Investigating the Spring to Summer Transition in Georgia

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Abstract

Some climate results are intuitive, even if a formal experiment or analysis has not been conducted to validate the findings. To the layperson in Georgia, the winters seem to be warmer than they were before, the spring season seems to be shrinking, and summer-like conditions appear much earlier than they have appeared in recent memory. The purpose of this study is to provide scientific and statistical evidence of these informal hypotheses. Specifically, the official daily temperature and precipitation records for the state of Georgia are analyzed to determine if the transition from spring to summer is growing shorter. Cluster analysis, and decision-tree procedures were used to develop definitions for and characterize the seasonal transitions. An empirical analysis of heat wave characteristics and several regression models were created to investigate the research questions.

Key Words: Observational study, temperature trends, linear regression, cluster analysis

1. Introduction

Ask a Georgia resident and he or she is likely to tell you that summer is getting longer and hotter these days. That the temperature goes from cold to hot with no warm, in between. But, is this really true? Perhaps they are right. After all, in June 2011, Georgia state climatologist David Stooksbury predicted a hotter than normal summer (Provano and Morris, 2011). And, looking back, 2011 was very warm. But is this a defensible argument based on many years worth of Georgia's weather data? Can one objectively come to the conclusion that the summer is getting longer or hotter?

As one season ends, the following season begins. But, this phenomenon does not occur in a discrete fashion as the calendar suggests. Rather, the conversion of the seasons is much less crisp. When the calendar changes and a new season begin, it usually still feels like the previous season. For example, the spring night of March 21 is usually just as cold as the winter night of March 20. A few weeks may pass before it begins to feel like the season that the calendar says it is. Another example – it is not blazingly hot on June 21, but by July 10, Georgia is in the thick of its summer season. By the last few weeks of the season, change is again in the air and signs of the approaching season begin to appear. There appears to be a spin-up involved in the season change process that the calendar seems to miss. We call this "spin-up" the transition period between the previous season and the new one. By analyzing this transition period, we can investigate the arrival of the new season.

For this study, we look at the preponderance of evidence in the temperature records to come up with a conclusion about whether or not the spring-to-summer transition is decreasing and/or the summer temperature is increasing. We approach the problem from an empirical standpoint. To this end, only temperature and precipitation data is used in our study because we are not attempting to explain *why* the phenomenon is occurring nor are we trying to predict what will happen to the seasons in the future. In this regard, this study should be considered an observational study and not an experiment.

The remainder of this paper is organized as follows. Section 2 discusses the data that was used in the study. Section 3 reports on the characteristics of the spring to summer transition using definitions derived from our conceptual model. The section answers our question, "Is the spring-to-summer transition warming up over the years so much that it feels more and more like summer?" Section 4 reports the characteristics of the spring to summer transition based on the results of a cluster analysis. This section addresses our research question, "Is the spring to summer transition shortening while the summer gets longer?" Section 5 examines the arrival of heatwave-like conditions in Georgia. Here we answer, "Are heatwave conditions arriving earlier these days?" Section 6 looks at the temperature changes in April and May. In section 7, we round up the paper with results, discussions, and provide an overall answer to our primary question, "Is summer arriving earlier than normal in Georgia as the spring-to-summer transition gets shorter?".

2. Data

We used the National Oceanic and Atmospheric Administration's National Climatic Data Center website (http://www.ncdc.noaa.gov/cdo-web/search) to collect 18 years worth (1994-2011) of daily temperature and precipitation records from 20 Georgia cities. The 20 stations are located across the entire state (about 6-7 stations in northern, middle, and southern Georgia) and were selected to ensure that a cross-section of Georgia climate was obtained. In addition, each station had reported weather data for a considerable amount of time (at least two decades) and had little-to-no missing temperature and/or precipitation values.

Taking into consideration the three leap years (2002, 2006, 2010), a station with a complete record would report data for all of the 3,653 days during this ten-year time span. This implies that a full dataset would contain 73,060 temperature and precipitation records. Our dataset had just 69,734 values for maximum temperature, a coverage value of 95.4%. Upon closer inspection, it was clear that the weather records of Dublin and Thomasville were the least complete. As a result, the data from these two cities were eliminated from the study. After removal, our coverage improved to 98.3%. The 64,659 remaining records were used. No effort was made to impute missing values because we believe that the data length was large enough to remove the records without losing much information, especially since the data covered 98.3% of all possible records.

The set of weather stations can be thought of as the realization of a systematic sample of Georgia weather stations with relatively long weather records. The list of stations was obtained along with their respective records lengths. Stations with long records were selected first and their Georgia region notated. Once 6 or 7 stations from a particular region were selected, no more stations from that region were selected, regardless of their record length. At the end of the list, the selection process was repeated using a slightly lower record count threshold. The selection process stopped once 20 weather stations were selected.

Since we are interested only in whether or not the summer season is getting longer, we did not collect any other climate variables that are otherwise essential in predicting temperature (e.g. atmospheric pressure, relative humidity, wind speed, wind direction, and cloudiness). As a result, our findings are based on the analysis of the precipitation and maximum and minimum temperature time series at the various sites.

3. Conceptual Model

We created a conceptual model of the passage of the seasons as four overlapping time periods (Figure 1). We assume that each calendar season is 13 weeks long and begins on the 21st of the transition month. In addition, we define the first two weeks of each season as the transition period between the previous season and the current season. Furthermore, the last two weeks of each season is defined as the transition period between the current season and the next season. For example, the four week spring-to-summer transition runs from June 7 to July 5 of each year. Note that June 7 is two weeks before the beginning of summer (assuming summer begins June 21) and July 5 is two weeks after the beginning of summer. The average maximum and minimum temperature across all 18 cities were calculated for the four weeks of the spring-to-summer transition (2002 to 2011) and are listed below in Table 1:

Table 1: The Average Temperature across 18 Weather Stations across Georgia during the spring-to-summer Transition

Spring-to-Summer Transition	***Maximum (F)***	***Minimum (F)***
2002	87.58	66.68
2003	86.24	68.01
2004	88.26	69.93
2005	87.20	68.61
2006	90.94	66.42
2007	89.68	67.00
2008	91.45	66.52
2009	92.34	69.15
2010	91.96	70.47
2011	93.30	68.14

To ascertain the sign and significance of any trend, a linear regression was fit to both the maximum and minimum temperatures (Figure 2). The high temperature during the spring-to-summer transition has indeed increased over recent memory (slope = 0.75, $F(1,8) = 46.76$, $p < 0.001$). However, the low temperature has remained relatively constant over this same ten-year period (slope = 0.13, $F(1,8) = 0.595$, $p = 0.463$). This suggests that the recent spring-to-summer transition is a time with high daytime highs arnd seasonally cool nighttime lows. Said another way, the spring-to-summer transition is a time of large diurnal swings in temperature forced by increasingly hotter high temperatures.

4. Cluster Analysis

In this study, we created an 8-cluster solution to classify and partition the weather records from the 18 Georgia weather stations. We appended to the data a seasonal indicator indicating the calendar season of each record (we assume that the 21st of the transition months is the start of the next season, regardless of year). Since our interest is in seasonal transitions, we included the season indicator into the clustering technique to provide for an easy identification of records that exhibited similar seasonal characteristics. We assumed that four season clusters would be identified rather easily and that the other four mixture clusters would have to be subjectively interpreted to identify the four transitional periods. Since the correlation between the maximum temperature and minimum temperature was high (r = .869), the minimum temperature was dropped as an input. Similarly, because the precipitation signal is very noisy and contains many zeros, precipitation was dropped as an input to the clustering algorithm. Using SPSS's Quick Cluster technique, we created an 8-cluster solution using the 64,659 daily maximum temperature records and seasonal indicators from 2002 to 2011. (Our clustering solution converged in just 16 iterations, determined by a maximum absolute coordinate change for each center less than .001). Table 2 below provides the cluster distribution based on seasonal definitions.

Table 2: Cluster Distributions Based on Seasonal Definitions

Calendar	***Winter***	***Spring***	***Summer***	***Fall***	***N***
Cluster 1		*21.8%*	*76.7%*	*1.4%*	6,877
Cluster 2	*31.1%*	*27.8%*	*2.9%*	*38.3%*	11,718
Cluster 3	*62.8%*	*5.7%*		*31.5%*	5,582
Cluster 4	*49.8%*	*13.0%*	*0.2%*	*37.0%*	8,973
Cluster 5	*83.3%*	*0.4%*		*16.3%*	1,105
Cluster 6	*7.4%*	*40.9%*	*22.6%*	*29.2%*	14,120
Cluster 7	*71.7%*	*2.9%*		*25.5%*	3,181
Cluster 8	*0.4%*	*32.1%*	*58.2%*	*9.3%*	13,103
Total					64,659

We used a decision-tree procedure to determine the labels for each of the clusters. To begin, a cluster was identified as representing a season if the cluster contained at least 2,000 records from the calendar definition of that season and at least 70% of the records in the cluster were from the same season. Using this filter, we identified Cluster 1 as representing summer (76.7% of the 6,877 records were from the summer season) and Cluster 7 as representing Winter (71.7% of the 3,181 records were from the winter season). Interestingly enough, autumn and spring clusters could not easily be identified. Spring records loaded substantially onto cluster 2 (27.8%), cluster 6 (40.9%), and cluster 8 (32.1%) while autumn records were distributed among cluster 2 (38.3%), cluster 3 (31.5%), cluster 4 (37.0%), cluster 6 (29.2%), and cluster 7 (25.5%). This should not be that surprising since both autumn and spring can be thought of as transition seasons: autumn, from hot summer to cold winter and spring, from cold winter back to hot summer. In this manner, autumn and spring have similar characteristics even though they are separated by a full season. Since this study is only interested in whether or not summer is arriving earlier than normal, only clusters for the spring, spring-to-summer transition, and summer need be identified.

4.1 Clusters 2, 6, and 8

Twenty-seven percent of the records in Cluster 2 are from spring records while 38.3% of them are from autumn records and 31% from winter records. Since nearly 70% of the records are from autumn and winter, we believe cluster 2 represents the autumn-to-winter transition. Similarly, over 90% of the records in cluster 8 are from spring (32.1%) and summer (58.2%) records. This provides overwhelming evidence that this cluster represents the transition from spring to summer. However, only 41% of the records that loaded onto the sixth cluster are from spring records. While not a majority, only 29% of the records were from autumn and 22.6% were from summer. Nonetheless, we consider this cluster to represent spring in our solution. Since both autumn and spring are transition months and have similar characteristics, it is not surprising that the algorithm struggled to separate these two seasons. Because of this, we present our findings two ways: one using every record in the cluster and the other using only the records from the spring, spring-to-summer, and summer clusters that are from calendar spring and calendar summer. Using a similar logic, six of the eight clusters were able to be identified (Table 3 below).

Table 3: The Identification of the 8-Cluster Solution

Cluster Number	***Identification***
1	SUMMER
2	FALL → WINTER
3	WINTER →SPRING
4	NONE
5	NONE
6	SPRING
7	WINTER
8	SPRING→SUMMER

We were not able to isolate the summer-to-autumn transition, nor were we able to identify the autumn season. Hence, clusters 4 and 5 have not been identified.

4.2 Discussion

To investigate whether there are a similar number of days each year in each cluster, we created a crosstab of year by cluster number (where the number of days in each year are tallied) and computed the chi-square statistic. Using all values in each cluster, we find that these two variables are not independent of each other (X2(63) = 2681.52, p < .001). This provides evidence that the season lengths are changing over time.

Because we are just concerned about differences in summer-like conditions and because about 1 in 3 records in the spring cluster were from autumn records, we re-run the analyses using only data from spring and summer from clusters 1, 6, and 8. Again, we see that the percentage of days in each of the clusters is not consistent throughout the years [X2(18) = 1784.594, p < .001]. The average number of spring and summer days in each cluster per city is provided in table 4 below:

Table 4: The Average Number of Days in Clusters 1, 6, and 8.

Cluster	*Spring*	*Spring-to-Summer*	*Summer*	*Total*
2002	45.6	75.7	36.1	157.4
2003	65.2	75.9	7.9	149.1
2004	57.6	70.2	26.0	153.7
2005	52.9	70.3	24.3	147.6
2006	44.4	61.0	49.8	155.2
2007	52.2	66.8	40.7	159.7
2008	51.7	65.7	34.0	151.4
2009	52.4	61.0	28.9	142.3
2010	40.1	61.3	57.2	158.6
2011	35.6	49.8	71.6	156.9

If summer is arriving earlier, then we would expect that over time, the number of days in the spring season and spring-to-summer transition states to decrease while the number of days in the summer season increases. That is, over time, clusters 6 (spring) and 8 (spring-to-summer) should have a decreasing slope, while cluster 1 (summer) should have an increasing slope. The cluster solution suggests that the average number of summer days in Georgia is indeed increasing (slope = 4.24, F(1,8) = 7.91, p = .023). There is also marginal evidence that the spring season (slope = -1.75, F(1,8) = 4.86, p = .059) is decreasing and substantial evidence that the length of the spring-to-summer transition period is decreasing (slope = -2.36, F(1,8) = 35.11, p = .0004). These three findings provide even more evidence that summer-like conditions are arriving earlier than normal in Georgia. For each year, the percent of spring and summer records that were classified in clusters 1, 6, and 8 are reported in the table 5 below:

Table 5: Percent of Spring and Summer Records that were Classified in Clusters 1, 6, and 8

Cluster	***Spring***	***Spring-to-Summer***	***Summer***
2002	29.0%	48.1%	22.9%
2003	43.8%	51.0%	5.3%
2004	37.4%	45.6%	16.9%
2005	35.9%	47.6%	16.5%
2006	28.6%	39.3%	32.1%
2007	32.7%	41.8%	25.5%
2008	34.1%	43.4%	22.5%
2009	36.8%	42.9%	20.3%
2010	25.3%	38.7%	36.1%
2011	22.7%	31.7%	45.6%

Over the decade (2002-2011), the percent of spring and summer days found in the spring cluster (cluster 6) decreased from 29.0% to 22.7%, the days in the spring-to-summer cluster (cluster 8) decreased from 48.1% to 31.7%, while the days in the summer cluster

(cluster 1) increased from 22.9% to 45.6%. This provides additional evidence that the summer season is getting longer in Georgia.

5. Heatwave Analysis

Summer is oftentimes characterized by a string of consecutive days over some threshold temperature, usually 85 or 90°F. According to one definition, a heatwave is a prolonged period of excessively hot weather which may be accompanied by high humidity. Hence, a heatwave is generally considered to be a summertime phenomenon. In this study, we investigate to determine the first day of the first heatwave of the year. If the start date occurs earlier and earlier each year, then this provides evidence that summer is arriving earlier than normal and that consequently, the transition from spring to summer is shortening. Here, we identify a stretch of 3 consecutive days with high temperatures above 90°F as a heatwave. We also measure the start of 5 consecutive days of at least 90°F temperature. This metric may capture persistence characteristics that the 3-day heatwave does not. Moreover, days that are excessively hot tend to coincide with evenings that are warmer than normal. Because of this, we also identify the first 5-day stretch with low temperatures that never fall below 70°F. Again, a negative slope would suggest that the heatwave phenomenon is being observed earlier and earlier in the year. In this study, we test to see if a) the heatwave phenomenon is being observed earlier than normal (using the year variable) and b) to determine if the slopes vary depending on what region of the state one is in (location variable).

5.1 Three Day Heatwave

Our first generalized linear model attempted to predict the first arrival of the 3-day heatwave using data from years in which each location experienced at least one 3-day heatwave. We chose three locations for this study: Atlanta, Macon, and Moultrie, GA. Atlanta, GA is located in the northwestern portion of the state while Macon is located in the central part of the state. Moultrie is about 50 miles away from Valdosta in south Georgia. The weather data at these locations were assumed to be representative of the weather patterns in each of the three regions of the state (north, central, and south). We used two predictors in our GLM, year (centered about 1993) and location. Years in which a 3-day heatwave was not experienced were removed from the analysis. As a result, 43 of the 54 data points were used in this model.

This statistically significant model (F(5,37) = 2.71, p = .0351) created by SAS's PROC GLM procedure included the interaction term and was able to explain 27% of the variance in our dependent variable. However, the interaction term was not found to be significant predictor (F = 0.41, p = .6681). Because of this, we removed the interaction term and re-ran our model with just the main effects included as predictors.

The second model was also found to be statistically significant (F(3,39) = 4.37, p = .0096). This main effects model can explain 25% of the variance in the dependent variable. The year term was not found to be a significant (Type III, F(1) = 0.33, p = .5709) predictor; however, the location parameter was a significant predictor (F(2) = 5.78, p = .0064) of the arrival of the 3-day heatwave. The results of a contrast show that the arrival of the heatwave in Atlanta is statistically different than the arrival of the heatwave in either Macon or Moultrie (F(1) = 10.97, p = .0020). On average, Moultrie residents (south Georgia) can expect that the first 3-day heatwave of the year will arrive on or about May 23rd, the 143rd day of the year. The heatwave will arrive in Macon ten days later on June 2nd and in Atlanta nearly a month later on or around June 18th.

5.2 Five Day Heatwave

Similar to the 3-Day Heatwave second model, the 5-Day Heatwave model included only main effects. Forty-two of the 54 model data points were used to create and analyze the model. This model, which is statistically significant (F(3,38) = 4.33, p = .0102), explains about 25.5% of the variance in the dependent variable. In this model, location is not found to be a significant predictor (F(2) = 2.47, p = .0982) of the heatwave arrival date. Interestingly, the year variable is the significant predictor in the model (Type III, F(1) = 5.25, p = .0275). Since summer heat typically migrates from southern regions poleward, it is no surprise that southern regions of the state experience the 3-day heatwave before northern portions of the state. It takes about a month for the entire state to experience consistent heatwave-like conditions. (According to the 5-Day Heatwave model, Moultrie residents can expect to have their first 5-day heatwave on June 20th, the 171st day of the year. Macon residents experience this extreme heatwave just 8 days later on June 28th, while Atlanta residents experience this intense heat on the July 12th.) This explains why the location parameter was not a significant predictor of the 5-day heatwave onset. We believe that the year variable is a significant predictor of the onset because it is capturing some of the leading modes of interannual variability of temperature, specifically, the El Nino-Southern Oscillation (ENSO) signal.

5.3 Five Day Low Temperature Model

Similar to the second 3-Day Heatwave Model and the 5-Day Heatwave model, the 5-Day Low Temperature model included only main effects. 47 of the 54 model data points were used to create the model. This model is statistically significant (F(3,43) = 3.00, p = .0409). In this model, year is a significant predictor (F(1) = 6.79, p = .0126) while location is not (F(2) = 0.56, p = .5777). Again, it appears that the low temperature trend is associated with some type of interannual climate variability.

We have determined that Georgia climate can be considered relatively homogeneous. As expected, the southern parts of the state warm earlier in the year than the more northern parts. In fact, the start of the 3 day heatwave usually arrives in south Georgia in late May while it begins in middle Georgia in early June and in north Georgia in mid-June. It takes about a month for the entire state to experience persistent heatwave-like conditions (determined by at least 5 consecutive days of 90-plus degree heat) for the first time. The onset of these persistent heatwave-like conditions are most likely related to interannual patterns of variability, including the El Nino Southern Oscillation (ENSO) phenomenon. In future studies, if the researcher wants to predict the onset of heatwave-like conditions, other climate indices (like the North Atlantic Oscillation, Arctic Oscillation, Pacific Decadal Oscillation) and other climate variables (that capture synoptic and mesoscale processes, concentrations of atmospheric moisture, and teleconnections to the climate indices) should be included in the model since our spatiotemporal models leave between 75 and 81% of the variability unexplained.

6. April and May

6.1 Comparison to Climatological Norms

In this study, we investigate to see if the spring months are warmer than normal in recent memory. From 2007-2011, Atlanta’s high and low temperatures in April was 72.7°F and

51.0°F respectively. The average May high temperature was 80.3°F while the average low temperature was 59.6°F. Macon, about two hours south of Atlanta, was as expected several degrees warmer. The historical high in Macon is 77.6°F in April and 85.0°F in May. However, Macon's average low temperatures are just 0.4 degrees warmer than Atlanta's low temperatures. Moultrie, about another two hours below Macon (and about 60 minutes above the Florida border) has an Average April high temperature of 79.7°F, an average April low of 54.5°F, an average high of 86.3°F and an average low temperature of 62.1°F in May.

In this analysis, we determine the number of days above the 2007-2011 climatological average high and low temperatures for all three locations. This will help us see if the perceived phenomenon (an early onset of summer) is limited to a specific part of the state or if it is felt across the state. To formally test for a relationship between location and climatological patterns, we perform four chi-square tests of independence. A large chi-square statistic would indicate that the climate in the various locations is not similar enough to consider them jointly and should probably be analyzed separately. A small chi-square statistic suggests that the regional climates are similar.

From 2007-2011, Atlanta experienced 85 April days (57%) with high temperatures above its climatological average. Similarly, Macon experienced 86 days with above average temperatures. Moultrie had 93 of its 150 April days (62%) warmer than normal. When compared together, there is no evidence ($X^2 = 2.0778$, $p = 0.35$) of a relationship between the proportion of days with high temperatures above their respective averages and their location in the state.

Interestingly, 61% of the days in Atlanta had an April low temperature that was warmer than normal. This does not appear to be consistent across the regions of the state ($X^2 = 12.0745$, $p = 0.0024$). In fact, Macon (which is in central Georgia) had 55% of their lows below the climatological average. Similarly, Moultrie (which is in southern Georgia) had 56% of their lows below their climatological average.

There is no evidence of a relationship between the proportion of anomalously high temperatures and location in May. Neither the high temperature analysis ($X^2 = 0.9136$, $p = 0.63$) nor the low temperature analysis ($X^2 = 3.09$, $p = 0.21$) found significant relationships. Generally speaking, between 59% and 68% of the May days in Georgia had above average low temperatures, while between 54% and 59% of the days had anomalously warm high temperatures. This analysis suggests four important findings:

1) There are more days in April and May with warmer than normal high and low temperatures than there are days with cooler than normal temperatures.
2) The proportion of days with above average April and May temperatures is relatively consistent throughout the state. This implies that the entire state is under similar synoptic and mesoscale meteorological conditions in these two months.
3) It may be prudent to investigate changes in April low temperatures by statewide region. While no post-hoc analysis was formally performed, it is clear that the northern part of the state (Atlanta) behaves differently than the middle and southern parts of the state (Macon and Moultrie) when it comes to April low temperature.
4) For the past five years, the last two months of spring (April and May) appear to be warmer than normal.

6.2 April Temperatures

A panel plot of the April and May monthly average high and low temperatures in each city over an 18-year time span (1994-2011) was created (not shown). Each plot contains at least one periodic signal that dominates its structure. It appears that there is a periodicity of $n=4$ in the high temperature graphs and a periodicity of $n=7$ in the low temperature graphs. In order for a linear trend to appear, the signal must be decomposed into its periodic and linear components. To remove the periodicity, we applied the lag-d differencing operator ∇_d , defined as $\nabla_d = X_t - X_{t-d}$ with $d=4$ for the April high temperature time series, $d=7$ for the April low temperature series, $d=2$ for the May high temperature series and $d=3$ for the May low temperature series. The partial autocorrelation functions of the April periodicity-removed time series (not shown) are well within confidence limit bounds, suggesting that the periodicity was successfully eliminated.

From initial visual inspection of the three April high-temperature periodicity-removed time series, it appears as though there is a slight general increase in April high temperatures over time. The periodicity-removed temperature difference range was largest in Atlanta (from -10.6°F in the 1998-1994 value to 5.6°F in the 2011-2007 value). However, this increase is not supported by a linear regression predicting the periodicity-removed temperature trends over time (b = 0.423, F(1,12) = 2.202, p = 0.164).

Visual inspection of the three April low temperature periodicity-removed time series suggest a steady April low temperature over the years (not shown). Upon closer visual inspection of the data, it appears as though there are three distinct signals embedded. From lag period 1 to lag period 3, the temperature difference is increasing. From periods 4 to 8, the difference has a negative slope and is decreasing. But from period 9 to 11, the difference increases again. To test this, we partitioned the data into these three groups to see if any large and significant slopes would be uncovered using just these smaller time frames. Several large slopes were identified (e.g. lag 9 – lag 11 analysis for all three cities) even though none of the slopes were significant (Moultrie was close, p=.058). This was not surprising since the regression degrees of freedom were very small (either 2 or 4). Using these small sample sizes, even moderate-to-large effect sizes may appear statistically insignificant. Nevertheless, the analysis of the r-squared values of each model is encouraging. Since each model contained just one predictor, a lag time step indicator, the model r-square value identifies the amount of variability of the lagged temperature differences explained by the indicator. With the exception of the middle years in Macon (R^2 = 27.5%), the lagged indicator explained between 56.3% and 99.2% of the lagged temperature differences, depending on the location and partition of the time series. Despite the fact that the slopes were statistically insignificant (most likely due to the small sample sizes), the r-square analysis provides additional evidence that the lagged April low temperature differences are linear with the sign of the slope depending on time. Since the third time phase represents temperature differences from 2011-2004 to 2009-2002 and has a positive slope, this suggests that Georgia residents may be observing an increase in April low temperatures over the past decade.

6.3 May Temperatures

Unlike in April, in May, there is a clear temperature dependence on location (not shown). The blue Atlanta (in north Georgia) graph is consistently below the Macon and Moultrie graphs. This suggests that northern Georgia does not reach as high of temperatures as does middle or southern Georgia. So, even though the percentage of days above average in May does not appear to vary by region (our earlier study), there does appear to be differences in the actual temperatures.

In addition, it appears as though the May high temperature has a 2-year, 3-year, and 4-year periodicity. Similar to the April analysis, we attempt to remove this periodicity by applying the ∇_2 difference operator. However, the differencing operation was not successful in removing all periodicity because the graph of the residuals still has consistent interannual periodicity (not shown). To protect degrees of freedom, we elected not to re-difference the signal. Rather, we isolate phases of the signal and regress the time differences in the last phase as we did in the April low temperature case.

The last warming trend captured in the data started at indicator 14: the difference between the 2009 and 2007 May high temperatures. This means that May 2009 was warmer than 2007, May 2010 was warmer than 2008, and May 2011 was warmer than 2009. A positive slope means that the 2009-2011 difference was larger than the 2008-2010 difference, which in turn, was larger than the 2007-2009 difference. Hence, a positive slope would indicate increasing May temperatures over time.

This slope was positive for all three regions for the last time phase. The one-predictor regression could explain between 78.30% and 99.99% of the variability of the lag-differenced temperatures. Interestingly enough, Macon's slope was marginally statistically significant (slope = 5.22, t = 8.37, p = .075) while Moultrie's slope was statistically significant (slope = 4.41, t = 84.87, p = .008). Despite being able to explain 78.3% of the variance in the temperature variable, Atlanta's effect was not large enough to be considered statistically significant. At least two of the three findings provide evidence that May high temperatures in Georgia are higher in recent years (since 2007) than in years past.

The last major warming trend of May low temperatures occurred at lag indicators 12-14. Generally speaking, the difference in May low temperatures from 2007 to 2010 was larger than the difference from 2006 to 2009, which in turn was larger than the difference from 2005 to 2008. This difference is statistically significant only in middle Georgia (Macon, p = .041). The increase was small in both Atlanta (slope = .27, p = .667) and Moultrie (slope = .62, p = .260). The sign of the difference actually reverses during the last lag indicator. The difference in temperature from 2008 to 2011 was smaller than the difference from 2007 to 2010.

Taken all of the analyses together, it is clear that the May high temperature in Georgia has been increasing over the past decade. Low temperatures in May are slightly warmer than normal but this difference is insignificant. This means that unless a Georgia resident lives in the middle of the state (e.g. Macon), they may not notice this increase in low temperatures. Moreover, last year's average May temperature was about 4-5 degrees cooler than the average low in 2010.

To conclude, it is the warmer than normal April low and May high temperatures that lend residents to believe that summer is arriving faster and spring is getting shorter. Residents with long memories may also recognize that the month of April nowadays is slightly warmer than April two decades ago (even though this warming is not significant).

6.4 Discussion

In the state of Georgia, the summer months of June, July, and August are typically hot, regardless of the year under consideration. So, for there to be a perception that summer is arriving earlier and earlier each year, summer-like conditions must be observed earlier in the year, perhaps in May or even April. To investigate this, we perform two analyses. From the first analysis, we observed that over the past five years (from 2007-2011):

- There were more days in April and May with warmer than normal high and low temperatures than there are days with cooler than normal temperatures. This provides evidence of warmer than normal spring seasons in recent years.
- The proportion of days with above average April and May temperatures is relatively consistent throughout the state. This implies that the entire state is under similar synoptic and mesoscale meteorological conditions in these two months.
- The northern part of the state (Atlanta) behaves differently than the middle and southern parts of the state (Macon and Moultrie) when it comes to changes in April low temperature.

From the second analysis, we hypothesize that the anomalously warm low April temperatures followed by the anomalously warm high temperatures in May provide evidence of a warmer than normal spring season.

7. Results and Discussions

We investigated several metrics to see if summer was arriving in Georgia earlier than the calendar says that it should. If summer was arriving earlier than normal, we would expect:

- the temperatures in the transition period to be more like summer than spring in the latter years.
- the transition period from spring to summer to be shorter while summer-like characteristics persist longer.
- summer-like phenomenon, like heatwaves, appear earlier than normal.

Using empirical calendar definitions of the transition periods and the temperature records from 18 Georgia cities, we found that the maximum temperatures of the four-week spring-to-summer transition have indeed been increasing over the past decade. The average temperature increased nearly six degrees from 87.6°F in 2002 to 93.3°F in 2011. The minimum temperature did not increase very much during this same time period.

To investigate the length of the spring-to-summer transition, we performed a cluster analysis using the temperature records from the same 18 Georgia cities. The clustering solution was able to identify separate clusters for the summer season, the spring season, and the spring-to-summer transition. We found that the average number of days in the clusters identified as spring and spring-to-summer transition decreased over time while the average number of days in the summer cluster increased. To investigate whether heatwaves were occuring earlier in the year, we used daily temperature records from 1994-2011 from three Georgia cities: Atlanta, Macon, and Moultrie.

Results from a generalized linear model (with just year and location as predictors) suggest that the temporal variable is not a statistically significant predictor of the start of the 3-Day heatwave, while the spatial variable is. This is because the southern parts of the state warm earlier in the year than the northern part. However, results from two separate GLMs suggest that the temporal variable is a significant predictor of the start of the 5-Day heatwave and the 5-Day low temperature trend, but the location parameter is not. Further analysis shows that it takes about a month from the first 3-Day heatwave for the entire state to experience persistent heatwave-like conditions (determined by at least 5 consecutive days of 90-plus degree heat) for the first time. We believe that the location is not significant in these models because by late June/early July, the entire state is warm enough to experience heatwave-like conditions. Furthermore, the temporal variable was most likely found to be significant because it captures some interannual temperature variability possibly related to ENSO.

In our final study, we test to see if the spring months of April and May have been warmer than their long term climatological average temperatures. To do this, we collected the daily high and low temperatures in April and May from 2007-2011 and compared these to the climatological average temperatures at the Atlanta, Macon, and Moultrie weather stations. We found that there are more days in April and May with warmer than normal high and low temperatures than there are days with cooler than normal temperatures. This suggests a warmer than normal spring. In addition, we found that the proportion of days with above average April and May temperatures is relatively consistent throughout the state. However, the northern part of the state behaves differently than the middle and southern parts of the when it comes to changes in April low temperature. A larger percentage of April nights in Atlanta (61%) were warmer than its climatological average as compared to Macon (55%) and Moultrie (56%). This phenomenon may be related to the Urban Heat Island Effect that traps heat in urban settings.

To see if April and May are getting warmer, we analyzed 18 April and May monthly high and low temperatures (1994-2011). A graph of the four time signals suggests additional interannual periodicity in the signals. So, after differencing the time signals, we created four separate linear regressions of temperature on time. We found that over the course of the 18 years:

- there is a slight general increase in April high temperatures over time, but this increase in not statistically significant.
- when broken into three distinct temperature regimes, there is an increase in April low temperatures over the past decade.
- the increase in May high temperature over time is statistically significant in middle and south Georgia, but is not significant in north Georgia.
- low temperatures in May are slightly warmer than normal but this difference is insignificant.

In conclusion, we believe the Georgia residents' assertion that summer is arriving earlier. In our studies, we have found evidence that the transition period from spring is getting shorter and hotter while the summer period is getting longer. In addition, April low temperatures and May high temperatures are warmer than normal. On the other hand, heatwaves have not arrived earlier in the year, as originally hypothesized. We conclude therefore that it is not the persistence of excessively hot days strung together that makes one believe that summer has arrived early. Rather, it's the shortening of the transition period between spring and summer and the warmer than normal temperatures during the spring and the transition to summer that is most responsible for the feeling that summer has arrived before the calendar says it should.

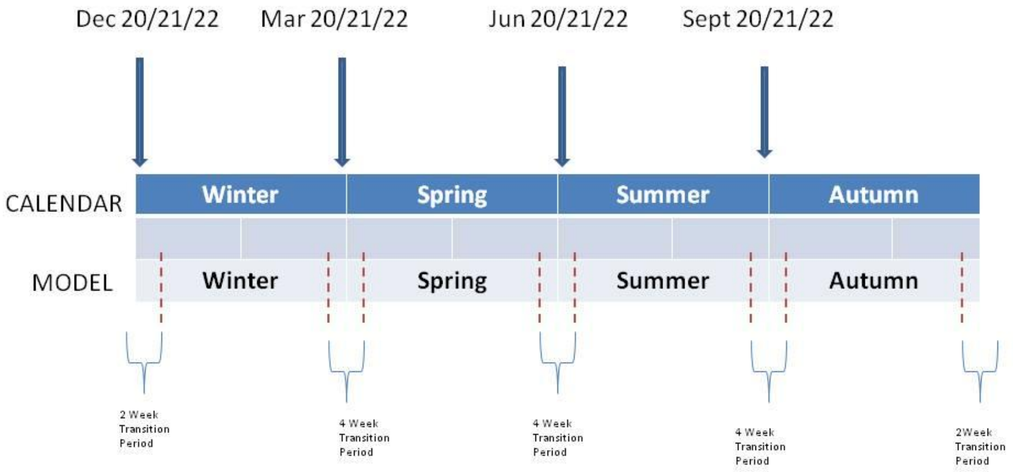
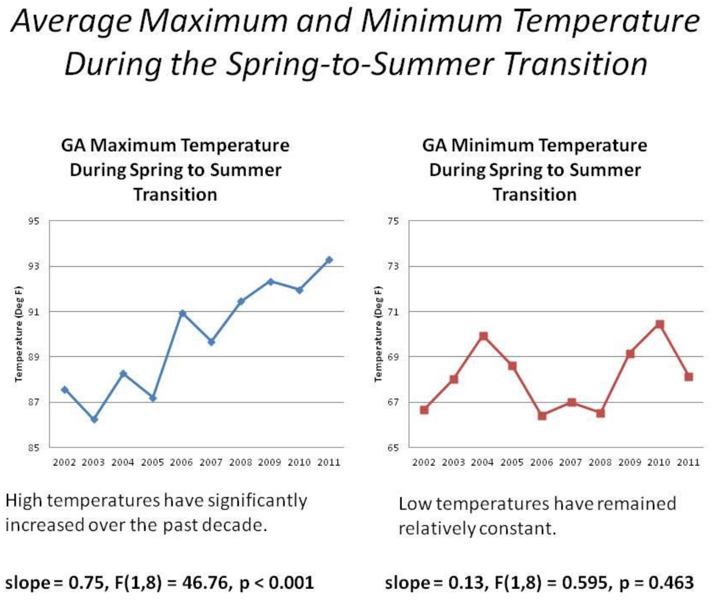


Figure 1: Calendar Seasons vs. Conceptual Model of Seasons



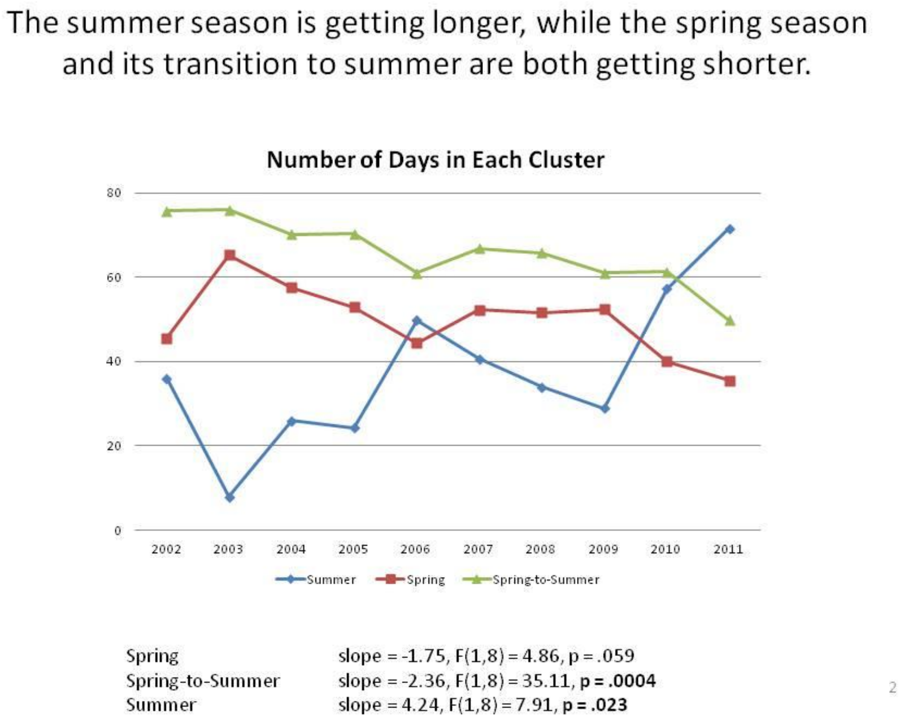
High temperatures have significantly increased over the past decade.

slope = 0.75, F(1,8) = 46.76, p < 0.001

Low temperatures have remained relatively constant.

slope = 0.13, F(1,8) = 0.595, p = 0.463

Figure 2: Average Temperatures during the Spring-to-Summer Transition Period



The summer season is getting longer, while the spring season and its transition to summer are both getting shorter.

Number of Days in Each Cluster

Spring	slope = -1.75, F(1,8) = 4.86, p = .059
Spring-to-Summer	slope = -2.36, F(1,8) = 35.11, **p = .0004**
Summer	slope = 4.24, F(1,8) = 7.91, **p = .023**

Figure 3: Number of Days in Each Empirical Cluster

References

Brockwell, P. J. and R. A. Davis. *Introduction to Time Series and Forecasting: Second Edition*. Springer, 2002.

National Climatic Data Center. Data Retrieved May 5, 2012, from http://www.ncdc.noaa.gov/cdo-web/search.

Provano, Joel and Morris, M. (2011, June 7). Georgia climatologist predicts hotter-than-normal summer. Atlanta Journal-Constitution. Retrieved from http://www.ajc.com