Understanding Meteorological Changes Following Severe Defoliation during a Strong Hurricane Landfall: Insights from Hurricane Michael (2018)

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ABSTRACT: Despite prompting persistent meteorological changes, severe defoliation following a tropical cyclone (TC) landfall has received relatively little attention and is largely overlooked within hurricane preparedness and recovery planning. Changes to near-track vegetation can modify evapotranspiration for months after tropical cyclone passage, thereby altering boundary layer moisture and energy fluxes that drive the local water cycle. This study seeks to understand potential spatial and temporal changes in defoliation-driven meteorological conditions using Hurricane Michael (2018) as a testbed. In this sensitivity study, two Weather Research and Forecasting (WRF) Model simulations, a normal-landscape and a post-TC scenario, are compared to determine how a defoliation scar placed along Michael’s path alters surface heat fluxes, temperature, relative humidity, and precipitation near the storm’s track. In the month following the foliage reduction, WRF resolves a 0.7°C 2-m temperature increase, with the greatest changes occurring at night. Meanwhile, the simulations produce changes to the sensible and latent heat fluxes of +8.3 and −13.9 W m\textsuperscript{−2}, respectively, while average relative humidity decreases from 73% to 70.1%. Although the accumulated precipitation in the defoliated simulation was larger along a narrow corridor paralleling and downwind of the hurricane track, neither simulation satisfactorily replicated post-Michael precipitation patterns as recorded by NCEP Stage IV QPE, casting doubt as to whether the downwind enhancement was exclusively due to the defoliation scar. This sensitivity analysis provides insight into the types of changes that may be possible following rapid and widespread defoliation during a TC landfall.

KEYWORDS: Hurricanes/typhoons; Atmosphere–land interaction; Hydrometeorology

1. Introduction

Tropical cyclones (TCs) are intense low pressure systems that can devastate low- and midlatitude coastal communities across the globe. A comprehensive awareness of both the direct and indirect impacts that TCs can inflict on a community is fundamental for effectively communicating the likelihood and severity of a potential hazard (Pielke 2007). Direct impacts during a tropical cyclone may include damaged windows and roofs, coastal erosion, and fallen trees. However, fallen trees and damaged crops may lead to indirect impacts, such as loss of future revenue for farmers or increased risk of wildfires (Liu et al. 2003). Meanwhile vegetation that is not completely killed is stripped of leaves and limbs, a process known as defoliation. Significant defoliation can occur during TC landfalls (Boose et al. 1994) and temporarily blanket the ground in leaves and debris.

While only a few studies have examined post-TC atmospheric conditions, insights can nonetheless be gleaned from investigations into analogous forms of landscape transformation. For instance, industrial deforestation of tropical forests can also modify local atmospheric circulations (Eltahir 1996). In the Amazon, vegetation plays a vital role in large-scale circulation, and when synoptic events are not heavily influencing the weather, the removal of forested landscapes can redistribute precipitation both spatially and temporally (Eltahir 1996; Negri et al. 2004). The impacts of land surface changes can either exacerbate or mitigate hydrological processes, with the sign of change dependent upon factors such as antecedent soil moisture and vegetation species/phenology (Liang and Evans 2015). Evapotranspiration (ET) in the Amazon provides a local moisture source for 25%–50% of its precipitation, and a reduction in ET has been shown to increase the risk of forest fires in global climate simulations (Cochrane and Laurance 2008). Other examples of natural and anthropogenic disturbances that can cause extensive landcover change include wildfires, insect infestations, and urban development (Flannigan et al. 2000; Forney et al. 2022; Forrester et al. 2018; Shepherd et al. 2002). For instance, model simulations have been used to study hydrometeorological variations due to the presence of large cities (e.g., Shem and Shepherd 2009). Shepherd et al. (2010) used Weather Research and Forecasting (WRF) Model simulations over Houston, Texas, to determine how urbanization, an extreme form of landscape modification, leads to enhanced convective processes, a phenomenon known as the “urban rainfall effect.”

Specific to TC disturbances, the reduction of vegetative cover caused by TCs alters heat and moisture fluxes between the surface and the atmosphere (Pielke 2001). For example, the reduced shade fraction in defoliated regions would logically permit greater incident shortwave direct and diffuse radiation at the surface, leading to an increase in near-surface temperature. If conditions are favorable for convective development, this surface warming
would also bolster the environmental lapse rate, enhancing static instability and, if sufficient moisture is available, cumulus cloud formation. As temperature and moisture patterns supporting convection are altered, then by extension, cascading changes to the regional hydrometeorology are possible as well (Bounoua et al. 2002; Cochrane and Laurance 2008; Pielke 2001).

Miller et al. (2019) and Hosannah et al. (2021) both assessed post-TC landscape changes over Puerto Rico following Hurricane Maria (2017) and their impact on precipitation and the local water cycle. Miller et al. (2019) found that hurricane defoliation strengthened the relationship (i.e., increased the correlation) between precipitation and the Gálvez–Davison index (Gálvez and Davison 2016), an operational forecasting tool that indicates the likelihood of convective precipitation. Additionally, Hurricane Maria likely altered the island’s hydrological patterns over a 6-week period as landscape greenness recovered, by perturbing cloud and precipitation development, surface runoff, and sediment transport to the coast (Miller et al. 2019). In a follow-up study, Miller et al. (2020) utilized WRF simulations to compare changes in the surface energy budget and precipitation following the landfall of a hypothetical storm on the coast of Georgia. Using Hurricane Maria as a benchmark, four levels of defoliation were tested, which showed that a Maria-type defoliation event would reduce latent heat flux and increase sensible heat flux following landfall as well as redistribute precipitation near the landfall location (Miller et al. 2020). However, these findings were inconsistent with Hosannah et al. (2021) who found up to a 150 W m\(^{-2}\) decrease in sensible heat flux over most of Puerto Rico using the Regional Atmospheric Modeling System (RAMS) while latent heat and humidity were simulated to increase. The abrupt transformation of forest to bare soil and grass was proposed 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.

Despite the efforts described above, previous TC defoliation studies have either (1) analyzed pre- versus poststorm observed changes where causality is ambiguous (Miller et al. 2019), 2) conducted model simulations several months after the most severe defoliation had been ameliorated (Hosannah et al. 2021), or 3) simulated immediate poststorm hydrometeorology from a hypothetical TC (Miller et al. 2020). Thus, no effort to date has engaged immediate poststorm effects following an observed TC. This study will build upon previous work using Hurricane Michael (2018) as a testbed, whereby the sensitivity of modeled post-TC meteorological conditions to reduced vegetation will be assessed. Hurricane Michael is selected as an illustrative example, and the focus of this study will be on the sensitivity of the meteorological changes to reduced vegetation, rather than the explicit representation of pre- versus post-Michael conditions.

2. Methods

a. Study area

This research uses Hurricane Michael (2018) as a testbed. It made landfall on the northern Gulf of Mexico coast between Panama City and Apalachicola, Florida, near Mexico Beach and Tyndall Air Force Base as a category-5 storm. Although it weakened to a category-4 storm within 1 h of landfall, Michael was nonetheless the third-strongest hurricane to make landfall on the contiguous United States, with a pressure of 919 hPa, maximum winds of 257 km h\(^{-1}\) (160 mi h\(^{-1}\)) (Beven et al. 2019), and 4.5-m storm surge (Bilskie et al. 2022). Hurricane Michael formed on 7 October 2018 and made landfall on 10 October 2018, ultimately leading to the loss of 16 lives and $25.5 billion in damage (Beven et al. 2019). In addition, as much as 98% of mature longleaf pine canopy nearest to the center path was destroyed (Zampieri et al. 2020), causing an estimated $3.3 billion in timber and agriculture losses alone (Beven et al. 2019).

Figure 1 shows a map of the study area through which Michael passed that experienced hurricane-force winds, from the central northwestern Florida coast through the southwest corner of Georgia. The impact of Michael’s rare category-5-strength winds passing over this vegetated landcover made it a desirable sample point for post-TC research.

b. Model initialization

WRF Model, version 3.8 (Skamarock and Klemp 2008), simulations are used to investigate the mechanisms underlying post-Michael hydrometeorology through considering solely the role of defoliation. A WRF-based numerical modeling experiment is performed by comparing a control simulation with normal vegetation conditions against an experimental simulation with reduced vegetation along Michael’s track. The simulations are initialized on 0000 UTC 6 October 2018 and continue through 0000 UTC 12 November 2018. The first seven days, which include Hurricane Michael’s passage, are discarded as spinup time. The 3-km-grid-spacing WRF
domain (Fig. 1) is initialized with boundary conditions from the 12-km North American Mesoscale (NAM) Forecast System analyses retrieved from the National Center for Atmospheric Research (NCAR) Data Archive and updated at 6-h increments. NAM analyses were chosen so that a 3-km convection-permitting resolution could be achieved using a single domain. Table 1 shows parameterization selections, which have been successfully implemented in other similar contexts (Boadh et al. 2016; Miller et al. 2020; Zaitchik et al. 2013). The WRF output is written to disk in 3-h increments.

Defoliation was introduced within the experimental simulation by editing the "wrfswin" files that update the leaf area index (LAI), green vegetation fraction (VEGFRA), sea surface temperatures, and other surface variables (sea ice, albedo, and ocean current velocity) within the land surface model. While LAI and VEGFRA are usually used to adjust the seasonal landscape transition from winter denudation to summer greening, the experimental simulation introduced a defoliation scar along Michael’s track coincident with its landfall on 10 October 2018. The shape and magnitude of the defoliation scar were constructed using a radial exponential decay model inspired by the Interagency Performance Evaluation Task Force (IPET) Rainfall Analysis (Brackins and Kalyanapu 2020). While designed to produce a two-dimensional rain rate around a TC, the IPET model is solely a function of the storm’s radius of maximum wind (RMW) and central pressure deficit (CPD). Thus, the spatial configuration of the IPET rain rate mirrors the gradient wind field, and it is easily adapted to represent defoliation (Fig. 2a). The grid cell receiving the greatest precipitation in the IPET rainfall model received the greatest defoliation (i.e., 100% reduction) in the wrfswin LAI and VEGFRA fields, whereas grid cells receiving one-half of maximum IPET precipitation received a 50% reduction in LAI and VEGFRA. Future studies engaging weaker TCs should consider capping the maximum defoliation at a lower percentage than the 100% that was allowed for Michael because of its extremely powerful category-5 classification at landfall. This approach is advantageous because it relies entirely upon the WRF geography data’s existing LAI and VEGFRA fields and does not require users to perform post-TC remote sensing analyses, which would only then require assumptions about how to replace the remotely sensed vegetation scar for the control scenario. Hurricane Michael’s RMW and CPD values as it traversed the northern Gulf of Mexico and southeastern United States were retrieved from the International Best Track Archive for Climate Stewardship (Knapp et al. 2018).

Figure 2a shows the resultant LAI field that was assimilated into the experimental WRF simulation beginning on 1800 UTC 10 October 2018. The width and inland extent of defoliation produced by the modified IPET algorithm matches the shape of decreases in November 2018 MODIS Terra normalized difference vegetation index (NDVI) well (Fig. 2b). Although the landscape had 3 weeks to recover before these data were collected, the November 2018 NDVI mosaic is the first full-month post-Michael NDVI composite available for analysis. However, based on findings of several studies employing high-resolution satellite imagery (~30 m), the LAI field (Fig. 2a) was reduced more severely than what is indicated by the 0.05° monthly NDVI imagery shown in Fig. 2b. For instance, Hu and Smith (2018) found numerous locations in post-Maria Puerto Rico experiencing NDVI reductions > 0.60 when analyzing 30-m Landsat-8 Operational Land Imager (OLI) imagery. (NDVI ranges between 0 and 1, so a 0.60 reduction

<table>
<thead>
<tr>
<th>Setting</th>
<th>Scheme</th>
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<tbody>
<tr>
<td>Boundary layer</td>
<td>YSU</td>
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<tr>
<td>Land surface</td>
<td>Unified Noah LSM</td>
</tr>
<tr>
<td>Shortwave/longwave radiation</td>
<td>RRTMG</td>
</tr>
<tr>
<td>Microphysics</td>
<td>WSM6</td>
</tr>
<tr>
<td>Cumulus</td>
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<td>Boundary conditions</td>
<td>NAM analysis</td>
</tr>
<tr>
<td>Horizontal grid</td>
<td>483 x 344</td>
</tr>
<tr>
<td>Horizontal grid spacing</td>
<td>3 km</td>
</tr>
</tbody>
</table>

**TABLE 1. WRF configuration and parameterization schemes.**

![A) Defoliated LAI for WRF Experiment](image1)

**FIG. 2.** (a) Spatial pattern of reduction applied to LAI and VEGFRA land surface variables. The reduction decreases with increasing distance from the center track and coastal landfall site (i.e., the most severe reduction in vegetation is at the landfall site and gradually tapers off beyond the RMW). (b) Observed percent reduction in NDVI from MODIS Terra accessed from the NASA Giovanni web platform. November 2018 monthly NDVI (first whole month post-Michael) is compared with the November 2000–17 average. Michael’s track is marked by the black line.
and not defoliation; thus, the extent of defoliation at this location is presumably even greater. Aside from Hurricane Michael, a field study following Hurricane Maria reported that defoliation during Hurricanes Irma and Maria corresponded to 95%–171% of the historical annual total (Liu et al. 2018), while another analysis estimated that Maria alone killed or severely damaged 23–31 million trees in Puerto Rico (Feng et al. 2018).

Given the multitude of recent studies indicating the astonishing defoliation that is possible during strong TCs, the defoliation algorithm described above opted for a larger percent decrease than indicated by the November 2018 NDVI in Fig. 2b. This decision was explicitly motivated by the aforementioned post-Michael and post-Maria remote sensing analyses (Feng et al. 2018; Hu and Smith 2018; Miller et al. 2019; Worley et al. 2022) as well as the multiple field studies that documented high concentrations of tree mortality and litterfall near the sites of strong hurricane landfalls (Liu et al. 2018; Rutledge et al. 2021; Zampieri et al. 2020). In a true post-TC setting, the dislodged foliage would be deposited on the ground for decomposition, but the method employed herein simply removes it from the landscape altogether. Future studies may nonetheless seek to improve upon this approach.

c. WRF validation

Before comparing the two landscape scenarios, the WRF simulations are validated against hourly surface observations from within zone 1 (Fig. 1) to assess their reliability for this analysis. Hourly surface observations from five regional airports (Table 2) were downloaded from the NCEI Global Surface Hourly dataset (Smith et al. 2011), and the coefficients of determination $R^2$ between both the defoliated and control 2-m temperature (T2M) versus the observed values were used to show the suitability of WRF as an atmospheric analytical tool in this context. According to Table 2, WRF-simulated temperatures explain approximately 80% of the observed temperature variability at three of the five sites (Tallahassee, Florida; Bonifay, Florida; and Dothan, Alabama), and approximately 70% of the variability at another (Apalachicola, Florida). WRF reproduced surface temperatures at Albany, Georgia, with the least precision ($R^2 = 0.568$). Because several of the sites are located near urban centers (i.e., Tallahassee and Albany), the absence of an urban canopy model parameterization in Table 1 may have impeded stronger correlations against observed 2-m temperatures.

The sensitivity of regional meteorological conditions to the post-TC defoliation is determined by comparing the two simulations, and the model validation above succeeds in providing a reasonable assurance that WRF is an appropriate tool for this analysis. Observation stations nearer to Michael’s path were desired, but data availability proximate to the TC track was sparse because of the destruction of surface weather stations during the storm.

3. Results

The control and defoliated simulations are compared to determine the sensitivity of post-TC meteorological conditions to associated changes in vegetation. For each physical variable (temperature, latent heat flux, etc.), the mean difference between the simulations is computed and 95% confidence intervals are constructed around the mean. If the 95% confidence interval does not contain zero, then the changes are described as statistically significant.

a. Response of surface energy fluxes

For both sensible and latent heat fluxes, changes are most dramatic closest to the landfill site where defoliation was most extreme (Figs. 3a,b). When viewed diurnally, increases in sensible heat flux and decreases in latent heat flux are dominant from 1500 to 2100 UTC (1000–1600 LT) during the period of greatest incoming solar radiation (Fig. 3d). However, these differences diminish between 0000 and 1200 UTC (1900–0700 LT) when incoming shortwave energy ceases during the overnight hours. However, during this same 12-h period, the upward ground heat flux increases (Figs. 3d,e) as Earth radiates excess energy that was absorbed by the soil during the day. Figure 3e shows the defoliated versus control ground heat flux for the entire month following the landfill. Daytime hours are marked by an increase in ground heat absorption, which is then accompanied by an increased release at nighttime, yielding an overall more amplified ground heat flux diurnal pattern. At one point during the simulation on 1800 UTC 14 October 2018 when incoming solar radiation was strong, sensible heat flux just inland of the coastal landfill increased by ~40 W m$^{-2}$ while the latent heat flux decreased by ~80 W m$^{-2}$. In contrast, changes to the ground heat flux

<table>
<thead>
<tr>
<th>Station</th>
<th>Location</th>
<th>Identifier</th>
<th>Defoliated</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tallahassee, FL</td>
<td>72214093805</td>
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<td>0.857</td>
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<tr>
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<tr>
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<tr>
<td>Bonifay, FL</td>
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<td>0.794</td>
<td>0.809</td>
<td></td>
</tr>
<tr>
<td>Dothan, AL</td>
<td>72226813839</td>
<td>0.878</td>
<td>0.882</td>
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are more subtle (Fig. 3c), which is somewhat expected given its smaller contribution to the surface energy budget.

The change in sensible and latent heat fluxes following defoliation are determined by calculating the mean differences between the two simulations (i.e., defoliated minus control) (Table 3). When averaged over zone 1, sensible heat flux increases by +1.5 W m\(^{-2}\), whereas, in zone 2, which is the area nearest the landfall, the sensible heat flux increases +8.3 W m\(^{-2}\) (Table 3). Latent heat flux for both zones shows a reduction, with a −2.8 and −13.9 W m\(^{-2}\) change in zones 1 and 2 (Table 3), respectively. The changes over zone 2 become most apparent in the upper 25% of the latent and sensible heat flux distribution (Table 4).

b. Response of temperature and humidity

The perturbations to the surface energy budgets shown in section 3a would logically alter surface air temperature as well. Figure 4a shows 2-m temperature increases over the same areas that also experienced the greatest sensible heat flux increases and latent heat flux decreases in Figs. 3a and 3b. The mean increase nearest the landfall locations is approximately 2°C, while 2-m temperature averaged over all of zone 2 detects 0000 UTC (1900 LT) temperature increases of >1.5°C on eight separate days (Fig. 5c). When averaged over the entire 29-day analysis period, zone 1 experienced a statistically significant average increase in 2-m temperature of 0.2°C while in zone 2, nearest the landfall (Fig. 1), temperatures increased by 0.7°C (Table 3). In fact, temperature in the defoliated region increased every day during the study period in comparison with the control run, with one exception, although small, on 25 October from 2100 to 0300 UTC (Fig. 5c). The propagation of surface energy perturbations into near-surface meteorological changes is also evident in Fig. 5, which shows the 3-hourly differences between the defoliated and control simulations for sensible and latent heat flux differences for the study period at each model output time step within analysis zone 2. (c) Time series of defoliated vs control ground heat flux over zone 2.

<table>
<thead>
<tr>
<th>TABLE 3. Differences in mean atmospheric variables for the 29-day study period from 12 Oct to 10 Nov 2018 following landfall. Statistically significant changes (marked with asterisks) between the defoliated and control simulation are determined by the bounds of the 95% confidence intervals.</th>
</tr>
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<tbody>
<tr>
<td>Zone 1</td>
</tr>
<tr>
<td>Sensible heat flux (W m(^{-2}))</td>
</tr>
<tr>
<td>Latent heat flux (W m(^{-2}))</td>
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<tr>
<td>T2M (°C)</td>
</tr>
<tr>
<td>q2 (g kg(^{-1}))</td>
</tr>
<tr>
<td>RH (%)</td>
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<tr>
<td>Precipitation (mm)</td>
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<th>TABLE 4. Quartiles for field variables in defoliated and control simulations over zone 2.</th>
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<tbody>
<tr>
<td>Control</td>
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<tr>
<td>25th</td>
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<td>Sensible heat flux (W m(^{-2}))</td>
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<td>Latent heat flux. (W m(^{-2}))</td>
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<tr>
<td>T2M (°C)</td>
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<tr>
<td>q2 (g kg(^{-1}))</td>
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<tr>
<td>RH (%)</td>
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as well as 2-m temperature and relative humidity averaged over zone 2.

Although the 2-m specific humidity (q2) changes were small and statistically insignificant (Table 3) following the TC, 2-m relative humidity (RH) exhibited greater shifts. Figure 4b shows the temporally averaged change in RH due to defoliation, illustrating peak RH decreases exceeding -7.5% nearest to the site of landfall (Fig. 5d). Because the q2 remained virtually unchanged, the reductions in RH (Table 3) were likely driven by the higher saturation vapor pressures associated with warmer temperatures (Fig. 4a).

Within the diurnal cycle, the greatest increase in zone 2 temperature was observed during the late evening and overnight hours (Fig. 4c), with the greatest increase occurring at 0000 UTC. Even though the sensible heat flux increases are greatest at 1800 and 2100 UTC, the increase in 2-m temperature appears more closely associated with the ground heat flux (Fig. 3d). As solar radiation is more effectively absorbed by the soil during the day (owing to the newfound lack of vegetation and shade), the excess energy is then radiated from the surface into the atmosphere overnight, boosting temperatures by approximately 1°C (Fig. 4c). At 0000 UTC, RH consequently decreases most considerably (>4%), coincident with the largest defoliation-related warming. RH decreases remain between 2% and 4% throughout the rest of the diurnal cycle, likely due to the increases in air temperature rather than reduced water vapor content (Table 3).

c. Impact on precipitation

While changes in mean 3-hourly accumulated precipitation over both zones 1 and 2 were negligible (<0.04 and <0.07 mm, respectively) (Table 3), the control (Fig. 6a) and defoliated (Fig. 6b) simulations contain one broadscale difference: An enhancement of precipitation just downwind (i.e., east) of the defoliated path. Although the NCEP Stage IV (Lin 2011) precipitation totals (Fig. 6c) also show that a corridor of precipitation was detected in this area, the defoliated scenario simultaneously fails to replicate other areas of the precipitation within the Stage IV observations. The interpretation of this east-of-track enhancement in conjunction with defoliated scenario’s other precipitation errors will be discussed in section 4. Objectively, the mean cumulative precipitation over zone 2 was 83 mm in the defoliated simulation versus 76 mm in the control scenario. Meanwhile, the observed Stage IV precipitation was 114 mm. If the same statistics are reproduced over the entire region depicted in Figs. 6a–c, the performance of both simulations improve, resolving a mean precipitation total of 86 and 77 mm for the defoliated and control scenarios, respectively, and 96 mm observed by the Stage IV product (Fig. 6c).

In addition to the total precipitation, the 0000 UTC (Fig. 4c) peak of increased air temperature may have perturbed the
diurnal cycle of precipitation by further destabilizing the atmosphere to vertical parcel ascent. Although precipitation changes were not statistically significant in Table 3 at all 3-hourly time steps, Fig. 6d shows statistically significant increases in precipitation along and slightly downwind of the track at 0000 UTC. At the same time, mean-layer convective available potential energy (MLCAPE) shows increases along and east of track in southwest Georgia. While the precipitation increases in Fig. 6d do not spatially coincide with the MLCAPE increases in Fig. 6e, precipitation exploiting the more destabilized atmosphere in the defoliated simulation may not appear until subsequent time steps. Figure 6f shows the precipitation changes at 0300 UTC, which indicate an area of increased precipitation in the same region characterized by MLCAPE increases at 0000 UTC. While the 0300 UTC precipitation increases are not statistically significant at the 95% confidence level, their spatial alignment with 0000 UTC MLCAPE suggests a connection between the defoliated-zone warming, instability, and lagged precipitation to be investigated in future studies.

4. Discussion

Heat fluxes, temperature, relative humidity, and precipitation all responded to modeled defoliation in some capacity. The changes in sensible and latent heat flux found here are comparable to Miller et al. (2020) who simulated a 17%–26% increase in sensible heat flux and a 14%–29% decreased latent heat flux. However, other post-TC studies have documented a sign reversal for both fluxes (Barr et al. 2012; Hosannah et al. 2021). In their examination of post-Maria land–atmosphere interactions in Puerto Rico, Hosannah et al. (2021) simulated 75–150 W m$^{-2}$ decreases in sensible heat flux and a 25–125 W m$^{-2}$ 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. (2020) employed a model over coastal Georgia, a study site that would more closely align with the present precipitation and atmosphere conditions.
results. However, the latter two study sites, a mangrove forest (Barr et al. 2012) and tropical rain forest (Hosannah et al. 2021), respectively, would likely have higher soil moisture content, which can likely explain the sign of changed heat fluxes following hurricane defoliation.

The greatest average temperature change within the simulations occurred near the end of the diurnal heating cycle each day. The counterintuitive temperature increases during nighttime hours is posited to be a response to the lagged release of the ground heat storage. Figure 3c faintly shows that the ground absorbs more energy over the defoliation scar during the 1-month postlandfall analysis. However, the average ground flux change in Fig. 3c is necessarily small because it contains the offsetting effects of increased downward ground flux during peak diurnal heat followed by increased upward ground flux at night (Figs. 3d,e). As the temperature forcing from incoming shortwave radiation wanes as the sun descends daily, then the longwave thermal radiation emitted from the defoliation scar becomes a more prominent temperature forcing overnight.

Although the simulations showed no net increase in 3-hourly precipitation within the analysis zones, the spatial pattern of precipitation in the defoliated scenario shows a pattern of rainfall in the downwind (east in this case) direction of the defoliated land surface. This corresponds to the findings of Miller et al. (2020) who theorized that precipitation formed along an enhanced surface convergence zone near the TC track with precipitating clouds then advected downstream of the westerly steering-level wind direction. However, the downstream precipitation enhancement cannot be conclusively attributed to the reduced vegetation. Even though the defoliated precipitation demonstrates a clear spatial proximity to the defoliation scar, the lack of tighter correspondence between either simulation (Figs. 6a,b) and the observed precipitation (Fig. 6c) is reason for pause. While the defoliated simulation produced more precipitation east of the track, like the observations, it also failed to reproduce a relatively large area of precipitation west of the track over the Florida Panhandle. Consequently, it is unclear whether the defoliated simulation’s east-of-track enhancement is a genuine response to vegetation scar, or simply another symptom of the internal model error that also led to the west-of-track discrepancy.

While the shifts in precipitation noted in Fig. 6 are unlikely to cause drought or flooding over the scale of 1 month, the seasonality of the study period likely muted greater precipitation responses to the defoliation. Studies of landscape effects on weather typically target synoptically mild settings when large-scale influences on weather are small and local scale factors become more dominant (Miller and Mote 2017). Because such environments are most common in the summer months (e.g., Reesman et al. 2021), the October–November analysis period herein would have experienced more frequent synoptic dynamical influences that superseded landscape effects. Because Hurricane Michael made landfall in mid-to-late autumn, the 1-month simulation period concluded only a few weeks before meteorological winter. Additionally, synoptically mild days with legitimate defoliation-influenced rainfall are not likely to be significant precipitation days (Debbage et al. 2017; Doswell et al. 1996), allowing their signature to be masked by a few synoptically driven, heavier precipitation days. Nonetheless, modified energy fluxes and temperature patterns were present in the defoliated scenario, suggesting that physical mechanisms to modify precipitation were present.

This study was limited by several methodological choices. For instance, the representation of the defoliation scar within the WRF Model was produced using the modified IPET algorithm. This approach is desirable because it allows the researchers to leverage the existing LAI and VEGFRA fields within the WRF geography data, but it also sacrifices accuracy near the landfall where post-TC remote sensing analyses may better capture the shape and magnitude of landscape change. Meanwhile, the reduction of the LAI and VEGFRA fields successfully implemented a less-vegetated land surface, but there is no way to transfer the removed vegetation to the ground as litterfall and detritus, which may impact the surface energy budget in a way not resolved by this study. Although Miller et al. (2020) and Reesman (2022) found that defoliation-related atmospheric changes were robust across a WRF ensemble, the comparison of the defoliated and control scenarios could be strengthened by conducting a larger ensemble of model runs. While many of the meteorological changes were statistically significant on the daily scale and consistent across the entire model run (Figs. 3c, 4, and 6d), their authenticity could be bolstered by conducting additional defoliated simulations using different parameterization schemes to better characterize changes due to the defoliation versus those arising from internal model error.

5. Conclusions

This sensitivity study of post-Michael meteorology to reduced vegetation shows that multiple regional atmospheric processes were disrupted, such as increased sensible heat flux and 2-m air temperature and reduced latent heat flux and relative humidity. Meanwhile, the diurnal cycle of ground heat flux became more amplified, absorbing more energy during the day and releasing more at night. Through the analysis of WRF Model outputs, this study presents evidence that a large, near-instantaneous reduction in vegetation can change moisture and energy budgets following strong TCs.

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%. Although somewhat counterintuitive, the greatest 2-m temperature change occurred at night and is attributed to increased downward ground heat flux during the day. The stored ground energy was then reradiated as longwave upwelling radiation during the overnight hours unexpectedly raising temperatures in the absence of diurnal heating. While the defoliation-related perturbations to temperature and humidity patterns could logically alter local forcings for convection initiation, 3-hourly precipitation amounts remained unchanged in the reduced vegetation scenario, and neither
scenario convincingly reproduced the spatial patterns of post-Michael precipitation observed in the Stage IV product. By better understanding post-TC conditions, meteorologists and emergency managers can achieve a more holistic view of the persistent, indirect impacts of TCs as well as facilitate clear and accurate information about the totality of TC risks. Aside from hydrometeorological effects, one of this study’s most consequential findings from a policy and disaster-recovery perspective relates to the nocturnal temperature increases. Not only do TCs form when air temperatures are near their seasonal maximum, but rampant, often weeks-long power outages following the storm exacerbate the human heat stress risk. For instance, according to the Louisiana Department of Health (LDH), 9 of the 31 deaths attributed to Hurricane Laura were heat related (LDH 2021). Because nighttime minimum temperatures have been found to strongly associate with heat mortality (Laaidi et al. 2012; Ragettli et al. 2017), the prospect that hurricanes perturb the surface energy budget to yield warmer overnight conditions warrants future exploration. (Further emphasizing the idea of indirect TC impacts, an additional 9 deaths were attributed to carbon monoxide poisoning, which often results from improper home generator usage. Thus, 18 of Laura’s 31 deaths arose from power outages in the days and weeks after the storm, rather than the direct TC hazards often emphasized by media outlets.) The findings of this study can be used by the emergency management community to better anticipate the holistic spectrum of risks posed by strong TCs. Meanwhile, journalists and media outlets might use these findings to better communicate the indirect, persistent hazards that can linger for months following landfall so that residents can make more informed, a priori decisions to evacuate. With TCs projected to strengthen in future climate regimes (e.g., Knutson et al. 2015) and continued population growth in coastal regions (NOAA 2013), a more comprehensive picture of both direct and indirect TC hazards is required.

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Data availability statement. Three-hourly sensible, latent, and ground heat fluxes as well as 2-m relative humidity, temperature, and precipitation for the control and defoliated WRF simulations are available on Zenodo (https://doi.org/10.5281/zenodo.7617761).

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