiration and shade, thus altering boundary layer moisture and energy fluxes that drive the local water cycle, for many months after tropical cyclone passage. Understanding the potential for any hydrometeorological impacts arising from such abrupt land surface change is important for guiding future post-hurricane preparedness and recovery planning in coastal communities.

This thesis investigates spatial and temporal changes in defoliation-related precipitation and cloud activity in the month following Hurricane Michael’s (2018) passage through Florida, as well as the potential modification of flash flood frequency one year following the storm. Two Weather Research and Forecasting (WRF) model, version 3.8, simulations are employed to determine the degree to which defoliation from Michael alters heat fluxes, temperature, relative humidity, cloud fraction, and precipitation during the one-month post-storm study period near the storm’s track. A preliminary analysis of historical flash flood reports is also performed to assess relative changes in flash flood frequency near the defoliated area during the year after landfall.

In the month following Michael, modeled 2-m temperature increased by 0.7 C°, with the greatest temperature change occurring at night, and sensible heat flux increased by 8.3 W m⁻². Average relative humidity decreased from 73% to 70.1%, and latent heat flux decreased by an average of 13.9 W m⁻². The discrepancy between the decrease in latent heat flux and increase in sensible heat flux approximately matches the increased daytime downward ground heat flux.
Additionally, the defoliated simulation demonstrated decreased low-cloud fraction while mid-level cloud cover showed an increasing trend, indicating a potential ascension in the cloud base height. Coupled with the reduction in relative humidity, this suggests that with less near-surface moisture, air parcels needed to ascend higher to reach saturation. Precipitation accumulation change is insignificant when averaged over one month, yet evidence of redistribution nearest Michael’s track is found.
Chapter 1. Introduction

Tropical cyclones are standalone mesoscale low-pressure systems completely embedded in tropical or equatorial air masses, ranging from weak easterly waves to hurricanes or typhoons. An awareness of both direct and indirect impacts that tropical cyclones can have on a community and the environment is pivotal for effectively communicating the likelihood and severity of a potential hazard (Pielke et al. 2007). Furthermore, understanding the compounding processes that lead to hazards, both before and after a TC has occurred, can reduce loss of life, and improve scenarios of recovery, particularly for vulnerable regions recovering from a hurricane. Direct impacts during a tropical cyclone may include damaged windows and roofs, coastal erosion, and fallen trees. But in addition to direct impacts, indirect impacts can arise and could continue to affect a region for some time. For instance, carbon monoxide poisoning from improper use of generators used to combat power outages, diseased livestock from mosquitoes or unclean standing water, or economic losses from damaged bridges and roads can all be considered indirect impacts. But some indirect impacts remain less apparent.

Hurricane-impacted areas are also physically and economically vulnerable in less apparent ways following landfall. This is especially true in rural communities where hard-hit and water-dependent agriculture industries are major sources of local livelihood. Fallen trees and damaged vegetation may lead to indirect impacts such as loss of future revenue for farmers or increased risk of wildfires. Such a pattern is even witnessed in the paleo-record with Liu et al. (2003) identifying a possible link between hurricanes and wildfires in a study of back barrier lake sediment cores from Alabama. The presence of charcoal fragmentation on top of sand deposits for four separate events in a 1,250-year proxy record suggests a correlation between intense hurricanes and wildfires (Liu et al. 2003).
Tropical cyclone-induced defoliation is another such indirect impact. The reduction of vegetative cover caused by the hurricane alters heat and moisture fluxes between the surface and atmosphere (Pielke 2001). For example, following an initial increase in evaporation of soil moisture (owing to the precipitation deposited by the storm), reduced shade in defoliated regions will likely increase shortwave direct and diffuse radiation reaching the surface, which in turn increases the net radiation at the surface, leading to an increase in near-surface temperature. In turn, the greater environmental lapse rate would likely contribute to enhanced static instability and, if enough moisture is available, cumulus cloud formation. A change, whether in magnitude or distribution, of cloud cover and precipitation is then possible as temperature and moisture patterns for convection and cloud formation are altered (Bounoua et al. 2002, Cochrane and Laurance 2008, Pielke 2001). Likewise, the reduction in near-surface moisture might contribute to increased plant stress, and consequent longer-term decreases in latent heat flux and evapotranspiration (ET) might be expected (Farooq et al. 2009). Depending on the magnitude of the precipitation changes, residents and industries near the storm’s track, such as farmers, may benefit knowing about these unforeseen impacts.

Moreover, communities can benefit by recognizing that following hurricane defoliation, surface runoff may be increased during heavy synoptically-driven precipitation events, important in context to the recovery for farmers and timber growers. After a disturbance, the lack of vegetation leads to reduced interception by the canopy. A heavy rainfall event in a short amount of time could lead to more surface runoff, which is important to consider as the frequency of severe rainfall events is expected to increase with a warming planet (Myhre at el. 2019). With higher-intensity landfalling hurricanes (Kossin et al. 2020) and more severe non-hurricane
related rainfall (Myhre at el. 2019), post-hurricane flash flooding would logically become more frequent as well.

The purpose of this thesis is to address the knowledge gap in defoliation-induced changes to the energy and moisture budgets in hurricane-affected areas, particularly related to temperature and water availability for agriculture. Additionally, establishing well-informed emergency planning and mitigation immediately following a storm event is imperative in maintaining public safety for coastal towns and cities. The need for clear and accurate information regarding risks, at any temporal stage of the storm, is imperative as human development in coastal cities continues to increase (Pielke et al. 2007) and the average potential intensity of tropical cyclones increases globally (Kossin et al. 2020). Past research has often singularly focused on the impacts of extreme weather on biota, whereas this research instead aims to look at the topic from a perspective that considers how hurricane-induced defoliation of vegetation may then affect subsequent weather.

This research will determine the boundary-layer temperature and moisture changes and their effect on clouds and precipitation during a one-month period following a strong hurricane landfall. Additionally, historical reports of flash flooding events will be used to determine if defoliation alters the frequency of flash flooding one year after landfall. Hurricane Michael (2018) will serve as a case study to address the following two research questions: [Q1] How does defoliation alter sensible and latent heat flux, surface temperature, relative humidity, cloud fraction, and precipitation within the month following hurricane landfall? [Q2] How does defoliation change flash flooding frequency one year following hurricane landfall? It is hypothesized that: [H1] Severe and abrupt defoliation from a hurricane alters surface properties and thus heat and moisture fluxes, thereby redistributing clouds and precipitation; [H2]
Defoliation from a hurricane alters landcover by reducing vegetation and interception and thus increases surface runoff and flash flooding events.

In Chapter 2 of this thesis, previous studies about land surface changes and their effect on the atmosphere and surface runoff are reviewed. In Chapter 3, the research design and methods are detailed, including a summary of the Hurricane Michael (2018) case study, data analysis methods, and model specifications of the two Weather Research and Forecasting (WRF) simulations. Chapter 4 reports model validation and the responses of surface energy fluxes, temperature, and humidity and how those impact local cloud and precipitation activity. Post-Michael flash flood frequency is examined against the historical frequency. Further, Chapter 4 discusses and contextualizes the results, inferring connections between landcover change and local hydrometeorology. Finally, Chapter 5 concludes by providing a synthesis of the land-atmosphere interactions in response to Hurricane Michael-induced defoliation, suggestions for implementation of the results, and recommendations on future work.
Chapter 2. Literature Review

Conceptually, the organization of this section is based on the idealized flow of processes, including the following: [1] hurricane landfall, [2] hurricane-induced landcover change and the response of surface-atmosphere interactions, and [3] implications on local atmospheric moisture and the consequences for surface runoff (not related to the response of atmospheric moisture).

2.1. Tropical Cyclones

Tropical cyclones (TCs) serve as an important mechanism for transporting heat and energy from the equator to the poles (Laing and Evans 2015). However, this process has been exacerbated in recent years due to the planet’s warming air and sea surface temperatures, a rate that has doubled since 1981 following human industrialization (NOAA 2020). While TCs intensity has been projected to increase (Emanuel 1987, Knutson et al. 1998, 2015), recent research has shown this to be playing out in observational data (Kossin et al. 2020). Although TC frequency (number of storms per year) has not been increasing globally, there are more major TCs (Category 3 or above on the Saffir-Simpson hurricane scale) occurring. Kossin et al. (2020) found that all ocean basins apart from the northern Indian Ocean have been adding to the global increase in TC intensity, and that the upper limit on potential intensity is also increasing, with the greatest change occurring in the North Atlantic, which has seen a nearly 50% increase in exceedance of potential intensity per decade since 1980 (Kossin et al. 2020). Moreover, the Gulf of Mexico/Caribbean basin merits close attention due to its impacts on the heavily populated coastal plains.

Forecasting the formation and track of hurricanes has been improving significantly over the past 40 years, however, the need for better intensity forecasting remains (Elsberry et al. 2007). Forecast errors in intensity and of rapid intensification can lead to under-preparedness,
less evacuation time, and increased risk of danger for coastal communities. Through numerical modeling, Emanuel (2017) demonstrated that rapidly intensifying storms directly preceding landfall, will become significantly more common by the end of this century. Equally important to note, hurricane speed of motion is decreasing (Hall and Kossin 2019), and regions of favorable hurricane development are getting larger, extending more poleward by one-degree latitude per decade (Kossin et al. 2014). Negative physical and economic impacts will become more prevalent as storms are becoming stronger, slower and wetter, are impacting higher latitudes, and are predicted to undergo more rapid intensification (Emanuel 2017, Hall and Kossin 2019, Kossin et al. 2014, Kossin et al. 2020).

Hurricane climatology is clearly changing for the worst, and it supports why understanding all potential threats is imperative. From 1980–2011, there was an estimated $417.9 billion in damage from hurricanes in the U.S. alone (Smith and Katz 2013). Damage is primarily caused by intense winds, storm surge, rainfall, flooding, and tornadoes, and although each hazard may differ in strength with each storm, societal and environmental impacts can be harmful both during and well after a storm has passed out of an area. For example, in 2017, Hurricane Maria rapidly intensified just before its landfall as a Category-5 storm in Dominica. Then, Maria’s 250-km hr$^{-1}$ peak winds devastated the island of Puerto Rico, destroying infrastructure and forest stands (Pasch et al. 2019). Miller et al. (2019a) found that Maria likely altered the island’s hydrometeorological patterns following the initial disturbance as vegetation recovered over a six-week period. Hydrologic changes occurred in both the atmosphere (hindered cloud and precipitation formation) and in rivers and estuaries (increased surface runoff and coastal water turbidity) (Miller et al. 2019a). In addition to extreme wind speeds, tornadoes spawned from hurricanes can cause significant changes to the landscape. Notably, Hurricane
Ivan (2004) produced a record number of 117 tornadoes in states spanning from Alabama to Pennsylvania (Stewart 2004).

2.2. Land-Atmosphere Processes

High winds from hurricanes and hurricane-induced tornadoes not only splinter maritime forests along the coast, but also agriculture fields and timber crops well inland. Trees and vegetation that are not completely killed are stripped of leaves and limbs, a process known as defoliation. Severe defoliation blankets the ground in leaves and debris, quickly altering the environment extending from the tree canopy all the way down to ground surface. Boose et al. (1994) showed that abrupt landfall of an intense hurricane impacts forest stands by creating vast yet random patterns of defoliation. In a comparable way to how a hurricane alters the landscape, large-scale deforestation of tropical forests forces a modification in the environment and local atmospheric dynamics (Eltahir 1996). Defoliation also brings about a fire and human health concern, whereby dead debris and dry conditions might exacerbate heat waves, as seen in the Amazon forest following logging or pastureland conversion (Cochrane and Laurance 2008). Evapotranspiration (ET) of the Amazon makes up 25 to 50% of the precipitation, so a reduction in ET has been shown to increase the risk of fires in Global Climate Models (Cochrane and Laurance 2008). Other examples of disturbances that can cause extensive landcover change include wildfires, insect infestations, and urban development (Flannigan et al. 2000, Forrester et al. 2018, Shepherd et al. 2010). Flannigan et al. (2000) predicted that fire seasons will have a much greater impact of forests and vegetation, through earlier and longer fire seasons.

Altered land surface characteristics, whether caused by natural or anthropogenic factors, subsequently changes thermal fluxes, and by extension, the expected local energy budget (Zheng and Eltahir 1998: Figure 2.1). A sudden lack of vegetative cover can impact several land-
atmosphere interactions, including surface roughness, evaporation, transpiration, interception, and precipitation (Figure 2.2). Although the sign of change can vary (Pielke et al. 2011), several studies have identified or inferred modified latent and sensible heat fluxes at local and regional levels after land use/cover changes (Barr et al. 2012, Hosannah et al. 2021, Miller et al. 2019a). For instance, in a model-based study of landscape denudation caused by a mountain pine beetle infestation, Forrester et al. (2018) identified a reduction in latent heat flux as high as 60 W m$^{-2}$. Meanwhile, reduced shading and canopy interception of incoming radiation increased summer soil temperature at the top layer by up to 1 Kelvin.

Figure 2.1. Net radiation is the sum of net shortwave and net longwave radiation (Modified from the COMET Program’s Introduction to Tropical Meteorology Ch 6.3.1.1).
Figure 2.2. Atmosphere-surface processes involving energy and moisture on a vegetated land surface, focusing on radiative transfer, evaporation, transpiration, interception, precipitation, and flood flow (The COMET Program’s Introduction to Tropical Meteorology Ch 6.2.2).

Two studies assessing hydrometeorological interactions over the island of Puerto Rico following Hurricane Maria (2017) discuss in detail the mechanisms by which land-atmosphere processes impact precipitation (Miller et al. 2019a, Hosannah et al. 2021). In an observational study, Miller et al. (2019a) found hurricane defoliation to strengthen the relationship between precipitation and the Gálvez-Davison Index (GDI; Gálvez and Davison 2016), an index that increases with greater heat and moisture concentrations. On the other hand, Hosannah et al. (2021) utilizing the Regional Atmospheric Modeling System (RAMS), found up to a 150 W m\(^{-2}\) decreased sensible heat over most of the island, while latent heat and humidity were simulated to increase. The abrupt transformation of forest to bare soil and grass was simulated to produce increased albedo. Hosannah et al. (2021) argued that increased cover of grass leads to increased transpiration, latent heat flux, a shallower boundary layer, and thus more lower clouds and
rainfall, forced by both mechanical and thermal turbulence. However, this set of processes is contingent upon soil moisture.

On a global scale, Bounoua et al. (2002) found that land use changes led to reduced latent heat and warming in the tropics and the opposite in the middle latitudes. This suggests that, when averaged globally, the impact is not significant, but it can be significant when assessing responses in the seasonal-to-annual and regional scales following a disturbance (Bounoua et al. 2002). While Pielke et al. (2011) found that large-scale changes to the land surface are required to alter weather patterns, a change in temperature and latent heat flux will likely lead to a change in the local water cycle, including cloud formation and precipitation. A local change in precipitation could arise as temperature increases and convective instability leads to a conducive environment for buoyant uplift, which is summarized well by Forrester et al. (2018).

2.3. The Local Water Cycle

2.3.1. Atmospheric Moisture

Following an initial increase due to high soil moisture achieved from the hurricane’s rainfall, defoliation will result in less ET and moisture flux from the landscape into the atmosphere, ultimately altering the local water cycle. Altered water cycling can be identified in measurements of humidity, clouds, and precipitation patterns. ET increases the moisture gradient between the surface and lower atmosphere, cools the air, and increases relative humidity, reducing the capacity to evaporate more water (Laing and Evans 2015). Cloud formation and development therefore can be modified by surface temperatures including over urban areas (Inoue and Kimura 2004). Through a satellite imagery study, low-level clouds were shown to form more frequently over urban areas with low normalized difference vegetation index (NDVI) in the early afternoon on clear summer days in Tokyo (Inoue and Kimura 2004). Additional
influencing factors that can alter cloud patterns include season, time of day, latitude, proximity to
the sea, lifting mechanisms, and aerosol composition (Laing and Evans 2015). Aerosols, which
can act as cloud condensation nuclei, can impact droplet size and thus collision coalescence rates
(Laing and Evans 2015). Thus, while land-use/land-cover changes have been linked to cloud
formation, the process is also subject to several other factors.

Not only has land cover change been shown to alter humidity and cloud patterns, but also
precipitation. Precipitation varies in space and time based on environmental conditions. Eltahir
(1996) and Negri et al. (2004) assessed Amazonian deforestation, with the former focused on the
effect on atmospheric circulations, and the latter focused on events during the dry season in the
absence of synoptic forcing. Both found that vegetation plays a vital role in large-scale
circulation, and when synoptic events are not heavily influencing the weather, defoliation can
redistribute precipitation both spatially and temporally. While Eltahir (1996) determined that
deforestation alters large-scale atmospheric circulation, at the regional scale Negri et al. (2004)
found that rainfall probabilities increased over the deforested region. The hydrological impacts
of land use changes can be exacerbated or mitigated by factors such as antecedent soil moisture
and vegetation species/phenology (Laing and Evans 2015). Miller et al. (2019b) utilized WRF to
look at sensible/latent heat flux and precipitation totals following landfall of a hypothetical storm
that produced Hurricane-Maria-like vegetation reduction on the coast of Georgia, USA. By only
changing the landcover and testing varying levels of defoliation (full, 75%, 50%, and 25%),
(Miller et al. 2019b) projected that a full Maria defoliation event would produce a reduction in
latent heat and an increase in sensible heat after landfall leading to precipitation being
redistributed within a portion of the domain.
In addition to a successful history of modeling a hypothetical scenario like the present research (e.g., Miller et al. 2019b), WRF has also been used to model precipitation variations over human development, also known as “urban rainfall effect” (Shem and Shepherd 2009, Shepherd et al. 2010). Shepherd et al. (2010) used WRF model simulations over Houston, Texas, USA, to simulate how coastal urbanization, an extreme form of landscape modification, leads to a secondary outflow effect and enhanced convective processes. Also, Niyogi et al. (2011) found storm bifurcation over urban areas in addition to changes in daytime convection through observational and model analyses over Indianapolis, Indiana, USA.

2.3.2. Rainfall-Runoff

Apart from impacting energy and moisture patterns in the weeks following hurricane defoliation, there may also be an enhanced risk of flash flooding when threatened by synoptic-driven rainmakers, such as a squall line or another hurricane (Segal et al. 2002). For a change in runoff or river discharge to be observed, the area would require a heavy rainfall event in a short amount of time (Ohana-Levi et al. 2015). Nonetheless, defoliated coastal vegetation would see reduced rainfall interception by the tree canopy, allowing more precipitation to reach the surface, accumulate, and enter the terrestrial stream network (Schelker et al. 2013). Research has shown that in areas of rapid urbanization or agriculture conversion, noticeable increases in surface runoff have occurred when impacted by high concentrations of precipitation (Ohana-Levi et al. 2015). This yields hydrographs with larger, more responsive peak streamflow, likely enhancing the risk of flash flooding. Ohana-Levi et al. (2015) compared natural land cover to urbanized surfaces in a satellite imagery and modeling study and found that natural land surface had decreased runoff while metropolitan land showed increased surface runoff. Urban sprawl is associated with up to a 30% increase in modeled surface runoff in one of the studies subbasins,
with 89–93% of the change explained by NDVI (Ohana-Levi et al. 2015). Miller et al. (2019a) similarly used observations and Global Land Data Assimilation System (GLDAS) model data to show how 32% less rainfall produced 85% more runoff over the island of Puerto Rico after Hurricane Maria made landfall.
Chapter 3. Research Design

3.1. Study Area and Event Summary

This thesis is a case study on the unprecedented Hurricane Michael, which made landfall on the northern Gulf of Mexico coast between Panama City and Apalachicola, Florida, USA, near Mexico Beach and Tyndall Air Force Base. Figure 3.1 shows a map of the study area through which Michael passed. The area that experienced hurricane-force winds, from the central northwest Florida coast through the southwest corner of Georgia, is mostly rural with pastureland, agriculture fields, and pine plantations as the primary land uses. Between farms, the landscape mostly consists of woody wetlands and evergreen forests (https://nassgeodata.gmu.edu/CropScape/). The Category-5 strength wind speeds passing over primarily vegetated landcover made it an obvious choice for addressing the research questions.

Figure 3.1. Study area in central northwest Florida to southwest Georgia, USA. Hurricane Michael’s track is represented by the black solid line and the direction of movement is northeastward through the area of study.
The area is familiar with the risk of hurricanes, which begins on 1 June and extends through 30 November (i.e., the North Atlantic hurricane season). Moreover, with the Gulf of Mexico as a consistent source of moisture, conducive environments for severe weather can be set up year-round along the northern Gulf coastal plains. During the cooler months, northerly winds prevail, pushing squall lines associated with cold surges through the region. Additionally, in spring the warm, moist Gulf air mixing in with cold surges can stir up tornadic activity. For example, over a 20-year period, thunderstorms and tornadoes have been reported in every month of the year in Bay County, Florida (Figure 3.2). Even when considering the likelihood of smaller-scale severe weather that can occur throughout the year, Hurricane Michael was the strongest storm to ever hit the Florida panhandle and resulted in $25.5 billion in damage and 16 deaths in the U.S. (Beven et al. 2019).

![Monthly tornado and thunderstorm wind frequencies for Bay County, Florida: 1998-2018](image)

Figure 3.2. Monthly tornado and thunderstorm wind frequency obtained from Storm Reports for Bay County, Florida: 1998-2018.
Hurricane Michael is a unique case to study, in part due to the conditions leading up to its historic landfall. Approximately one month prior to Michael’s cyclogenesis, Tropical Storm Gordon had tracked through the northeastern Gulf of Mexico (Brown et al. 2019), mixing the water column on the shelf along the way. Gordon was then followed by an atmospheric heatwave, ultimately leading to a marine heatwave (Dzwonkowski et al. 2020). Michael initially formed on 7 October 2018 near the Gulf of Honduras and moved into the Gulf of Mexico just days later. Before making landfall on 10 October 2018, Michael interacted with the warm shelf water which led to a rapid intensification just before landfall (Dzwonkowski et al. 2020). Although Michael’s track was well-forecast, the intensity was not well-predicted.

As a Category-5 storm, Michael was the third-strongest hurricane to make landfall on the contiguous U.S. up to that point, with a pressure of 919 mb and maximum winds of 257 kph (160 mph) (NOAA 2019). After landfall, the hurricane weakened but continued northeastward into southwest Georgia, steered by the westerlies (Beven et al. 2019). The substantial wind defoliated an estimated area spanning over 12,000 km², extending from Florida through Georgia and parts of Alabama (The Weather Channel 2018). Figure 3.3 shows surface browning from this severe defoliation event in before-and-after satellite images. Zampieri et al. (2020) found up to 98 percent loss of mature longleaf pine canopy nearest to the center path. Michael caused an estimated $3.3 billion in timber and agriculture losses alone (Beven et al. 2019). Beyond the terrestrial impact, river runoff from Michael caused blooms of phytoplankton in the coastal shelf waters, including K. brevis, which is responsible for red tide (D’Sa et al. 2019).
Figure 3.3. Aqua and Terra MODIS imagery a day before and after Hurricane Michael made landfall, showing defoliation and surface browning corresponding with Michael’s track (Modified from The Weather Channel 2018).

### 3.2. Model Initialization

Weather Research and Forecasting (WRF) model version 3.8 (Skamarock et al. 2008) simulations are used to investigate the mechanisms behind post-Michael hydrometeorological land-atmosphere interactions through considering solely the role of defoliation on subsequent processes. WRF is a robust tool for studying water cycling after a change in the land surface, with proven capabilities in simulating regional weather in response to landcover changes (Miller et al. 2019b, Shem and Shepherd 2009, Shepherd et al. 2010). The Advanced Research configuration of WRF (WRF-ARW) allows hindcasts to be performed at higher resolutions.
capable of representing small-scale processes such as regional precipitation (Skamarock and Klemp 2008). Additionally, WRF’s series of input files allows users to manipulate the landscape conditions ingested by the model to study hypothetical scenarios. Such capabilities are possible with the use of boundary conditions to initialize the scenarios, as well as the model physics schemes, dynamics, numerics, and data assimilation.

A WRF-based numerical modeling experiment is performed to determine whether 1) Michael’s defoliation altered hydrometeorological processes, and 2) if so, what processes it affected. A control simulation with normal vegetation conditions is compared against an experimental simulation with post-Michael defoliation to show the physical mechanisms driving cloud and precipitation responses. Aqua and Terra Moderate Resolution Imaging Spectroradiometer (MODIS) images qualitatively inform the spatial pattern of the near-track defoliation scar as well as cloud patterns. MODIS satellite images are accessed through Worldview (https://worldview.earthdata.nasa.gov/).

Because the MODIS-derived vegetation indices cannot be inserted directly into WRF due to frequent cloud-contaminated imagery, defoliation is applied to the experimental simulation by applying a change to the leaf area index (LAI) variable. The defoliation is applied using a parametric TC precipitation model developed by the Interagency Performance Evaluation Task Force Rainfall Analysis (IPET) (Brackins and Kalyanapu 2020), which incorporates wind and pressure along the hurricane track. Though the purpose of this thesis is to assess the effects of wind, not precipitation, IPET’s method of reconstructing a TC precipitation field largely reflects its wind field as well, and it is transferrable to this application (Brackins and Kalyanapu 2020). Areas receiving the greatest precipitation in the IPET rainfall model received the greatest defoliation according to the WRF LAI. Figure 3.4 shows the reduction pattern applied in the
wrflowinput file, which tapers off to 50 percent reduced along the edge of the storm’s wind field. The green vegetation fraction (VEGFRA) field is also changed using the same proportional reduction, spatially and in magnitude, as the LAI adjustments (Figure 3.5).

Figure 3.4. Spatial pattern of reduction applied to LAI and VEGFRA variables, showing a decreasing reduction proportion with distance from the center track and coastal landfall site.

Figure 3.5. Example of reduction applied to VEGFRA variable, which shows the most severe reduction in vegetation at the landfall site, tapering to a 50 percent reduction proportion at the edge of the hurricane track.

The experiment is run from 00 Z 6 October 2018 to 00 Z 11 November 2018. Hurricane Michael’s passage is included within the spin-up period, permitting the analysis of post-
hurricane data. The single domain (Figure 3.6) with a horizontal grid spacing of 3 km is initialized with 12 km North American Mesoscale (NAM) Forecast System analyses boundary conditions. NAM analyses boundary conditions are downloaded from the National Center for Atmospheric Research (NCAR) Data Archive and applied once to the first timestep of the simulations and in six-hour increments thereafter. NAM analyses were chosen as atmospheric boundary conditions to run a single-domain simulation (i.e., no nesting required) that maintains the target ratio of 3–4x between the WRF domain grid spacing and its boundary condition grid spacing. A domain with three-kilometer grid point distance provides suitable space to account for convection without the use of a cumulus parameterization scheme. Table 3.1 shows parameterization selections, which were made based on earlier research (Boadh et al. 2016, Givati et al. 2016, Miller et al. 2019b, Zaitchik et al. 2013). The Yonsei State University (YSU) planetary boundary layer (PBL) scheme, Unified Noah land surface model, Rapid Radiative Transfer Model for GCMs (RRTMG) shortwave/longwave scheme, and the WRF Single-Moment 6-class (WSM6) microphysics are selected. No convective parameterization scheme is selected because of the model’s convection-allowing grid spacing. Model output is written in a 3-hr temporal resolution.

<table>
<thead>
<tr>
<th>Table 3.1. WRF configuration and parameterization schemes.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Setting</td>
</tr>
<tr>
<td>Boundary Layer</td>
</tr>
<tr>
<td>Land Surface</td>
</tr>
<tr>
<td>SW/LW Radiation</td>
</tr>
<tr>
<td>Microphysics</td>
</tr>
<tr>
<td>Cumulus</td>
</tr>
<tr>
<td>Boundary Conditions</td>
</tr>
<tr>
<td>Horizontal Grid</td>
</tr>
<tr>
<td>Horizontal Grid Spacing</td>
</tr>
</tbody>
</table>
3.3. Data Analysis Methods

Verification of model performance is performed using surface observations of temperature and relative humidity from five airports within the study area (Figure 3.7). Hourly temperature and humidity are downloaded from the National Oceanic and Atmospheric Administration’s National Centers for Environmental Information Climate Data Online (NOAA NCEI CDO). Additionally, one-hour observed precipitation is obtained from National Centers for Environmental Prediction (NCEP) Stage IV data (Du 2011) and used to validate model output. NCEP Stage IV data incorporates both radar estimates and rain gauge observations. The coefficient of determination ($R^2$) between the observations versus the defoliated simulation output is evaluated to test the validity of model output. The defoliated run is chosen to compare to observations because of its representativeness of the post-Michael land surface.

Absolute differences between the two simulations (i.e., defoliated minus control) are calculated for sensible and latent heat fluxes, air temperature, humidity, cloud moisture, and
precipitation. Results are compared spatially and temporally using summary statistics and significance tests for the five airports as well as two analysis zones designated within the model domain. Zone 1 includes a large area covering portions of Florida, Alabama, and Georgia, and Zone 2 covers the landfall and immediate surrounding areas (Figure 3.8).

Figure 3.7. Five airport validation stations: (1) Tallahassee, Florida, (2) Albany, Georgia, (3) Apalachicola, Florida, (4) Bonifay, Florida, and (5) Dothan, Alabama.
Figure 3.8. Two data analysis zone boxes for model output analysis. Zone 1 includes parts of Florida, Georgia, and Alabama (map extent), while Zone 2 consists of an area over the landfall track (red box).

The following variables are utilized for spatial or statistical analysis: upward sensible heat flux at the surface (HFX), upward latent heat flux at the surface (LH), upward heat flux at the ground level (GRDFLX), two-meter air temperature (T2), two-meter specific humidity (Q2), and surface runoff (SROFF). After converting the input variables to their respective units of hectopascals (hPa) and Celsius, relative humidity (RH) is calculated using four equations below. First the dimensionless mixing ratio (r) is calculated in Equation 1 to be used to find the vapor pressure (e) in Equation 2, which is based on the atmospheric surface pressure (PSFC in hPa) and the dimensionless ratio of the molecular weight of water vapor to dry air (ε =0.622). Then, the saturation vapor pressure (eₚ) is calculated using Equation 3, which incorporates the reference saturation vapor pressure (e₀=6.112 millibars), two-meter air temperature (T2 in Celsius), and values from Bolton’s (1980) formula.
\[ r = \frac{Q^2}{1-Q^2} \quad (1) \]

\[ e = \frac{PSFC+r}{\varepsilon+r} \quad (2) \]

\[ e_s(T2) = 6.112 \exp\left(\frac{17.67 T^2}{T^2+243.5}\right) \quad (3) \]

\[ RH = \frac{e}{e_s} \times 100 \quad (4) \]

To analyze cloud activity, a WRF-Python (Ladwig 2017) script is run through model output to delineate between the low-, mid-, and high-cloud fractions. Accumulated total grid scale precipitation in millimeters (RAINNC) is used to determine precipitation for each three-hour time step. This requires subtracting back-to-back timesteps to produce the accumulation occurring between the two. Spatially-averaged rainfall in millimeters is calculated by dividing the 2-d rainfall sum for each time step by the number of grid points in each zone: Zone 1 having 13,952 and Zone 2 with 1,643 points. The absolute difference of the two simulations is calculated for sensible heat, latent heat, temperature, relative humidity, cloud fraction, and precipitation. These variables are also analyzed spatially to reveal any patterns of change following defoliation. Differences are then compared temporally by each 3-hour time step. Spatial and statistical analysis are performed and graphs were created using R and Python scripting languages, JMP software suite, and Panoply netCDF Data Viewer.

### 3.4. Flash Flood Analysis Methods

To preliminarily analyze the response of flash floods to defoliation, the frequency of storm events reported from the 20 years before Michael is compared to the year following Michael in ten Florida counties. NOAAs NCEI Storm Events Database (https://www.ncdc.noaa.gov/stormevents/), a source that categorizes events based on state and county, and storm type, is used to access historical storm reports. Presently, the database includes
48 event types with availability from 1996–2020. Events are included in the database based on impact (e.g., loss of life/injury, property damage, or destruction of commerce), generation of media attention (i.e., rare event), and/or whether it holds meteorological significance (i.e., record-breaking). “Flash flooding” is a specific designation of storm event in the database, which is distinct from the broader “flood” category.

Miller et al. (2016) utilized Storm Data, as the dataset is often called, and summarizes well the uncertainty that arises from reporting accuracy. For example, there are pitfalls of using reported wind data due to inconsistent entry methods or wind criteria (Miller et al. 2016). The reports also have a caveat in that the events must be observed and reported, which introduces bias because of differing likelihood of observation and reporting across space (i.e., less representation in more rural areas). For these reasons, the use of Storm Data reports is a preliminary analysis on possible patterns in flash flood frequency. Flash flood report counts from Bay, Calhoun, Franklin, Gadsden, Gulf, Jackson, Leon, Liberty, Wakulla, and Washington (Figure 3.9) counties between 9 October 1998 and 9 October 2018 are used to contextualize the post-Michael year within the historical record. Twenty years is chosen to due to data availability, but it still encapsulates a climatological-scale average of flash flooding.

In addition to using the Storm Data, river gage height data from nearby watershed before and after Michael are compared to rainfall events over the area. From 1 September to 30 November, several case studies of gage height versus precipitation are used to assess any possible modification in river and stream gage height responses to rainfall. Gage height time series for Econfina Creek near Bennett, Florida, and Chipola River near Altha, Florida, are obtained from the United States Geological Survey (USGS) National Water Information System (https://waterdata.usgs.gov/fl/nwis/rt). A time series of satellite-derived, area-averaged daily
accumulated precipitation from the same period is accessed for the Integrated Multi-satellite Retrievals for Global Precipitation Measurement (IMERG) and used for comparison against the responses of the target gages (Huffman et al. 2019). The area selected encapsulates both gages.

![Map of Florida counties](image.png)

Figure 3.9. Ten Florida counties (red circle) used for Storm Data search of flash flood reports and of the two USGS river gages (blue circle) (Modified from U.S. Census Bureau 2003)

### 3.5. Limitations

Though WRF is a robust tool for investigating regional weather interactions, there are associated limitations within this study. The theoretical defoliation applied to the WRF model land surface assumes defoliated material vanishes, when in reality debris would likely stay on the ground for some time. Model sophistication does not allow for manual reduction to include such cases of debris on the ground or heterogenous patterns of foliage that remain. Additionally, model bias exists within both simulations from boundary conditions and parameterization selections. For validation of WRF simulations, a linear regression is chosen as an appropriate test of the reliability of the output data and does not represent performance of the defoliation. This use of a linear regression does not violate linear model assumptions.
Chapter 4. Results and Discussion

4.1. Model Validation

Because the defoliated simulation output should theoretically correspond more closely to observational data, the WRF model is validated against the observations using the defoliated output instead of the control. The coefficient of determination ($R^2$) of the defoliated scenario versus observational data for 2-meter temperature was used to show the reliability of the simulations for this case study (Figure 4.1). The six-pane figure includes a map of the five surrounding airport observation stations with the Michael track and five linear regression plots of defoliated versus observed temperature. Station 1 (Tallahassee) and Station 5 (Dothan) show a strong positive correlation with $R^2$ values of 0.86 and 0.88, respectively. While Station 3 (Apalachicola) and Station 4 (Bonifay) fell just below with $R^2$ values of 0.69 and 0.79, Station 2 (Albany) did not perform as well with $R^2 = 0.57$. Station 2 in Albany, Georgia, had the lowest correlation, likely due to its distance inland away from the coastal landfall site and its nearness to the passage of the eyewall, which resulted in missing observations from 11–17 October 2018. Closer observation stations were considered but data availability was sparse within proximity to the TC track due to the destruction of surface weather stations during Michael’s passage. The study period shows a strong correlation, apart from one station, indicating acceptable performance of the model when regarding temperature as a representative variable of model performance.
Figure 4.1. Correlation coefficients of the defoliated simulation and observed post-Michael two-meter temperature. The first pane shows a map of station locations (numbered 1–5) around Michael’s center path (black line). The remaining five panes show linear regressions used to establish $R^2$ for each of the five stations from 12 October to 10 November 2018.

In addition to temperature, relative humidity (RH) was similarly used to infer model performance. Table 4.1 shows $R^2$ values for the linear relationship between the defoliated simulation versus observations at the five stations. Again, Stations 1 (Tallahassee) and 5 (Dothan) show the strongest correlation, with $R^2$ values of 0.63 and 0.69, respectively. Stations 2 (Albany), 3 (Apalachicola), and 4 (Bonifay) correlated poorly, with $R^2$ values of 0.32, 0.53, and 0.45, respectively. The linear relationship between modeled and observed RH was much weaker than that of temperature. To better diagnose the reproduction of observed RH, a single week was chosen to focus in on a period after antecedent moisture from the hurricane had presumably evaporated while also choosing a time that is early in the model, maximizing model reliability.

Figure 4.2 shows time series plots of modeled and observed relative humidity between 18–25 October 2018 for each of the five observation stations. Again, Station 5’s observations
agreed best with the defoliated simulation output when compared to the other stations, yet there were still some instances in the latter half of the week where the simulation underpredicted RH. At Station 1, with the second-best $R^2$ (Table 4.1), humidity was underpredicted by $\sim20$–$40\%$ for five of the seven days. Percent RH was also generally underpredicted for Stations 2 and 4 as well, with $\sim30$–$50\%$ error every day during 18–25 October 2018. Humidity was largely underpredicted for every station on 22 October 2018, except for Station 3, which overpredicted humidity on six of the seven days.

The large RH errors (compared to temperature) could be attributed to the compounding error of calculating the value using three other variables. The calculation is made based on modeled surface pressure, temperature, and specific humidity, so with each inclusion of a new variable, the error associated with each variable is added with it. Alternatively, feedbacks within the model could have also led to compensating error. Similar modeling studies have also determined that RH performed more poorly than air temperature. For example, Zhang et al. (2012) implemented a new land surface dataset in a WRF modeling study over Hawaii and found that temperature correlated more strongly than RH. Furthermore, precipitation on the windward side of mountains and total cloud fraction were modeled well with a newly modified land surface.

Table 4.1. Correlation of post-Michael relative humidity for one month using $R^2$ values from the linear relationship between the defoliated scenario and observations.

<table>
<thead>
<tr>
<th>Station</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.628</td>
</tr>
<tr>
<td>2</td>
<td>0.319</td>
</tr>
<tr>
<td>3</td>
<td>0.528</td>
</tr>
<tr>
<td>4</td>
<td>0.447</td>
</tr>
<tr>
<td>5</td>
<td>0.686</td>
</tr>
</tbody>
</table>
Observed versus modeled accumulated precipitation is shown in Figure 4.3 with the defoliated scenario chosen as the standard for comparison (for the reason mentioned at the beginning of this section). Figure 4.3a shows observed accumulated precipitation from NCEP Stage IV data over the one-month period while Figure 4.3b shows the simulated accumulated rainfall. Simulated precipitation patterns broadly agree with observations over the study areas but deviate in their detail. For instance, both maps show the most precipitation occurring in the western half of the domain and offshore, and both the observations and simulation depict the same corridor of reduced precipitation in the central Florida panhandle, with the defoliated scenario slightly shifting this zone northwestward of the track. A few specific areas of larger disagreement occur in the western side of the plots near Mobile Bay in Alabama and in the central portion of the domain where Alabama, Georgia, and Florida meet. The greatest area of
rainfall in the defoliated plot (Figure 4.3b) is shifted farther inland into Georgia and just to the east of the track, with no analogous feature in the NCEP Stage IV plot (Figure 4.3a).

Some deviation between the two could be attributed to biases within the “observations” themselves. Because the Stage IV data incorporate radar estimates, non-precipitation-related features picked up on radar, including those due to anomalous beam curvature, ground clutter, poor instrument calibration, and unreliable ground truth validation (Habib et al. 2009, Matyas 2010) could confound error diagnoses in the model rather than the validation dataset. Habib et al. (2009) found that Stage IV performed well when averaged over an entire year, but on a single incident-scale basis, 50% of rainfall events reached up to ±25% bias. While underestimation comprised 65% of the resultant bias, it is noted that small rainfall events (<0.5 mm hr⁻¹) were overpredicted by 60–90% (Habib et al. 2009). Considering these findings, Stage IV precipitation data were only used at the temporal scale of one month, as opposed to looking at individual events, to avoid possible validation data biases.

The purpose of the model validation above is to verify that the WRF simulation reasonably replicated the post-Michael weather patterns over the northeast Gulf of Mexico coastline. While the model accurately resolved post-Michael temperature compared to observations, the RH and precipitation hindcasts deviated more noticeably from the observations. However, ultimately, the effect of defoliation on regional precipitation is determined by comparing the control and experimental simulations, and the model validation above succeeds in providing a reasonable reassurance that WRF is capably reproducing post-Michael atmospheric circulations.
Figure 4.3. Accumulated precipitation (mm) over a one-month period following Hurricane Michael. (A) Observed precipitation from Stage IV. (B) Defoliated scenario precipitation, with the track of Hurricane Michael (black line).

4.2. Response of Surface Energy Fluxes

The sensible and latent heat fluxes in response to defoliation are compared by calculating the raw differences between the two simulations (i.e., defoliated minus control) (Table 4.2). Additionally, the 95% confidence intervals (CIs) of the differences are used to communicate statistical significance. When the bounds of the CIs do not incorporate zero, this indicates a statistically significant change between the simulations. Mean differences in sensible heat flux increases most dramatically closer to the landfall site where defoliation was most extreme. Zone
1 sensible heat flux increases by +1.5 W m\(^{-2}\) whereas in Zone 2, the area nearest the landfall, the sensible heat flux increases +8.3 W m\(^{-2}\) (Table 4.2). Furthermore, when looking at points just inland of the coastal landfall site, instantaneous sensible heat flux increased by up to ~40 W m\(^{-2}\) on 14 October 2018 at 1:00 pm LT within Zone 2 (not shown). Figure 4.4 shows the mean difference of sensible heat flux through the one-month period. Similarly, latent heat flux for both zones shows a reduction, with a -2.8 W m\(^{-2}\) and -13.9 W m\(^{-2}\) change in Zones 1 and 2 (Figure 3.8), respectively. Areas nearest to the site of landfall saw the greatest reduction in latent heat (Figure 4.5). For example, instantaneous latent heat decreases as large as ~80 W m\(^{-2}\) were documented such as occurred on 14 October 2018 at 1:00 pm local time (LT) within Zone 2 (not shown). To put the 8.3 W m\(^{-2}\) change in perspective, the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) discusses four scenarios of representative concentration pathways (RCPs) through 2100. The scenario with the highest greenhouse gas emissions, RCP8.5, includes a global radiative forcing >8.5 W m\(^{-2}\) (IPCC 2014). Although this is at the global level, it puts the values found here in perspective.

<table>
<thead>
<tr>
<th>Zone</th>
<th>LH (W m(^{-2}))</th>
<th>Upper 95%</th>
<th>Lower 95%</th>
<th>SH (W m(^{-2}))</th>
<th>Upper 95%</th>
<th>Lower 95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-2.8</td>
<td>-2.84</td>
<td>-3.46</td>
<td>1.5</td>
<td>1.89</td>
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</tr>
<tr>
<td>2</td>
<td>-13.9</td>
<td>-11.0</td>
<td>-16.8</td>
<td>8.3</td>
<td>9.8</td>
<td>6.9</td>
</tr>
</tbody>
</table>
Figure 4.4. Sensible heat flux difference (W m$^{-2}$) (defoliated minus control) map over the one-month period following Hurricane Michael.

Figure 4.5. Latent heat flux difference (W m$^{-2}$) (defoliated minus control) map over the one-month period following Hurricane Michael.
Figure 4.6 shows the temporal variations in sensible and latent heat flux averaged over Zone 2 at each respective 3-hr timestep of model output. From 00 to 12 Z (7:00 pm–7:00 am LT) there is little to no change but increased sensible heat and decreased latent heat was shown from 15–18 Z (10:00 am–1:00 pm LT). Looking specifically on 21 October 2018, a sunny day with little observed cloud cover, Figure 4.7 shows a time series of the diurnal pattern of the modeled turbulent heat fluxes. On 21 October 2018, both fluxes peak at 1:00 pm LT with sensible heat flux consuming more of the surface net radiation than latent heat during the day, which led to the highest increase in temperature of the simulation that evening at 7:00 pm LT.

Figure 4.6. Box plot of sensible (dotted) and latent (solid) heat flux differences (W m$^{-2}$) within Zone 2 versus each 3-hr Z simulation output time for the one month following Michael.
As both the mean changes in Table 4.2 and the diurnal trace in Figure 4.7 indicate, the increase in sensible heat exceeds the reduction in latent heat within Zone 2. In Section 2.2, the changes in the surface energy budget were posited to primarily impact these two variables; however, the defoliation is clearly impacting additional terms in the surface energy balance in order to conserve energy. The increase in sensible heat is smaller than the decrease in latent because of ground storage. A bare ground will likely absorb more insolation than a vegetated surface because of reduced radiation interception by the canopy. Thus, because of the conductive flux into the surface, energy is being stored in the ground, rather than the atmosphere, accounting for the apparent discrepancy in the surface energy balance. This effect can be seen at 1:00 pm LT on 21 October 2018, when the downward ground flux of heat is \(~50–100\) W m\(^{-2}\) greater over the defoliated zone when compared to the control run (Figure 4.8).
For the month after landfall, defoliation led to altered sensible and latent heat fluxes of the surface energy balance with the changes in heat flux primarily occurring during the day, when buoyant forces and thermal turbulence are expected to prevail. Sensible and latent heat fluxes prevail during the day as the sun is out and heating the surface, warming surface air parcels and leading to turbulent mixing, whereas this process is not active at night. Another post-hurricane defoliation study simulated a 17–26% increase in sensible heat flux and a 14–29% decreased latent heat flux (Miller et al. 2019b) while others have found the reverse (Barr et al. 2012, Hosannah et al. 2021). Hosannah et al. (2021), examining post-hurricane land-atmosphere interactions in Puerto Rico, simulated 75–150 W m$^{-2}$ decreases in sensible heat and a 25–125 W
m² increase in latent heat flux. Discrepancies between these previous investigations likely occurred from varying soil moisture content within each study. For example, Miller et al. (2019b) employed a model over coastal Georgia, a study site that would more closely align with the present results. However, the latter two study sites, a mangrove forest and tropical rain forest, respectively, would likely have higher soil moisture content, which can likely be attributed to the sign of changed heat fluxes following hurricane defoliation.

4.3. Response of Temperature

Air temperature averaged over Zone 2 is plotted against each 3-hr Z time and illustrates increased temperature over 1.5 C° at 00 Z (7:00 pm LT) on eight separate days (not shown). The greatest median increase in temperature occurred at nighttime, when averaging within Zone 2 (Figure 4.9), with on average, the greatest increase occurring at 00 Z. Average temperature increases and CIs for both zones are shown in Table 4.3. Zone 1 had an average increase of 0.2 C° while Zone 2 increased on average by 0.7 C°. Figure 4.10 illustrates the spatial pattern of increased temperature, which resembles that of the increased sensible heat flux pattern. To identify an example of warming on a specific day, 22 October 2018 was chosen to represent a day early in the simulation, when model drift is minimal, and on a day with clear skies and abundant insolation to warm the surface. Differences in simulated temperatures for 22 October 00 Z show warming over 6 C° in parts of the analysis zone closest to the point of landfall (Figure 4.11). Temperature increased every day during the study period when compared to the control run with one exception, though small, on 25 October from 21 to 03 Z (4:00–10:00 pm LT), which corresponded with a low-pressure system moving over the area and the three outliers in Figure 4.9.
Table 4.3. Differences in mean two-meter air temperature within areal extents of Zone 1 and 2 over the one-month period with their confidence intervals.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Temperature (°C)</th>
<th>Upper 95%</th>
<th>Lower 95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.2</td>
<td>0.22</td>
<td>0.19</td>
</tr>
<tr>
<td>2</td>
<td>0.7</td>
<td>0.75</td>
<td>0.63</td>
</tr>
</tbody>
</table>

Figure 4.9. Box plot of temperature differences (°C) within Zone 2 at respective Z times over the one-month period.
Figure 4.10. Mean temperature difference (C°) map over the one-month period following Hurricane Michael.

Figure 4.11. Temperature difference map (C°) for 22 October 2018 00 Z.
The greatest average change in temperature occurred as the sun was going down each day. The counter-intuitive temperature increases during nighttime hours is due in part to a lagged release of the ground heat storage. This lag can be seen by looking at the upward ground heat flux variable of the defoliated scenario in Figure 4.12, which shows the upward heat flux from the surface for 4:00 am LT, the morning prior to the greatest areal averaged increase in temperature of 1.8 °C. Additionally, Figure 4.8 shows that over the defoliation scar, the ground surface absorbs significantly more heat during the afternoon, which then forces a greater temperature increase as the sun begins to descend and longwave thermal radiation is emitted. For instance, Miller et al. (2019b) found similar results in their analyses of Hurricane-Maria landcover change, which they attribute to surface browning. The same argument can be applied here, except that their study included vegetation recovery. In contrast, Barr et al. (2012) detected decreases in daytime and nighttime air temperature; however, their study was focused on hurricane defoliation over a mangrove forest with high soil moisture and inundation. Because this thesis is centered on mostly upland pine forests and agriculture fields, we would not expect the same reasoning to apply.

Figure 4.12. Upward ground heat flux (W m⁻²) for the defoliated scenario on 21 October 2018 at 09 Z.
4.4. Response of Humidity

RH varied following the hurricane-induced defoliation. However, two-meter specific humidity variation was small and statistically insignificant (Table 4.4). Averaged over the entire month and over the space of the data analysis zones, specific humidity decreased by -0.006 g kg\(^{-1}\) in Zone 1 and -0.022 g kg\(^{-1}\) in Zone 2. RH decreased on average by 0.9% averaged over Zone 1 and -2.9% in Zone 2. The most substantial differences of -7–8% was seen in RH on 21 October 2018 (not shown), which was highlighted in the time series graphics in Section 4.1. Figure 4.13 shows the temporally averaged change in RH due to defoliation, illustrating peak mean RH decreases exceeding -7.5% nearest to the site of landfall.

Table 4.4. Average humidity differences within areal extents of Zone 1 and 2 over the one-month period plus confidence intervals.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Avg Specific Humidity (g kg(^{-1}))</th>
<th>Upper 95%</th>
<th>Lower 95%</th>
<th>Avg Relative Humidity (%)</th>
<th>Upper 95%</th>
<th>Lower 95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.006</td>
<td>0.009</td>
<td>-0.021</td>
<td>-0.9</td>
<td>-0.78</td>
<td>-0.96</td>
</tr>
<tr>
<td>2</td>
<td>-0.022</td>
<td>0.027</td>
<td>-0.070</td>
<td>-2.9</td>
<td>-2.6</td>
<td>-3.1</td>
</tr>
</tbody>
</table>

Figure 4.13. Mean relative humidity (%) difference map over the one-month period following Hurricane Michael.
As shown in Equations 3.1–3.4, the calculation for finding RH is a function of specific humidity, surface pressure, and temperature. However, given the insignificant changes in specific humidity shown in Table 4.4, the change in RH must be driven mostly by the change in temperature, with temperature’s role in the calculation of RH presented in Section 3. As temperature increases, the air capacity to hold moisture increases, decreasing the RH. Confirming this result, Scholl et al. (2021) found similar decreases in evaporative fraction, a variable based on RH, in their analyses of the role of ET in cloud response to Hurricane Maria, which they attribute to drought.

4.5. Impact on Cloud Fraction and Precipitation

Given the changes to surface temperature and moisture patterns, the tendency for near-surface air parcels to generate clouds and precipitation could logically be altered. For instance, Figure 4.14 examines a specific day, 17 October 2018, when a well-mixed boundary layer transitioned to a near-saturated level at 850-hPa, indicating the likely presence of scattered cloud cover (Figure 4.14a). The change in low- and mid-cloud fraction resolved by WRF over the defoliated zone is clear at 21 Z. The difference map (i.e., defoliated minus control) in Figure 4.14b shows decreased low-cloud cover over Michael's path extending well into Georgia. In contrast, Figure 4.14c displays areas of increased mid-cloud fraction in roughly the same areas experiencing reduced low-cloud fraction. Synthesizing these two findings, the WRF simulations may be indicating an increase in cloud base height in the defoliated scenario. The sounding of the same day in Tallahassee, Florida (Figure 4.14a), shows weak winds and a well-mixed boundary layer. This archetypal day with weak synoptic forcing represents conditions during which substantial greatest impacts on convective uplift would be expected.
Figure 4.14. Low- and mid-cloud fraction difference maps versus a nearby sounding. (A) Sounding from Tallahassee for 18 October 2018 at 00 Z. Green curved gridlines denote dry adiabats (°C), blue curved gridlines indicate saturation adiabats (°C), and purple slanted gridlines indicate saturation mixing ratio lines (g kg\(^{-1}\)). (B) Change in low-cloud fraction (defoliated minus control) and (C) the change in mid-cloud fraction for 17 October 2018 21 Z.

When averaging over the span of the month within the spatial extent of Zones 1 and 2, Figure 4.15 shows on average fewer low clouds and more mid-level clouds. The box plot shows the difference in low-cloud fraction in purple, with median values at or below 0%, while the orange box, mid-cloud fraction, displays an interquartile range above zero. The difference in high clouds in green shows little to no change. Figure 4.15 depicts the changes in 21 Z cloud fraction, the time when the greatest change was detected, at three altitude ranges. The interquartile range of the low- and mid-cloud fraction vary little during all Z-times except 15, 18, and 21 Z (not shown). The median change in low-cloud fraction is negative at 21 Z, meaning that fewer low clouds were present in the defoliated scenario. Meanwhile, the mid-cloud fraction interquartile range shifts positively, ranging from 0 to an approximate +5% change at both 18 Z (not shown) and 21 Z, indicating greater mid-cloud coverage in the defoliated scenario.
Meanwhile, high-cloud fraction changed little at each 3-hour increment, including 21 Z (Figure 4.15).

![Figure 4.15. Differences in low (purple), mid (orange), and high (green) cloud fraction (%) over Zone 1 (solid) and Zone 2 (dotted) averaged over one month for 21 Z.](image)

The absolute difference in low- and mid-cloud fraction (i.e., defoliated minus control simulation) for both zones is shown in Table 4.5, including respective CIs of simulation differences. High-cloud fraction is excluded from the table as it varied minimally between the two models. Low- and mid-cloud fraction are significant at the 95% level for Zone 1, the larger of the two analysis areas. In the same way as Figure 4.15, the CIs also reveal a clear negative shift in the low-cloud fraction and positive shift in mid-cloud fraction. When considering this redistribution of cloud fraction, (i.e., coincident decrease in low clouds and increase in mid-level clouds), particularly at 18 and 21 Z, changes suggest cloud base level has moved higher, best
shown in the afternoon within the larger Zone 1. Zone 2 had a statistically significant change in mid-cloud but not low-cloud fraction.

Table 4.5. Mean low- and mid-cloud fraction and accumulated precipitation differences and CIs.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Low-Cloud (%)</th>
<th>Upper 95%</th>
<th>Lower 95%</th>
<th>Mid-Cloud (%)</th>
<th>Upper 95%</th>
<th>Lower 95%</th>
<th>Precip. (mm)</th>
<th>Upper 95%</th>
<th>Lower 95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.2</td>
<td>0.008</td>
<td>-0.45</td>
<td>0.5</td>
<td>0.82</td>
<td>0.10</td>
<td>0.04</td>
<td>0.06</td>
<td>0.01</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td>1.22</td>
<td>-0.27</td>
<td>0.9</td>
<td>1.65</td>
<td>0.08</td>
<td>0.07</td>
<td>0.16</td>
<td>-0.03</td>
</tr>
</tbody>
</table>

The shift from low- to mid-level clouds logically arises from the following processes. As the surface warms, an air parcel rises, and as the parcel rises, its temperature decreases adiabatically decreases, and RH increases until reaching saturation. With less near-surface moisture, as shown in Figure 4.13 and Table 4.4, the parcel will theoretically have to go higher to reach saturation and form a cloud. Thus, a higher cloud base is proposed to occur. Supporting this interpretation, Scholl et al. (2021) found higher cloud bases in their analyses of hurricane defoliation and cloud formation in Puerto Rico, which they attribute to greater diurnal temperature cycling and increased evaporative demand. The same argument applies here, except that upslope cloud formation plays a significantly less role in the present research, because of low relief of the Florida panhandle. In contrast, Inoue and Kimura (2004) observed a higher frequency of low-level clouds over urban areas during an 11-year analysis correlating observed NDVI to cloud activity near Tokyo; however, their study was focused on comparing low-level cloud activity in urban areas to nearby rural regions. Because this thesis is centered on an abrupt land surface change in a rural area, we would not expect the same reasoning to apply.

Notably, there is more precipitation on average in the defoliated scenario directly to the east of the track extending from offshore all the way inland to Georgia that does not appear in the control simulation (Figure 4.16). No considerable precipitation amount changes were found in Zone 1 (+0.04 mm) or Zone 2 (+0.07 mm) (Table 4.5). Resultant changes in Zone 2 accumulated
precipitation are not statistically significant while it is in Zone 1. Figure 4.16 shows the spatial pattern of accumulated rainfall for the two simulations. Both plots (Figure 4.16a) show the least amount of rainfall in the eastern side of the map. Furthermore, rainfall over Alabama (top left of figures) shows mostly agreeable precipitation patterns, except toward coastal Alabama, where the defoliated scenario (Figure 4.16b) shows an area of great rainfall accumulation. Based on the comparison of the simulations, precipitation was indeed redistributed throughout the domain, with a specific enhancement of precipitation just downwind of the defoliated path. While this feature is visually evident, the statistical comparisons performed over the zones in Figure 4.17 would likely have dampened out the small downwind feature described above.

Figure 4.17 illustrates the percent error of simulated precipitation against Stage IV observations (Figure 4.3a). Both simulations were compared against Stage IV precipitation to determine if one particular simulation better matched the observed outcome (i.e., Does the removal of post-Michael vegetation, as would have actually occurred, improve WRF’s hindcast of precipitation?). Red areas within the plots indicate the simulation had less rainfall than was observed, and blue indicates the simulation has more rainfall than the observations. The defoliated scenario overpredicted rainfall over the area of enhanced precipitation downwind of the track, a pattern that is present but of less magnitude in the control simulation (Figure 4.17a). While neither hindcast is appreciably more accurate than the other, both simulations resolve alternating bands of high and low precipitation as shown in the Stage IV observations in Figure 4.3a; however, the corridors are not intuitively oriented with respect to Michael’s track.
Figure 4.16. Accumulated precipitation (mm) over one month after Hurricane Michael. (A) Control scenario precipitation and (B) defoliated scenario precipitation, with a black line representing the track of Hurricane Michael.
Figure 4.17. Percent difference of the (A) control simulation and (B) defoliated simulation from Stage IV observed data (i.e., $(\text{Precip}_{\text{Obs}} - \text{Precip}_{\text{Sim}})/\text{Precip}_{\text{Sim}}$) for the one-month period following Hurricane Michael (black line).

Seasonality likely dampened any precipitation changes, as Hurricane Michael was a late season landfalling TC. Michael made landfall in mid-to-late fall, and the one-month simulation period concluded only a few weeks before meteorological winter. Therefore, precipitation regimes would have been mostly non-convective, typical of the northern cool season. Nonetheless, modified heat and moisture fluxes were present in the defoliated scenario when
compared to the control simulation, suggesting that physical mechanisms were in place to modify precipitation. Additionally, days with minor defoliation-influenced rainfall may be masked by synoptically-driven days with large precipitation totals.

Although there was no net increase in precipitation (<0.1 mm) within the analysis zones, the spatial pattern of precipitation in the defoliated scenario shows a pattern of rainfall in the downwind direction of the defoliated land surface. This corresponds to the findings of Miller et al. (2019b) who also reported an increased amount of precipitation downwind of a defoliated area, with results showing that convective precipitation formed near the area of altered land cover with precipitating clouds then advected downwind. Figure 4.18, taken from their study, shows how an area of reduced precipitation was fixed upwind and directly over the hurricane defoliation, corresponding to the area of initial onset of convection. Then, a thermally enhanced pressure gradient causes the area of increased precipitation to be pushed downstream. A similar pattern is seen in the defoliated scenario in Figure 4.16b, however, the enhanced simulated rainfall accumulated closer to the defoliation scar. Figure 4.19, also from Miller et al. (2019b), serves as a schematic to describe the mechanisms by which precipitation patterns are altered. With significant increases in sensible heat flux, one can anticipate an area of lower pressure to form on a sunny day, which would then lead to locally modified synoptic flow, with enhanced flow upwind of defoliation and retarded flow downwind as the pressure gradient force (PGF) is directed back toward the defoliated area.
Figure 4.18. Enhancement of precipitation downwind of a modeled hurricane defoliation on the Georgia coast. The red area indicates the zone of strong convection where convection initiates, denoted by an “A.” The light blue area represents where enhanced precipitation would fall, also indicated by “B.” The gray-toned grid squares represent the green vegetation fraction (Modified from Miller et al. 2019b).

Figure 4.19. Illustration showing altered momentum and flow over a defoliated landscape (Modified from Miller et al. 2019b).
The results shown above are contingent upon the model dynamics and physics shown in Table 3.1, and a different combination of parameterizations, grid spacing, and domain size may have produced a different result. As such, the model setup choices with RRTMG shortwave/longwave scheme, the YSU PBL scheme, and the WSM6 microphysics scheme certainly played a role in the estimation deviations. Because the 3-km model grid spacing allowed the cumulus physics to be turned off, this placed greater emphasis on the YSU PBL scheme to account for turbulent heat and moisture exchange. Boadh et al. (2016) found that the YSU PBL scheme outperformed others but that most PBL schemes have a humid bias.

4.6. Preliminary Flash Flood Results

As described in Section 2.3.2, the reduced vegetation canopy would logically alter the surface hydrology near the defoliated zone. Table 4.6 lists the number of flash flood reports per year preceding Hurricane Michael in the ten surrounding counties (note that 1998 only includes days after 9 October and 2018 only includes days before 9 October). From 9 October 1998 to 9 October 2018, ten Florida panhandle counties collectively experienced an average of 9.1 flash floods per year, with a maximum of 55 flash floods reported in 2014 (Table 4.6). The average was high due in part to a severe weather outbreak that occurred in the spring of 2014, which led to 35 flash flood reports during a 15-day period in April and 27 of the reports made on 15 April 2014. The year following Michael, from 11 October 2018 to 11 October 2019, saw 11 flash flood events, which falls in the 75th percentile of the historical annual record. However, when excluding reports made on the anomalous day of 15 April 2014 (not shown), the 20-year average reduces to 7.8 flash floods per year, putting 11 flash flood reports within the 85th percentile.
Table 4.6. Flash flood report counts for ten Florida counties 20 years prior to Hurricane Michael.

<table>
<thead>
<tr>
<th>Year</th>
<th>Number of FF Reports</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998</td>
<td>0</td>
</tr>
<tr>
<td>1999</td>
<td>1</td>
</tr>
<tr>
<td>2000</td>
<td>7</td>
</tr>
<tr>
<td>2001</td>
<td>5</td>
</tr>
<tr>
<td>2002</td>
<td>10</td>
</tr>
<tr>
<td>2003</td>
<td>1</td>
</tr>
<tr>
<td>2004</td>
<td>0</td>
</tr>
<tr>
<td>2005</td>
<td>1</td>
</tr>
<tr>
<td>2006</td>
<td>2</td>
</tr>
<tr>
<td>2007</td>
<td>0</td>
</tr>
<tr>
<td>2008</td>
<td>5</td>
</tr>
<tr>
<td>2009</td>
<td>2</td>
</tr>
<tr>
<td>2010</td>
<td>5</td>
</tr>
<tr>
<td>2011</td>
<td>0</td>
</tr>
<tr>
<td>2012</td>
<td>6</td>
</tr>
<tr>
<td>2013</td>
<td>39</td>
</tr>
<tr>
<td>2014</td>
<td>55</td>
</tr>
<tr>
<td>2015</td>
<td>23</td>
</tr>
<tr>
<td>2016</td>
<td>13</td>
</tr>
<tr>
<td>2017</td>
<td>5</td>
</tr>
<tr>
<td>2018</td>
<td>2</td>
</tr>
</tbody>
</table>

The more numerous flash flood reports in the year following Michael may possibly be attributed to the reduced interception mentioned in Section 2.3.2. Supporting this interpretation, Ohana-Levi et al. (2015) found similar stream discharge increases in their analyses of a Mediterranean watershed, which they attribute to long-term urbanization. The same argument applies here, except that the land cover change is abrupt.

To support the Storm Data analysis, observed river gage height and precipitation were compared against each other before and after Michael. During the month before Michael, Chipola River gage height experienced a <2 ft response to 63 mm of rain during 5–9 September (Figure 4.21a,c). Following Michael, 40 mm of rainfall on 8–9 November resulted in a 6 ft increase in gage height. At Econfina Creek, 40 mm of rain led to <1 ft of increased gage height, while after Michael, 25 mm of rain increased gage height by nearly 3 ft (Figure 4.21a,b). The response of gage height to rainfall amounts anecdotally shifts before and after Hurricane
Michael, when comparing nearby stream and river gages to rainfall events over the area. While this analysis is a purely exploratory look through the lens of post-hurricane defoliation, much more rigorous work would need to be performed to firmly link hurricane defoliation to altered hydrology. The isolated before-and-after comparisons listed above ignore other important factors such as antecedent soil moisture, changes to channel morphology, rainfall intensity and duration, etc., which are all influential in determining the response in river stage height.

![Figure 4.20](image_url) Comparison of accumulated rainfall and nearby river gages for 1 September to 30 November 2018. (A) Time series of area-averaged accumulated precipitation (mm) from IMERG. Time series of gage heights for (B) Econfina Creek near Bennett, Florida, and (C) Chipola River near Altha, Florida. The blue line represents gage height level (ft), the green baseline denotes the period of approved USGS data, the red line indicates flood stage, and the red line indicates measured gage height.

Though not a hydrological model, WRF’s land surface parameterization does estimate surface runoff (Figure 4.22), and so this variable was analyzed during a heavy precipitation event that occurred on 2 November 2018. The defoliated surface runoff is identical to the control run
(Figure 4.21), highlighting the weakness of the out-of-the-box Unified Noah land surface parameterization of WRF. Though the land surface model tries to partition precipitation into surface and sub-surface runoff, it does not recognize the altered vegetation conditions and does not look at the leaf area index to inform the modeled surface runoff. Instead, utilization of a coupled atmosphere-hydrology model such as WRF-Hydro (Gochis et al. 2020) would aid in future work examining the possible influence of a devegetated landscape on surface runoff.

Because the change in precipitation was small, there may not be an impact of flash flood frequency due to altered patterns of convective rainfall. But when affected by synoptic-scale weather and/or severe rainfall events within a brief period, conditions could be conducive for enhanced flash flooding due to the lack of vegetation. This historical analysis in Table 4.6 is inherently limited because it does not consider the inter-annual variability that may exist due to forcings such as ENSO. For instance, strong El Niño winters can lead to extreme rainfall in the southeast US, which can lead to an enhanced risk of flash flooding (Gershunov and Barnett 1998, Laing 2004).

Figure 4.21. Modeled surface runoff (mm) for 2 November at 00 Z for (A) the control simulation and (B) the defoliated simulation.
Chapter 5. Conclusions

The direct impact of tropical cyclone wind is proposed to lead to indirect hydrometeorological changes through a series of physical processes following Hurricane Michael. Abrupt and severe defoliation altered regional weather patterns through several mechanisms, including reductions in radiative interception by the canopy, ET, and plant interception. These altered processes following defoliation resulted in increased sensible heat flux and 2-m air temperature and reduced latent heat flux and relative humidity. Together these factors drive the local water cycle and impact cloud and precipitation activity. Additionally, when affected by heavy rainfall events after the landscape change, one might expect more surface runoff and thus flash flooding.

Because hurricanes can already cause considerable damage during the period of landfall, it is essential that those impacted be knowledgeable of the risks that may persist well after the storm has left the area. Communities recently hard-hit by a hurricane are at an increased level of vulnerability which heightens the likelihood of consequences from a hazard and the possibility of hindered recovery efforts. Despite the devastating nature of hurricanes, little research has investigated how/if they modify hydrometeorological patterns via landscape changes, yet those that have mostly conclude such changes occur (Barr et al. 2012, Hosannah et al. 2021, Miller et al. 2019a, Miller et al. 2019b, Scholl et al. 2021). Results from more research on this topic have the potential to improve the understanding of weather responses in the weeks following hurricane landfall. Further investigation of these mechanisms could be considered when local weather forecasting offices implement area-specific public products such as Hurricane Threats and Impacts graphics (UCAR 2019).
The results of this research show the altered transfer of energy and moisture that occurs after a severe and abrupt change in land cover by directly comparing two model simulations in which the only difference is the land surface. Through the analysis of WRF model outputs, this study presents evidence that a reduction in vegetation can change moisture and energy budgets of a local region. Defoliation from a hurricane was shown to alter turbulent fluxes of sensible and latent heat, temperature, relative humidity, cloud cover, and precipitation patterns during a one-month simulation after Hurricane Michael’s landfall. Within the analysis zone closest to the defoliation scar, simulated sensible heat flux increased by 8.3 W m\(^{-2}\) and temperature increased by 0.7 °C. Modeled latent heat flux decreased on average by -13.9 W m\(^{-2}\) and relative humidity decreased by -2.9%.

The greatest temperature change occurred at night and is attributed to increased downward ground heat flux during the day. Additionally, the defoliated simulation demonstrated decreased low-cloud fraction while mid-level cloud cover showed an increasing trend, indicating a potential ascension in the cloud base height. With less near-surface moisture at the initiation of uplift, an air parcel would have to go higher to reach saturation. Although the accumulated precipitation change is insignificant when averaged over one month, evidence of redistribution nearest to the defoliation track is found. In particular, directly downwind of the track, a small patch of enhanced precipitation is simulated to occur. These results are promising even with such a short experimental period and while considering the seasonal environmental factors. For the year after Michael, flash floods reports fell within the 85th percentile of the previous 20 years in addition to a potential enhanced river response to subsequent rainfall events.

Incorporating these results into post-hurricane preparedness will allow for more informed Hurricane Threats and Impacts communications. For example, public products could include
warnings for increased air temperature following a hurricane, which could be important for communities and agriculture industries alike. For instance, higher temperatures could result in a heat wave that cripples recovering communities, particularly before electrical services can be restored, and has the potential to accelerate crop spoilage. The greatest change in temperature at night combined with increased upward ground heat flux could suggest higher soil temperatures, which can impact vegetation and critters as well as biogeochemical processes. Lu and Xu (2014) noted that increased soil temperature leads to elevated rates of microbial activity and the decomposition of organic matter, leading to enhanced emission of nitrous oxide, a potent greenhouse gas.

Future research is recommended to test these methods following a summertime landfalling storm to encapsulate the time with the greatest potential of convective summertime rainfall. During this time maximum insolation produces afternoon thunderstorms, so impacts of land cover change would result in greater differences in cloud formation and precipitation. Additionally, analyzing surface interactions at smaller temporal scales, as opposed to a monthly average, could illustrate day-to-day variation better. Future work should also focus on utilizing coupled models to research the complex interactions between various components of the earth system, including the relationship among hurricane disturbances, vegetation, and local weather.

Though a case study on Hurricane Michael, this project connects atmospheric and land surface processes in a way that could be transferable to a much broader range of locations and disturbance events. While it is common for researchers to focus on how the changing climate affects the earth’s surface, the effect of the land surface on local climate is less frequently engaged. This paradigm will aid in bettering our knowledge of how landscape changes impact hydrometeorological phenomena in the changing climate.
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Vita

Shannon Alexis Nelson, best known as Lexi, was born in Pensacola, Florida, in 1996. After graduating from Booker T. Washington High School in 2014, she earned an Associate in Arts from Pensacola State College in Environmental Sciences. In 2019, she graduated *cum laude* with a Bachelor of Science in Environmental Studies - Natural Science from the University of West Florida (UWF). While at UWF she conducted a senior research project testing the application of a near-infrared camera for the measurement of beach sand moisture, guided by Louisiana State University alumnus Dr. Phillip Schmutz. In Fall 2019, she began the Master of Science in Oceanography and Coastal Sciences program at LSU and joined Dr. Paul Miller in the Coastal Meteorology (COMET) Lab. During this time, she was accorded an Honorable Mention in the 2020 National Science Foundation Graduate Research Fellowship Program competition and anticipates receiving her degree from LSU in the Summer of 2021.