Floridian Heatwaves in a Warming World: Frequency, Intensity, Duration, and Connections to Extreme Precipitation Events

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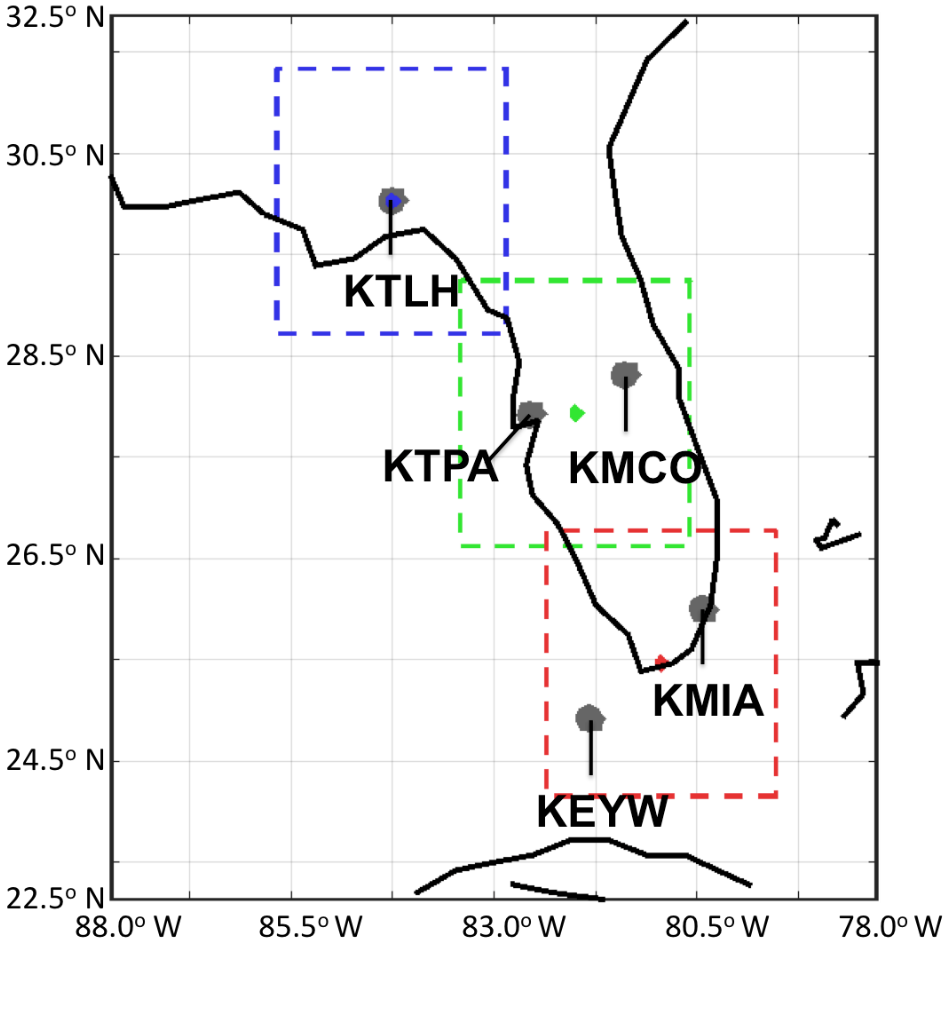

1. Abstract

There exists broad scientific consensus that heatwaves are increasing in frequency, duration, and intensity in a warming world, and are generally the most strongly linked extreme weather event to anthropogenic climate change. Due to its predominantly maritime climate, few studies have examined heatwaves in Florida. However, Florida's older-skewed population and increasingly urbanized land areas make it particularly susceptible to heat impacts on human life and health in the 21st century. For the first time, this study established an objective metric, climatology, and trend analysis for heatwaves in seven major cities (Tallahassee, Jacksonville, Daytona Beach, Orlando, Tampa, Miami, and Key West) across Florida from 1950–2015.

Specific objectives of this study were to:

- Develop objective temperature metrics for heatwaves in Florida using a percentile-based heatwave definition applied to station daily temperature data. The current definition of a heatwave according to the American Meteorological Society (AMS) glossary of meteorology is "A period of abnormally and uncomfortably hot and usually humid weather". Currently, there is no universally accepted definition of heatwaves, with different approaches used for length, magnitude, and temperature variable.
- Establish a heatwave climatology and trend analysis for Florida, 1950–2015. Specific aspects addressed in the trend analysis include: frequency, duration, intensity, and sub-regional differences.
- Evaluate the large-scale characteristics associated with heatwaves in Florida by examining the evolution of synoptic-scale flow patterns (e.g., 500-hPa geopotential heights), using composite analysis.
- Investigate linkages between Floridian heatwaves and subsequent extreme precipitation events. This association is particularly important to Florida's weather and climate, given the presence of two adjacent large moisture sources.
- Following an ingredients-based methodology (lift, moisture, instability) for flash flooding, elucidate the dynamic and thermodynamic mechanisms responsible for extreme precipitation events that follow a Floridian heatwave, and compare these events to lesser events.

Results show that the frequency and duration of Floridian heatwaves have increased over the past 66 years, but the intensity of heatwaves has not changed significantly. Because heatwaves are generally associated with high-pressure systems that act to warm and moisten the incipient air mass, particularly in maritime tropical climates like Florida, it is hypothesized that anomalously extreme precipitation events are enhanced at and just following the end of a heatwave. The dynamic-thermodynamic evolution of, and physical mechanisms responsible for, extreme precipitation events in the three days following a heatwave were investigated. Results show that anomalously large subtropical moisture transport and moisture convergence related to the position of the Bermuda High, along with increased instability, are key features in determining whether an extreme precipitation event will follow a Floridian heatwave.

2. Research Results

a. *Heatwave metric*

Heatwave events were identified separately for summer (Jun–Aug) and winter (Dec–Feb) months. The 95th percentile for maximum, minimum, and mean daily temperatures were calculated. The 95th percentile was used instead of the 99th because there were not a substantial number of events that exceeded the 99th percentile, and a larger event database was desired for precipitation event compositing purposes (section 2c). To be considered a heatwave event, the daily maximum, minimum, or mean temperature had to exceed the 95th percentile for three consecutive days with a gap of at least four consecutive days between events. Using the heatwave metric for each temperature variable, trends in frequency, intensity, and duration at each location were then investigated.

b. *Heatwave trends*

While data from all seven stations were analyzed, results presented here are limited to Tallahassee (KTLH), Tampa (KTPA), and Key West (KEYW). These were chosen because they best represent the three sectors of Florida (North, Central, and South) defined for our precipitation analysis, and because they show the most interesting results in heatwave trends.

To investigate the frequency of heatwaves during our climatology period, histograms of summer heatwave frequency for each temperature variable are shown in Fig. 1. Seven of the nine histograms in Fig. 1 exhibit statistically significant trends using a threshold p-value of > 0.01. The exceptions, daily maximum temperature at KEYW and KTPA, are most susceptible to suffer afternoon sea breezes, as both airports are surrounded by water. Thus, maximum temperatures at these locations are largely regulated by sea surface temperatures (SSTs) and are therefore less susceptible to a positive heatwave frequency trend, despite global and regional climate change.

The most pronounced heatwave trends across our entire climatology are found in daily minimum temperatures at both KTPA and KEYW, particularly since the late 1990s (Fig. 1). It is well established that minimum temperatures are increasing more rapidly than maximum temperatures due to increased concentrations of greenhouse gases such as carbon dioxide and water vapor. However, the minimum temperature heatwave frequency increase at KTPA and KEYW is much more dramatic than at KTLH (Fig. 1) or any of our other stations (not shown), which is suggestive of the importance of increased amounts of evaporation. While we are not aiming to quantify the respective importance of increased urbanization and anthropogenic climate change, we note that while the KTPA area has experienced rapid urbanization over the past few decades, KEYW has not. The fact that both stations have seen a similar frequency increase in minimum temperature heatwaves (Fig. 1) suggests that increased urbanization has played a relatively minimal role. Finally, winter heatwave trends at all stations were largely similar to summer trends, relative to seasonal climatology differences.

To investigate intensity and duration trends of Florida heatwaves, daily departures were calculated for each temperature variable at each airport over the length of each heatwave event. Figure 2 shows line graphs of temperature departures averaged over all summer heatwaves at KTLH, KTPA, and KEYW. At all three stations, there has been an insignificant change in heatwave intensity over the past 66 years. However, Fig. 2 suggests that the duration of heatwaves at KTLH, KTPA, and KEYW has been increasing. The duration increase is more robust for minimum temperature events than for maximum and mean temperature events. At KTPA and KEYW, the differences in duration trends between minimum and maximum temperature events can also be connected to the regulation of maximum temperature by surrounding bodies of water. Interestingly, the most dramatic increase in heatwave duration since 2000 in our entire study occurred for minimum temperatures at KTLH (Fig. 2b), where average heatwave duration for 2010–2015 was three times as large as for 1950–1959. We suggest this may be related to the lack of summer precipitation and sea breezes at KTLH compared to stations in the Florida peninsula and Keys, both of which act as natural limitations to maximum temperature heatwaves; this is discussed further in section 4.

c. *Extreme Precipitation*

To analyze precipitation following heatwaves, we combined heatwave events from all three temperature metrics, with no redundancy. Precipitation event analysis was limited to heatwaves from 2002–present due to availability of reliable gridded precipitation data. Area-averaged precipitation was calculated over 3°×3° boxes for three Florida sectors: North, Central, and South (see cover figure). The North sector was centered on KTLH, the Central region halfway between KMCO and KTPA, and the South box halfway between KMIA and KEYW.

After ranking all area-averaged precipitation events, the Top 25% and Bottom 25% events in each sector were composited. The objectives of the composite analysis were to identify the dynamic and thermodynamic mechanisms responsible for extreme precipitation events, as well as elucidate dynamic and thermodynamic differences between heatwaves that end with an

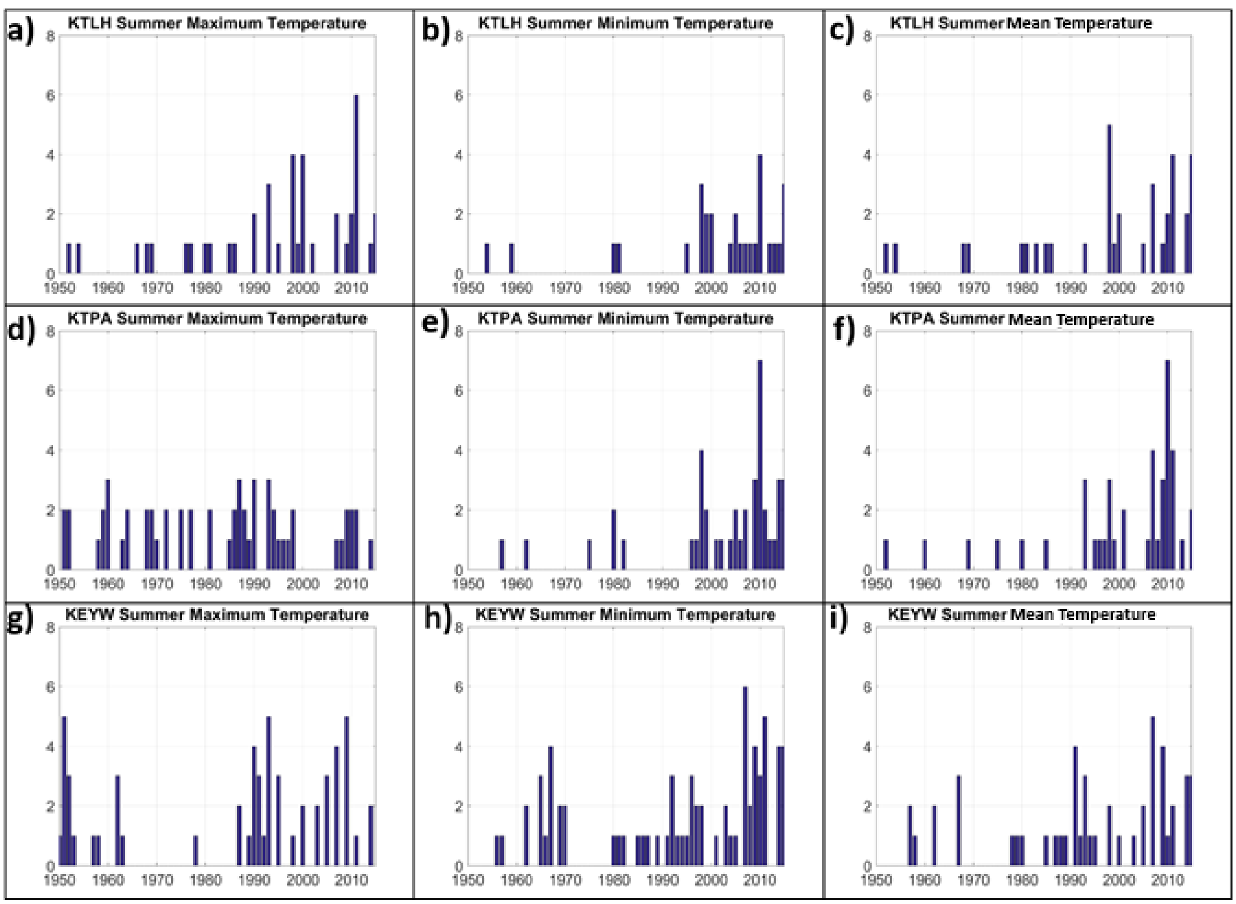

Figure 1: Histograms depicting the number of summer heatwave events in each year from 1950–2015 at (a–c) Tallahassee (KTLH), (d–f) Tampa (KTPA) and (g–i) Key West (KEYW), using (left) daily maximum, (center) daily minimum, and (right) daily mean temperatures.

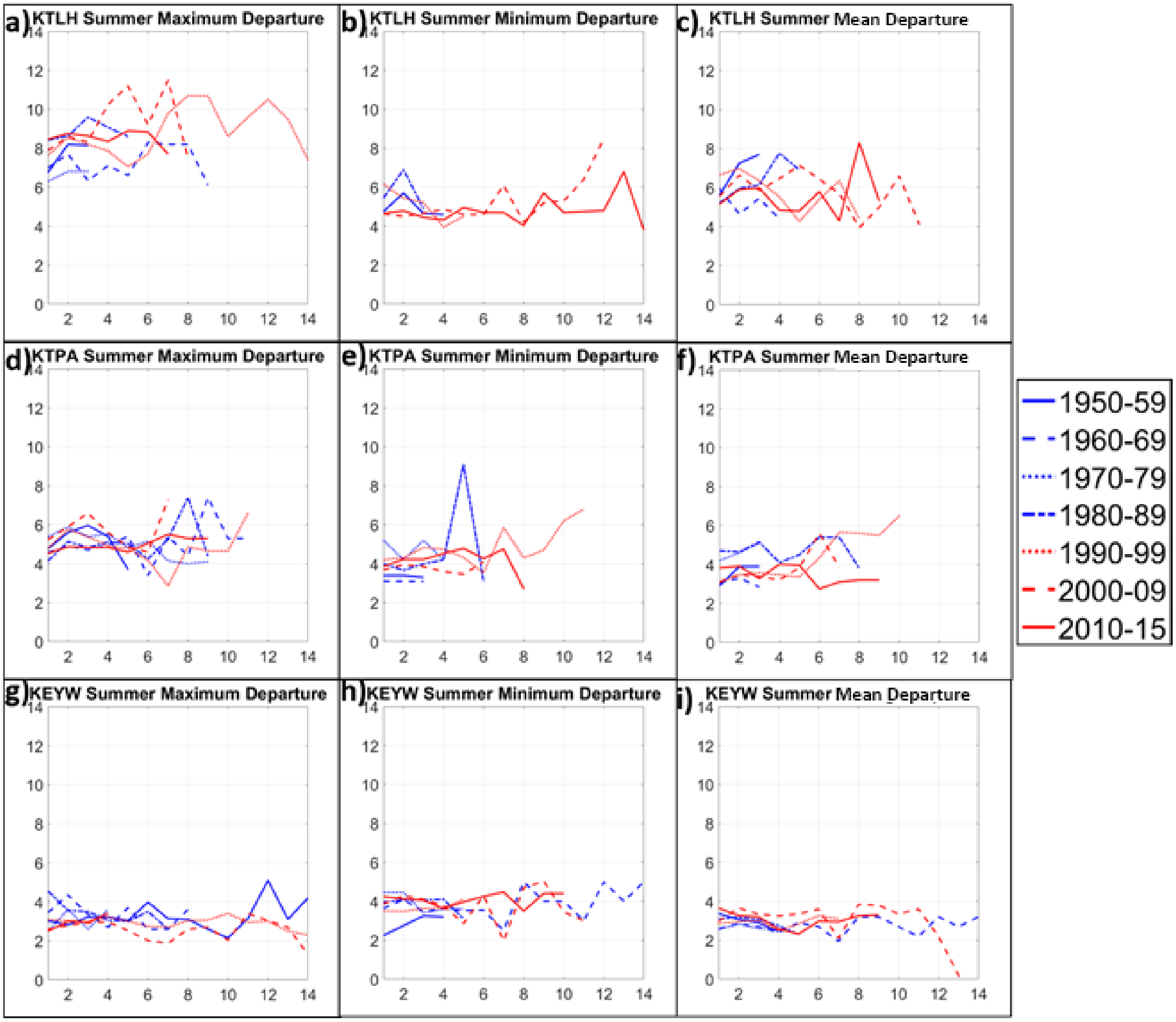

Figure 2: For each decade since 1950, line graphs of temperature departure (°F) averaged over all summer heatwave events at (a–c) Tallahassee (KTLH), (d–f) Tampa (KTPA) and (g–i) Key West (KEYW), using (left) daily maximum, (center) daily minimum, and (right) daily mean temperatures. The x-axis shows heatwave duration (days).

extreme precipitation event and those that do not. Although we did not separate precipitation events by season, most of the cases in the Top 25% in each sector were during summer, when thermodynamics are more conducive to extreme precipitation. Composites were produced for every 6 h in the 72-h period following the end of a heatwave. Composite anomalies were computed with respect to a monthly weighted 30-year (1981–2010) climatology.

Using an ingredients-based methodology for extreme precipitation (lift, moisture, instability), we found that Floridian heatwaves are associated with anomalously large amounts of moisture, facilitating an environment that is highly conducive to extreme precipitation after the heatwave ends. Ascent was primarily forced by lower-tropospheric surface convergence. A saturated lower- and mid-troposphere and moderate CAPE was observed in composite soundings of the Top 25% of precipitation events (Fig. 3). Moderate CAPE, which has been previously shown to be conducive to flash flooding, was enabled by relatively steep mid-tropospheric lapse rates and an anomalously moist lower troposphere (Fig. 3). In comparison, Bottom 25% precipitation events had no CAPE and a much drier lower- and mid-troposphere (Fig. 3). In all, our composite analyses of lift (surface convergence), moisture (large amounts column water vapor) and instability (CAPE) elucidate the dynamic and thermodynamic mechanisms that are required in order to produce extreme precipitation events at the conclusion of Floridian heatwaves.

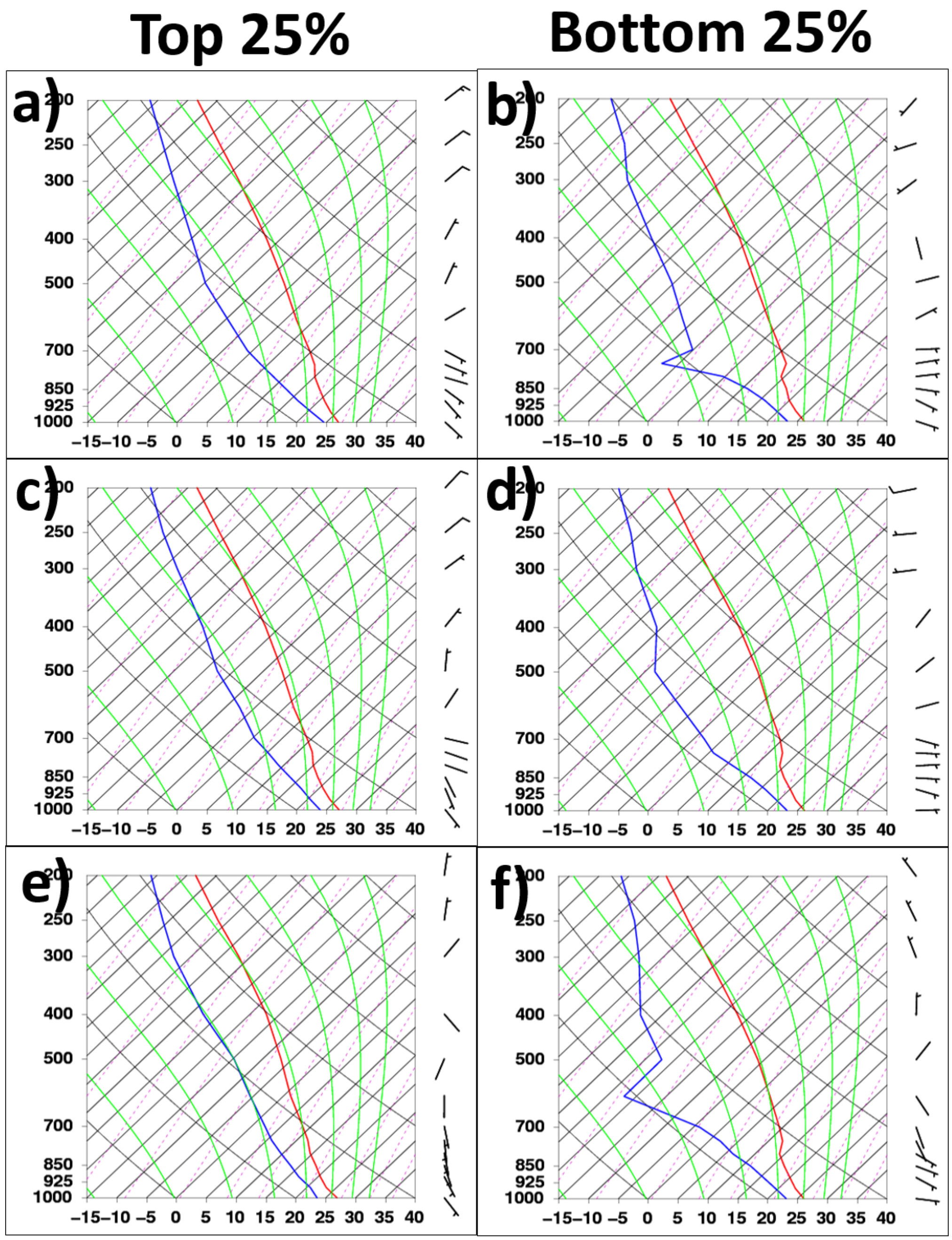

Figure 3: For the (left) Top 25% and (right) Bottom 25% (right) of precipitation events in the South sector: NARR composite soundings for (a, b) day 0, (c, d) day +1, (e, f) day +2, where day 0 is 1200 UTC on the last day of the heatwave. Plotted are temperature (red, °C), dewpoint (blue, °C), and wind (barbs, kt).

3. **Impact Statement**

The funds provided by the ERAU Internal Grant had a very significant positive impact on our research activity and professional development, especially that of my undergraduate research assistant, Shealynn Cloutier-Bisbee. It has resulted in two manuscripts currently in peer review and multiple presentations at leading atmospheric science conferences (see sections 7 and 8). Shealynn is the first author on one of the manuscripts, which is highly unusual for an undergraduate student. The research experience she has gained as a result of this FIRST grant will be invaluable throughout the remainder of her undergraduate career and will be an immense positive for her graduate school applications.

In addition, this FIRST award helped to continue to develop the student and faculty research culture within ERAU Meteorology and Applied Aviation Sciences, something that I have been and continue to be committed to enhancing. It has also helped to further ERAU Meteorology's reputation in climate change research, especially with respect to Florida's climate and propensity for extreme weather events. Finally, the proof-of-concept results and peer-reviewed manuscripts will serve as a basis for a planned external research proposal to the National Science Foundation (NSF) in the coming months, described in section 6.

4. **Project Scope Changes**

The main premise and primary objectives of this research did not change from the original proposal. However, the scope did broaden slightly, as Part II of this project (section 5) used numerical model simulations to analyze future heatwaves and extreme precipitation events in Florida. This work was done in conjunction with researchers at the University at Albany, led by Ajay Raghavendra, an ERAU alumnus who is currently a Ph.D student in atmospheric science.

5. **Future Research**

Part II of this project (Raghavendra et al. 2017) investigates projected future changes in Floridian heatwaves and impacts on subsequent precipitation. It is well established that surface temperatures and water vapor concentrations have been increasing and will continue to do so within a warming world. Because the Florida peninsula in summer has a built-in climatological mechanism for surface convergence and ascent (dual sea breezes) any increases in moisture and/or instability would have profound impacts on the frequency and intensity of extreme precipitation events and flash floods in Florida. As heatwaves are projected to increase exponentially in frequency and duration over the next century, the resulting air mass modification and consequences for flash flood risks need to be thoroughly investigated

In addition, specific future work stemming from this observational-based study should include an analysis of precipitation events for each individual temperature variable (i.e., minimum temperature), to investigate whether certain types of heatwaves (i.e., daytime only, nighttime only) are more likely to be followed by extreme precipitation events. In addition, the role of SSTs\ in air mass modification needs to be quantified for stations such as KTPA and KEYW, which are surrounded by warm water. This should be accomplished by running high-resolution numerical model simulations and associated sensitivity experiments to determine whether similar precipitation events would occur with normal SSTs.

6. Plan for External Funding

Based on the preliminary research results that stem from this ERAU FIRST grant, I plan to submit an external research proposal to the NSF Climate and Large-Scale Dynamics (CLD) Program by the end of the calendar year. This proposal will utilize the research results detailed in Cloutier-Bisbee et al. (2017) as a basis to expand the study in both scientific scope and geographical focus.

External Proposal Objectives:

1) Using numerical simulation sensitivity experiments, quantify the importance of SSTs to air mass modification during and after Florida heatwaves, particularly in the context of extreme precipitation events. In addition, comparatively quantify the role of SSTs for stations surrounded by water (e.g., KEYW) and stations located inland (e.g., KTLH).
2) Quantify whether a Florida heatwave makes an extreme precipitation event more likely, and if so, by how much.
3) Analyze the predictability of extreme precipitation events associated with Florida heatwaves, by using reforecast and operational numerical weather prediction models.
4) Expand the analysis of heatwaves and subsequent precipitation events to other major population centers in the southeastern U.S., such as Atlanta, Nashville, and Charlotte. Specifically, how do heatwave trends, and dynamic and thermodynamic mechanisms for precipitation at these locations compare and contrast to the Florida results detailed here.

7. Peer-Reviewed Publications

Cloutier-Bisbee, S.R., A. Raghavendra, and S. M. Milrad, 2017: Floridian heatwaves and extreme precipitation. Part I: Observations and Trends. *Clim. Dyn.,* submitted.

Raghavendra, A., A. Dai, S. R. Cloutier-Bisbee, and S. M. Milrad, 2017: Floridian heatwaves and extreme precipitation. Part II: Future climate projections. *Clim. Dyn.,* submitted.

8. Conference Presentations

Cloutier-Bisbee, S. R., S. M. Milrad, and A. Raghavendra, 2018: Floridian heatwaves and extreme precipitation. Part I: Observations and Trends. 31st Conference and Climate Variability and Change, 98th Annual American Meteorological Society Annual Meeting, 7–11 January, Austin, TX.

Raghavendra, A., A. Dai, S. R. Cloutier-Bisbee, and S. M. Milrad, 2018: Floridian heatwaves and extreme precipitation. Part II: Future climate projections. 31st Conference and Climate Variability and Change, 98th Annual American Meteorological Society Annual Meeting, 7–11 January, Austin, TX.

Cloutier-Bisbee, S., S. M. Milrad, and A. Raghavendra, 2017: Floridian heatwaves in a warming world: Frequency, intensity, and duration. 16th Annual AMS Student Conference, 21–22 January, Seattle, WA.

Milrad, S. M., 2017 (Invited Speaker): Climate change and extreme weather. Bermuda Institute of Ocean Sciences (BIOS), 19 July, St. Georges, Bermuda.