May 2022

Changes in Heat Metrics Following a Major Hurricane and Implications on Heat Stress

Cade Reesman
Louisiana State University and Agricultural and Mechanical College

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CHANGES IN HEAT METRICS FOLLOWING A MAJOR HURRICANE AND IMPLICATIONS ON HEAT STRESS

A Thesis

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

in

The Department of Oceanography and Coastal Sciences

by
Cade Reesman
B.S., Mississippi State University, 2020
August 2022
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Abstract

Tropical cyclones modify surface-atmosphere interactions in several ways, including the destruction of patches of tree canopy, increasing the direct and diffuse (shortwave) radiation reaching the surface. This addition of radiation at the surface impacts the sensible, latent, and substrate heat (energy) fluxes, generating heat anomalies along the hurricane’s track, which, among other effects, contributes to the higher post-hurricane surface air temperatures. This study consists of a case study on Hurricane Laura (2020) to examine hurricane defoliation impacts on heat stress metrics. Normalized difference vegetation index (NDVI) data from NASA’s Moderate Resolution Imaging Spectroradiometer (MODIS) identified the spatial extent of defoliation produced from Hurricane Laura (2020) in southwestern Louisiana. This defoliation extended for 135 km cross-track along the coastline with remnants of the modified landscape conditions persisting for one year following landfall. The Weather Research and Forecasting (WRF) model version 4.2 was utilized to examine the severity of heat metric changes associated with the defoliation through a post-Laura, defoliated numerical weather simulation and a control, normal foliage simulation. In Cameron, Louisiana, the site of Hurricane Laura’s landfall, at least 10 days exceed $+1.0^\circ C$ in daily average heat index change during the month following Hurricane Laura. Four additional WRF simulations were performed with altered landfall years of 2017 and 2018 to determine the sensitivity of Hurricane Laura-like defoliation on heat metrics to different synoptic conditions. Synoptic conditions modulated the overall magnitude of average change in heat metrics, but heat stress metrics experienced significant increases despite different synoptic conditions. The wetland dominated southwest coast of Louisiana did not show the greatest potential for warming, but coastal Louisiana still experienced an average warming of $0.95^\circ C$ in nighttime heat index in Cameron, Louisiana, following Hurricane Laura. Overall, the greatest
heat stress metrics change occurred during the nighttime from 0000 Coordinated Universal Time (UTC) to 0600 UTC when communities are most prone to heat mortality, with an average increase of 0.25°C in heat index at 0600 UTC across southwest Louisiana. Tropical cyclone-related heat events present a unique opportunity to investigate the severity of an often-times overlooked impact from tropical cyclones.
1. Introduction

Extreme heat events following tropical cyclones are an emerging compound event with grave consequences. The ability for tropical cyclones to generate heat anomalies along their track is a secondary hazard not generally perceived or communicated to the public. Tropical cyclones modify surface-atmosphere interactions through the sensible, latent, and/or substrate heat fluxes, temperature, and available water, as they defoliate the landscape, leading to an influx of radiation at the surface and increasing surface temperatures. Increases in temperature subsequently enhance heat stress metrics, compromising the human body’s ability to cope with extreme conditions. Hurricane Laura (2020) can be used to examine hurricane defoliation impacts on heat stress metrics. Of the 31 total fatalities from Hurricane Laura, the Louisiana Department of Health (2021) confirmed nine of them to be heat-related deaths, providing motivation for this study. This research aims to examine the magnitude of heat metric changes to better understand the extreme heat events occurring in post-hurricane environments. Tropical cyclone-related heat events present a unique opportunity to investigate the severity of an often-times overlooked impact from this hazard.
2. Review of Literature

Land surface alterations modify surface-atmosphere interactions by impacting the sensible, latent, and/or substrate heat fluxes, which can subsequently modify temperature and available water. Whether land-surface changes are anthropogenic or natural, examples such as deforestation, wildfires, and tropical cyclones all disrupt the local surface energy and water budgets. Many of these natural disasters also cause power outages, putting communities at increased risk of heat-related mortality and exacerbating the heat stress caused by the land cover disturbance. This section will focus on the impact of three different land cover disturbances (i.e., anthropogenic deforestation, wildfires, and tropical cyclone defoliation) on heat metrics. Lastly, a review of the vulnerability of communities to heat-related mortality is included to assess the societal significance of the exacerbated heat metrics (i.e., temperature, heat stress indices, and sensible/latent heat) from land cover disturbances.

2.1. Anthropogenic Deforestation Effects on Temperature

Largely due to population growth and agricultural expansion (Allen and Barnes 1985), deforestation is a common land cover disturbance with impacts on heat metrics. Deforestation represents one of the largest areal land cover disturbances on the planet with East and West Africa experiencing forest declines of around 83 and 93 percent since 1900 (Aleman et al. 2018). Deforestation results in both global and local effects on surface-atmosphere interactions, including through removal of CO₂ from the atmosphere, which should theoretically lead to a warming effect globally (Costa and Foley 2000). Similarly, tropical afforestation should lead to a cooling effect globally (Bala et al. 2007). Most research suggests that the cooling biophysical
effects from a higher albedo in the underlying soil surface than the dark tree canopy (Münch et al. 2019) is not significant enough to make a difference in lower latitudes (Li et al. 2016).

Locally, deforestation leads to an increase in extreme temperatures with higher maximum temperatures specifically during the dry season (Voldoire and Royer 2004). The surface temperature and the 2-m surface air temperature differ after deforestation, with the surface temperature experiencing a higher increase in maximum temperature locally (Winckler et al. 2019). The change in surface temperatures as a response to the deforestation is dependent on the change in solar radiation absorbed and latent heat flux (Schultz et al. 2017). The decrease in forest canopy exposes the surface to an increase in absorbed direct and diffuse radiation, altering the surface energy budget and leading to an increased sensible heat flux. The latent heat flux is typically reduced because of the decrease in vegetative transpiration and changes in the overall net radiation (Lejeune et al. 2015). Additionally, the latitudinal location of deforestation plays a role in the impact of heat metrics, with low to mid-latitudes experiencing the most noticeable local changes (Prevedello et al. 2019). Although deforestation is projected to decrease in the future (Nepstad et al. 2009), the mitigation of localized impacts on heat metrics is imperative. Most importantly, the impacts of deforestation on the local climate could potentially last for decades after the land cover disturbance (Zeppetello et al. 2020).

2.2. Wildfire Effects on Temperature

Similar to deforestation, wildfires abruptly alter land cover, which also can be studied to examine heat metrics following land cover disturbances. Wildfires consume plant canopy (Ice et al. 2004), and the observed decrease in plant canopy causes additional direct and diffuse
radiation to reach the surface while albedo generally decreases (Flint and Caldwell 1998; Tsuyuzaki et al. 2009). The extra radiant energy is “spent” in the form of increased sensible heat flux, resulting in higher land surface temperatures after wildfires in areas of high burn severity (Vlassova et al. 2014). At the same time, transpiration decreases due to the removal of vegetation, which in turn decreases the latent heat flux (Beringer et al. 2003) and increases the Bowen ratio (Bowen 1926). Surface radiometric temperatures are elevated up to 15 years after wildfire, and heat fluxes are affected for a few years after the wildfire (Amiro et al. 1999). Excluding land cover effects, the high temperatures and air pollutants produced from wildfires can also spark high-mortality heat waves (Shaposhnikov et al. 2014). As wildfires become more probable in an increasingly warm climate (Westerling and Bryant 2008), the demand for future research on post-wildfire environments is vital.

2.3. Tropical Cyclone Defoliation

Tropical cyclone hazards are generally perceived to be wind damage, heavy rainfall, storm surge, riverine flooding, and severe convective weather; however, tropical cyclones can also generate heat anomalies along their tracks through defoliation. In this process, tropical cyclones destroy large patches of tree canopy, resulting in increased direct and diffuse radiation reaching the surface, and this influx of radiation at the surface contributes to higher post-storm surface air temperatures (Fernandez and Fetcher 1991). Typically, the decrease in vegetation associated with defoliation reduces plant transpiration, modifies sensible and latent heat fluxes, and increases surface air temperature (Figure 1; Barr et al. 2012). The severity of tropical cyclone defoliation is difficult to measure and depends on elevation, vegetation size, distribution, and tree type (Tanner et al. 1991). Concurrently, the diurnal temperature cycle is expanded as
heat radiates outward more efficiently with less vegetation (Scholl et al. 2021), particularly in open areas where the sky view factor is large.

![Diagram of Hurricane Defoliation Feedback](image)

Figure 1. Conceptual graphic explaining feedback from tropical cyclone defoliation.

Regarding moisture, the additional incoming shortwave energy caused by the removal of the canopy ultimately leads to a reduction in relative humidity (RH) as the increase in air temperature leads to an increase in saturation vapor pressure which decreases the RH (Lugo 2008). After the disturbance, the increase in soil temperatures can alter lapse rates, perhaps driving a shift from statically stable to statically unstable conditions, which then allows enhanced water vapor and CO$_2$ transport vertically (Barr et al. 2012). In addition to heat and water, the increased soil temperatures also likely lead to an increase in respiration, which causes a carbon loss (Barr et al. 2010). Not only is the transport of CO$_2$ affected, but emissions of nitrous oxide (N$_2$O) also increase from the tropical cyclone defoliation (Steudler et al. 1991). Although local
changes to forest canopy are more effective in surface warming, N₂O is a greenhouse gas capable of contributing to a warming in the atmosphere and impacting the radiation budget (Erickson and Ayala 2004).

More recently, Hurricane Laura (2020) can be used to examine defoliation impacts on heat stress metrics. For example, the National Weather Service (NWS) issued 10 heat advisories in September 2020 in Lake Charles, Louisiana, following the landfall of Hurricane Laura on 27 August 2020. Figure 2 illustrates the impact of Laura on the post-hurricane environment in the Lake Charles area with a potential increase in heat metrics reflected by the increase in heat advisories; these heat advisories account for half of all the advisories/warnings issued in September 2020 in Lake Charles.

Figure 2. Advisories/warnings issued by NWS Lake Charles in September 2020.
Collectively, these impacts from tropical cyclone defoliation persist years after landfall as changes in heat metrics were found to last between to 2 to 6 years in mangrove vegetation (Zhang et al. 2016). As tropical cyclones are projected to increase in intensity (Pielke et al. 2005), the impacts on heat metrics should prompt further research in the scientific community.

Recently, Nelson (2021) found changes in sensible, latent, and substrate heat fluxes and temperature while performing a numerical modeling case study on the abrupt defoliation from Hurricane Michael (2018). The sensible heat flux in Nelson’s study had increases up to 8.3 W m\(^{-2}\) in the defoliated zone closest to landfall while the latent heat flux decreased by an average of 13.9 W m\(^{-2}\). The greatest surface temperature increase occurred during the nighttime nearest to the landfall location due to increased downward ground heat flux at night. Additionally, Nelson (2021) study found surface temperature increased by an average 0.7 C° near the defoliated zone with the greatest change in surface temperature occurring along the hurricane’s track (Figure 3). Nelson also documented decreases in RH by 2.9%, as expected due to the increased temperatures altering the saturation vapor pressure.
Figure 3. Mean temperature difference (°C) map during the one-month period following Hurricane Michael. Taken from Nelson (2021).

2.4. Extreme Heat Events

Extreme heat events or heat waves are considered the primary cause of weather-related mortality in the United States, surpassing tropical cyclones and floods (Luber and McGeehin 2008). Heat events are often identified using heat index, and the same metric also serves as the issuance criterion for NWS heat-related watch, warning, and advisory products. Factors such as duration of heat, nighttime temperature, potential for cooling lake breeze, dry desert heat, terrain, time of the year, mass outdoor gatherings, and recent power outages influence the vulnerability and mortality of extreme heat events (Hawkins et al. 2017). Additionally, air pollutants can increase the severity of extreme heat events, increasing the risk of mortality (Analitis et al.
Heat waves can be forecasted by examining maximum temperature, meaning even minimal changes in temperatures can promote additional extreme heat events (Gasparrini and Armstrong 2011). According to Anderson and Bell (2009), the most susceptible communities to extreme heat events have a higher income, unemployment, population, and urbanicity.

Extreme heat events affect the human body in various forms ranging from minor sunburns or dehydration to mortality (Thomas et al. 2012), while also impacting power consumption (Zuo et al. 2015). Demographics most vulnerable to extreme heat events are the young and elderly population with people aged greater than sixty-five years being most vulnerable (Wilson et al. 2011). Additionally, people with mental health disorders and substance misuse are far more susceptible to the impacts of extreme heat events (Cusack et al. 2011).

Meanwhile, extreme heat events have a substantial impact on the power consumption of communities. In response to these extreme heat events, massive amounts of electricity must be used for air conditioning, placing greater demands on power generation. With a higher need for energy production, an increase in greenhouse gas emissions will occur which has significant implications on the environment and health of humans (Matzarakis and Nastos 2011). These extreme heat events are measured and forecast through the evaluation of heat stress metrics.

2.5. Heat Stress Metrics

Heat stress metrics are either direct measurements (e.g., air temperature) or derived parameters (e.g., heat index) that describe the severity of heat-related events and often possess a strong correlation with associated mortality. Heat stress metrics include variables such as temperature, heat index, apparent temperature, equivalent temperature, humidex, wet bulb...
temperature, mean radiant temperature, and discomfort index (Buzan et al. 2015). To investigate heat mortality, atmospheric and environmental factors must be examined other than the sole observation of temperature (Zhang et al. 2012). Although heat index algorithms can be inconsistent across studies (Anderson et al. 2013), heat index is more strongly linked to heat-stress-related mortalities than temperature (Metzger et al. 2010). Heat index quantifies the effects of heat and moisture on the human body’s ability to dissipate heat through evaporation (Delworth et al. 1999). The human body’s ability to cool through evaporation in high temperatures is inhibited by humidity reducing the evaporative rate at the surface skin (Sherwood 2018). Additionally, clothing tends to lower the heat tolerance of individuals due to less surface skin available to dissipate heat through evaporation (Boden et al. 2013).

Similar to heat index, the apparent temperature is identified by a person’s perceived air temperature incorporating humidity (Steadman 1984). The equivalent temperature differs from the physiological equivalent temperature referring to the air temperature, indoors, at which the heat budget of the human body is balanced with the same core and skin temperature as the outdoor conditions (Höppe 1999). More accurately, the equivalent temperature deals with moist enthalpy which incorporates temperature and humidity into one measurable value (Fall et al. 2010). Humidex is another temperature-humidity index but differs from the heat index as it uses dew-point temperature instead of RH (Santee and Wallace 2005). Similarly, the discomfort index formula also incorporates proportional temperature and RH components to measure human thermal comfort (Poupkou et al. 2011). The various heat stress metrics mentioned above display the wide range of methods for characterizing extreme heat impacts on susceptible communities.

Heat index is a more common and efficient indicator of heat-related mortality than temperature (Yin and Wang 2018). The National Weather Service Forecast Office (NWSFO)
New Orleans, bordering NWSFO Lake Charles, issues a heat advisory when a heat index ≥108°F is forecasted over a 24–72 hour period. The correlation between mortality and heat index is strongest during a three-day period (Sung et al. 2013). Although heat mortalities depend on local climate, heat fatalities generally occur after reaching a heat index of 26.7°C (80°F) (Maung and Tustin 2020). Meanwhile, average heat index values of 37.2°C (99°F) are associated with worker fatalities (Roelofs 2018); a common range of heat-related fatalities occurs at a heat index of 28.9°C–40.9°C (84.0°F–105.7°F) (Arbury et al. 2014). However, the minimum temperature is the most significant temperature indicator in assessing heat mortality, with higher minimum temperatures leading to a higher heat mortality (Ragettli et al. 2017). Consequently, increases in nighttime temperature are more fatal than increases in daytime temperature (Laaidi et al. 2012).

2.6. Post-hurricane Heat Stress

Tropical cyclone defoliation alters the vegetative surface and thereby impacts the surface energy budget and turbulent fluxes. Heat stress metrics are primarily calculated using surface temperatures, so the increase in temperatures in post-storm environments could exacerbate extreme heat events. Increases in daytime and nighttime temperatures further increase the likelihood of heat stress and mortality in post-storm environments. Referencing the heat index equation (Rothfusz and NWSSR Headquarters 1990), increases in temperature leads to a higher heat index, indicating more heat stress. Defoliation reduces RH as the increase in temperature leads to an increase in saturation vapor pressure which decreases the RH, so theoretically, the heat index or heat stress will not reach its maximum value with a reduction in RH given an increasing temperature. Although the maximum heat index will be achieved through high temperatures and high RH (Hass et al. 2016), an increase in temperatures is still significant
enough to increase heat stress in post-tropical-cyclone environments. The highest mortality risk occurs from hot daytime temperatures followed by hot nighttime temperatures which aligns with previous temperature modeling in post-hurricane environments (Murage et al. 2017; Nelson 2021). With the intensity of natural disasters expected to rise in our changing climate, further research investigating the extreme heat events following land cover disturbances should be prioritized.

Recent examples of Hurricanes Laura and Ida support the above text confirming post-hurricane heat stress. The Louisiana Department of Health (2021) reported that nine of Hurricane Laura’s 31 storm-related deaths were heat-related. Among the nine heat-related deaths, none of the fatalities occurred near the landfall location where the largest tropical cyclone impacts were expected (Figure 4). Instead, the heat-related deaths occurred in Beauregard, Rapides, Vernon, Grant, and Jackson parishes (Figure 4). All parishes which experienced at least one heat-related death from Hurricane Laura were directly located on or on the eastward side of the hurricane track. Louisiana Department of Health (2021) also reported 13 of Hurricane Ida’s 29 storm related deaths due to excessive heat (Figure 5). Hurricanes Laura and Ida both illustrate the high proportion of storm-related fatalities arising from heat stress in major hurricanes rather than the wind, surge, and precipitation hazards.
Figure 4. Hurricane Laura heat-related deaths by parish, as reported by Louisiana Department of Health (2021).
Figure 5. Louisiana Department of Health (2021) tweet from 14 September 2021.
3. Research Objectives

This study addresses the following core science question: Does hurricane-related defoliation increase heat stress metrics during the landscape’s recovery? Hurricane Laura (2020) in southwest Louisiana, a high-end Category 4 storm considered to be one of the strongest storms making landfall, with wind speeds up to 150 mph, is used as the focus of this research. Laura defoliated much of the area, yielding an opportunity to investigate the impact on subsequent heat metrics.

This primary research question will be investigated via four project objectives:

Objective 1: Identify the spatial extent of the defoliation produced from Hurricane Laura as well as the temporal period during which modified landscape conditions persisted (i.e., the recovery period).

Objective 2: Examine the changes in land-surface temperatures associated with Hurricane Laura defoliation through satellite observations.

Objective 3: Examine the magnitude of heat metric changes associated with Hurricane Laura defoliation through a reduced foliage numerical weather simulation versus a control, normal foliage simulation.

Objective 4: Repeat Objective 3 except artificially altering the landfall year to determine post-hurricane heat metric sensitivity to synoptic weather conditions.

The purpose of this project is to examine the potential effects of an altered post-Hurricane Laura surface energy budget on the exceptional heat indices apparent in Southwest Louisiana. Hurricane Laura was classified as a high-end Category 4 storm considered to be one of the
strongest storms making landfall with wind speeds up to 150 mph. Laura defoliated much of the area, yielding an opportunity to investigate the impact on subsequent heat metrics.
4. Data and Methods

Objective 1 utilizes NASA’s Moderate Resolution Imaging Spectroradiometer- (MODIS-) detected Normalized Difference Vegetation Index (NDVI) to identify the spatial extent of the defoliation at a spatial resolution of 0.05° x 0.05°, and the temporal coverage of recovery of the defoliated areas. NDVI estimates the density of green on the surface through differences in visible and near infrared sunlight reflected by vegetation cover (Weier and Herring 2000). Because NDVI can account for changes in greenness at the surface, this parameter represents an appropriate tool for this analysis. To assess the spatial extent of Hurricane Laura’s defoliation, the average monthly September NDVI values for the year 2020 were obtained and compared to the average monthly September NDVI values for the previous 20 years (2000–2019). The percent difference was calculated between the two images to generate an anomaly map showing the overall change in NDVI directly following the landfall of Hurricane Laura. To determine the temporal coverage of vegetation recovery, the same technique is repeated while substituting each successive month for up to one year following landfall (i.e., August 2021). For instance, the temporal recovery during December 2020 is measured using the December 2020 NDVI versus the average monthly December NDVI between 2000–2019. This technique was repeated for each month following Laura’s landfall for up to one year, yielding 12 anomaly maps used to assess the temporal recovery of the defoliated surface.

For Objective 2, MODIS-Aqua Daytime and Nighttime 3-min Climate Modeling Grid (CMG) Land-surface Temperature (LST) products, at a spatial resolution of 0.05° x 0.05°, are used to analyze the effect of hurricane defoliation on surface temperature. To observe changes in temperature from hurricane defoliation, the MODIS LST monthly temperature averages for September 2002–2019 versus September 2020 LST were obtained over Louisiana. Differences in
September 2020 temperature from the previous 18-year monthly average were then mapped along with Hurricane Laura’s storm track to reveal potential changes due to hurricane defoliation. Additionally, September monthly LST datasets were extracted for both daytime and nighttime to assess diurnal differences. Objective 2 employs a satellite component to pair with the numerical weather simulations performed in Objectives 3 and 4 to complete a more thorough analysis.

To accomplish Objective 3, the Weather Research and Forecasting (WRF) model version 4.2 (Skamarock et al. 2019) is used to simulate air temperatures under both post-Laura and normal vegetation levels to quantify the effect of defoliation on heat-related variables. WRF is initialized over the domain shown in Figure 6 using boundary conditions from the North American Mesoscale (NAM) model from 27 August to 1 October 2020 allowing one-week spin up time for the model. Additional WRF parametrization schemes shown in Table 1 align with similar research in WRF land surface alterations (Miller et al. 2020). However, because WRF does not account for changes in land-surface characteristics such as hurricane defoliation, the default land-surface characteristics were overwritten to represent a defoliated land-surface. To represent the defoliated surface into the model simulation, the results found in the September NDVI analysis from Objective 1 were applied to WRF low-level input files (i.e., wrflowinp_d01.nc). The percent difference taken from the 2020 September NDVI and 2000–2019 September NDVI was applied to the leaf area index (LAI) and vegetation fraction (GVF) variables inside the low-level WRF input files to initialize the defoliated weather simulation as shown in Figure 7. The input landscape for defoliated model simulation, which contains the strongest defoliation along the coastline as well as another corridor of reduced LAI/GVF farther inland north of Lake Charles, is also shown in Figure 7.
Figure 6. Hurricane Laura’s storm track mapped over the WRF domain containing the locations of weather observation stations located in Orange, Texas (pink star), Lake Charles (black star), Lake Arthur (yellow star), and Vernon (green star) in Louisiana. Statistical analyses were performed within the red-dashed box.
Table 1. WRF Parameterization schemes

<table>
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Figure 7. Leaf area index difference between the defoliated simulation and the baseline simulation input in the wrflowinp files.

Specific heat stress metrics were computed from the WRF model output to assess the overall impact on the surface energy budget from hurricane defoliation. This study computed the
heat index and apparent temperature as representatives of heat stress metrics. The heat index quantifies the effects of heat and moisture on the human body’s ability to dissipate heat through evaporation (Delworth et al. 1999). Equation 1 displays the equation used in this study to calculate the heat index (Rothfusz and NWSSR Headquarters 1990), composed of 2-m temperature (T) and 2-m RH (R). Because the heat index is designed to be computed when temperatures exceed 26.7°C (80°F), the apparent temperature is also used in this study to be a more representative metric when temperatures do not reach 26.7°C (80°F). The apparent temperature is identified by a person’s perceived air temperature incorporating humidity (Steadman 1984). Equation 2, composed of 2-m temperature (T) and vapor pressure (e), shows how the apparent temperature was computed in this study. Difference maps for each of these heat stress metrics were generated between the control and post-Laura WRF simulations.

\[
HI = -42.379 + 2.04901523T + 10.14333127R - 0.22475541TR \\
- 6.83783 \times 10^{-3}T^2 - 5.481717 \times 10^{-2}R^2 \\
+ 1.22874 \times 10^{-3}T^2R + 8.5282 \times 10^{-4}TR^2 - 1.99 \times 10^{-6}T^2R^2 
\] (1)

\[
AT = -1.3 + 0.92T + 2.2e 
\] (2)

Objective 3 focuses on southwestern Louisiana, as shown by the hurricane track in Figure 6. The “post-Laura” heat indices were compared between the control and defoliated simulations to determine the magnitude and spatial patterns of post-hurricane warming. Six-hr interval maps of heat indices were generated to show a time series of the changes in heat metrics throughout the day; additionally, daytime and nighttime heat metric changes were calculated with the daytime hours consisting of 1500, 1800, and 2100 Coordinated Universal Time (UTC) while the
nighttime hours consist of 0300, 0600, and 0900 UTC; Central Daylight Time is 5 hours earlier, while Central Standard Time is 6 hours earlier. Average change in heat stress metrics and other parameters were taken from the red dashed box in Figure 6 to represent a location in southwest Louisiana which experienced large amounts of defoliation. Additionally, four local weather stations shown in Figure 6 were selected to validate model output with observed temperatures: Orange 9 N (Orange), Lake Charles Regional Airport (Lake Charles), Lake Arthur 7 SW (Lake Arthur), and Vernon, Louisiana (Vernon). These represent the closest stations not decimated by the storm, and they are used as model validation as well as reference points in the ensuing figures. Table 2 lists the stations’ attributes as well as missing temperature data.

Table 2. Weather stations used to validate the WRF model from [https://xmacis.rcc-acis.org/](https://xmacis.rcc-acis.org/)

<table>
<thead>
<tr>
<th>Weather Observation Stations</th>
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<tr>
<td>Station Name:</td>
<td>Orange 9 N</td>
<td>Lake Charles Regional AP</td>
<td>Lake Arthur 7 SW</td>
<td>Vernon Louisiana</td>
</tr>
<tr>
<td>State:</td>
<td>TX</td>
<td>LA</td>
<td>LA</td>
<td>LA</td>
</tr>
<tr>
<td>County:</td>
<td>Orange County (FIPS 48361)</td>
<td>Calcasieu Parish (FIPS 22019)</td>
<td>Cameron Parish (FIPS 22023)</td>
<td>Vernon Parish (FIPS 22115)</td>
</tr>
<tr>
<td>Station Ids:</td>
<td>416680 (Coop)</td>
<td>412436 (Coop)</td>
<td>03937 (WBAN)</td>
<td>165065 (Coop)</td>
</tr>
<tr>
<td></td>
<td>USC00416680 (GHCN)</td>
<td>USC00412436 (GHCN)</td>
<td>165078 (Coop)</td>
<td>USC00165065 (GHCN)</td>
</tr>
<tr>
<td></td>
<td>ORET2 (NWSLI)</td>
<td>USC00416680 (GHCN)</td>
<td>LCH (FAA)</td>
<td>LWR1 (NWS LI)</td>
</tr>
<tr>
<td></td>
<td>LCH (FAA)</td>
<td>LCH (FAA)</td>
<td>72240 (WMO)</td>
<td>LCH (NWS LI)</td>
</tr>
<tr>
<td></td>
<td>KLCH (ICAO)</td>
<td>USC00003937 (GHCN)</td>
<td>LWRL1 (NWS LI)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>USC00165065 (GHCN)</td>
<td>LCH (NWS LI)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Latitude:</td>
<td>30.2263 degrees</td>
<td>30.1255 degrees</td>
<td>30.0206 degrees</td>
<td>31.0167 degrees</td>
</tr>
<tr>
<td>Longitude:</td>
<td>-93.7394 degrees</td>
<td>-93.2277 degrees</td>
<td>-92.7681 degrees</td>
<td>-93.1869 degrees</td>
</tr>
</tbody>
</table>
In Objective 4, the modeling experiment described in Objective 3 is repeated in an identical WRF configuration. However, the boundary conditions used to initialize the WRF run are switched to 27 August – 1 October 2017 and 27 August – 1 October 2018. These two years were purposefully selected to represent years with active hurricane seasons in southwest Louisiana, providing a broader sample size to gauge the sensitivity of heat metric changes to synoptic conditions. In 2018, Hurricane Michael made landfall on October 10 as a Category 5 storm in Mexico Beach, Florida. In 2017, Hurricane Harvey made landfall on August 25 on San Jose Island, Texas. Objective 4 is limited to years after 2011 due to operational lifetime NAM boundary conditions in the model simulations. Essentially, the hurricane-related defoliation pattern produced by Hurricane Laura in 2020 was identically replicated in each of the emphasized years, but the ambient conditions are modified to yield a different sample synoptic condition. Observing multiple synoptic conditions in this experiment determine the robustness of defoliation-related warming to the ambient conditions. With three different synoptic conditions (i.e., 2017, 2018, 2020), any changes in heat metrics can be more closely associated with the land surface alteration from Hurricane Laura. Two control simulations and two experimental WRF model simulations are performed for Objective 4 to assess potential impacts of underlying synoptic conditions on changes in heat metrics following hurricane defoliation. Between Objectives 3 and 4, six model simulations are performed in total.
5. Results

5.1. NDVI Analysis

The NDVI satellite observations confirm sizeable defoliation concentrated along Hurricane Laura’s path. Monthly percent difference maps illustrate the landscape’s recovery up to one year after landfall. Figure 8 illustrates the changes in NDVI following Hurricane Laura from 2020 to 2021 compared to the previous 20-year and 21-year monthly averages, indicating a decrease in vegetation or defoliation in southwest Louisiana shown by the substantial reductions in NDVI. As expected, the month following landfall, September 2020, displayed the largest differences in NDVI (Figure 8a) along the southwest Louisiana coastline extending about 135 km eastward to Marsh Island. In October, foliage scarring was still prominent along Laura’s track (Figure 8b). September and October illustrate the difference in sustained winds during the storm’s landfall shown by a gradient of larger decreases to the east of landfall with darker blue hues due to the stronger wind field of the righthand quadrant of the hurricane.
The coastline exhibited a slower recovery than inland areas, and November NDVI percent difference compares closely to the October NDVI analysis barring the landscape’s recovery in southeast Louisiana (Figure 8c). As the winter season approaches, the defoliated surface was still recovering and apparent in December (Figure 8d). The pocket of scarring in southwest Louisiana was still prominent four months after landfall in December 2020 with Hurricane Laura defoliation extending approximately 140 km inland. The winter decline on vegetation began to show in February with larger decreases in foliage shown throughout Louisiana (Figure 8f), though the mark from Laura is still apparent in February. March showed the largest decreases in net NDVI as the consistent areas of defoliation seen in previous months continue to reflect enhanced decreases in NDVI. The spring season swept through the state, showing a net decrease in NDVI across the entire state; however, the defoliation was slightly apparent in southwest Louisiana though a pocket of landscape recovery was visible just 30 km inland (Figure 8h). The defoliated surface appeared to have recovered during the month of May with some areas associated along Laura’s track experiencing increases in NDVI for the first time in 8 months (Figure 8i). The summer months resembled a recovering landscape along the coastline; however blue hues are still visible nearly 100 km inland along Laura’s track (Figure 8j-k). A smaller extent of decreasing around Laura’s track suggested the foliage had recovered in most areas. One year following landfall, decreases in NDVI were subtly evident in southwest Louisiana (Figure 8l). Overall, decreases in NDVI along the coast, which experienced the largest storm impacts, appear to last ~1 year after landfall (Figure 8m). Similarly, hurricane defoliation was shown in September 2021 through large decreases in NDVI in southeast Louisiana associated with another major hurricane, Hurricane Ida (2021).
The sizeable difference in NDVI during the month of September highlights the spatial expanse of defoliated surface resulting from Laura’s strong winds and surge. The evidence of significant defoliation confirms the basis of studying Hurricane Laura as mechanism for altered surface heat fluxes which ultimately may have impacted heat metrics. The decreases in vegetation in southwest Louisiana reduce the landscape’s ability to produce evapotranspiration, which subsequently reduces the latent heat flux. Again, the basis of this study is focused on a feedback loop centered around defoliation (Figure 1). Because defoliation is indicated in Figure 8, this study can confidently proceed in assessing the impacts on heat metrics.


5.2.1. Model validation

Before trusting the WRF simulation to determine the presence of defoliation-related warming, the accuracy of the WRF simulation was assessed to establish its reliability as an analytical tool. The mean daily temperatures derived from the WRF control simulation were compared to observed mean daily temperatures from each station in Table 2. Table 3 shows the model performance at each available station for the baseline simulation. The daily temperature averages were used to calculate a linear regression to assess the model’s performance, with large R² values serving as evidence that WRF was reproducing the historical weather patterns accurately. The 2020 WRF simulations performed accurately with even the lowest R² values exceeding 0.8. The Vernon weather station had the highest accuracy between the WRF simulation and the station temperatures despite being the farthest inland station used. The lowest mean absolute error (MAE) in the WRF model simulations occurred at Vernon with a 0.858 C°
MAE between the observed and baseline temperatures. Of the four stations, the model performed most accurately at the two stations along the storm’s path, Lake Charles and Vernon, in terms of $R^2$ values. The model performed the least accurately at the Orange station - the only station on the western side of the storm’s path and contained missing data during the first two days of the month from Hurricane Laura. Additionally, Orange experienced the highest MAE in the baseline WRF simulation.

In terms of mean error between the WRF simulation and the observed station temperatures, all stations except Lake Arthur experienced the model simulation returning lower than expected temperatures. The model performed most accurately in terms of mean error for Lake Charles and Lake Arthur. When analyzing the MAE, the baseline simulation for Vernon had the smallest MAE, and the largest MAE occurred in the baseline model for Orange. Assessing the stations’ mean daily temperature data, the WRF model performed accurately given the $R^2$ values in Table 3, so WRF is a reliable analytical tool for assessing changes to the heat metrics following Hurricane Laura.

Table 3. Table showing mean error (observed – baseline), mean absolute error, and $R^2$ values for the WRF control simulation at each station

<table>
<thead>
<tr>
<th>Station</th>
<th>Mean Error (°C)</th>
<th>Mean Absolute Error (°C)</th>
<th>R-squared</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orange</td>
<td>0.516</td>
<td>1.216</td>
<td>0.814</td>
</tr>
<tr>
<td>Lake Charles</td>
<td>0.187</td>
<td>0.996</td>
<td>0.883</td>
</tr>
<tr>
<td>Lake Arthur</td>
<td>-0.075</td>
<td>0.908</td>
<td>0.857</td>
</tr>
<tr>
<td>Vernon</td>
<td>0.376</td>
<td>0.858</td>
<td>0.952</td>
</tr>
</tbody>
</table>
5.2.2. Changes in Air Temperature

Because Hurricane Laura’s Category-4 winds decimated most of the surface weather stations along the hurricane’s track, satellite data can be utilized to perform basic inferences on the effect of hurricane defoliation on heat metrics. MODIS-Aqua observations from the Monthly Daytime 3-min CMG LST product have indicated an increase in daytime LSTs following Hurricane Laura when compared to the previous 18-year monthly mean September LSTs (Figure 9). The cluster of red hues in Figure 9 located just north of Lake Charles mirrors the large cluster of decreases of LAI in Figure 7. Additionally, nighttime LST anomalies during the month following Laura’s landfall shows a more widespread increase in LSTs (Figure 10). While Figure 9 shows larger increases in temperature farther inland, Figure 10 displays the largest increases in LST occurring eastward of the landfall location along the coastline. The plumes of increasing nighttime temperatures are concentrated along the eastward side of Hurricane Laura’s track. The changes in heat metrics such as nighttime LSTs illustrate the hurricane track’s inland push up to the Lake Charles area with an increase in temperature greater than 1.4 °C. The increase in LSTs shown in Figures 9 and 10 may be indicative of increases in other heat metrics as well.
Figure 9. Difference between MODIS-Aqua September daytime 3-min CMG land-surface temperatures in 2020 and the monthly average from 2002–2019.

Figure 10. Difference between MODIS-Aqua September nighttime 3-min CMG land-surface temperatures in 2020 and the monthly average from 2002–2019.
Comparing the 2020 defoliated versus normal landscape WRF simulations, model output reveals that hurricane-induced defoliation increased the 2-m temperature along Hurricane Laura’s track (Figure 11a). The largest increases in temperature occurred at landfall associated with the strongest wind speeds, and therefore largest defoliation, with warming also located near the Texas-Louisiana border in southwest Louisiana. Table 4 lists spatially averaged temperature differences at various time intervals within southwest Louisiana denoted by the bounding box in Figure 11. The 2-m temperature experienced an overall average increase of 0.12 °C across the entire month of September. Splitting the data into diurnal phases, notable differences between the daytime and nighttime 2-m temperature changes emerged. During the day, temperature increases concentrated along the storm’s eastern path (Figure 11b), whereas nighttime temperature increases were exacerbated along the coastline near landfall (Figure 11c). Daytime temperature differences appeared slightly higher than nighttime differences aside from the landfall location along the coastline. In southwest Louisiana, daytime temperatures experienced an average increase of 0.13 °C while nighttime temperatures increased by 0.12 °C (Table 4). Farther inland, the defoliated temperature changes veer northeastward toward southwest Mississippi while nighttime temperature increases however hugged closer to the storm track northward. Overall, the average increases in daily average, daytime, and nighttime 2-m temperature were all statistically significant within a 95% confidence interval supporting an increase in 2-m temperature following hurricane defoliation.
Figure 11. Average difference between defoliated and baseline simulations in average 2-m temperature (a), average daytime 2-m temperature (b), and average nighttime 2-m temperature (c). The hurricane path is shown in black, and the dashed box represents the area in which statistical averages were calculated. The weather stations of Orange (purple star), Lake Charles (black star), Lake Arthur (yellow star), and Vernon (green star) were plotted as well.
Table 4. Average differences in 2-m air temperature between the defoliated and baseline simulation with the standard deviation at different time steps within the dashed box in Figure 11. * indicates the defoliated mean differs significantly from the control with 95% confidence.

<table>
<thead>
<tr>
<th>Time Interval (September 2020)</th>
<th>Average Temperature Difference (°C)</th>
<th>Defoliated – Baseline</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily Average</td>
<td>0.12*</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>Daytime</td>
<td>0.13*</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>Nighttime</td>
<td>0.12*</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td>1200 UTC</td>
<td>0.07*</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>1800 UTC</td>
<td>0.11*</td>
<td>0.23</td>
<td></td>
</tr>
<tr>
<td>0000 UTC</td>
<td>0.16*</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>0600 UTC</td>
<td>0.13*</td>
<td>0.13</td>
<td></td>
</tr>
</tbody>
</table>

Observing finer, 6-hour increments, the highest increase in 2-m temperature occurred at 0000 UTC or 7:00 PM CDT. At 0000 UTC, the largest increases were on the eastward side of the storm’s landfall with an average increase of 0.16 °C in southwest Louisiana (Figure 12a; Table 4). Additionally, no real impact on temperature was shown on the westward side of Laura’s path at 0000 UTC.

Even as diurnal cooling progressed, southwest Louisiana continued to experience increases in temperatures with an average increase of 0.13 °C at 0600 UTC (Figure 12b; Table 4). Larger increases in temperature emerge on the western side of the storm’s path between Orange and Lake Charles through the night. As the largest impacts remain along the coast, the area of the greatest 0000 UTC warming shrinks spatially. By 1200 UTC, the increases in temperature were much smaller than the other intervals presented (Figure 12a-c), yet nonetheless slightly warmer than the baseline simulation with an average increase of 0.07 °C. The 1200 UTC temperature patterns mirrored those at 0600 UTC but with smaller increases in 2-m temperature (Figure 12c). At mid-day 1800 UTC, with an average increase of 0.11 °C (Figure 12d), the highest increases occur east of Vernon and into southwest Mississippi farther inland than the
previous 6-hr increments. At each 6-hr increment, average increases in 2-m air temperature all proved statistically significant with 95% confidence. Even at finer temporal periods, the increases in temperature following Hurricane Laura are significant.

6-hr 2-m Air Temperature Differences

Figure 12. Difference in 2-m temperature between defoliated and baseline simulations at 0000 UTC (a), 0600 UTC (b), 1200 UTC (c), and 1800 UTC (d). Hurricane Laura’s path shown in black, and the statistical averages calculated within the dashed box. Weather stations of Orange (purple star), Lake Charles (black star), Lake Arthur (yellow star), and Vernon (green star) were plotted.
5.2.3. Changes in Humidity and Derived Heat Stress Metrics

As described in Section 3.2, human heat stress is a function of both temperature and humidity. While Section 5.2.2 establishes that southwest Louisiana experienced minor increases in 2-m air temperature, coincident changes to RH can either exacerbate or ameliorate the human health effect of the warming. RH was expected to decrease with increasing temperature and saturation vapor pressure, and Table 5 lists the average change in RH across multiple time intervals in southwest Louisiana represented by the bounding box shown in Figure 13. As expected, RH decreased in defoliated areas with an average decrease of 0.6% in Southwest Louisiana (Table 5; Figure 13a). Daytime and nighttime humidity difference maps highlighted differences; daytime RH showed decreases in areas which experienced increases in temperature during the daytime (Figure 13b). Daytime RH experienced an average decrease of 0.7% in southwest Louisiana (Table 5). Nighttime RH decreases were not as apparent as the daytime with an average decrease of 0.4% (Table 5; Figure 13c). The statistical averages calculated showing decreases in RH during the full day, daytime, and nighttime were all statistically significant with a 95% confidence interval. Contrary to the 2-m temperature output, the diurnal RH exhibited a strong decrease at landfall in both the nighttime and daytime. Overall, the RH decreases mirrored the temperature increases, creating an opportunity to investigate the influence of changes in temperature and RH on heat stress.
Table 5. Average differences in 2-m relative humidity between the defoliated and baseline simulation with standard deviation included at different time steps within the dashed box in Figure 13. * indicates the defoliated mean differs significantly from the control with 95% confidence.

<table>
<thead>
<tr>
<th>Time Interval (September 2020)</th>
<th>Average Relative Humidity Difference (%)</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily Average</td>
<td>–0.6*</td>
<td>0.99</td>
</tr>
<tr>
<td>Daytime</td>
<td>–0.7*</td>
<td>1.06</td>
</tr>
<tr>
<td>Nighttime</td>
<td>–0.4*</td>
<td>0.94</td>
</tr>
<tr>
<td>1200 UTC</td>
<td>–0.2</td>
<td>0.74</td>
</tr>
<tr>
<td>1800 UTC</td>
<td>–0.6*</td>
<td>0.80</td>
</tr>
<tr>
<td>0000 UTC</td>
<td>–1.0*</td>
<td>0.92</td>
</tr>
<tr>
<td>0600 UTC</td>
<td>–0.5*</td>
<td>1.02</td>
</tr>
</tbody>
</table>
Figure 13. Average difference between defoliated and baseline simulations in average 2-m relative humidity (a), average daytime 2-m relative humidity (b), and average nighttime 2-m relative humidity (c). Hurricane Laura’s path shown in black with the dashed box illustrating area of statistical averages shown in Table 5. Weather stations of Orange (purple star), Lake Charles (black star), Lake Arthur (yellow star), and Vernon (green star) plotted.
Six-hr 2-m RH interval maps show the largest decrease at 0000 UTC or 7:00 PM CDT. The 0000 UTC output highlighted the largest decreases east of the landfall location associated with the maximum landfall wind speeds (Figure 14a). Overall, southwest Louisiana experienced an average decrease of about 1% during September at 0000 UTC with a small gap north of Lake Charles exhibiting slight increases in 2-m RH. At 0600 UTC, southwest Louisiana experienced an average decrease in 2-m RH of 0.5% with the largest decrease at landfall (Table 5; Figure 14b). The morning hour of 1200 UTC showed the least change in 2-m RH among the other 6-hr intervals, with an average decrease of only 0.2% (Figure 14c). Although they are mostly small differences, most of the change represents decreasing 2-m RH primarily near the coastline. Output from 1800 UTC showed larger decreases in RH than 1200 UTC and 0600 UTC with an average decrease of 0.6% in southwest Louisiana (Table 5; Figure 14d). Toward the middle of the day at 1800 UTC, consistent decreases in RH appeared along the storm’s path. The largest decreases in 2-m RH occurred at 0000 UTC, but 1800 UTC showed noticeable differences farther inland as well. With the smallest amount of change in RH occurring at 1200 UTC not statistically significant, all other 6-hr increments experienced statistically significant change in RH following Hurricane Laura.
Overall, the heat index responded with larger increases than the 2-m temperature (Figure 15a), despite the reductions in RH. Table 6 compares the average differences in heat index from the region defined by the dashed lines in Figure 15. In total, southwest Louisiana experienced an average increase of 0.15°C (Table 6). The daytime heat index showed a larger spatial extent of
increasing values than the nighttime heat index with increases moving northeastward across central Louisiana into southwest Mississippi; however, nighttime heat index illustrated a higher magnitude of increases concentrated along the storm path (Figure 15b and 15c). Daytime heat indices in southwest Louisiana saw an average increase near 0.12 C° (Table 6). Meanwhile, nighttime experienced larger increases in heat index with a larger concentration in southwest Louisiana averaging an increase of 0.20 C° (Figure 15c; Table 6). The coast, which encountered the storm’s maximum storm surge, experienced much higher heat indices during the nighttime. All statistical average changes in heat index during the day, daytime, and nighttime were statistically significant with a 95% confidence interval. In Figure 15c, nighttime heat index experienced an average increase of 0.95 C° in Cameron, Louisiana. The large increases in heat index expanded all the way east to Vermilion Bay. Among the four stations, Lake Charles experienced the largest increase in heat index values during the nighttime with an average increase of 0.17 C°. After observing larger temporal periods, the changes in temperature outweighed the changes in RH in terms of heat index.
Figure 15. Average difference between defoliated and baseline simulations in average heat index (a), average daytime heat index (b), and average nighttime heat index (c). Hurricane Laura’s path shown in black with the dashed box illustrating area of statistical averages shown in Table 6. Weather stations of Orange (purple star), Lake Charles (black star), Lake Arthur (yellow star), and Vernon (green star) plotted.
Table 6. Average differences in heat index between the defoliated and baseline simulation with the standard deviation at different time steps within the dashed box in Figure 15. * indicates the defoliated mean differs significantly from the control with 95% confidence.

<table>
<thead>
<tr>
<th>Time Interval (September 2020)</th>
<th>Average Heat Index Difference (°C)</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily Average</td>
<td>0.15*</td>
<td>0.34</td>
</tr>
<tr>
<td>Daytime</td>
<td>0.12*</td>
<td>0.37</td>
</tr>
<tr>
<td>Nighttime</td>
<td>0.20*</td>
<td>0.31</td>
</tr>
<tr>
<td>1200 UTC</td>
<td>0.10</td>
<td>0.28</td>
</tr>
<tr>
<td>1800 UTC</td>
<td>0.07</td>
<td>0.35</td>
</tr>
<tr>
<td>0000 UTC</td>
<td>0.18*</td>
<td>0.39</td>
</tr>
<tr>
<td>0600 UTC</td>
<td>0.25*</td>
<td>0.34</td>
</tr>
</tbody>
</table>

Six-hr interval maps of the changes in heat index revealed the largest increase in mean heat index across southwest Louisiana occurred at 0600 UTC with an average increase near 0.25 °C (Table 6). However, the largest increase in heat index at a given point occurred at 0000 UTC along the coast and north near Lake Charles (Figure 16a). The 0000 UTC conditions showed large increases in heat index east of the storm path but decreases in heat index shown west of the storm path in southwest Louisiana likely due to wind speed differences (Figure 16a). The differences seen west of the storm track contributed to an average warming of just 0.18 °C in southwest Louisiana (Table 6). The 0600 UTC output showed more uniform increases of heat index in southwest Louisiana (Figure 16b) with the largest increases at the coastline and farther inland, just south of Vernon. At 1200 UTC, much smaller increases in heat index were resolved compared to 0600 UTC with an average increase of only 0.10 °C in southwest Louisiana (Figure 16c; Table 6). Near morning time at 1200 UTC, increases were concentrated primarily along the coast and near Lake Charles along the storm’s path. As the day progressed to 1800 UTC, heat index values experienced little to no change in southwest Louisiana with an average increase of 0.07 °C due to the increases shown south of Vernon (Figure 16d). At 1800 UTC, increases in heat index were mixed until moving farther inland where larger increases emerged between Lake
Charles and Vernon propagating northwest across Louisiana into Mississippi. Statistically, the change in the 6-hr increments of 1200 and 1800 UTC were not significant with 95% confidence interval meaning the largest implications of heat index occur during the nighttime and after mid-day.

### 6-hr Heat Index Differences

Figure 16. Difference in heat index between defoliated and baseline simulations at 0000 UTC (a), 0600 UTC (b), 1200 UTC (c), and 1800 UTC (d). Hurricane Laura’s path shown in black with the dashed box illustrating area of statistical averages shown in Table 6. Weather stations of Orange (purple star), Lake Charles (black star), Lake Arthur (yellow star), and Vernon (green star) plotted.
As described in Section 3.2, heat index is not a suitable measure of human heat stress once air temperature falls below 26.7°C (80°F), which can occur during the overnight hours. Thus, apparent temperature, which is better designed for sub-26.7°C temperatures, was analyzed during the month of September. Overall, the daily average change in apparent temperature was less than the daily average change in heat index with an increase of 0.10 C° (Table 7). The apparent temperature illustrated the largest increases along the coast near Laura’s landfall with the changes mirroring the same spatial pattern of increases shown from the other heat metric outputs (Figure 17a). Spatially, increases in apparent temperature were larger during the day while the largest concentration of warming occurred along the coastline at night (Figures 17b and 17c). Although nighttime apparent temperature change did not appear as prevalent as the nighttime heat index, substantial warming on the coastline was evident in both (Figures 15c and 17c). Statistically, the average apparent temperatures during the daytime experienced an increase of 0.10 C° while nighttime apparent temperatures had an average increase of 0.12 C° (Table 7). The daily, daytime, and nighttime average apparent temperature changes were all lower than heat index change, but the average change in apparent temperature was statistically significant at almost all time intervals, except 1800 UTC, with a 95% confidence interval. The apparent temperature likely experienced dampened increases due to tempered vapor pressure in Equation 2, whereas the reduced RH in Equation 1 had less of an impact on heat index.
Figure 17. Average difference between defoliated and baseline simulations in average apparent temperature (a), average daytime apparent temperature (b), and average nighttime apparent temperature (c). Hurricane Laura’s path shown in black with the dashed box illustrating area of statistical averages shown in Table 7. Weather stations of Orange (purple star), Lake Charles (black star), Lake Arthur (yellow star), and Vernon (green star) plotted.
Table 7. Average differences in apparent temperature between the defoliated and baseline simulation with the standard deviation at different time steps within the dashed box in Figure 17. * indicates the defoliated mean differs significantly from the control with 95% confidence.

<table>
<thead>
<tr>
<th>Time Interval (September 2020)</th>
<th>Average Apparent Temperature Difference (°C)</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily Average</td>
<td>0.10*</td>
<td>0.18</td>
</tr>
<tr>
<td>Daytime</td>
<td>0.10*</td>
<td>0.22</td>
</tr>
<tr>
<td>Nighttime</td>
<td>0.12*</td>
<td>0.14</td>
</tr>
<tr>
<td>1200 UTC</td>
<td>0.08*</td>
<td>0.12</td>
</tr>
<tr>
<td>1800 UTC</td>
<td>0.08</td>
<td>0.23</td>
</tr>
<tr>
<td>0000 UTC</td>
<td>0.12*</td>
<td>0.19</td>
</tr>
<tr>
<td>0600 UTC</td>
<td>0.13*</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Six-hr interval differences in apparent temperatures revealed similar spatial pattern to the 6-hr interval differences in heat index (Figures 16 and 18). Throughout the day, the magnitude of change differs between the heat index and apparent temperature. Spatially, changes in heat index and apparent temperature were most similar at 0000 UTC with large increases east of the storm path and decreases west of the path (Figures 16a and 18a). However, the largest statistical average increase occurred at 0600 UTC, with an increase of 0.13 °C in apparent temperature while the change in heat index also reached its maximum, at 0.25 °C (Tables 6 and 7; Figures 16b and 18b). In the morning, 1200 UTC output showed similar spatial trends between heat index and apparent temperature (Figures 16c and 18c) and similar mean differences with a change of 0.10 °C in heat index and 0.08 °C in apparent temperature (Tables 6 and 7). As solar radiation increased during the daytime, 1800 UTC output showed no change in apparent temperature but a slight decrease in the magnitude of change in heat index from 1200 UTC (Table 7). The differences in the change between heat stress metrics at 1800 UTC is shown from the differences in heat stress metric change near Lake Charles in Figures 16d and 18d. To summarize, increases in apparent temperature were smaller than the increases in heat index at all time intervals, except 1800 UTC, following Hurricane Laura.
Cameron, Louisiana, experienced the brunt of the hurricane force winds at landfall which represents an ideal location to observe the temporal range of heat metrics during the month of September (Figure 19). The increases in heat index appeared to be most persistent among the heat metrics. Overall, the heat index was an average 2.53°C warmer than 2-m temperature in the
defoliated model simulation. The heat metrics generally decline near September 18, mirroring the cooling in 2-m air temperature. Among the heat metrics, the baseline simulation heat index was surprisingly warmer than the defoliated simulation towards the end of the simulation which may be a result from the model drifting from the boundary conditions with time. The largest difference among heat metrics occurs around September 22–23 with the heat index increases nearing +3.0°C or +5.4°F (Figure 19). Over the entire month, at least 10 days exceeded +1.0°C in heat index change following Hurricane Laura. The largest average change in heat metrics occurs in the heat index with an average change of +0.66°C across the entire month of September while the apparent temperature experienced an average increase of +0.41°C. With numerous days experiencing substantial increases in heat indices throughout the month, potential heat mortality was possible throughout the entire month of September.

Figure 19. Time series of heat metrics at 3-hr intervals in the baseline simulation (dashed) and the defoliated simulation (straight lines) (top) and a time series of the change in heat metrics (bottom) in Cameron, Louisiana, during September 2020.
Because heat stress can be more fatal at different times of the day and its impacts are exacerbated from power outages, hourly averages calculated at each 3-hr interval in Cameron, Louisiana, can be used to assess timing of potentially fatal heat stress from Hurricane Laura. The average change in 2-m temperature and the average defoliated RH at each 3-hour interval explain the diurnal heat index evolution. Figure 20 highlights a 3-hr time period from 0000 UTC to 0300 UTC in which the maximum heat index change occurred. The maximum heat index occurred while the 2-m temperature change neared its maximum and defoliated RH values increased during the nighttime. Because RH peaks during the nighttime due to falling temperatures (and the associated lower saturation vapor pressure), heat index values were exacerbated due to the coupling of the largest change in 2-m temperature at night. Subsequently, the change in heat index neared its minimum from 1500 UTC to 1800 UTC due to decreases in 2-m temperature and the lowest average RH values (Figure 20). The largest magnitude of heat stress occurred during the hours of 0000 UTC to 0300 UTC in Cameron, Louisiana.
Figure 20. Hourly averages at each 3-hr interval for 2-m temperature difference, defoliated relative humidity, and heat index difference in Cameron, Louisiana.

Even though the control simulation was used to assess the model accuracy in Section 5.2.1, in some instances, the defoliated model simulation more closely matched than the control simulation, suggesting the storm did in fact cause heat metric changes. The two stations which experienced the largest amount of storm damage, Lake Charles and Lake Arthur, both show the defoliated simulations performing marginally more accurately than the baseline simulations in terms of $R^2$ values (Table 8). Lake Charles experienced the largest amount of defoliation from Hurricane Laura, and the WRF defoliated simulation outperformed the baseline simulation by about 0.02 in terms of $R^2$ values. Orange and Lake Charles also encountered lower mean errors
in the defoliated model simulations than the baseline simulations. The largest difference between the defoliated and baseline simulations at one station occurs in Lake Charles with the defoliated model outperforming the baseline model by about 0.093 °C.

Table 8. Average error, average absolute error, and R² values for the WRF control and defoliated simulations at each station.

<table>
<thead>
<tr>
<th>Station</th>
<th>Baseline Error (°C)</th>
<th>Defoliated Error (°C)</th>
<th>Baseline Error (°C)</th>
<th>Defoliated Error (°C)</th>
<th>Baseline R²</th>
<th>Defoliated R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orange</td>
<td>0.516</td>
<td>0.392</td>
<td>1.216</td>
<td>1.214</td>
<td>0.814</td>
<td>0.806</td>
</tr>
<tr>
<td>Lake Charles</td>
<td>0.187</td>
<td>0.083</td>
<td>0.996</td>
<td>0.903</td>
<td>0.883</td>
<td>0.904</td>
</tr>
<tr>
<td>Lake Arthur</td>
<td>-0.075</td>
<td>-0.200</td>
<td>0.908</td>
<td>0.914</td>
<td>0.857</td>
<td>0.862</td>
</tr>
<tr>
<td>Vernon</td>
<td>0.376</td>
<td>0.403</td>
<td>0.858</td>
<td>0.890</td>
<td>0.952</td>
<td>0.945</td>
</tr>
</tbody>
</table>

5.3. Sensitivity to Synoptic Atmospheric Patterns

Before leveraging the 2017 and 2018 control versus defoliated simulations to determine the robustness of the hurricane-warming signal, the accuracy of the WRF control runs was compared to the observed conditions at the same four stations in southwest Louisiana. Figure 21 illustrates the synoptic conditions during September 2020 with a geopotential height anomaly map at 500 hPa. The synoptic conditions following Hurricane Laura showed the highest geopotential height anomaly along the West Coast corresponding to an atmospheric ridge and lower heights near the Great Lakes correlating to an atmospheric trough (Figure 21). Overall, the majority of continental United States experienced positive geopotential height anomalies in September 2020. Synoptically, 2017 differs the most from 2020 with decreases in 500 hPa geopotential height anomalies in southeastern United States hinting at more dynamically active conditions (Figure 22). In 2018, synoptic conditions were similar to 2020 as the majority of
continental United States showed increases in 500 hPa height anomalies with the largest increase in anomalies located in northeastern United States (Figure 23). Different landfall years provided an opportunity to investigate heat metric responses to different synoptic conditions following a major hurricane.

Figure 21. Composite monthly mean plot of 500 hPa geopotential height during September 2020.
Figure 22. Composite monthly mean plot of 500 hPa geopotential height during September 2017.
Figure 23. Composite monthly mean plot of 500 hPa geopotential height during September 2018.

5.3.1. Model Validation

The 2017 WRF simulation performed much more accurately than the 2018 simulation according to R² values (Tables 9 and 10). The model performed most accurately at the Vernon station with the highest R² value among the stations. Similar to 2020 and 2018, the model simulation performed the least accurate at Orange; also, Orange contained three days of missing
data in 2017 likely from Hurricane Harvey. The 2017 model error shows the model simulation appeared more accurate than the other landfall years aside from the Lake Charles weather station. Orange had the lowest mean error among the stations as the baseline simulation was 0.024°C cooler than the station average. Surprisingly, Lake Charles model output contained the highest mean error and MAE among the stations. Nonetheless, the 2017 baseline simulation performed with satisfactory accuracy to examine the background synoptic influences on post-hurricane heat metrics.

Table 9. Table showing average error, average absolute error, and R² values for the 2017 WRF control simulation at each station.

<table>
<thead>
<tr>
<th>Station</th>
<th>Average Error (°C)</th>
<th>Average Absolute Error (°C)</th>
<th>R-squared</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orange</td>
<td>0.024</td>
<td>0.743</td>
<td>0.781</td>
</tr>
<tr>
<td>Lake Charles</td>
<td>1.209</td>
<td>1.266</td>
<td>0.874</td>
</tr>
<tr>
<td>Lake Arthur</td>
<td>–0.508</td>
<td>0.648</td>
<td>0.869</td>
</tr>
<tr>
<td>Vernon</td>
<td>0.647</td>
<td>0.781</td>
<td>0.920</td>
</tr>
</tbody>
</table>

The 2018 control simulation performed the least accurately among the three study years (Table 10). Among the four stations, the WRF simulation performed the most accurate in Lake Charles according to R² values though not as high as the 2020 simulations. Orange and Lake Arthur both showed the WRF simulation overestimating the station temperatures with warmer temperatures denoted by negative mean error values, and Lake Arthur experienced the highest MAE among the other stations. The 2018 landfall year produced MAE values all greater than one degree Celsius. The large errors are cause for pause, but since the analysis ultimately compares the defoliated to the control simulation and not the observations, the 2018 output will cautiously be included in the analysis.
Table 10. Table showing average error, average absolute error, and $R^2$ values for the 2018 WRF control simulation at each station

<table>
<thead>
<tr>
<th>Station</th>
<th>Average Error (°C)</th>
<th>Average Absolute Error (°C)</th>
<th>$R^2$-squared</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orange</td>
<td>-0.357</td>
<td>1.077</td>
<td>0.421</td>
</tr>
<tr>
<td>Lake Charles</td>
<td>0.876</td>
<td>1.043</td>
<td>0.729</td>
</tr>
<tr>
<td>Lake Arthur</td>
<td>-1.119</td>
<td>1.277</td>
<td>0.511</td>
</tr>
<tr>
<td>Vernon</td>
<td>0.545</td>
<td>1.007</td>
<td>0.676</td>
</tr>
</tbody>
</table>

5.3.2. Heat Metric Response Under Different Synoptic Conditions

Model simulation output from 2017 and 2018 synoptic were compared to the 2020 model simulation to determine the impact of differing synoptic conditions on the post-hurricane heat metrics. Table 11 lists changes in average 2-m temperature within the bounding box in Figure 24 between a defoliated surface and normal vegetative surface. The 2020 model simulation displayed the largest differences at each time interval compared to the other years with varying synoptic conditions (Table 11). For each landfall year, 0000 UTC showed the largest increase in 2-m temperature despite different synoptic set-ups. For both 2017 and 2018, nighttime 2-m temperature increases were larger than daytime despite the 2020 model simulations showing consistent increases during day and night. Figure 24 shows spatial increases in 2-m temperature regardless of landfall year.
Table 11. Average 2-m temperature difference at different time intervals for each simulated landfall year within the bounding box in Figure 24. * indicates the defoliated mean differs significantly from the control with 95% confidence.

<table>
<thead>
<tr>
<th>Time Interval</th>
<th>2017</th>
<th>2018</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily Average</td>
<td>0.08*</td>
<td>0.06*</td>
<td>0.12*</td>
</tr>
<tr>
<td>Daytime</td>
<td>0.05*</td>
<td>0.06</td>
<td>0.13*</td>
</tr>
<tr>
<td>Nighttime</td>
<td>0.10*</td>
<td>0.07*</td>
<td>0.12*</td>
</tr>
<tr>
<td>1200 UTC</td>
<td>0.07*</td>
<td>0.01</td>
<td>0.07*</td>
</tr>
<tr>
<td>1800 UTC</td>
<td>0.05*</td>
<td>0.00</td>
<td>0.11*</td>
</tr>
<tr>
<td>0000 UTC</td>
<td>0.14*</td>
<td>0.07</td>
<td>0.16*</td>
</tr>
<tr>
<td>0600 UTC</td>
<td>0.09*</td>
<td>0.06</td>
<td>0.13*</td>
</tr>
</tbody>
</table>
Figure 24. Average difference between defoliated and baseline simulations in average 2-m temperature in 2020 (a), 2017 (b), and 2018 (c). The hurricane path is shown in black, and the dashed box represents the area in which statistical averages were calculated. The weather stations of Orange (purple star), Lake Charles (black star), Lake Arthur (yellow star), and Vernon (green star) were plotted.

Changes in 2-m RH also have major implications on the heat index equation, they are examined each year as well. Table 12 compares the average changes in 2-m RH over southwest Louisiana (i.e., bounding box from Figure 25), incorporating the different landfall years’
synoptic conditions. Differing synoptic conditions all produced reductions in average 2-m RH in each different time interval listed in Table 12. Each landfall year showed larger average decreases during the daytime than the nighttime regardless of synoptic conditions. The largest decreases in 2-m RH occurred at 0000 UTC for each landfall year similar to 2-m temperature changes (Table 12). Figure 25 shows similar spatial patterns for each landfall year. The decreases in 2-m RH in Figure 25 correspond to the increases in 2-m temperature in Figures 24. Average 2-m RH in southwest Louisiana experienced decreases in each model simulation year.

Table 12. Average 2-m relative humidity difference at different time intervals for each simulated landfall year within the bounding box in Figure 25. * indicates the defoliated mean differs significantly from the control with 95% confidence.

<table>
<thead>
<tr>
<th>Time Interval</th>
<th>2017</th>
<th>2018</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily Average</td>
<td>–0.40*</td>
<td>–0.33*</td>
<td>–0.60*</td>
</tr>
<tr>
<td>Daytime</td>
<td>–0.50*</td>
<td>–0.50*</td>
<td>–0.70*</td>
</tr>
<tr>
<td>Nighttime</td>
<td>–0.27*</td>
<td>–0.17</td>
<td>–0.40*</td>
</tr>
<tr>
<td>1200 UTC</td>
<td>–0.07</td>
<td>–0.06</td>
<td>–0.18</td>
</tr>
<tr>
<td>1800 UTC</td>
<td>–0.49*</td>
<td>–0.20</td>
<td>–0.60*</td>
</tr>
<tr>
<td>0000 UTC</td>
<td>–1.02*</td>
<td>–0.62</td>
<td>–1.00*</td>
</tr>
<tr>
<td>0600 UTC</td>
<td>–0.28*</td>
<td>–0.06</td>
<td>–0.50*</td>
</tr>
</tbody>
</table>
Figure 25. Average difference between defoliated and baseline simulations in average 2-m relative humidity in 2020 (a), 2017 (b), and 2018 (c). The hurricane path is shown in black, and the dashed box represents the area in which statistical averages were calculated. The weather stations of Orange (purple star), Lake Charles (black star), Lake Arthur (yellow star), and Vernon (green star) were plotted.
Combining the changes to 2-m air temperature and RH, Table 13 highlights the average changes in heat index across southwest Louisiana, producing similar results for each landfall year. The alternative synoptic conditions produced lower averages than the 2020 model simulations; however, all model simulations follow a similar pattern. Average increases in heat index occurred during the nighttime in all model simulations (Table 13). In 6-hr increments, the model simulations experienced the largest increases at 0600 UTC even with different synoptic conditions, and the heat index increases across the entire domain showed similar spatial patterns. Figure 26 highlighted the largest change in heat index occurring along the coast east of the landfall location in all simulation years. The 2017 simulation resembles 2020 but with a more concentrated spatial area of increases that do not extend as far north as the 2020 model simulation (Figure 26a-b). Though 2018 experienced a decrease in heat index near Lake Charles, the 2018 model simulation experienced larger increases north of Lake Charles than the 2020 landfall year (Figure 26a, 26c). Although the three landfall years simulated with three different synoptic conditions showed slight differences, the model simulations agree that heat index increased following hurricane defoliation.

Table 13. Average heat index difference at different time intervals for each simulated landfall year within the bounding box in Figure 26. * indicates the defoliated mean differs significantly from the control with 95% confidence.

<table>
<thead>
<tr>
<th>Time Interval</th>
<th>2017</th>
<th>2018</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily Average</td>
<td>0.07*</td>
<td>0.10*</td>
<td>0.15*</td>
</tr>
<tr>
<td>Daytime</td>
<td>0.02*</td>
<td>0.06</td>
<td>0.12*</td>
</tr>
<tr>
<td>Nighttime</td>
<td>0.15*</td>
<td>0.18*</td>
<td>0.20*</td>
</tr>
<tr>
<td>1200 UTC</td>
<td>0.06</td>
<td>0.02</td>
<td>0.10</td>
</tr>
<tr>
<td>1800 UTC</td>
<td>0.01</td>
<td>−0.04</td>
<td>0.07</td>
</tr>
<tr>
<td>0000 UTC</td>
<td>0.17*</td>
<td>0.12</td>
<td>0.18*</td>
</tr>
<tr>
<td>0600 UTC</td>
<td>0.16*</td>
<td>0.16</td>
<td>0.25*</td>
</tr>
</tbody>
</table>
Figure 26. Average difference between defoliated and baseline simulations in average heat index in 2020 (a), 2017 (b), and 2018 (c). The hurricane path is shown in black, and the dashed box represents the area in which statistical averages were calculated. The weather stations of Orange (purple star), Lake Charles (black star), Lake Arthur (yellow star), and Vernon (green star) were plotted.
Lastly, the synoptic conditions’ influence on the apparent temperature following a major hurricane is examined, which demonstrated the smallest change in heat stress metrics among all landfall years. Average change in apparent temperature, taken from the bounding box shown in Figure 27, showed 2020 experienced the largest increase compared to the other years (Table 14). All landfall years shared the largest increase in apparent temperature at 0600 UTC with higher nighttime changes than daytime (Table 14). Even with different synoptic conditions, 2017 and 2018 model simulations showed similarities to the 2020 model simulation in terms of temporal averages. The overall magnitude of the change in apparent temperature among the different landfall years resembles Figure 27. Altering the synoptic conditions still produced similar results in apparent temperature in the post-Laura simulation.

Table 14. Average apparent temperature difference at different time intervals for each simulated landfall year within the bounding box in Figure 27. * indicates the defoliated mean differs significantly from the control with 95% confidence.

<table>
<thead>
<tr>
<th>Time Interval</th>
<th>2017</th>
<th>2018</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily Average</td>
<td>0.07*</td>
<td>0.05*</td>
<td>0.10*</td>
</tr>
<tr>
<td>Daytime</td>
<td>0.02*</td>
<td>0.03</td>
<td>0.10*</td>
</tr>
<tr>
<td>Nighttime</td>
<td>0.10*</td>
<td>0.08*</td>
<td>0.12*</td>
</tr>
<tr>
<td>1200 UTC</td>
<td>0.09*</td>
<td>0.02</td>
<td>0.08*</td>
</tr>
<tr>
<td>1800 UTC</td>
<td>0.02*</td>
<td>−0.02</td>
<td>0.08</td>
</tr>
<tr>
<td>0000 UTC</td>
<td>0.09*</td>
<td>0.05</td>
<td>0.12*</td>
</tr>
<tr>
<td>0600 UTC</td>
<td>0.10*</td>
<td>0.08</td>
<td>0.13*</td>
</tr>
</tbody>
</table>
Figure 27. Average difference between defoliated and baseline simulations in average apparent temperature in 2020 (a), 2017 (b), and 2018 (c). The hurricane path is shown in black, and the dashed box represents the area in which statistical averages were calculated. The weather stations of Orange (purple star), Lake Charles (black star), Lake Arthur (yellow star), and Vernon (green star) were plotted.
As with 2020, a time series of heat metric evolution at Cameron, Louisiana, was generated to compare the robustness in apparent temperature change in each year (Figure 28). According to Figure 28, differing synoptic conditions like 2018 can produce higher magnitude change in heat metrics such as apparent temperature. Although the 2020 post-Laura simulation experienced a larger average increase, the 2018 landfall year experienced larger magnitude differences due to different synoptic conditions that may not be as representative of a post-hurricane environment. Among the landfall years, the average change in apparent temperature only stayed positive throughout the entire simulation in 2017. The synoptic conditions of 2020 and 2017 produced similar impacts on changes in heat metrics. While different synoptic conditions for each model simulation reproduced overall increases in heat metrics, the magnitude of change among simulation years varied.

Figure 28. Time series of average apparent temperature change at 3-hr intervals during September for 2020, 2018, and 2017 simulations at Cameron, Louisiana.
6. Discussion

6.1. Implications of Spatial and Temporal Defoliation

The decreases in NDVI percent difference (Figure 8a) closely replicated the 2020 heat metric changes, specifically during the nighttime (Figures 8 and 15c). The similarity between the NDVI September differences and the average September heat metric differences supports the idea of a hurricane defoliation-heat relationship. Average differences in 2017 heat metrics also resemble Figure 8a in southwest Louisiana with large differences along the coast and widespread changes over the whole southwest. Additionally, Figure 8a showed a slight semblance of red over Lake Charles just south of the Lake Charles station possibly contributing error as satellite NDVI measurements can sometimes struggle over water (Ke et al. 2015). Erroneous increases in NDVI over the lake may introduce error into the model simulation by giving WRF the false impression that vegetation thickened as a result of Laura. Because Figure 8a represents the largest NDVI decreases, this month should experience the most significant warming from the effects of the defoliated surface compared to other months. The average heat metric difference maps from all three simulation years resolve the largest differences occurring at the landfall site and correspond to the large amounts of defoliation along the coastline (Figure 8a). Additionally, the western portion of the domain in Texas shows increases in NDVI during September potentially explaining the reductions in heat metrics shown in Texas near the western boundary the model domain.

Temporal coverage of Hurricane Laura’s defoliation showed lasting impacts with some areas not seeing increases in NDVI for the entire year following landfall. Slow foliage recovery supports prolonged changes in surface heat fluxes in turn impacting heat metrics months after
landfall. Plant recovery from defoliation can be highly variable depending on many factors such as gas components (Ferraro and Oesterheld 2002). October through February NDVI highlighted Hurricane Laura’s structure with the strongest sustained wind speeds to the east of landfall associated with the front-right quadrant yielding the largest decrease in NDVI percent difference. Additionally, the winter season may delay the landscape recovery due to the decrease in solar radiation and low number of growing-degree days (GDD), suggested in Figure 8g. Subsequently, the winter season masks the scaring due to the landscape beginning to drop leaves. Future research may examine Atlantic hurricane defoliation as most of the U.S. East Coast experiences colder temperatures, which may delay landscape recovery longer than southwest Louisiana.

The biogeography of southwest Louisiana offers clarity on the magnitude of change in heat stress metrics. A Chenier-Plain is located in southwest Louisiana, leading to slight differences in soil type and elevation likely impacting the change in heat metrics. Instances of finer grain soil in southwestern Louisiana limit soil moisture and prevent tree growth (Fearn 1995). Subsequently, hurricane defoliation was less pronounced in areas with lower vegetation cover. Higher elevated surfaces produce different vegetation types than lower elevated surface (Jin et al. 2008). Hurricane defoliation and changes in heat stress metrics was more dramatic in areas with larger vegetation cover, so differences in elevation in southwest Louisiana tempered the overall magnitude of change in heat stress metrics. Additionally, the southwest Louisiana coast consists of marshes which experience recovery times close to one year following hurricanes compared to longer recovery times for forested areas (Chabreck and Palmisano 1973). The primarily wetland-dominated coast of southwest Louisiana consists of high daytime latent heat fluxes which could mitigate the increases in heat metrics (Pokorný et al. 2010). Figure 29 shows the overall land cover of Louisiana highlighting the coastline consisting of lakes and
marshes. Additionally, Figure 29 shows an area with potentially slower landscape recovery north of Lake Charles near the Texas border in a denser forested region which resembles the longer temporal decreases in the monthly NDVI maps (Figure 8). The horizontal distribution of lakes in southwestern Louisiana explains the more marginal defoliation spanning from Orange eastward to Lake Arthur represented in Figure 8b.

**Landsat Imagery of Southern Louisiana**

![Landsat Imagery of Southern Louisiana](image)

*Figure 29. Landsat imagery of southern Louisiana denoting Hurricane Laura’s landfall by a yellow star.*

Meteorologically, surface heat fluxes can drive and alter surface weather in weakly sheared environments due to potential influences on lapse rates (Barr et al. 2012). These weakly sheared environments dominate Louisiana during the summertime, so defoliated surfaces in southwest Louisiana shown in Figures 8j and 8k may promote lingering hydrometeorological effects over the defoliated surfaces (Nelson 2021, Miller et al. 2020).
6.2. Implications of Altered Heat Metrics in a Post-hurricane Environment

Altered surface energy fluxes lead to 2-m temperature increases in southwest Louisiana in September 2020. Elevated temperatures are not uncommon following land cover disturbances (Amiro et al. 1999). However, the spatial impact on 2-m temperatures from Hurricane Laura covers a larger area due to the 5.2-m storm surge and shoreline migration of nearly 40 m (Jafari et al. 2020). The average temperature increase of 0.12°C may seem underwhelming compared to previous studies, but land cover in southwest Louisiana is unique. For instance, a marshy coastline coupled with small lakes inland will support a stronger latent heat flux mitigating the increases in sensible heat and surface temperature, so the full warming potential from hurricane defoliation may not be realized in this landscape. A similar study investigating Hurricane Michael in Florida saw an average increase near 0.7°C, but Hurricane Michael was a stronger storm and made landfall on the panhandle of Florida (Nelson 2021). A Laura-type storm making landfall in Florida should see higher increases in temperatures due to the coastal structure between interior southwest Louisiana and interior Florida; coastal Louisiana contains further protrusion of wetlands inland which likely mitigate heat metric changes compared to a defoliated forested surface. Forested areas may never recover quite the same as before, prolonging any changes in heat metrics (Tanner et al. 1991). Interior Florida contains denser forested areas with longer recovery times and likely more persistent changes in heat metrics. Additionally, differing algorithms to represent defoliation in a numerical weather simulation will yield different results. Miller et al. (2020) quantified the extent of LAI recovery after Hurricane Maria (2017) from an analysis focusing on one month before landfall versus five months following landfall to compile the model’s input files. Consequently, the case study in Georgia saw an average increase in 2-m
temperature near 0.5 C° in a region dominated by forested areas (Miller et al. 2020). The difference in temperature change in this study may stem from the NDVI’s capabilities on vegetation density performance (Ke et al. 2015).

The average decrease in RH following hurricane Laura is likely a result from the increase in temperatures because an increase in temperature leads to increase in saturation vapor pressure which decreases RH (Lugo 2008). During the nighttime, the RH is usually highest due to the cooler temperatures being closer to the dewpoint temperature. Theoretically, an increase in nighttime temperatures should also lead to a decrease in RH during the nighttime. In this study, the largest decrease in RH occurred during the daytime when RH values are typically near their lowest. Because the daytime and nighttime temperature change was similar, an increase in temperature during the day may have a larger impact on RH opposed to increases in nighttime temperatures with latent heat flux lower during the nighttime.

The Rothfusz regression equation (Equation 1) defines heat index as a function of temperature and RH. Because the 2-m temperature increased and 2-m RH decreased following hurricane Laura, these changes provide offsetting influences within the Rothfusz equation, and temper any heat index increases. Southwest Louisiana experienced an average increase of 0.15°C in heat index. The largest decrease in RH occurred during the daytime, and subsequently, the largest increase in heat index occurred during the nighttime. The nighttime and daytime average temperature changes differed by about 0.01 C°, which suggests the difference between the nighttime and daytime heat index increase is driven by the change in RH. For instance, even though 0000 UTC saw the largest temperature increase, it also experienced the largest RH decrease, and consequently did not experience the largest change in heat index among the 6-hr intervals. In contrast, 0600 UTC heat index experienced the largest increase most likely due to
substantial warming that coincided with a smaller change in RH during a time of day when RH
typically is at its highest as well. Although RH decreased, heat index values still showed
increases with the highest increases occurring in areas experiencing lower changes in RH.

According to the Weather Prediction Center, the heat index equation above is not
sufficient when heat index values are below 26.7°C (80°F), so apparent temperature was
examined in this study to add another metric for comparison and to better represent conditions
not valid for the Rothfusz regression equation. The apparent temperature is a function of
temperature and vapor pressure representing a heat metric independent of RH to study. The
vapor pressure is a function of dewpoint temperature and will increase with dewpoint
temperature according to the Clausius-Clapeyron equation. The decrease in RH following
hurricane defoliation likely corresponds to decreases in dewpoint temperature in turn mitigating
apparent temperatures. The average increase in apparent temperature was smaller than the
average increase in heat index most likely due to the inclusion of vapor pressure into the heat
metric. Additionally, the apparent temperature and heat index experienced their largest average
increase at 0600 UTC while the largest increase in 2-m temperature experienced occurred at
0000 UTC.

6.3. Implications of Synoptic Influences

The three study years modeled with different boundary conditions determine the impact
of differing synoptic conditions. All three years experienced increases in average heat metrics
across an entire month suggesting the strong likelihood for enhanced heat metrics following
severe and widespread defoliating events, independent of synoptic conditions. Synoptic
conditions most favorable for heat events include warm air mass advection and upper-level ridges (Pezza et al. 2012). The 2020 and 2017 heat metric output showed a continuous warming along the storm track as opposed to the 2018 output containing a break in increasing temperatures near Lake Charles best illustrated in Figure 26c. Synoptic conditions resembling a 2017 landfall support enhanced heat stress following a major hurricane though the change may not be as spatially impressive as seen in 2020. The 2018 synoptic conditions mitigated the increases in heat metrics but nonetheless permitted heat stress enhancement in a post-hurricane environment.

Although different synoptic conditions were found to modulate the magnitude of defoliation related warming, increases in heat metrics occurred in all three scenarios. Regardless of the fluctuating differences in heat metric changes caused from differing synoptic conditions, the average nighttime 2-m temperature, daytime RH, nighttime heat index, and nighttime apparent temperature all responded with statistically significant differences between the defoliated and control simulations. Synoptic conditions appeared to have the largest impact on the change in heat metrics at smaller hourly intervals compared to longer temporal periods. Spatially, synoptic conditions appeared to impact the spatial area of warming in southwest Louisiana with favorable synoptic conditions increasing the areal magnitude while less supportive synoptic conditions concentrated the warming more closely to the defoliated input parameters (Figure 7). Following a major hurricane, synoptic conditions tended to modulate the spatial extent and magnitude of change in heat metrics; nonetheless, increases in heat metrics were apparent regardless of synoptic conditions.
6.4. Implications on Heat stress

A larger increase in heat metrics than 2-m temperature indicate human heat stress is exacerbated in areas experiencing higher post-hurricane air temperatures. Though this study does not examine the first week following Laura’s landfall, Figure 19 heat index values exceed 35 °C, a common value for heat fatalities (Arbury et al. 2014), and likely much higher the week before this analysis began with a peak heat index value of 40.9 °C during the defoliated model simulation. Studies have shown that persistent minimum temperatures prove to be the most fatal (Laaidia et al. 2012; Ragettli et al. 2017); In Cameron, Figure 19 shows persistent minimum heat metrics persisting for the first 18 days of September, where the average defoliated nighttime 2-m temperature equated to 25.0 °C across the entire month following landfall, and the average nighttime heat index was 27.0 °C. Additionally, average defoliated minimum apparent temperature persisted the highest among heat metrics at 27.7 °C. In comparison, the average September minimum temperature in Cameron is usually 22.4 °C nearly three degrees Celsius less than the defoliated model simulation.

Based off the 2020 model simulations, heat fatalities would most likely be the most probable before 18 September 2020 due to the prominent minimum heat metrics shown in Figure 19. Additionally, power outages plague post-hurricane environments at the landfall locations for months, meaning that even as heat metrics decline after the first 18 days (though they still remain larger in the defoliated scenario), heat will still pose a health hazard to the remaining population without a means to cool off. Including different synoptic conditions, Figure 28 indicates the largest change in apparent temperature occurred after the first half of the month having potential impacts on travelling relief workers that may be unprepared for the extreme heat conditions (Varghese et al. 2019). Additionally, multiple heat spikes occurring during the same month may
have a devastating mental impact on survivors (Hansen et al. 2008). In the long term, the structures which have survived the extreme conditions are also susceptible to structural damage from mold growth due to the excessive heat (Gigli et al. 2005). Heat conditions following a major hurricane will be exacerbated through power outages and ill-prepared emergency managers (Executive Office of the President 2006).

This study confirmed the emergence of heat stress following Hurricane Laura but struggled to distinguish the areas in which heat fatalities occurred following Hurricane Laura. Referencing Figure 4, heat fatalities from Hurricane Laura all occurred at least 70 km inland with the furthest heat death occurring nearly 290 km inland. Surprisingly, Louisiana Department of Health (2021) did not report any heat fatalities near the landfall location where the largest increases in heat stress metrics occurred in this study. Heat fatalities occurring within the four southernmost parishes in Figure 4 can be explained from the spatial extent of increases (Figure 15), but the heat fatality in the northernmost parish, Jackson, was not supported from changes in heat metrics found in this study. However, hurricane preparedness could explain the inland location of the heat fatalities due to the lack of awareness of the underlying heat stress following hurricanes. Post-hurricane heat mortality could be mitigated with increased awareness of post-hurricane heat stress especially in areas which do not experience severe structural damage or long-lasting power outages similar to coastal communities.

The timing of the maximum increases in heat stress metrics indicate increased risk of heat mortality in post-hurricane environments. As mentioned earlier, heat mortality is most sensitive to changes in minimum or nighttime temperatures (Laaidia et al. 2012), and this study found that all heat stress metrics experienced the greatest change during the nighttime. More specifically, the largest change in heat stress metrics occurred from 0000 UTC to 0600 UTC meaning the
highest probability of heat mortality will occur from 0000 UTC to 0600 UTC in post-hurricane environments. More specifically, Cameron, Louisiana, recorded the largest change in heat index at 0300 UTC representing the highest potential for heat mortality at the landfall location. In conclusion, this study found the most probable timing for heat mortality to occur during the nighttime hours.

6.5. Limitations

Although all heat metrics saw an average increase across the entire month following the landfall of Hurricane Laura, the WRF analysis dealt with potential limitations. Overall, the defoliated model simulation likely underestimated temperature increases due to the satellite NDVI measurements. The LAI and GVF input variables are not the same as NDVI which may have led to an under-performing model. Coastal Louisiana is dominated by wetlands, and because NDVI measurements struggle over water (Ke et al. 2015), erroneous increases in NDVI could have mitigated changes in heat metrics near the coast.

In Section 5.3.2, NAM boundary conditions were limited to years after 2011 to analyze underlying effects of synoptic conditions. While 2020 and 2017 both experienced late-August hurricanes moving near southwest Louisiana, 2018 did not. Hurricane Laura made landfall on 27 August 2020, and Hurricane Harvey made landfall on 25 August 2017 meaning the boundary conditions for those model simulations are perhaps more consistent with a post-hurricane environment. However, Hurricane Michael made landfall in October 2018, so the 2018 synoptic conditions were likely less representative of a post-hurricane environment. The opportunity to use another landfall year with a similar temporal period representative of a major post-hurricane
synoptic environment such as 2005 with Hurricane Katrina could have further asserted the trends seen between the 2020 and 2017 synoptic conditions.
7. Conclusions

This study is the first to examine changes in human heat stress in a post-hurricane environment. While several studies have shown that hurricane defoliation generates heat anomalies along its path (Miller et al. 2020, Nelson 2021), the severity of positive anomalies (i.e., warming) is dependent on the extent of defoliation, land cover type, and synoptic conditions. This study illustrated the overall magnitude of Hurricane Laura defoliation reaching 135 km along the coast with landscape recovery lasting over one year in certain areas. In this study, all heat metrics observed experienced average increases across the entire month of September independent of landfall year. Synoptic conditions modulate the spatial extent and magnitude of heat metric changes following a major hurricane. Increases in air temperature outweigh the decreases in RH in terms of exacerbating heat metrics, particularly at night. The most susceptible time to experience elevated heat stress metrics in a post-hurricane environment occurred during the night from 0000 UTC to 0600 UTC. The wetland dominated southwest coast of Louisiana may not show the greatest potential in warming, but coastal Louisiana still experienced an average warming of 0.95 ºC in nighttime heat index in Cameron, Louisiana, following a major hurricane.

In general, this study verifies that elevated heat metrics following tropical cyclones have potentially dangerous effects on heat stress in already-decimated areas, especially because hurricane season coincides with the warmest time of the year most prone to heat waves (Zittis et al. 2016). With proper awareness of the underlying impacts of changes in heat metrics following a major hurricane, heat stress preparedness could reduce heat mortality in areas farther inland, such as in the areas where the bulk of Hurricane Laura heat-related deaths occurred. Rapid restoration of power supply following a hurricane offers the best combatant to extreme heat
events following a major hurricane; however, the scale of destruction can delay power restoration for weeks or even months following the storm. For example, Hurricane Laura was estimated to have knocked out power for nearly 600,000 people (Pasch et al. 2021), prompting the necessity to explore heat stress mitigation techniques.

Future work is needed to examine the magnitude of defoliated warming in different environments to identify the locations most prone to increased heat metrics following a major hurricane. Additionally, policy makers should enhance efforts to account for deadly heat conditions in relief efforts; one potential adjustment could be the emergence of ‘heat stress’ tents designed to mitigate the impacts of heat metrics on susceptible inhabitants. Operational forecasters may also need to loosen heat advisory thresholds following a major hurricane to account for power outages and relief workers exposed to enhanced heat stress metrics. With hurricane intensity projected to increase with climate change, post-hurricane heat stress will be more severe in the near future. The findings from this study are intended to promote awareness and further investigation into changes in heat metrics following a major hurricane and potential for heat mortality in post-hurricane environments.
8. References


Cade Reesman, born in Lawrenceville, Georgia, graduated from Mill Creek High School, Hoschton, Georgia in 2016. Following high school, Cade attended Mississippi State University to pursue his interests in meteorology. During his time at Mississippi State, Cade volunteered at the National Weather Service Forecasting Office in Jackson, Mississippi. In 2020, Cade graduated Magna Cum Laude with a major in Geosciences, a concentration in Professional Meteorology, and a minor in Geospatial and Remote Sensing. Promptly following graduation, he decided to enter the Department of Oceanography and Coastal Sciences at Louisiana State University to pursue his interest in coastal meteorology while working as a Graduate Research Assistant in The Coastal Meteorology Lab under Dr. Paul Miller. Cade plans to receive his Master of Science degree in August 2022 and will look to enter the workforce to serve the general public and industry in operational meteorology.