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Analyzing June Southeastern US CAPE Trends Between 1944–2023

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Abstract

Convective available potential energy (CAPE) describes the level of atmospheric instability and potential updraft strength that can contribute to thunderstorm development. Particularly high values indicate the possibility of severe convection, which can threaten life and property. Studies suggest that climate change will cause a change in dynamics contributing to CAPE; however, the resultant change in CAPE from these changes remains unclear. This highlights the need for trend analyses to determine where high CAPE values are becoming more or less common. Previous studies display particularly inconsistent CAPE trend results for the Southeastern US, a region that often experiences high CAPE during the summer months. These studies also fail to describe trends specific to peak heating times, when CAPE is typically highest. This research addresses these problems by using ERA5 reanalysis data to investigate long-term CAPE trends in the Southeast for 2000 UTC for the month of June. An 80-year analysis provides a more comprehensive and complete picture of CAPE fluctuations, and the regional aspect allows for the observation of more localized changes. Results display distinct differences in localized CAPE changes over time within the Southeast. Averaged regional trends also reveal non-linearities in CAPE trends throughout the analysis period.

1. Introduction

Between 2018 and 2022, a total of 53 billion-dollar disasters were attributed to severe thunderstorms in the US, costing $117.6 billion and claiming 231 lives (NCEI 2023). Each of these storms required strong atmospheric instability to develop and cause the destruction that occurred. Convective available potential energy (CAPE) acts as a metric that quantifies the level of instability. More specifically, CAPE indicates the amount of buoyant energy between the level of free convection and the equilibrium level (Blanchard 1998). A thermodynamic diagram displays CAPE as positive area, or the area between parcel and ambient temperature profiles when the parcel is warmer than its environment. Values of 1000-2500 J kg-1 indicate moderate atmospheric instability, while values above 2500 J kg-1 indicate strong instability (DeRubertis 2006). Particularly high CAPE values occur in the Southeastern United States, especially during summer, due to the region's relatively high surface specific humidity (Trapp et al. 2007). This underscores the need for a strong understanding of Southeastern CAPE and its connections to severe weather potential to better assess the region's current and future severe weather risk.

A trend analysis provides insight into long-term changes in a variable. Trends in CAPE are crucial for detecting climatic changes in severe thunderstorm potential and determining which areas have an increased risk. Previous research in this method focuses on past and future CAPE trends. While these are different methods used for different purposes, they are fundamentally connected. One may hypothesize that past CAPE changes will continue into the future, and if these trends and projections match, they support each other. Therefore, an analysis of both methods provides a broader understanding of this subject.

DeRubertis (2006) developed the first climatology of CAPE trends in the US. Using 0000 UTC radiosonde data for 1973–97, she determined that the highest daily averaged regional CAPE values, on average, exist in the Southeast during summer, with a mean value of 922 ± 146 J kg-1. A trend analysis of Southeast summer CAPE (SESC), through the Theil-Sen slope method, revealed a linear SESC trend of 13.23 J kg-1 yr-1 with significance at the $\alpha = 0.01$ level. She also found a general increase in the frequency of extreme SESC of at least 1800 J kg-1, which further backs up the conclusion of increasing CAPE.

Although DeRubertis' (2006) results follow general expectations, they come with a couple of major limitations. First, the assumption that 0000 UTC soundings can sufficiently represent SESC trends is questionable. Ideally, the CAPE values used would correspond to times of peak heating; however, 0000 UTC corresponds with 2000 EDT, which is well past peak heating. Because of this, one should interpret these results as trends in 0000 UTC SESC. Another limitation arises from the relatively short range of time used in the analysis, which raises questions about the accuracy of the results. Nevertheless, this work remains useful, especially when compared to subsequent studies which expand on it.

Trapp et al. (2007) extended this research into the future. They projected changes in mean SESC between 1962–89 and 2072–99 through the RegCM3 climate model under a high-end emissions scenario. Their results indicated increases of at least 300 J kg-1 throughout most of the Southeast, with a swatch of 500 J kg-1 or more throughout parts of the Gulf and Atlantic coast regions. This allows for some credibility to be given to DeRubertis' (2006) results since they align well with their conclusions — that SESC trends are upward. However, since Trapp et al. (2007) only used one emissions projection, one must use proper care in interpreting their results. Furthermore, this limitation emphasizes the need for further research on this subject.

Trapp et al. (2007) credited increases in surface specific humidity as the primary cause of increasing CAPE, which explains why the highest SESC increases were mainly in coastal regions. Riemann-Campe et al. (2009) supported this conclusion by expanding it to include previous CAPE trends. They also further expand the work of DeRubertis (2006) by using ERA-40 reanalysis data (Uppala et al. 2005) rather than radiosonde data to retrieve CAPE data. They determined trends between 1958–2001 through the Mann-Kendall trend test, which gives a two-tailed p-value indicating trend confidence. Only trends that exceeded a 95% confidence level ($p < 0.05$) were shown in the results. They found significant upward trends in SESC in Florida, the Gulf of Mexico, and parts of the Deep South. Other areas in the Southeast had no significant calculated trend; however, this does not indicate zero increases in those areas. They also calculated trends for 1958–78 and 1979–2001 because of the addition of satellite measurements into the dataset in 1978. Taking out the data without satellite measurements introduces significant discrepancies from the original results. It removes the significant SESC trends in the Deep South, much of the Gulf of Mexico, and most of north Florida, leaving central and southern Florida as the main area with significant increases. It even introduces a significant decrease in CAPE in a small area of the upper Southeast. Nevertheless, the relatively short time span of the 1979–2001 results is a disadvantage over using the 1958–2001 range, which one cannot discount merely for not having satellite measurements throughout its entirety.

Further research continued to support the conclusion of increasing SESC over time. After Riemann-Campe et al.'s (2009) work, multiple works of research focused again on CAPE projection, as Trapp et al. (2007) did. Diffenbaugh et al. (2013), Chen et al. (2020), and Glazer et al. (2021) used the RCP 8.5 climate change scenario each with uniquely different climate models and all found substantial increases in SESC between the late 20th century and late 21st century. Their work continued to follow expectations on the impacts of a warming climate, and it agreed with the CAPE increases that Trapp et al. (2007) projected.

One more recent study, however, presents an opposing conclusion compared to previous results. Taszarek et al. (2021a) used ERA5 reanalysis data (Hersbach et al. 2020) for 1979–2019 to calculate trends in CAPE using a Theil-Sen slope analysis. They calculated downward trends in SESC for much of the region and found significant decreases (up to approximately 100 J kg-1 per decade) through much of Kentucky, Virginia, North Carolina, and Georgia. They also observed significant upward trends in the southern half of Florida, which is consistent with the results of Riemann-Campe et al. (2009). However, the introduction of decreasing SESC contradicts all previous work in this area and shows the need for continued work to better understand past and potential CAPE trends.

This paper aims to reduce confusion caused by differing results in the literature on SESC trends through an 80-year localized SESC trend analysis. It also aims to address the remaining research gap originating from DeRubertis' (2006) study — the failure to evaluate trends corresponding to typical peak heating — by analyzing trends for these specific times. A comparison of these results to the past literature may then increase confidence where agreements exist.

2. Data

The ERA5 reanalysis provides the CAPE data used in this study at 1-hour resolution. It also has a 31-km spatial resolution (approximately 0.25°) — a major improvement from previous ECMWF reanalysis datasets. The timespan of data availability highlights another improvement; ERA5 reanalysis contains data from 1940 to the present. This provides the opportunity for a more comprehensive CAPE analysis.

This study uses 80 years of ERA5 CAPE data spanning between 1944–2023 for the area bounded by 75.5°W–91.75°W and 24.5°N–38.5°N, which encompasses the entire Southeast US region, along with part of the nearby Atlantic Ocean and Gulf of Mexico, and analyzes hourly data trends and changes at 2000 UTC, which corresponds a to typical peak heating time within the Southeast. The month of June was chosen for analysis because of the typically hot and humid conditions that occur in this month and its proximity to the typical spring severe weather season in the Southeast.

3. Methods

This analysis contains three components: a regional trend analysis, an investigation of spatial CAPE changes, and an analysis of localized CAPE trends . For all components, 2000 UTC June CAPE values for each grid cell were averaged for each year to calculate yearly trends. Further averaging was completed to compute CAPE differences depending on the length of the periods compared.

3.1 CAPE Trend Analysis

The trend analysis utilized in this research uses averaged CAPE values over the entire Southeast region for each year to produce three methods of trend measurement. The first method uses a least-squares linear regression (LSLR), which describes the linearized relationship between independent and predictor variables (Wilks 2011). It gives a constant trend based on the slope of the resultant regression equation. A polynomial fit of degree 5 then displays some of the finer details of trend variability that the LSLR misses. These methods give a broad picture of how June CAPE has changed and progressed in the Southeast as a whole.

The third method involves the nonparametric Theil-Sen estimator (Sen 1968), which DeRubertis (2006) and Taszerek et al. (2021a) use. It calculates the median of all possible slopes within a dataset and provides a 90-percent confidence interval. This method is more resistant to outliers than the LSLR and serves as a beneficial tool in this trend analysis.

3.2 Spatial Differences in CAPE

An investigation into smaller-scale CAPE changes must accompany this trend analysis because spatial inhomogeneities are inevitable. Calculated differences between averaged values for different time periods account for this. First, calculated differences between decade 1 (1944–1953) and decade 8 (2014–2023) display CAPE changes from the beginning and ending time periods. Next, differences between decades 1–4 (1944–1983) and decades 5–8 (1984–2023) are calculated to provide larger-scale differences between the first and second halves of the analysis period. Finally, an analysis of four 20-year increments within the 80-year period show how these CAPE trends changed over time.

3.3 Localized CAPE Trends

The final portion of this study analyzes trends for six cities of interest over the 80-year period: Miami, Florida; Myrtle Beach, South Carolina; New Orleans, Louisiana; Johnson City, Tennessee; Roanoke, Virginia; and Montgomery, Alabama. These cities provide a set of diverse climates that exist within the Southeast and can provide a detailed picture of how their small-scale CAPE trends differ. First, in order to view these trends together on a plot, 3-year and 5-year running means of yearly CAPE were calculated for each city. Next, The LSLR regression slope provides a trend values for the cities, and corresponding t-tests allow for determining whether these slopes are meaningful. Corresponding Sen slopes may also provide support for the approximate trends determined from the LSLR slopes.

4. Results

4.1 Trend Analysis

LSLR and Theil-Sen slopes indicate modest upward trends in averaged regional CAPE for all analysis times, as shown in Table 1. They are all relatively similar, with values between 2.0–2.5 J kg^{-1} yr^{-1} — far lower than the value calculated by DeRubertis (2006). LSLR slopes are slightly greater than Theil-Sen slopes, with an average difference of 0.213 J kg^{-1} yr^{-1}. These slopes also demonstrate a slight downward trend for both trend methods as the time of day progresses.

Figure 1 displays the LSLR and Theil-Sen estimator lines for 2000 UTC over the line of averaged CAPE values along with a 90-percent confidence interval for the Theil-Sen estimator and a polynomial fit line. The confidence interval portrays a relatively high degree of uncertainty in the true slope due to non-linearities of the CAPE time-progression. The polynomial fit line also displays some of the resulting nonlinearities through the 80-year period, with overall increases and decreases throughout.

Due to these nonlinearities in the polynomial fit line (Fig. 1), the need for an incremental trend analysis arises. Four 20-year increments provide sufficient detail in analyzing these differing trends over the 80-year period. Widely varying slopes between the increments result from this segmented split. The first 20 years features a notable decrease in average CAPE, while the second and fourth 20-year segments have increasing trends. The third segment has a LSLR slope near zero, but a slightly decreasing Theil-Sen slope. However, due to the smaller time intervals, the Theil-Sen confidence intervals are much larger, indicating lower confidence in these trends. The third segment exhibits a particularly large level of uncertainty, with lower and upper confidence intervals displaying notable decreasing and increasing trends, respectively.

4.2 Spatial CAPE Changes

Maps of CAPE changes display key spatial inhomogeneities that cannot be viewed in the trend analysis. Plots of changes between the first and second half of the analysis period for each time (Fig. 3b) plots display increases in most areas, with the highest increases around parts of Southeastern Florida and the Eastern Gulf of Mexico

TABLE 1. LSLR and Theil-Sen slopes for analysis times.

	LSLR Slope (J kg^{-1} yr^{-1})	Sen Slope (J kg^{-1} yr^{-1})
1900 UTC	2.404	2.269
2000 UTC	2.359	2.104
2100 UTC	2.307	2.059

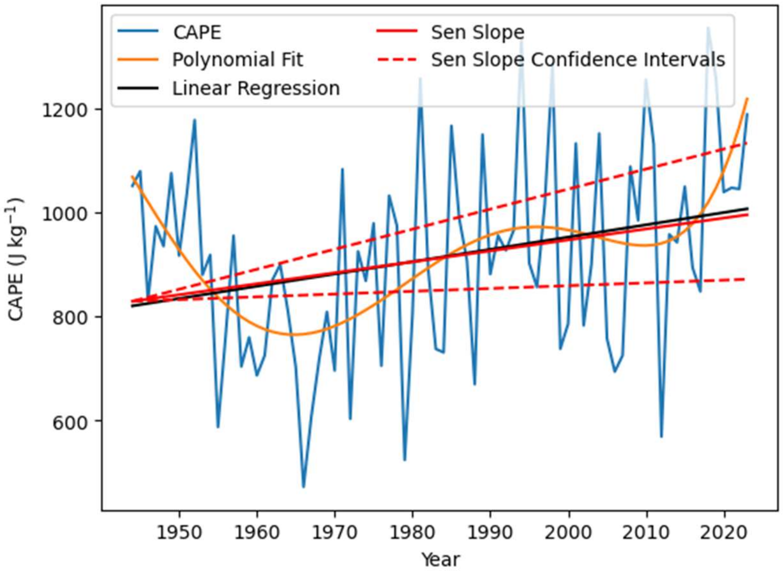

FIG. 1. Averaged June Southeastern US CAPE values at 2000 UTC, least-squares linear regression, polynomial fit of degree 5, and Theil-Sen slope fit with 90-percent confidence intervals.

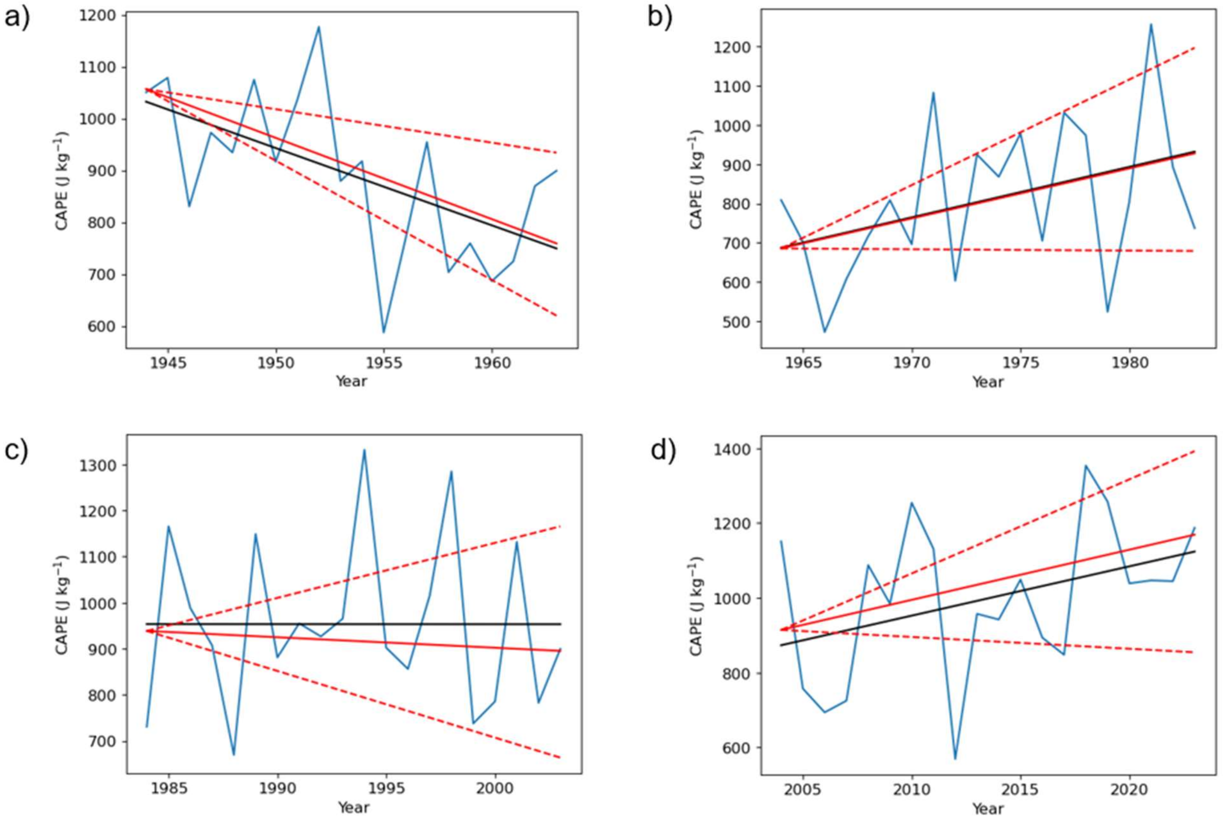

FIG. 2. Averaged June Southeastern US CAPE values at 2000 UTC, least-squares linear regression, and Theil-Sen slope fit with 90-percent confidence intervals for a) 1944–63, b) 1964–83, c) 1984–2003, and d) 2004–23. See Figure 1 for legend.

— consistent with the results of Reimann-Campe et al. (2009), with increases of average CAPE of approximately 300 J kg-1. Increases also exist throughout much of the Deep South region, along with Tennessee and Kentucky. Areas of no trend and slight decreases of up to 50 J kg-1 are more prominent in the Carolinas, Virginia, and West Virginia.

Figure 3a provides a similar analysis for CAPE changes between the first decade (1944–53) and final decade (2014–23). However, there are higher magnitudes of differences in CAPE compared to Figure 3b. The highest increases (>500 J kg-1) occurred in South Florida, with other notable increases in parts of Southeastern Louisiana and Southern Mississippi. Areas of decreasing CAPE are more widespread compared to Figure 3b, with the highest decreases (up to approximately 400 J kg-1) just off the Carolina coast. Other decreases exist in the same areas as described from Figure 3b, with the addition of parts of Georgia, Kentucky, and a small region of the Gulf of Mexico off the Florida panhandle coast. Overall, areas of increases and decreases are almost evenly split.

4.3 Analysis of Smaller Time-Scale CAPE Changes

Smaller time-scale changes in CAPE reveal more information on the complexities in the 80-year analysis that the polynomial fit line (Fig. 1) and 20-year incremental plots (Fig. 2) suggest. Figure 4 displays four 20-year analyses of localized CAPE changes that correspond to the plots in Figure 2.

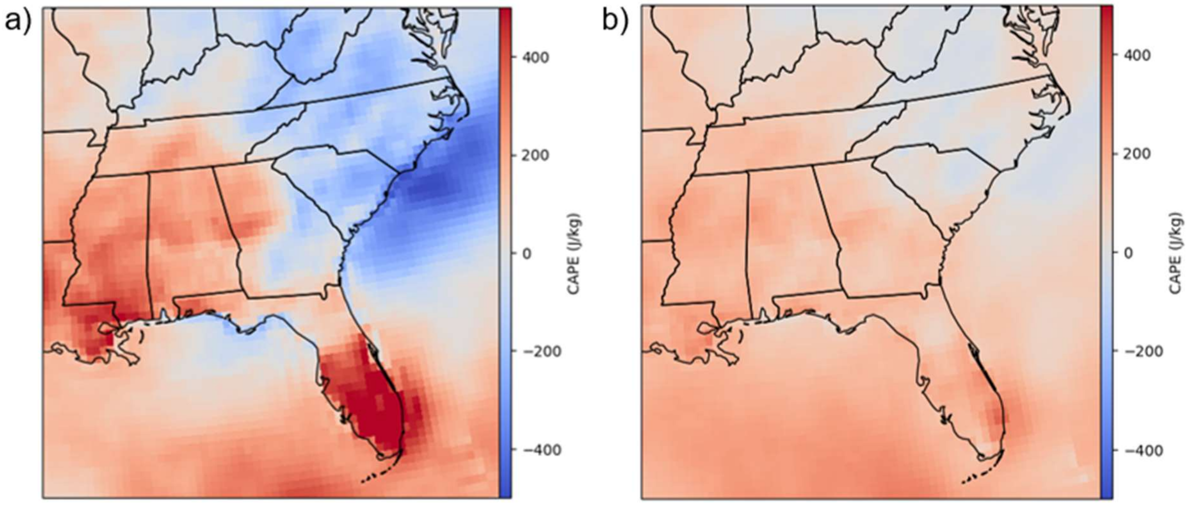

FIG. 3. Localized changes in June 2000 UTC CAPE between a) averaged decade 1 and decade 8 values and b) averaged decade 1–4 and decade 5–8 values. Red colors signify increasing average CAPE, while blue colors indicate a decrease.

4.3a Increment 1: 1944–53 to 1954–63

The first increment shows that an area of the Northeastern Gulf of Mexico and a section of the Atlantic Ocean just off the Carolina coast contributed most to the overall decrease, with drops of 300–400 J kg^{-1} common. Smaller decreases also exist within most of the remaining Southeastern region, with other small areas of no trend and very small increases, especially in Florida, Alabama, Mississippi, and Louisiana.

4.3b Increment 2: 1964–73 to 1974–83

The second increment reveals that areas of North Florida, South Georgia, and Southeast Alabama contribute most to the overall CAPE increase in that time period, with rises of up to 300 J kg^{-1}. Smaller, but notable increases occurred just offshore in the Atlantic Ocean, and Gulf of Mexico off the Florida coast. Most of the remaining regions in the Southeast had very small changes or no trend.

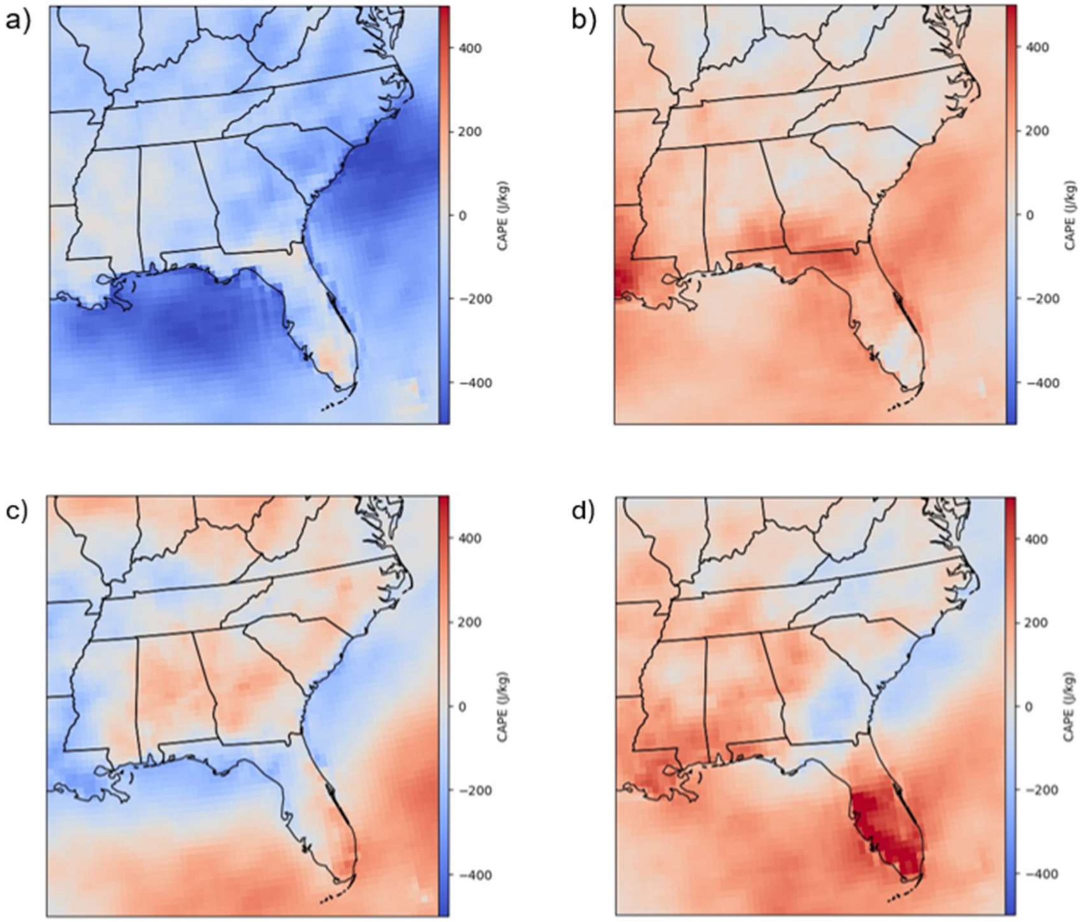

FIG. 4. Changes in average 2000 UTC June CAPE between a) decade 1–2, b) decade 3–4, c) decade 5–6, and d) decade 7–8. Red colors indicate increasing CAPE, while blue colors indicate decreases.

4.3c Increment 3: 1984–93 to 1994–2003

The plot for the third increment reveals why the LSLR and Sen slopes are nearly flat, as increases and decreases in CAPE are approximately split in half within the analysis region. The greatest decreases exist in Southeast Louisiana — close to 200 J kg^{-1}, while smaller decreases also occurred around parts of the Gulf and Atlantic coast. The highest increase (approximately 200 J kg^{-1}) occurred in Southeast Florida, with smaller increases primarily in Alabama and Georgia.

4.3d Increment 4: 2004–13 to 2014-23

The increasing trend in the fourth increment is clearly driven by the large CAPE increases in the Southern half of Florida, with some increases over 500 J kg^{-1}. There were smaller increases through much of the region, but small decreases also occurred — most notably in South Georgia and just offshore in the Atlantic Ocean off the South Carolina coast.

4.4 Localized CAPE Trends

A comparison of trends for each of the six cities reveals wide differences in trend direction and magnitude (Fig. 5; Table 2), but they generally follow the expectations provided from the previous analysis of spatial changes in CAPE (Fig. 3–4). Miami had the largest CAPE increase, followed by New Orleans, while Myrtle Beach had the largest CAPE decrease. The remaining cities had relatively small overall trends over the 80-year period. It is important to note that only Miami and New Orleans have meaningful LSLR slopes according to t-test values (using $p<0.05$); however, these cities found to not have meaningful LSLR have very similar Sen slope trend values, with differences not exceeding 0.224 J kg^{-1} yr^{-1} (Table 2).

5. Discussion

5.1 Contributors to the Overall Increasing Trend

The results of this study indicate a slight increasing trend in CAPE throughout the region as a whole (Table 1; Fig. 1). Although this trend, which equates to roughly 2.25 ± 0.2 J kg^{-1} yr^{-1}, may seem small, the areas contributing most to the increasing trend experienced large and potentially impactful increases in CAPE. For example, much of South Florida had increases greater than 500 J kg^{-1} between the first and last decades analyzed (Fig. 3a). Figure 5 reveals that most of this increase occurred within the past

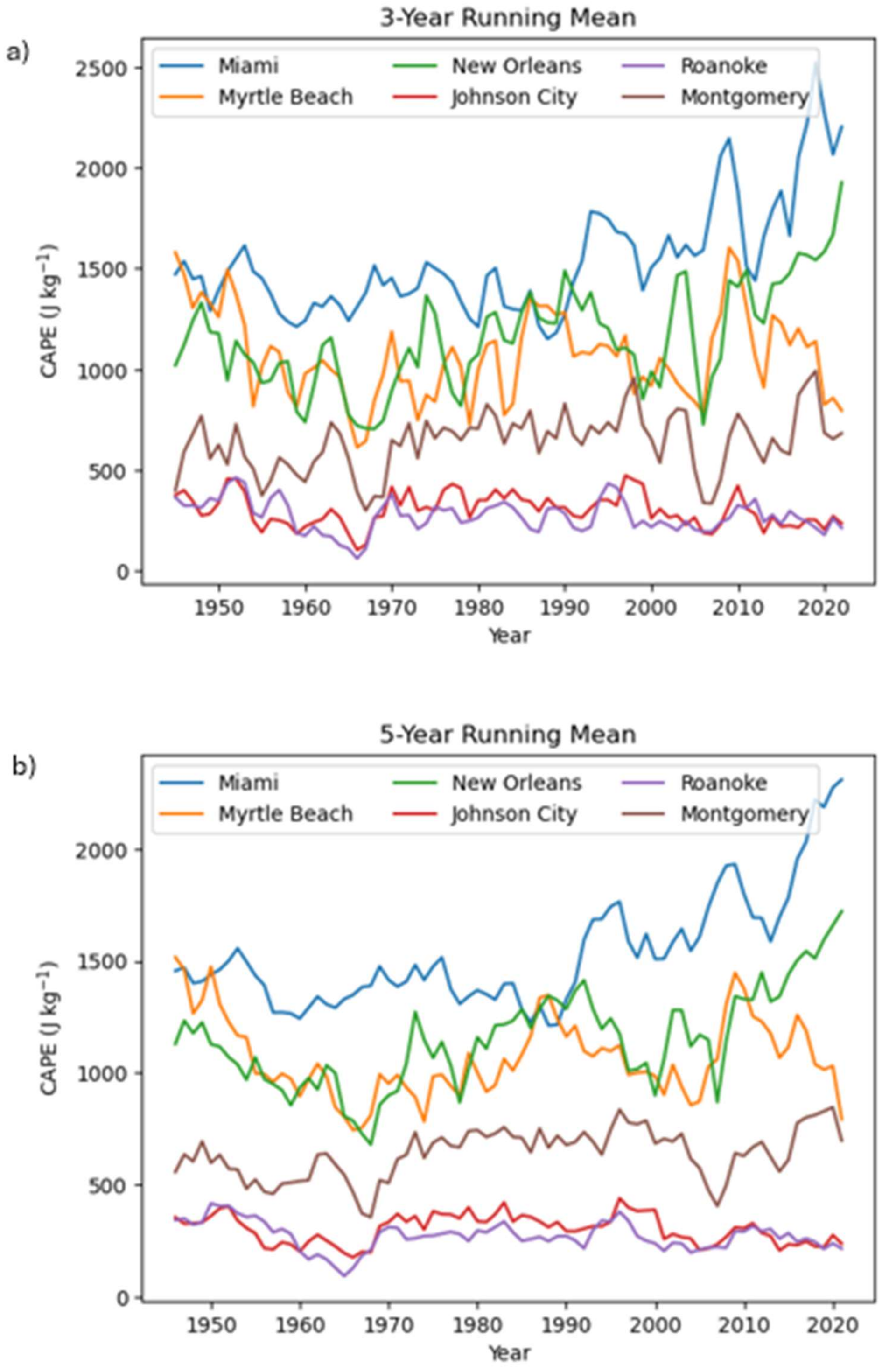

FIG. 5. a) 3-year running means and b) 5-year running means of averaged 2000 UTC June CAPE for each city.

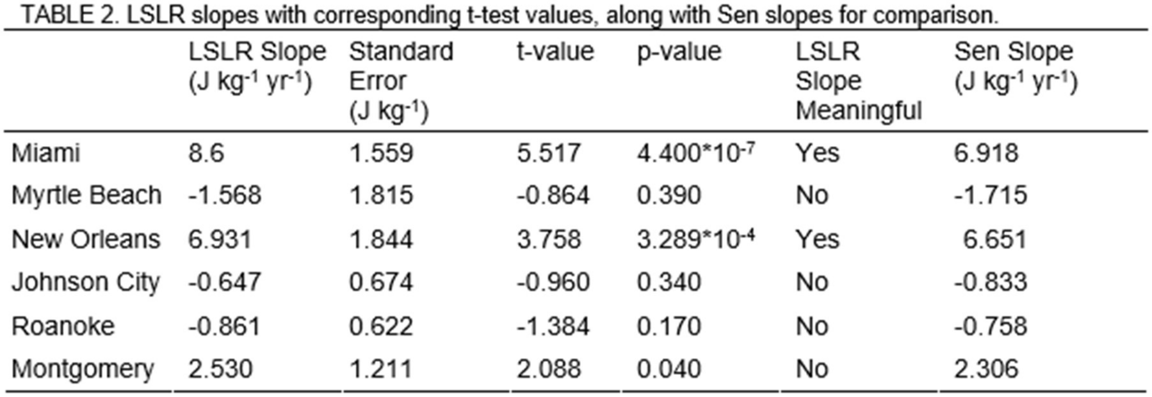

TABLE 2. LSLR slopes with corresponding t-test values, along with Sen slopes for comparison.

	LSLR Slope ($J\ kg^{-1}\ yr^{-1}$)	Standard Error ($J\ kg^{-1}$)	t-value	p-value	LSLR Slope Meaningful	Sen Slope ($J\ kg^{-1}\ yr^{-1}$)
Miami	8.6	1.559	5.517	$4.400*10^{-7}$	Yes	6.918
Myrtle Beach	-1.568	1.815	-0.864	0.390	No	-1.715
New Orleans	6.931	1.844	3.758	$3.289*10^{-4}$	Yes	6.651
Johnson City	-0.647	0.674	-0.960	0.340	No	-0.833
Roanoke	-0.861	0.622	-1.384	0.170	No	-0.758
Montgomery	2.530	1.211	2.088	0.040	No	2.306

two decades, with much smaller CAPE changes overall, and even some decreases in areas, within the previous increments.

A second area of interest arises in Southeast Louisiana, one of the highest contributors to the increasing CAPE trend, as shown in Figure 3. Increases occurred in this location in the second and fourth 20-year increments, with decreases in the first and third increments. Similar to South Florida, the highest increases occurred in the most recent increment; however, the magnitude of this increase is much smaller.

Contrasts to the rising CAPE trend exist mainly in the Carolinas, Virigina, and Southern West Virginia, with little to no trend between the first and second halves of the analysis period (Fig. 3b). Notable decreases in CAPE exist between the first and final decade (Fig. 3a), which mainly occurred in the first 20-year increment (Fig. 4a). In general, none of these regions experienced substantial CAPE increases in any of the four 20-year increments.

5.2 Oceanic Trends

Although the Gulf of Mexico and Atlantic Ocean basin are not a part of the Southeastern US region, this study includes small parts of them in the single rectangular analysis region in order to obtain data from all Southeastern US locations. Future research analyzing CAPE trends in this region should compare these results to those without any ocean basin data and determine if increasing trends still exist. Nevertheless, atmospheric conditions off the coast often have implications for the land nearby, and therefore this research analyzes it.

The decreasing CAPE off the Atlantic coast is of particular interest. Figure 3a shows especially displays this notable decrease off the Carolina coastline between decades 1 and 8. Figure 4a reveals that most of this decrease occurred in the first 20-year increment (contributing to the overall CAPE decrease in that period); however, slight decreases also occurred in the most recent 20-year increment. The expected response to this CAPE decrease would be a decrease in thunderstorm activity in this region. Future studies should aim to determine if this connection exists for the entire 80-year period and the first increment (1944–53 to 1954–63).

Figure 4a also shows that the Northeastern Gulf of Mexico was a main contributor to the decreasing Southeastern CAPE in the first 20-year increment. Another, smaller-scale decrease also occurred in the third increment, with relatively small increases in the other increments. Overall trends (Fig. 3) display little change in CAPE, especially between the first and final decades.

These areas of decreasing CAPE are in contradiction to expectations from recent increasing sea surface temperatures within the Gulf of Mexico and Atlantic Ocean. This may be due to differing upper-atmospheric trends in temperature and/or moisture; however, future studies are needed to produce a concrete determination on this.

5.3 Comparisons to Previous Research

Similarities and differences exist between the results of this study and the previous literature. The overall increasing Southeastern CAPE agrees with the results of DeRubertis (2006); however, the increase in this study was far smaller. The especially high increases in South Florida also agrees with the results of Riemann-Campe et al. (2009) and Taszarek et al. (2021a). However, the widespread CAPE decreases that Taszarek et al. find are in disagreement with this study. This is likely due to the different time periods used — they did not use 1944–78 or 2020–23.

This study's overall result of increasing CAPE also agrees with the future CAPE projections (Trapp et al. 2007; Diffenbaugh et al. 2013; Chen et al. 2020; Glazer et al. 2021). However, the widespread increases that these studies suggest disagrees with them; this study found a large area with no trend or a decreasing trend overall.

5.4 Limitations

Although the use of ERA5 reanalysis data is most desirable for this study, drawbacks exist. The greatest drawback is that it underestimates extreme CAPE values (Taszarek et al. 2021a; Wang et al. 2021), which would lead to lower average CAPE values than reality in this study. The resolution, though it has increased compared to previous reanalysis datasets, may be one of the reasons for this. CAPE develops on small spatial scales that a 0.25° likely cannot fully detail.

Another limitation arises from the fact that CAPE is not the single determining factor of thunderstorm development. Other variables, such as convective inhibition and wind shear, play a large role in this. For example, a location may have a very large CAPE value; however, if high CIN also exists, convection may not develop. Therefore, the results of this study must only be related to the *potential* for thunderstorm development.

The statistical analysis of the localized CAPE trends reveals another limitation, as only two of the six cities have meaningful LSLR slope trends. This is due to the high year-to-year variance of CAPE throughout the region. However, the relatively close Sen slope values found for these cities provide some support for the approximate trends given by the LSLR slopes.

5.5 Remaining Questions

The results of this work raise questions as to how CAPE will change in the near-future. Given the overall picture of CAPE trends, one may predict that it will continue to rise in an overall sense. However, the fluctuations seen in the incremental analysis (Fig. 2 and 4) raise uncertainty to this conclusion. To combat this uncertainty, future work should analyze CAPE trends on smaller time-scales than this study and place a particular emphasis on recent trends

Another area for future work relates to reasons for the CAPE trends described in this paper. Perhaps they are caused by changes in surface specific humidity (Trapp et al. 2007), or changes in average temperature. However, the analysis of these factors is beyond the scope of this study.

6. Conclusions

The analysis of CAPE trends in the Southeastern US provides a deeper understanding of how CAPE has changed over the past 80 years around this region and sheds new light on fluctuations that occurred. The following conclusions arise from this analysis:

- Overall, CAPE has risen over the past 80 years at a slow pace of roughly 2.5 J kg^{-1} yr^{-1}. This increasing trend is largely driven by increases in South Florida and Southeast Louisiana.
- Despite this trend, some locations in the Southeast have no trend or a decrease in CAPE.
- Trends on shorter time-scales have not been constant over the 80-year period, with major nonlinearities. For instance, the first 20 year period featured widespread CAPE decreases throughout the Southeast region.
- The largest increase in severe convection potential due to CAPE occurred in South Florida.

These findings have allowed for progress in understanding where the potential severe convection may have increased. If future studies combine these results with trends in CIN and windshear, confidence will increase greatly on which areas should be focused on the most for increasing severe weather.

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