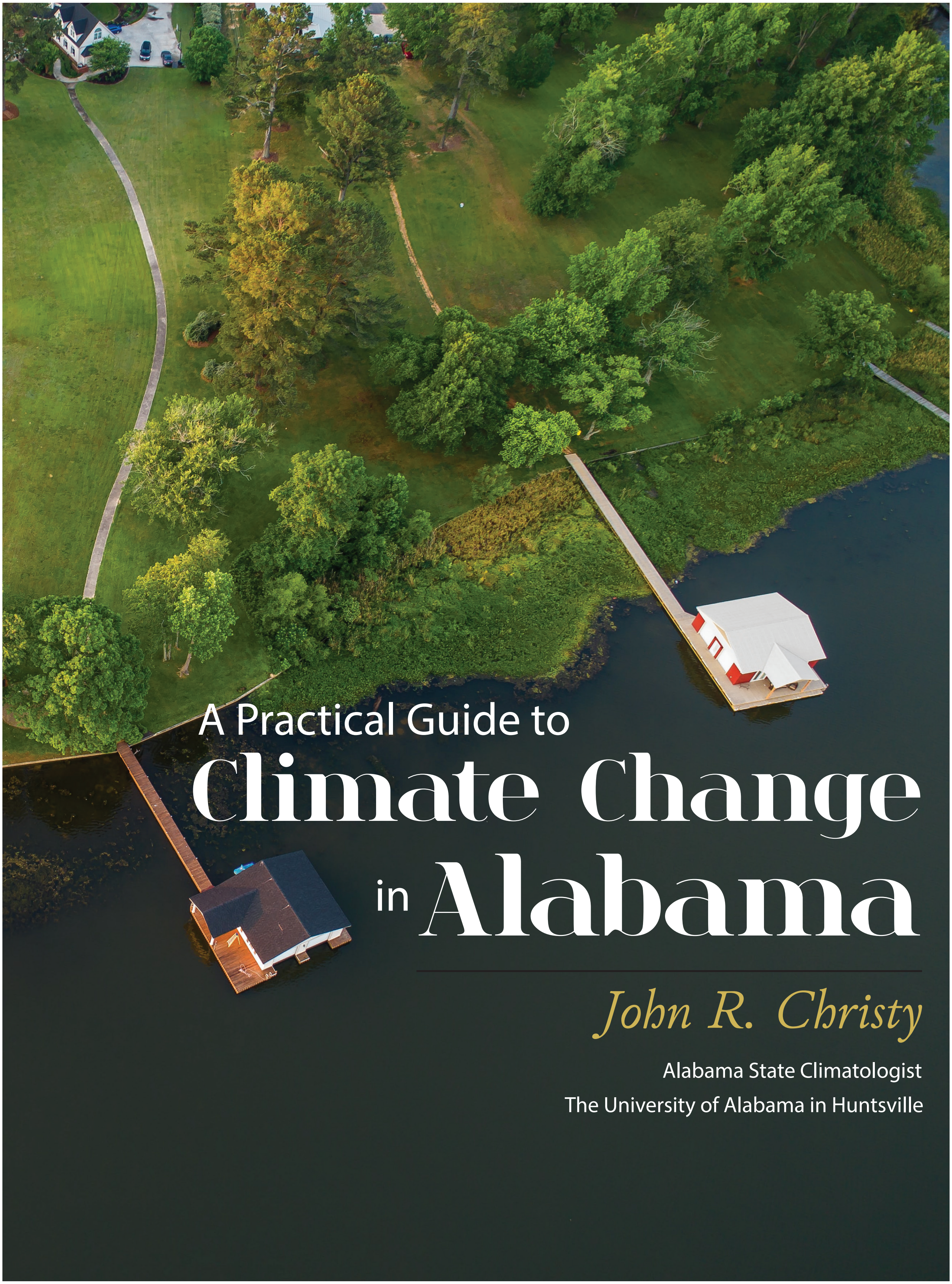

A Practical Guide to
Climate Change in Alabama

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Summary

Any climate variable will show some type of change between different periods whether they be weeks, months, years or millennia. Knowing "why" such changes occur however is often unsolvable because our climate system is an expression of two chaotic and turbulent fluids – the atmosphere and the ocean - which together can create an infinite variety of weather and climate patterns all on their own. This natural variability makes it difficult to determine the impact of extra greenhouse gases on the climate system because their influence is less than one percent of the total energy flows which already vary by more than this through time.

Upon examination of several important Alabama climate variables such as extreme summer heat, yearly rainfall, heavy rain events, droughts, snowstorms, hurricanes, and tornadoes, we find no significant changes associated with the increasing concentrations of greenhouse gases.

Over the past half-century, sea level has risen at variable rates along the Gulf Coast with a reasonable estimate for the Alabama portion of a continued rate-of-rise of about 1 to 1½ inch per decade.

The latest theoretical climate model simulations have been unable to replicate the types of changes in climate variables that Alabama has experienced since the late 19th century and so offer little guidance for the future. However, being better prepared for the extreme events that have already been observed, and will happen again, is a policy that is based on the evidence.

Climate Change in Alabama

What does "climate change" mean? And, what does it mean for Alabama? This issue is of great concern for many today whether one deals with policy, industry, academia, personal livelihood or the next-door neighbor. Since these arenas of life are tightly interconnected, the impact of any type of climate change on one aspect touches them all.

The current focus on climate change concerns the potential impact that extra greenhouse gases (GHGs) might have on the climate. These GHG emissions are entering the atmosphere as a result of (mostly) energy production which has powered modern economies and lifted billions out of poverty. The main human-generated GHG is carbon dioxide (CO_2) - a byproduct of combustion of carbon-based fuels such as coal, oil and natural gas, though other processes like cement production add to the total.

Fortunately, CO_2 is non-toxic in any foreseeable atmospheric concentration and is even a boon to the biosphere which ingests CO_2 as its (and thus our) life-sustaining food. Indeed, evidence is clear that over the past few decades the Earth has been "greening" as a result of this extra "plant food" humans have returned to the atmosphere. In fact, agricultural experts say CO_2 fertilization has facilitated an increase in food production. This agricultural greening also comes with more efficient water use by crops since less water is lost in transpiration as plants bring in the needed CO_2 more efficiently. Of course, increasing productivity also depends on other factors such as added nitrogen and mini-nutrients for sustained growth and nutrition, but there is no doubt, at present, that CO_2 has had a positive impact on food production worldwide. This benefit is likely to continue into the future.

Of concern then are that potential changes in the climate due to extra CO_2 (i.e. increased temperature, increased droughts, greater precipitation, etc.) might also impact food and natural biogenic production as well as societal priorities such as the availability of energy, economic development and improvement of public health. This is why the climate impact of increasing CO_2 is important to examine.

The policy dilemma is fairly clear – on the one hand, there is no question that carbon-based energy, due to its affordability, reliability and accessibility, enhances and extends human life (as well as plant life). Yet, on the other hand, could there be a serious or even existential downside to this low-cost source of energy?

In this report we concentrate on changes in climate and not their impacts on other aspects of society. The challenging question to answer here is, "How does/will the extra CO2 impact the climate of Alabama?" rather than addressing in any detail the policy side of the issue.

With so much attention drawn to this concept of "climate change", the Alabama State Climatologist has prepared this (largely) non-technical report to inform the reader about climate change in Alabama and what this may mean for our state. We shall focus on those aspects of climate, i.e. temperature, rainfall, hurricanes, tornadoes, sea level, etc., that are important for the people of Alabama and for our future economic development. A large portion of the references cited here were generated through the State Climatologist's Office as there are only a few scientific articles available which specifically address our state's recent climate. A relatively small number of published references will be cited, but this report will not be written in a scientific style where each assertion is normally referenced.

There is no shortage of assessments which claim to understand the topic of climate change, especially with claims (hypotheses) about how the increasing concentrations of GHGs might be involved. Many of these reports are published with the aid of environmental advocacy organizations which have specific policy goals in mind and so construct the assessments to support their goals. In this report, we shall let the observations and other scientifically-defensible information dominate the discussion. It is intended that the information provided herein should be reproducible and be able to withstand cross-examination. As has always been the case however, scientific understanding about a complex issue is never complete, i.e. there is an enormous amount that we don't know about the climate, so this report seeks to present the best information available at this time for Alabama. Updates will certainly be needed as new information is discovered.

It must be understood that the extra CO2 (along with other less impactful GHGs) has and will continue to cause a change in a small component of the energy-flow processes in the climate system, about 1 part in 200. Because this is such a small fraction of the overall system, teasing out its impact within the much more dominant and variable energy flows is exceptionally difficult.

While some parts of the climate's various energy flow processes in models are based on direct, fundamental physical concepts (e.g. fluid motion, radiative transfer, basic thermodynamics), the actual partitioning of energy flows is tied to many uncertainties as they try to estimate major effects of turbulence, land surface energy exchanges and clouds which are generally too small to directly represent. These uncertainties are seen in part by variable results among the latest theoretical models. For example, the global temperature impact of aerosols in these models over the past 170 years varies from -0.9 °C to +0.1 °C or an uncertainty range of 100% from the average! (IPCC, 2021). Such information exposes the serious ambiguities that inhabit current modeling experiments.

This "uncertainty" problem will be mentioned throughout the report, but the basic assumption from the start is that the extra GHGs will cause some level of extra warming. So, answering these related questions will be difficult: What will the magnitude and progression of this extra warming be? How much of the change we've seen is due to natural variability and how much to the extra GHGs? How confident can we be in future warming scenarios? These are critical and as yet unanswered questions, especially for the tiny portion (0.027%) of the globe we call Alabama.

There will be several charts in this document, most of which are derived from data in the digital climate archives created and maintained by the National Oceanic and Atmospheric Administration's National Centers for Environmental Information (NOAA/NCEI). Through the years NOAA/NCEI has provided increasing amounts of data on continuously-improving accessible platforms for extremely convenient analysis. This report would have not been possible without the excellent services of NOAA/NCEI. Additionally, some of the early data were manually keyed-in by the Climatology Office for a longer look at weather patterns.

As this report begins, one must step back and think about what exactly does the phrase "Climate Change" mean?

Climate Always Changes

"Change" implies that one may calculate a difference between at least two situations, in this case, a difference in the characteristics of atmospheric phenomena over various periods of time. How we define these characteristics is what we mean by "climate". These characteristics (i.e., temperature, rainfall, etc.) must then be measured with sufficient precision to determine whether we are confident that changes can be properly calculated across the time periods chosen for assessment.

There is then the question of what time periods do we consider? We can look back at Alabama's climate prior to just 20,000 years ago to see a long, cold period in which the state was partially covered with a blue spruce forest and endured weather now seen in the upper Midwest. It was a time when so much of the ocean was locked up in continental ice sheets that the coastline of Alabama extended 50 miles into the Gulf where trees were able to grow on dry land. Today, their drowned trunks reside 60 ft below the water surface. The "climate" has certainly changed (warmed dramatically) from this previous ice-age environment not so long ago.

If we go further back in time, Alabama resided under a shallow sea for millions of years. The ubiquitous limestone, embedded with marine fossils, stands as testimony to this submerged environment. Moving forward to the most recent, and relatively brief 10,000 years, various studies show that the temperature of the globe was quite warm at first but that many regions experienced a temperature decline, reaching their coldest point during the decades prior to about 1880. So, caution is advised when climate change assessments begin in the 19th century because they are starting during a period that was, for many places around the world, likely near the coldest in the last 10,000 years. With that being the case, a natural rebound of warming would not be unexpected. However, as we shall see, Alabama's recent climate does not fit this global pattern of warming since the 19th century.

So, there are many aspects to consider when defining climate change, such as which variables to study and which time periods to compare. However, one important point must be kept in mind. Because the climate system is a naturally-varying dynamical system in

which two turbulent fluids (atmosphere and ocean) interact, there will always be differences or "changes" in atmospheric characteristics between any two periods we chose – extra GHGs or not. In other words, no two millennia, no two centuries, no two months and no two weeks of Alabama's climate have ever been exactly the same. As a result, by the nature of the way the climate system works as a whole, there always has been and always will be "change."

Further, and this is very important, though we are able to measure many types of "change" to answer questions about "what" the climate has done, we are far more handicapped in answering the more difficult question, "why." This question is made so difficult because the natural climate system can create considerable change all on its own as will be shown for Alabama. Given that the natural system can produce tremendous variations, making useful predictions of the impact of one tiny component (extra CO_2) a murky, and some would say, almost impossible problem. As we shall see, various sophisticated and expensive attempts to do so simply don't agree with each other and don't agree with the actual observations.

Repeating, Alabama's "climate" *will* show change no matter which periods are selected for comparison.

Considering the length of our memories (i.e. a human life span) and the operating lifetime of the supporting infrastructure that we build to sustain us, it is reasonable to examine changes on time scales of 25 to 50 years. Scientifically, this is rather naïve because the flow of time and the ubiquitous dynamical change that continually occurs, are, for all practical purposes, eternal. But for general utility, given the time frames we humans build our climate-protection infrastructure and grow our food, documenting changes over this "blink-of-an-eye" period may have informative value for planning and adaptation.

Extremes

The key characteristics of climate that constrain ecosystems are generally those at the extremes, i.e. the hottest, coldest, wettest, driest, windiest, and so on. These extremes impose a limit as to which species of flora (including crops) and fauna (including sources of human protein) will be able to thrive in the state. But again, we see from the long history of climate that the collection of plants and animals which have inhabited the state has experienced dramatic changes as the climate has varied through enormous cycles.

There is this aspect too. The magnitudes of the extremes (and the related notion of "records") are dependent on the time sample over which measurements are available. This places considerable limitation on the usage of the term "record" as it carries the idea of "worst ever" or that popular term often used today - "unprecedented". As indicated earlier, if we could see the "record" or "worst" events calculated over a time sample different than today, say 1000 to 1200 C.E. rather than 1885 to 2020, we would likely be surprised at how the climate-extremes change from one period to the next (there will be an example later). Recall that the 19th century was one of the coldest centuries in the past 10,000 years, so the fact our record-keeping began in that period will influence all of our results.

Or, one could also think of it this way. We have observations for about 135 years in Alabama. Over this period, we can calculate the extreme values for every type of statistic desired, hottest day, hottest 3-days, hottest week, hottest fortnight, hottest month, etc. There are dozens and dozens of extreme parameters that may be determined. However, based on very simple statistics, we would expect fully half of these extremes to be exceeded in the next 135 years without any human influence at all. Extreme events will continue to occur naturally.

Too, various types of paleoclimate evidence (tree rings, ice cores, lake sediments, etc.) give us some glimpses into events prior to the 19th century and indicate that many ancient extremes appear well outside of our recent experience (i.e. being "worse" than our "worst ever") – all due to natural dynamical processes. The point here is to be cautious about those who attempt to stir up excitement about "record" events due to the fact we only have a tiny slice of time - that "blink-of-an-eye" - over which we have observations.

The two climate variables that impact our lives most readily are temperature and precipitation. We shall begin with these two because our earliest observations from the 19th century are mostly just temperature and precipitation – indicating that 150 years ago, these two components of the climate system were known to be important then too. We shall start with changes in temperature.

Changes in Temperature

As noted, some type of change will be found in a comparison between any two periods. With regards to temperature, there are a number of ways to investigate change. As a project to find an answer to the question "When was the hottest summer?", the State Climatologist built a dataset of Alabama temperatures that used information not readily available to the normal investigator and which began as early as 1872. The results of this and other efforts have been published in the scientific literature (Christy 2002, Christy and McNider 2016).

Some background is needed here. The temperature metrics most often recorded are the daily high extreme and daily low extreme, commonly referred to as the daily *high* and *low* temperatures. The former occurs most often in mid-afternoon and the latter near sunrise each day. As it turns out, the temperature of the summer months has less variation from year to year than other seasons and is therefore a more stable metric to consider in detecting long-term changes for discussion here. As well, the summer afternoon *high* occurs when the atmosphere is generally well-mixed in all directions (including vertically), so that the summer *high* is more representative of a larger volume of air, and therefore, again, is a more stable metric for analysis.

Then there is the situation in which between 1883 and the 1890s several Alabama sites were established as Cotton Region Stations which recorded observations only from mid-April through October each year for agricultural purposes, so winter data are not available. Finally, since our concern is to investigate whether "warming" is occurring, by looking at the time of day and time of year representing the warm extreme, we can better determine if change in this current upper constraint of heat is happening. In other words, are our *highs* moving even higher and thus becoming a threat to established species and activities? For these reasons, we shall focus on daily *high* temperatures in the summer to tease out long-term changes in climate.

The research paper, "When was the hottest summer?" was subtitled "A State Climatologist struggles for an answer" to remind the readers that building climate-type datasets can be quite difficult and produce results with some uncertainty (Christy 2002). In this and other publications, the author delved into the details that must be considered in the attempt to construct a dataset that is consistent through time so that "change" over time may be calculated with some level of confidence.

In Christy and McNider 2016, the focus was on three regions centered on the three largest metro areas in the northern and central part of the state; from north to south, they were Huntsville, Birmingham, and Montgomery. Each area utilized stations within a roughly circular region about 50 miles in radius (Fig. 1). Mobile was added for the analysis below using the identical processing and merging methods described in the paper for the other three regions. Below are the results for the four regions (Fig. 2) through the summer of 2021.

Guntersville, Alabama
Image by Nathan Anderson via Unsplash.com

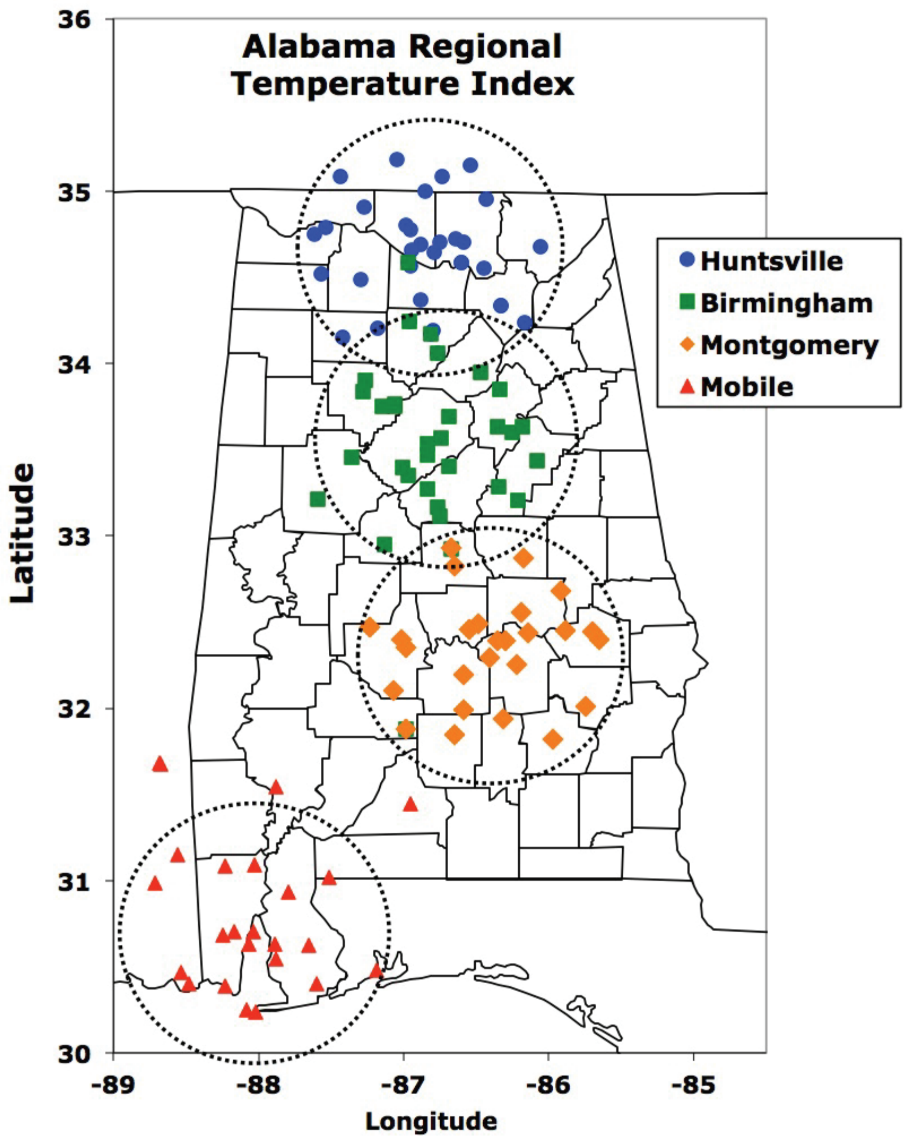

Figure 1. Four regions for which long-term summer high temperatures were constructed. The location of the stations used in the construction for each region are indicated by the symbols.

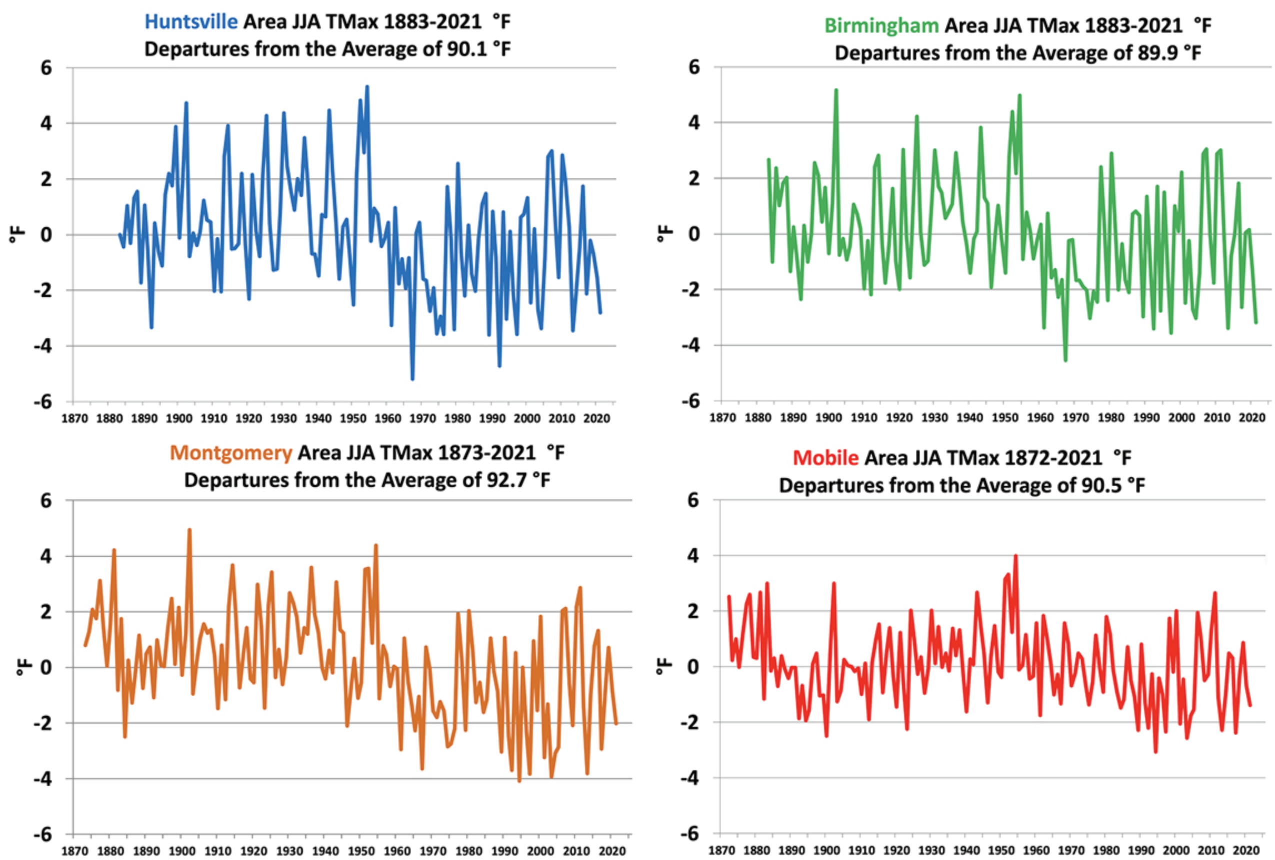

Figure 2. Summer (June, July, August) average daily high temperature departures from average (stated in titles) for four metro regions in Alabama ending with the summer of 2021.

For geographic reference, the distance from Huntsville (northern-most area) to Mobile (the southern-most) spans about 300 miles. The 4-region absolute temperature averages are fairly similar with Montgomery being the warmest at 92.7°F (33.7 °C). The impact of the moderating influence of the Gulf's waters is seen in Mobile where the range from warmest to coolest years is smaller than the other inland stations. Since each region was calculated from differing sets of stations, the very high correlation among them (especially the inland stations) gives good confidence in the results. Further, the correlation between the 4-station average and the NOAA/NCEI statewide temperature anomalies (1895-2020) is +0.99.

One common feature in these charts is the warmth in 1951-1954 and in particular the shift to cooler temperatures immediately thereafter. Indeed, regarding the idea of "change" one can see a sudden change in temperature between 1954 and 1955, though muted in Mobile. Looking at the three inland areas, we find a remarkable result that the 60 years ending in 1954 averaged 1.8 °F (1.0 °C) warmer than the 60 years after 1954. This 140+ year period of Alabama's climate indicates a lowering of temperatures over time, but would be better described as a shift to cooler temperatures at one point in time (1954/55). Note that Alabama temperature does not follow world-wide values which were coolest in the 19th century and warmest today.

In terms of "hottest" summers for the state as an average of these four regions, the top five rankings are 1954 (hottest), 1902, 1952, 1943 and 1925. The warmest summer, 1954, was 4.7 °F (2.6 °C) above average. The five coolest summers were 1967 (coolest), 1992, 1997 and a tie between 1994 and 2013. Indeed, the ten coolest summers occurred after 1960 and nine of the ten warmest summers before 1960.

Using now the NOAA/NCEI temperature data for Alabama that begins in 1895, there is a clear difference between the change in daily *high* temperatures and that of the *low* temperatures. Every trend calculation starting from 1895 through 2010 and ending in 2020 produces more warming in the *lows* than the *highs*. In fact, most of the trends for the *highs* are negative while all of the trends from the *lows* are positive no matter from which year one started. So, days are not warming while nights are clearly warming – a feature found in other studies of this type. This result will be discussed in the next section on extremes where we also find that extreme *highs* and *lows* are changing in different ways.

One can immediately see how determining the warming effect on Alabama of the extra GHGs is a problem as the temperatures of the recent decades (which should be responding to the warming influence of extra GHSs) have actually been cooler than earlier decades when this influence was essentially absent. A lesson here is that for small areas of the size of a state or two, the long-term natural variations are typically greater than that exerted by extra GHGs.

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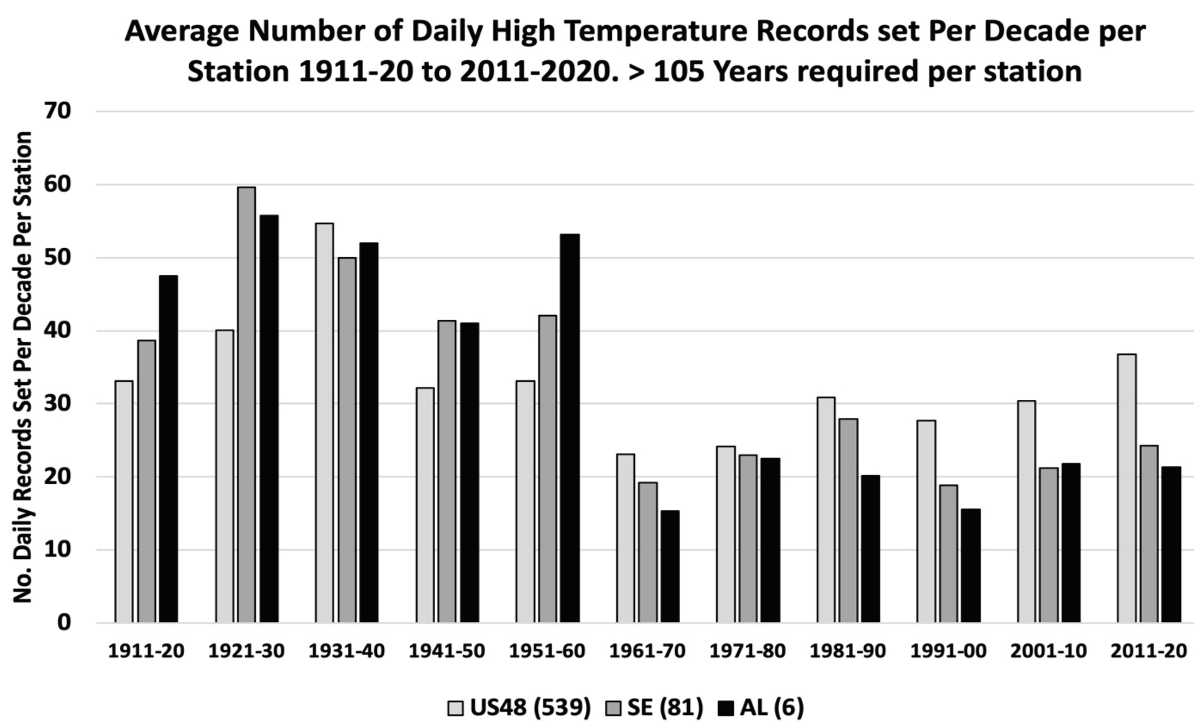

Figure 3. Total number per decade of daily high temperature records set per station for Alabama, the Southeast (AL, GA, FL, MS, NC, SC, TN) and the conterminous US. The number in parentheses is the number of stations used in each region. A station was required to have > 105 years of data to be included. Data source, NOAA/NCEI/USHCN.

Changes in Temperature Extremes

As noted earlier, a climate metric of considerable interest is the extreme of any parameter, and for temperature that would be the hottest or coldest. Are we experiencing more record hot or cold days over time? One way to look at this is to check each calendar day of the year and determine the year in which the warmest and coldest temperature was observed. For example, in the analysis to follow, we check all of the 1 January daily temperatures from 1911 to 2020 and determine the year in which the hottest 1 January occurred and the year in which the coldest was observed. After processing all days of the year one at a time for each station, we will then have the year of the hottest and coldest value for each day of the year. These will be composited into decade totals.

To perform this analysis, stations must have data essentially for all years, so for this we started in 1911. There are 11 decades in this sample, so that if weather were totally random, the expectation would be that about 33 daily records would occur in each decade (=366/11) on average per station.

Figure 3 may reveal a surprising result to many. For Alabama, as well as the Southeast (SE) and the 48 conterminous states (US), we see that a disproportionate number of *high* temperature records was set in the first 5 of these 11 decades. Recall that the expected value of 33 records per decade would represent random temperature changes and that a warming environment should be characterized by an increasing occurrence. Neither of these expectations is depicted, even for the US. In other words, the local and brief weather patterns that produce extreme *high* temperatures show a decline rather than a pattern of randomness (flat trend) or a pattern of experiencing more hot extremes over time (a rising trend). This is another example of an important metric that does not yet indicate an anticipated response to the warming effect of the extra GHGs since the considerable natural variations are dominant on these time and space scales.

There are a few relatively minor differences among these regions. Alabama experienced 68% of its *high* temperature records in the first 5 decades (about 50 records per decade), the SE – 63% and the US - 53%. Note that for the entire conterminous US, the average station experienced 55 of the 366 possible records in the single decade of the 1930s. This total was dominated by the Plains and Midwestern states when the Dust Bowl extremes occurred.

The same analysis was performed on the daily *low* temperature records for three regions already discussed and shown in Fig. 4. A different result is evident. Among the regions there are two similarities to note, (1) all experienced their fewest number of record *low* temperatures in one of the last two decades and (2) there has been a substantial decline since the 1980s. For Alabama and the Southeast, the frequency of cold records was highest in the 1960s through 1980s whereas the US experienced the most in the first two decades. This recent drop in the number of cold temperature records aligns with the result in the previous section which found that the average daily *low* temperature has been rising.

A decline in the number of record *low* temperatures (or warming in average *low* temperatures) would be expected in a warming environment. Given the two figures (p. 10 and 12), we have a confident expression of "what" has happened regarding "changes" in daily extremes. However, given the patterns of time-variation (and their differences) between *highs* and *lows*, the answer as to "why" these changes have occurred presents a challenge. There are six ideas to consider that help in this discussion.

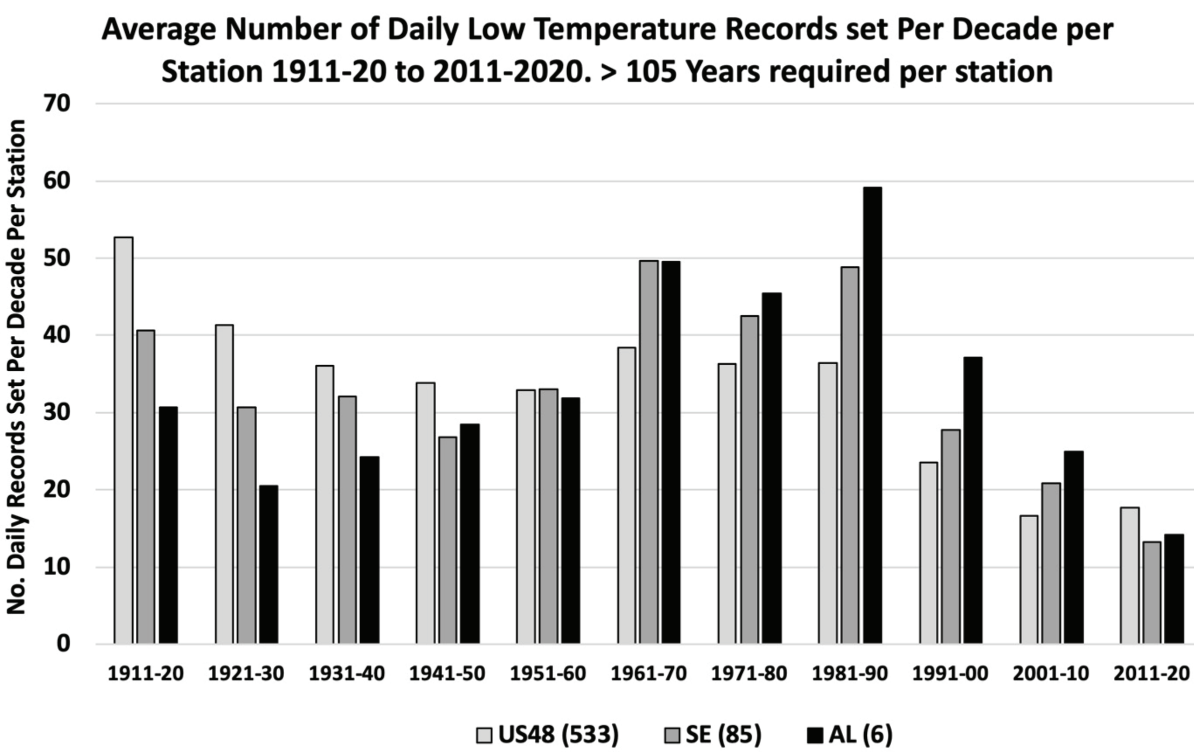

Figure 4. As in Figure 3 but for record daily low temperatures.

Mobile, Alabama
Image by Nico BHLR via Unsplash.com

Role of Moisture

High and *low* temperatures are highly dependent on moisture at the surface and in the atmosphere. When periods are moist, daily *highs* are suppressed by clouds (reduced solar heating) and evaporation (which cools the surface just as evaporating water cools your skin after a dip in the pool.) The opposite is true for *lows* which once the sun sets tend to stay warm during moist periods but cool off quickly during dry periods. During moist periods the ground does not cool as fast because the clouds and moisture in the air act as a (GHG) blanket and reduce the loss of heat from the surface. Also, wet soil is able to hold more heat than dry soil, leading to slower cooling. During dry conditions at night, the temperature falls quickly as the dry soil has a smaller amount of heat to begin with once the sun sets and the surface cools.

The difference between *high* and *low* temperatures is called the diurnal temperature range (DTR). The DTR increases when it is dry as *highs* go up, and *lows* decrease. The importance of moisture and land cover is critical to understanding temperature trends over any period and helps to understand trends in temperature which are due to changes not necessarily related to GHGs.

Models have had a particularly hard time replicating DTR changes as will be discussed below because all the "uncertainty" in turbulent interactions and the myriad number of not very well-known parameters that control surface temperatures in models. Also, the relatively unique downward trend of temperatures in Alabama and the Southeast over much of the last century may be tied to some degree to land cover changes as agricultural land was abandoned and replaced by forests. This will be discussed next.

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Role of Land Cover

Changes in land cover can also impact temperature and DTR trends. For example, urban surfaces (concrete, asphalt, roofing materials) tend to absorb more heat during the day than natural vegetative cover, and then release it more slowly at night making nights much warmer. In urban areas tall buildings can interfere with normal wind patterns and mix warmer air down to the ground causing *lows* to stay warm. In general, when human-built infrastructure begins to surround a weather station, the *lows* don't reach the same cool levels as before and so warmer temperatures, unrelated to large-scale climate change, result (see below). But what about changes from forest land to non-forest land then back to forest?

The rather flat or downward trend in temperature over most of Alabama's record is part of a larger downward trend in the Southeast and also in parts of the drier lower Midwest. These "warming holes" as they have been called are contrary to the upward trend in the rest of the U.S. There is still uncertainty on the full cause of these warming holes, but, from agricultural research carried out by the Office of State Climatologist it seems that part of the cooling can be traced to land cover change in Alabama and the Southeast.

Ellenburg et al. 2016 addressed this directly for our state. While Alabama was a major agricultural producer at the turn of the twentieth century, when forests were cut for lumber or converted into pasture and crop land, the 60 years that followed saw a drastic reversal of this deforested land back to forest. A major reason for that reforestation was that Alabama's rain-fed agricultural system in the first half of the 20th century was no match for the irrigating farmers in the west or the midwestern farms that were largely insulated from drought by their deep water-holding soils.

During this 60 years, the number of acres of corn and cotton decreased by 90% (Census of Agriculture, National Agricultural Statistical Service, www.nass.usda.gov). In addition to the loss of cropland, forests in the Southeast were rebounding from the significant cutting that went on from the 1880s to 1920s. Ellenburg et al. 2016 carried out detailed observational studies of differences in temperature and energy budgets over agricultural land and forested land. They found that energy losses were greater over forests than agricultural land which would lead to cooling. Thus, part of the downward or flat trends in temperature (especially maximum temperature) as seen above may be partly explained by this change in land cover as forests returned. But recall too that the temperature drop was more of a shift at one point in time and thus also consistent with a sudden change in general weather patterns.

Role of Short-Term Weather pattern variability

Extremes in daily temperatures are determined by relatively small scale (meso-scale) and short-lived weather patterns of which there are an infinite variety. This is a consequence of living in a climate system characterized by the interactions of those two turbulent and chaotic fluids – the atmosphere and the ocean. The patterns generated in such a chaotic system can cause daily temperature departures of 30, 40 and even 50+ °F from the typical average for the day.

For example, the all-time coldest reading observed in Alabama was -27 °F reported on 30 Jan 1966 by Ms. Lucille Hereford, the Postmistress and volunteer observer for New Market. The "normal" *low* temperature for that date was +30 °F, so the local weather pattern (there was a very unusual 8 inches of snow on the ground too) was such that it caused a departure from normal of -57 °F!

With the natural variation of weather patterns completely dominating metrics like daily extremes, they are not very useful in detecting a signal of extra GHG warming which, for sake of argument, could be about 1 °F for Alabama. This is especially true because these patterns that produce extremes can occur at any time and often cluster in particular decades. Professor Cliff Mass of U. Washington has a "golden rule" of climate extremes which helps explain this result, "The more extreme a climate or weather record is, the greater the contribution of natural variability."

On the warm side, the departures aren't as remarkable. Alabama's warmest observation for a daily *high* temperature was 112 °F taken by Josiah Kennedy in Centerville on 5 Sep 1925. The normal *high* for the day was 90 °F, so this departure was +22 °F, still a large value compared with 1 °F. [Daily *high* temperature records at other times of the year are often greater than +22 °F from normal.] Thus, the tremendous variation in weather patterns from day to day and week to week at this point don't inform us about the relationship between them and a possible background warming of 1 °F by extra GHGs.

Little River Falls near Galesville, Alabama
Image by Sam Dellaporta via Unsplash.com

Role of urbanization or land-cover changes

High and *low* temperature extremes respond differently to the expansion of built-up infrastructure around the station. As time has passed, many of our stations have experienced the addition of parking lots, buildings and general urbanization around what was once a fairly rural landscape. This infrastructure will affect the readings at the weather station. There are several research studies which demonstrate (and explain why) the *low* temperature will warm more than the *high* temperature as a response to these changes. This produces an asymmetric change in temperature over time such that the *lows* warm up more than the highs, or that the DTR (difference between *high* and *low*) decreases. This feature is found especially for stations which have seen rapid growth nearby. Thus the "why," at least in part, of the decline in the occurrence of record *low* temperatures in Fig. 4 may be explained by the warming of the nighttime temperatures due to human development around the stations.

Role of rainfall amount over time

Temperature and rainfall are highly correlated in Alabama, especially in the warmer half of the year. The highest temperatures often occur after a few weeks of minimal precipitation as the ground and vegetation dry out and the surface air loses the cooling effect of evaporation and transpiration as described earlier. There has been a tendency for fewer of these types of droughts in the more recent years, with NOAA's various Palmer Drought Indices showing positive trends, meaning dry spells have become less common over time since 1895 (see Fig. 11 later).

Birmingham, Alabama
Image by Zack Farmer via Unsplash.com

Role of extra GHGs

A final factor to check is whether the extra GHGs alone might be causing a different warming rate between *highs* and *lows*. To answer this question, 28 of the latest climate model simulations were tested for trends in *highs* vs. *lows* over the US since 1970 (the period when the impact of extra GHGs would be strongest). Eighteen of the simulations indicated the *high* should warm faster than the *lows*, and ten vice-versa (Fig. 5). Thus, the majority of models provide an answer in the opposite direction of what the observations show. However, the average (or consensus) of the model responses was not significantly different from zero, suggesting that, in the models, a differential warming of daytime *highs* versus nighttime *lows* is not influenced by increasing GHGs to a noticeable degree.

Keeping in mind all of the factors above that influence temperature we shall examine another metric with regards to extremely hot temperatures – simply counting the number of very hot days per decade to see if their numbers are changing.

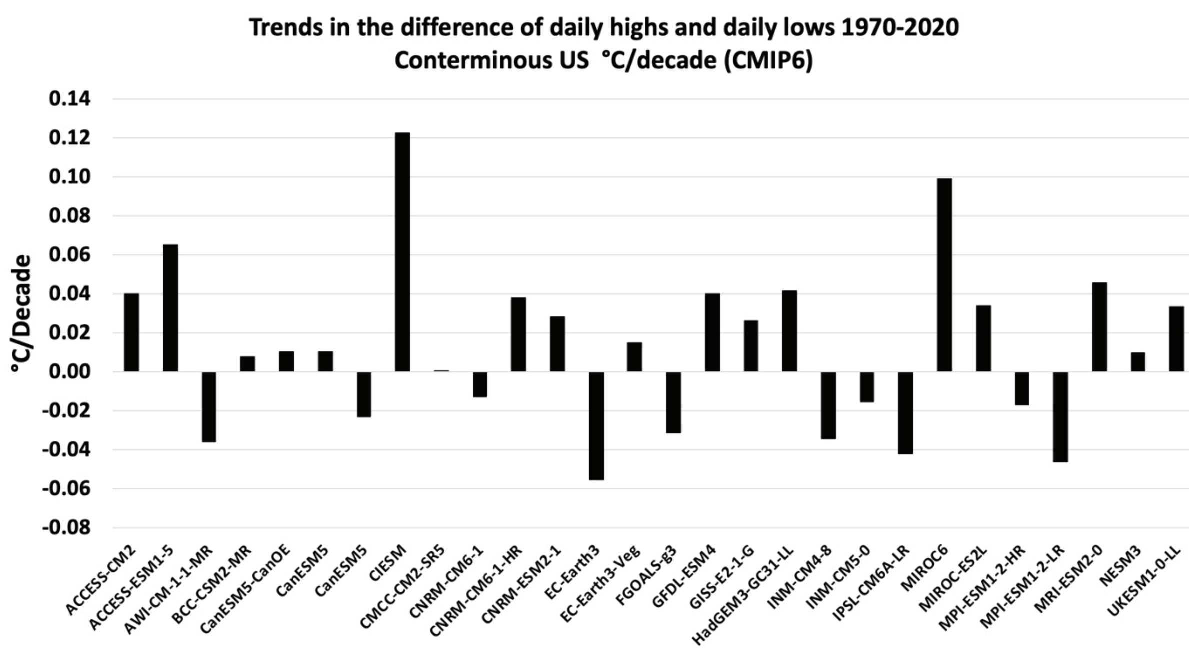

Figure 5. The difference in the trend between the average daily highs and daily lows for the conterminous US from 1970-2020 from 28 CMIP-6 climate model simulations. A positive value indicates the daily highs warmed more than the daily lows in these simulations.

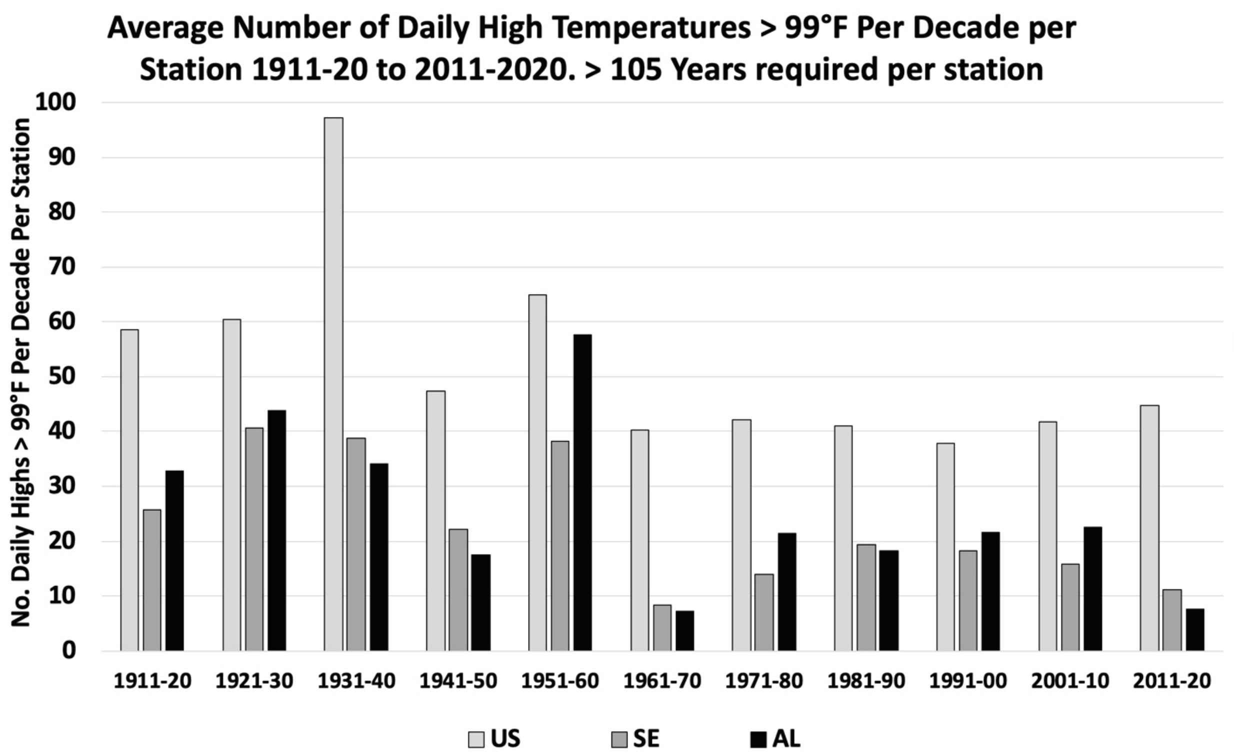

Figure 6. Number of hot days (highs > 99 °F) per station in AL, the SE and the conterminous US. The value represents the total events per decade at the average station in each region.

Figure 6 shows the number of days on which the average station in each region reached or exceeded 100 °F (a very hot day in Alabama). This result provides further evidence that daily extremes occur in the context of small scales and short time periods and are not yet useful as a detector of GHG influences. As noted, summer temperatures are highest in the SE when there has been little rain in the previous weeks, a condition that occurred more often before 1955 in the SE than after. In the conterminous US the major Dust Bowl of the 1930s was associated with weather conditions that produced the greatest number of hot days by far, about 97 per station per decade or 9.7 events per year for the average station across all 48 states. Over the entire 110-year period the average US station warmed to 100°F about 5 times per year.

For Alabama, the hot and dry summers of 1951-1954 provided the most 100+ °F days and hence the largest number in that decade (black bar). The latest decade in Alabama (and the SE) experienced a dearth of very hot days, barely exceeding the number in the cool 1960s. Of interest here is that when a sufficient number of stations began reporting in 1883, at least one station reported a temperature of at least 100°F in every year until 1965 when three stations reported the top state temperature as 99°F. Since then, Alabama did not see a 100°F temperature in the following years even though the number of reporting stations increased: 1974, 1994, 2001, 2003, 2013 and 2017.

As noted above (and later below), one cannot see a signature of the response to extra GHGs in this chart of threshold-exceedances of daily hot temperatures. The expectation is that one should see a rising trend of very hot days especially for a region as large as the conterminous US, but that is not the case. However, this chart does provide important information for the future; the heat of 1911 to 1960 is completely within the capability of the natural environment to generate – and especially in an environment that is being nudged toward warming by extra GHGs. It is entirely possible that between the GHGs and a tendency for nature to bounce up and down around an average value, that the next 50 years will see a return to the rate of 100 °F days as was seen in the early 20th century (and maybe more.)

Temperature Changes in the Future

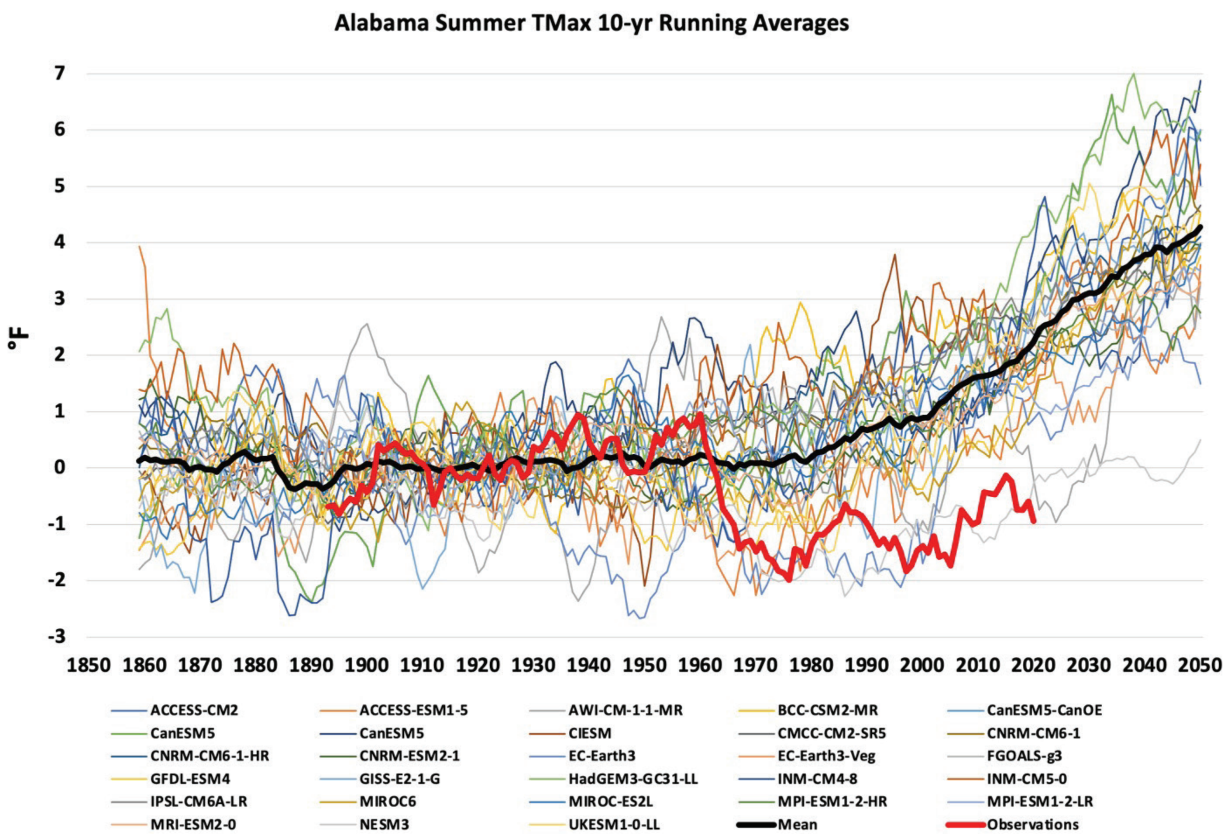

Figure 7. Time series of 28 CMIP-6 climate model values of June-August average daily high temperatures, the model average (thick black line) along with the observations (red). The values have been averaged over 10 years to focus on the longer-term changes such as impacted by GHGs. All of the time series are averaged to zero for the 1885-1934 period.

To see how the GHG hypothesis of temperature warming for Alabama presents itself, the output for the state from the 28 CMIP-6 climate models mentioned above was accessed and plotted. Note that a climate model is a hypothesis because the physical processes of the climate system have been "estimated" in the models (i.e. "hypothesized" since their true behavior is not exactly known) in an attempt to provide insight as to how the system responds to different influences.

The individual time series of the 28 different models, their average (thick black line, often called the "consensus") and of observations (thick red line) are shown in Fig. 7. As indicated earlier, the sudden drop in Alabama's temperature in 1955 and the subsequent lack of warming is a situation the models were unable to replicate. The temperature trend ending in 2021 and starting in 1883, 1940 or 1970 for every model was more positive than that of the observations.

In their average, the models produced trends significantly more positive compared with the actual trend. In fact, the actual 10-year average for 2012-2021 is almost 4°F below the value anticipated by the consensus of the 28 models for this most recent decade. It is clear that the consensus of the models (recall models are not "fact" but simply hypotheses that should be tested) for Alabama failed to reproduce the actual long-term temperature variations. This was the same result published for earlier versions of these models (CMIP-5) in which the conclusion states, "Seventy-seven CMIP-5 climate model runs are examined for Alabama and indicate no skill at replicating the long-term temperature and precipitation changes since 1895" (Christy and McNider 2016).

With the failure of these hypotheses (models) to reproduce the long-term changes in the climate that have occurred in Alabama, there is very little to say (with confidence) about the next few decades. In other words, the forecasting capability of the present level of climate modeling has not yet risen to the level that would provide confident answers for the next 25 to 50 years.

As the scales of time and space expand, the variability of the regional impacts of the ephemeral weather patterns tend to average out. However, even at the global average there are natural ups and downs of temperature on every time scale that confound the task of teasing out an impact from extra GHGs. Models have been touted to agree with global surface temperatures showing that only by including GHGs can models agree with observations. However, this "agreement" is not so much an outcome of increased scientific understanding but rather is created by a more down-to-earth reason in which models were essentially made to agree with the surface temperature record (e.g., "We have documented how we tuned … the model to match the instrumental record of warming." Mauritsen and Roeckner, 2020). In other words, that the global average surface temperature of models agrees somewhat with observations is primarily a contrived result.

A closer look, for example, at the bulk atmospheric temperature (surface to 35,000 ft) rather than surface temperatures is informative because the bulk atmosphere should respond more readily and more strongly to extra GHGs. As such, it represents a more useful metric to employ to detect the impact of GHGs. This is an area of significant research in which this office has played a major role. We (and others) show on average there is a highly significant mismatch between models and observations at the largest scales (see later). This again suggests limited credibility should be assigned to climate model projections.

We saw above that when spatially averaging up to the size of Alabama (or even the US) and temporally-averaging up to the seasonal period (or even a decade), there was still too much natural variability to find a clear GHG effect in the various hot temperature extremes we examined. The same factors – land cover, changes in moisture and natural variability which confound Alabama trends, may be going on in other regions too. However, in other regions these alternate factors, especially natural variability, may contribute to a warming rather the flat/falling trend we see in Alabama.

Climate Always Changes.

Another way to say this is that it is entirely possible that the natural climate system (i.e. an imaginary climate without extra GHGs) could have generated (or contributed substantially to) the results we now are experiencing. This statement is not consistent with that of the most recent United Nations report (which will be mentioned at the end) but has the pleasing feature of being consistent with various types of evidence.

As indicated, even at the scale of the US or the globe, there are fluctuations that are internal to the system that can generate multi-year to multi-century trends and extremes that never would have been observed in our "blink-of-an-eye" 135 years of observations. However, the larger the time and space scales, the more likely it is to detect the imprint of a tiny change in the energy flow such as is happening now from the extra GHGs.

It is generally agreed that the best metric for detecting a GHG impact is the global ocean heat content (i.e., measuring the amount of heat energy in the ocean). Yet even there we have natural variations (not to mention observational problems) that confound the ability to measure the impact of a tiny change in atmospheric energy flow. Recent estimates indicate that since 1990, the ocean has been picking up heat at a rate of about +0.6 Wm^{-2} (Bagnell and Devries, 2021). While many believe this extra heat is a consequence of extra GHGs (IPCC 2021), very recent changes in cloudiness may also be the cause, (Dubal and Vahrenholt 2021). In any case, this extra heat would translate to a temperature change over 30 years, if distributed evenly throughout the ocean depth, of a little less than 0.1 °F. This demonstrates that the oceans hold a tremendous amount of heat and change temperature slowly. But even slow changes can be important as tiny differences in temperature and/or salinity can alter ocean circulation patterns that influence climate patterns in the atmosphere. Unfortunately, such changes are not predictable with confidence at this time.

A lesson here is that Alabama should be prepared for the type of extremes noted above, from the 112 °F heat of 1925 and the summer-long baking of 1954 to the brutal -27 °F in 1966 and the chilliness of the summer of 1967. If such extremes have happened before, they can certainly happen again, and be even "worse." This is especially true for daily to seasonal temperature episodes, because they are dominated by the natural fluctuations of weather patterns whose variety is infinite, which means we haven't experienced them all in the past 135 years to know what magnitude of extremes may happen soon.

> As has always been the case however, scientific understanding about a complex issue is never complete, i.e. there is an enormous amount that we don't know about the climate.

Changes in Precipitation

Almost all of the precipitation that falls in Alabama reaches the surface as liquid. In every year, at least a little snow falls in the higher elevations, and in the average year, snow falls to a depth of a few inches somewhere in the state. Even so, snow does not materially impact the total water volume Alabama receives from precipitation which is described below. [But these snowy or icy periods can cause brief, but significant transportation and infrastructure problems.]

Alabama's annual liquid totals range from about 55 inches in the north to 65 inches near the coastal zone. About 40% of this rainfall flows into streams and rivers and eventually to the Gulf with the remaining being soaked into the ground and/or recycled into the air by vegetation and evaporation.

Some rainfall observations go back to the early 1800s and there are scattered data from U.S. Army Forts starting as early as the 1840s (Mt. Vernon, Livingston, Mobile, Auburn, Fort Deposit). However, continuous, daily precipitation totals start in 1872 in Mobile and later in the other settlements. The best records are those without gaps in the data, so we shall study these stations.

In terms of rough estimates of drought conditions from paleoclimate records (tree rings) there are data that go back 1200+ years. We shall start with these.

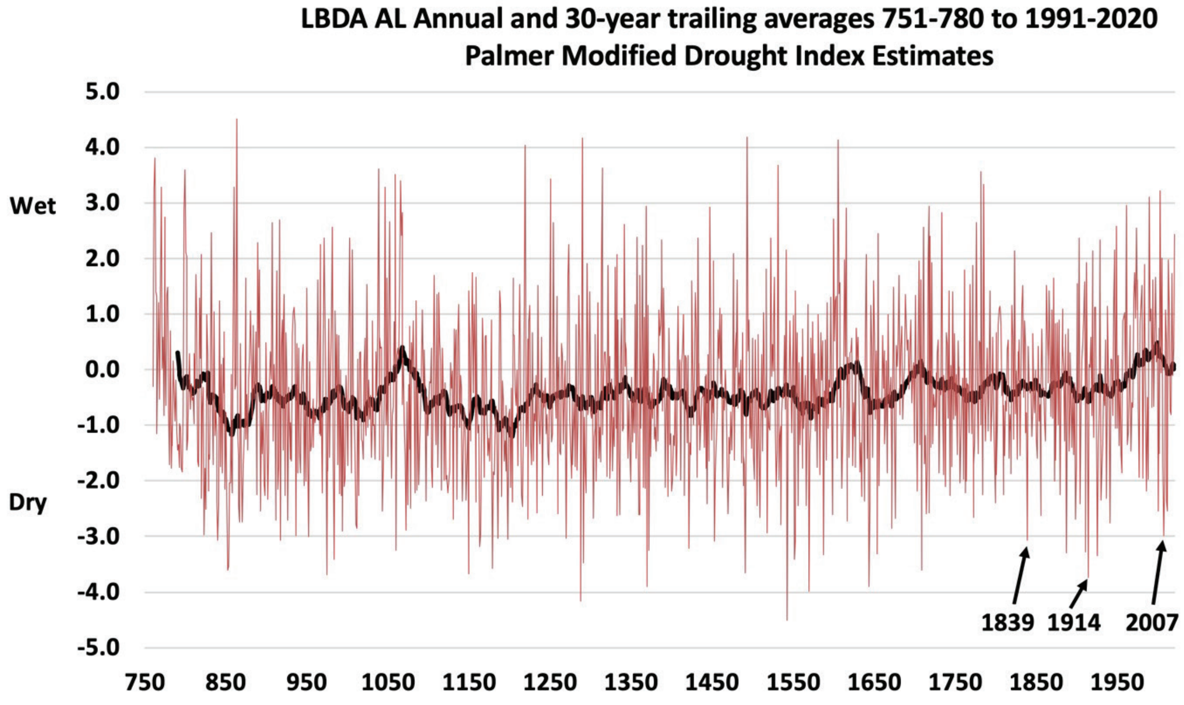

Figure 8. Annual values and running, 30-year trailing average (black line, e.g. the value at 1970 is the average of 1941 to 1970) of the NOAA Living Blended Drought Atlas (Gille et al. 2017). The values generally represent the condition in mid-summer based on the precipitation in the just-concluding growing season.

The long-term (1200+ years) estimates of drought and wetness suggest the current situation in Alabama is wetter than what was typical of the past (Fig. 8). Of particular interest here is that variations in moisture fluctuations over 30-year periods can be quite substantial and, unfortunately, essentially unpredictable. One sees ubiquitous “change” in multi-century, multi-decadal and interannual time periods. The multi-decadal dry periods within the period of 800 to 1250 C.E. are similar in timing to the mega-droughts of the western US. In terms of recent memory, the drought of 2007 (PMDI of -2.99) was exceptional for the state.

As an exercise regarding the meaning of “record events” mentioned earlier, we can examine two 130-year periods of the drought index which are 700 years apart. For the period 1890-2020, the “record” maximum and minimum values were +3.10 (1989) and -3.73 (1914). For the period 1190-1320 the maximum was +4.17 (1290) with the minimum just two years before at -4.17 (1288). For the entire period 760 to 2020 the “records” or “extremes” were +4.51 (863) and -4.50 (1542).

The point of this exercise is to demonstrate that “records” are indeed dependent on the time period selected and that the most recent period since 1890 did not experience the magnitude of extremes found in centuries immediately past. Thus, when claims of “all-time records” or “unprecedented events” are made, consider the time frame being examined relative to the much longer periods for which information is not available.

One of the driest years since statehood was 1839 (-3.06) when Huntsville, the only station reporting rainfall that year, recorded less than 30 inches. The Auburn Bulletin No. 18, 1890 reported the following regarding the subsequent growing season of 1840.

Fields early in June presented a bleak and barren prospect. Famine seemed imminent. Summer was also dry. [The] Warrior [River] at Tuscaloosa very nearly dried up resulting in the death of many great fish. The Alabama River was too low for navigation.

This is an example of a climate extreme that can threaten the survivability of the various species inhabiting the state. Keep in mind however, that the indigenous flora and fauna that exist today were able to survive such events and perhaps were even shaped by them for successful adaptation.

As with the temperature fluctuations, rainfall amounts also experience very large variations from month to month, year to year and decade to decade as shown in Fig. 8. Indeed, because of the very high variability of rainfall, it is even more difficult, and likely impossible, to detect the impact that the rising concentration of GHGs might assert. NOAA produces many useful products to describe the climate and one is statewide average precipitation. Since these NOAA products generally begin in 1895, data prior to that time were assembled for this report and geographically analyzed to give earlier estimates back to 1855 shown in Fig. 9.

” Fields early in June presented a bleak and barren prospect. Famine seemed imminent. Summer was also dry. [The] Warrior [River] at Tuscaloosa very nearly dried up resulting in the death of many great fish. The Alabama River was too low for navigation.

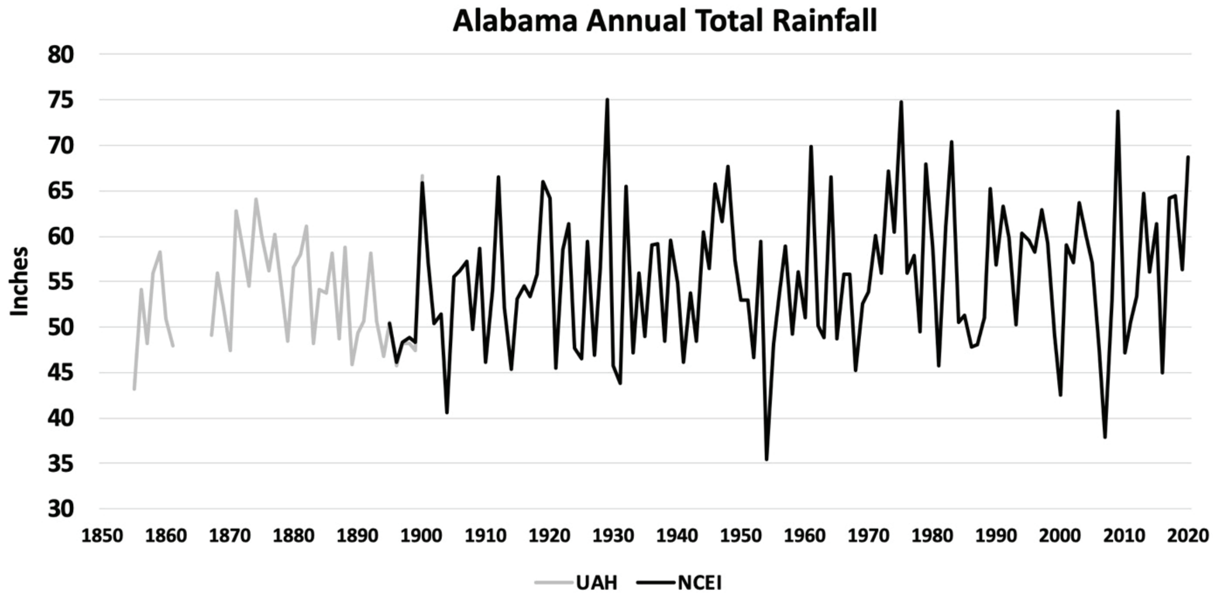

Figure 9. Annual total of geographically-averaged precipitation over the state. UAH assembled data prior to 1901 (gray) to begin the time series in 1855 to supplement NOAA/NCEI data starting in 1895. There are six years of overlapping data between UAH and NOAA/NCEI which produced a correlation of +0.999 between the two datasets.

Looking carefully at the instrumental record of annual Alabama precipitation amounts (Fig. 9), one finds a slight upward trend of about +2.8 in/century. For the nation as a whole since 1895 NOAA calculates the trend is similarly positive at +1.9 in/century. However, if starting in other years, for example looking at the last 60 years (starting in 1961) the trend is essentially zero. Thus, given the fact that fluctuations in Alabama's annual rainfall amounts are so large, ranging from 35 inches to 75 inches in a given year, relatively small trend values are of little consequence. In other words, the natural ecosystem of the state has adapted to such wide variations in rainfall that small trends will not exert a meaningful influence.

Examining the precipitation changes for the coming century as suggested from climate model simulations indicates on average that the annual statewide total would increase from about 55 inches to 59 inches (Fig. 10). Placing a trend on the 2001 to 2100 simulated values for the 40 available models indicates outcomes which vary from an increase of 11 inches to a decline of 7 inches. The chart displays the range of model results as a 10-year moving average which is applied to dampen some of the remarkable year-to-year variations shown in the model output.

As evident in the chart, precipitation is particularly difficult to simulate with the fairly crude approximations of its processes that are used in global climate models. While the variations from 10-year period to 10-year period are often realistic, the baseline amount of rainfall in the models varies by 30 inches, or ± 15 inches from the actual average. Placing confidence in these simulations of regional (i.e. state-sized) changes in precipitation is not recommended by the organization, the IPCC, which utilizes these models for assessment purposes.

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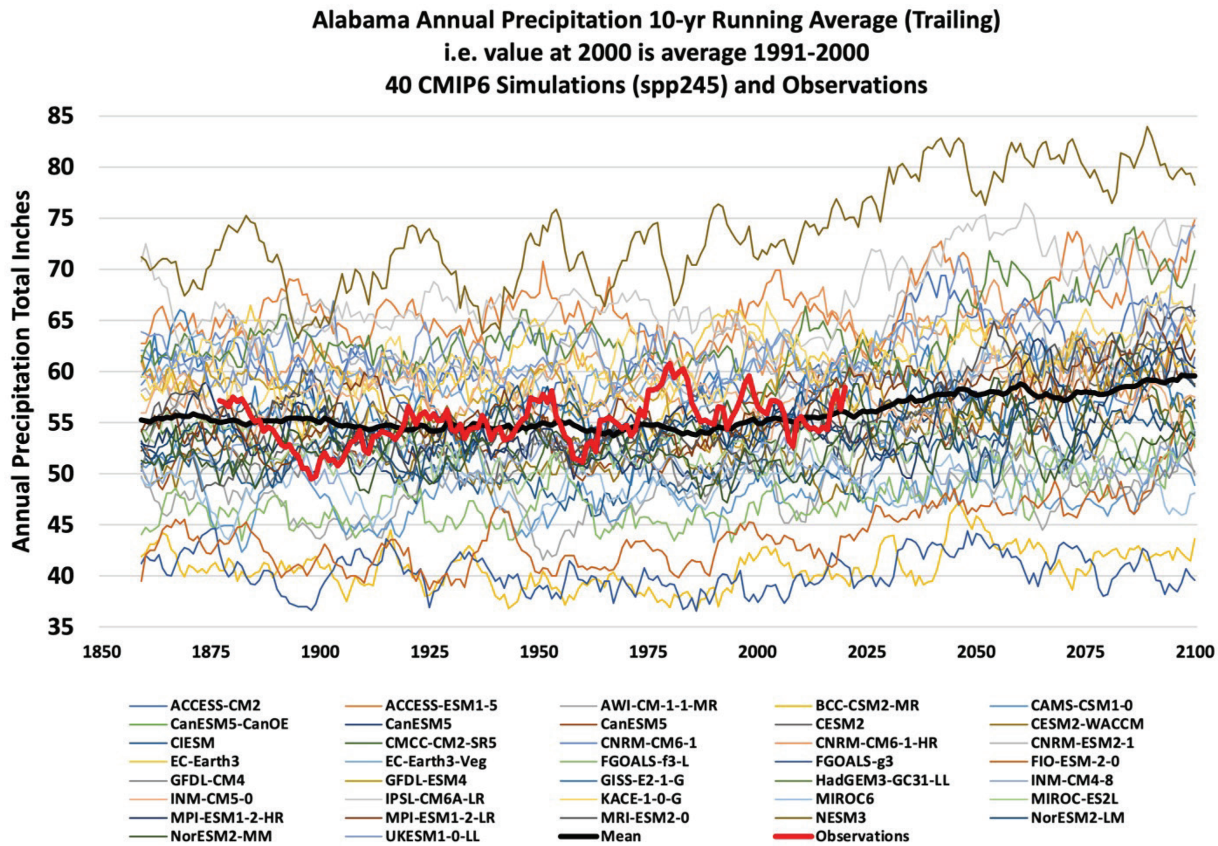

Figure 10. Ten year running means of annual statewide precipitation for Alabama as depicted by 40 simulations from CMIP6 output, their average (thick black line) and observations (thick red line). The simulations use observed forcing through 2014 and estimated forcing to 2100 using scenario ssp245.

Changes in Precipitation Extremes

A concern that has evidentiary support is that there has been an increase in the intensity of the heaviest rain events. In other words, some measures of extremely heavy downpours over short periods are seeing increasing amounts and/or occurring more often. This was a finding of the National Climate Assessment (USGCRP, 2017, Figs. ES.6 and 7.4) for a fairly large number of stations which extended over the eastern half of the country. For example, when considering the distribution of the heaviest 2-day rainfall totals through time since 1901, there was a clear tendency for more to have occurred in the more recent decades than earlier decades. This result was confirmed using SE stations by an independent study (McKitrick and Christy 2019 or MC2019). The basic scientific idea is that warmer air is able to carry more water vapor that is then available to rain out. In addition, the rainfall process itself is more efficient at converting water vapor to rain as the temperature of the environmental air increases.

Because these extremes are rather rare events, standard statistical approaches to study such events can be unstable. Could this increasing trend have been the result of the natural chaos of the climate system? MC2019 extended their study back to 1872 (i.e., 29 new years to examine) and discovered that the trend in the time-distribution of these extreme events was not significant for the SE stations (which included Montgomery and Mobile) even though it was significant when starting in 1901. This "non-result" was also the case when the most recent 40-year period was examined (when GHGs may have exerted some influence).

This is another example that shows how choosing different time periods can lead to differing statistical results. This means that ascribing a cause to such changes is fraught with uncertainty because the "change" is so often dependent on a particular sampling period. For the stations used in MC2019, there was no detectable signal of long-term change in the heaviest 2-day rainfall events even though the basic physics of the rainfall process would support a slight increase. [Recall the earlier point that one will always find at least some change in climate variables when comparing any two periods which is a feature of a chaotic and turbulent system.]

While this report does not specifically address the consequences of extreme rainfall events, present infrastructure that is intended to cope with flooding rains is usually not able to withstand the most extreme events that we know have occurred in the past. The trade-offs between costs and effectiveness to deal with such events is the bane of local, state and federal governments. The lesson from this report is that the worst flooding events (and driest droughts - see below) of the past are certain to occur again, and may be even more extreme no matter what influence extra GHGs might exert. Examining the longest-term datasets will provide the best range of potential events that can occur in the next 25 to 50 years for which adaptation should be considered.

Changes in Drought

NOAA/NCEI provides several types of metrics that quantify the length and severity of droughts and in Fig. 11 we show one - the Palmer Modified Drought Index. Drought is obviously a common feature of Alabama's climate and the tendency here, as noted earlier, is that recent times have experienced fewer droughts, even though these recent droughts reached the intensity of those in the past. As shown with the paleo representation of droughts (Fig. 8) it is evident that considerable variation occurs so that even with a slight trend toward more wetness, the droughts will still be consequential being at least of precendented intensity. Thus, severe droughts will always be in the offing in the coming century, but there is no tendency in the observations for higher frequency or greater intensity.

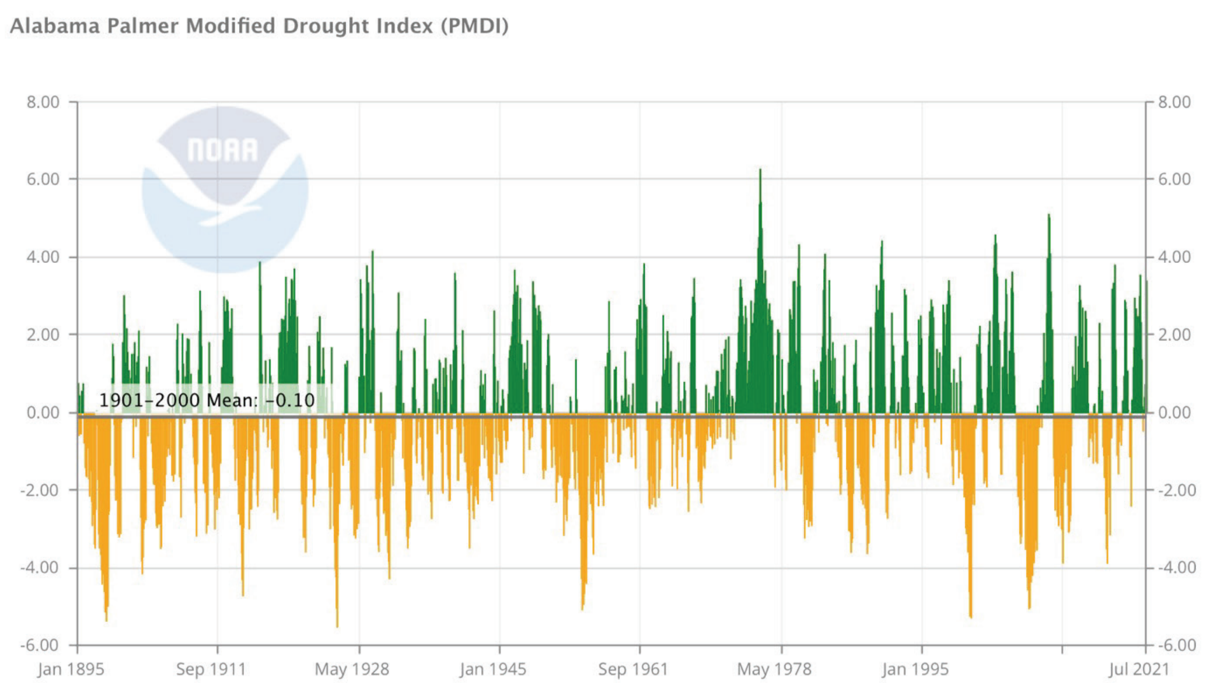

Figure 11. Monthly Palmer Modified Drought Index for Alabama (NOAA/NCEI).

Aerial of 459 Wednesday, January 29, 2014. Image by Tamika Moore | tmoore@al.com

Changes in Snowfall

Even though snow is a rather rare occurrence in Alabama, because the state lies on the southern fringe of such storms, this is a potentially sensitive indicator for change. In other words, because the occurrence is highly non-linear, like an "on-off switch" (it will snow if it is just cold enough but rain if it is not), a slight warming in the storm characteristics could mean a large decline in snowfall if some temperature threshold is reached.

Snow falls every year somewhere in the state, though in 1925, 1929, 1949 and 2005 only traces were recorded at the available stations. Snow can fall anywhere in the state too, for example, Mobile recorded 5 inches in Jan 1881. January 1940 was the coldest month for several stations and that was associated with considerable snow in Valley Head, Alabama's usual coldest spot, which recorded 25 inches for Nov to Apr (1939-40) in several snow events. The greatest 24-hour snowfall amount of 20 inches arrived on Walnut Grove during the famous March 1993 "Storm of the Century." Finally, the stillremembered New Year's Eve/Day storm of 1963/64 dumped 19.5 inches on Florence giving that station a winter total of 27.9 inches, the most ever recorded in the state for one season. The question now is, has snowfall been changing in Alabama?

Snow generally falls in erratic patterns in Alabama that don't lend themselves to systematic analysis to answer this kind of question with confidence. To enhance the statistics of the snowfall variable for the following analysis, several stations in the northern third of the state were selected to form a type of sampling database for which at least one station would experience a snow event. The seasonal total of snowfall was calculated over the winter season, i.e. each Nov to Apr period, with the designated year being the year in which April occurred. This is a metric that we can use to answer the question, how much snow fell at the snowiest station each year?

The station-mix experienced a bit of randomness over the years, but stations which started before 1900, and which generally dominated the greatest-total-per-year values, formed the backbone of the dataset, i.e. Ashville, Birmingham, Bridgeport, Florence/Muscle Shoals, Gadsden, Madison/Huntsville, Oneonta, Scottsboro, Talladega, and of course, Valley Head. Of the 125 years with measurable snow, these stations accounted for 92 of the snowiest station-years. While there have been rare occasions when a storm in south Alabama measured more than the north (e.g. Feb 2010), the statistics of these southern storms were too sparse to provide information on long-term changes.

The information in Fig. 12 indicates no meaningful trend in this metric of snowfall. Be aware that robust statistical analyses are difficult with snowfall because there are few stations that actually measure this hit-or-miss phenomenon. The figure does indicate that snowfall events continue to occur in Alabama with two of the fourteen 15+ inch seasonal totals happening within the last decade. So, this evidence, minimal as it is, does not suggest a lessening of snowfall as GHGs have increased.

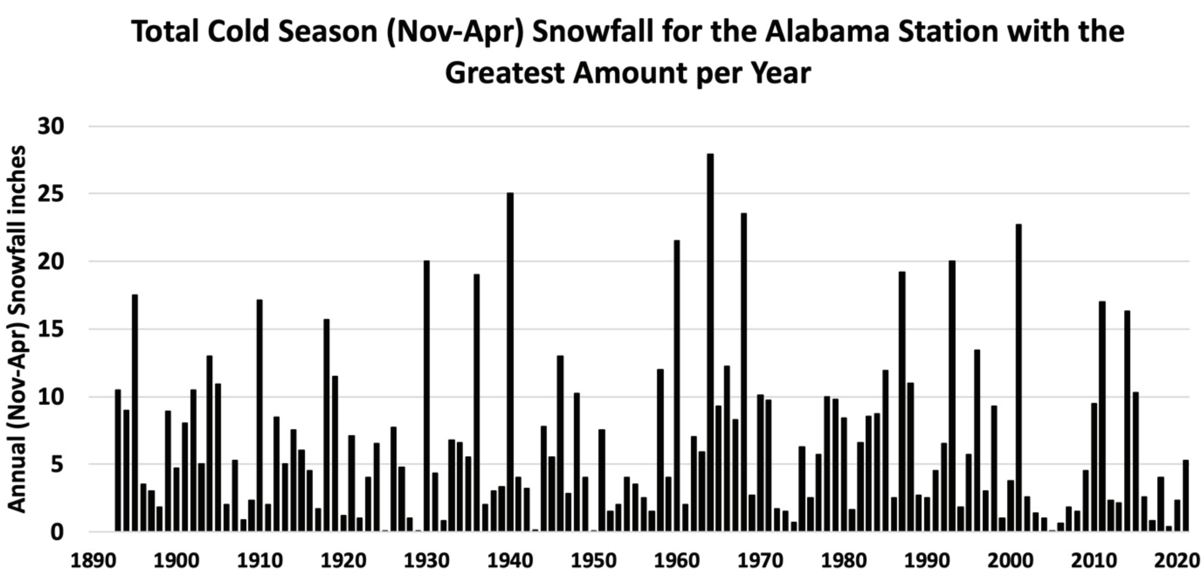

Figure 12. The amount of snowfall measured at the station in the northern third of Alabama with the most snow each year from 1893-2021. The value for each year is the 6-month total beginning with Nov of the year prior through Apr of the year designated. Out of 125 years with measurable snowfall, Valley Head accounted for the 42 snowiest values followed by Florence/Muscle Shoals with 25

Changes in Sea Level

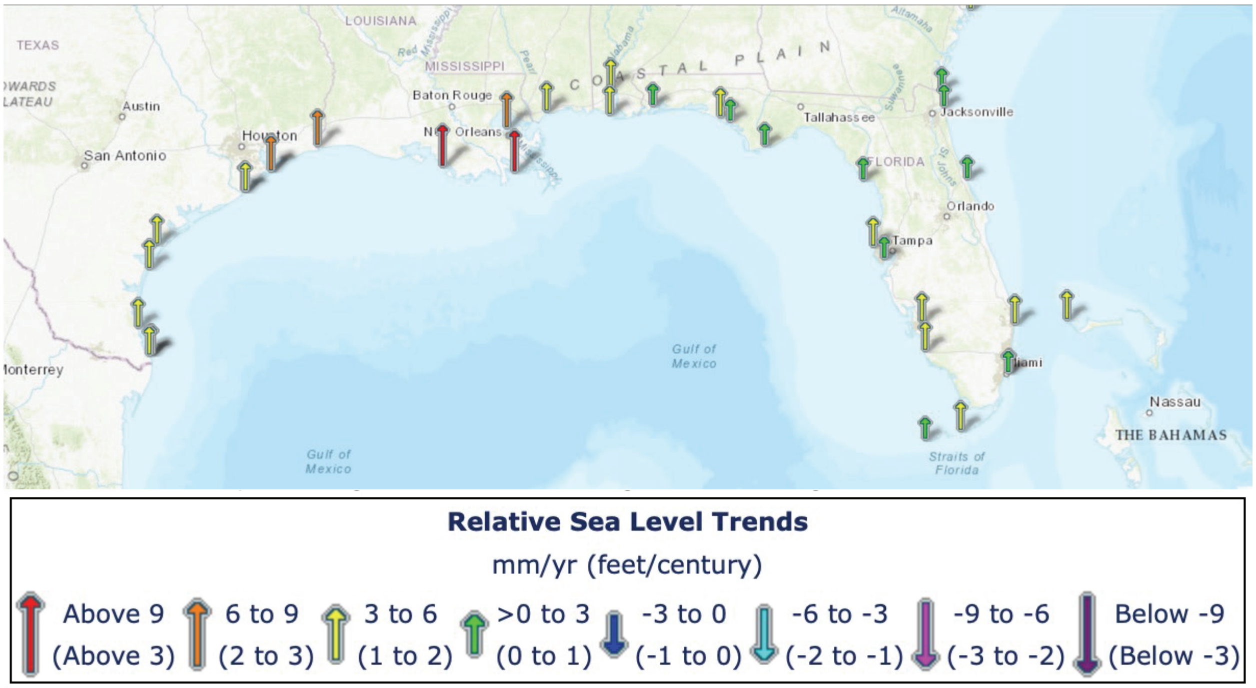

Figure 13. Relative change in sea level at various tide gauge stations along the southeastern US coastline (NOAA). These values essentially provide the net change when considering changes in land elevation as well as sea elevation.

The ocean contains such a huge amount of water that changing its total volume, and thus changing its elevation at the coast, means such changes will be very slow. When the vast ice sheets of the last ice-age melted from about 15,000 to 7,000 years ago, they caused the sea level to rise "rapidly" – about ½ inch per year (5 in. per decade) for 8,000 consecutive years. But the climate cooled somewhat after that and the sea level appears to have fallen a few feet to the 19th century (as some snow remained on land, piling up from winter to winter, not being able to melt in summer and return to the sea).

With general warming since about 1860, there has been again a net melting of land-ice (glaciers, ice caps) and thus rising seas. The word "again" is warranted as the sea in the last warm era (about 125,000 years ago) before the last ice-age cycle (120,000 to 15,000 years ago) actually leveled off around 15 to 20 ft higher than it is today. Thus, based on the last interglacial warm period, there is quite a bit of sea level rise to be anticipated, extra GHGs or not.

This very brief history reminds us that sea level is another of the dynamic, climate-related variables that undergoes constant change and should not be expected to stay at a constant level. One might think that determining the height of the sea is simple, i.e., measure the level at a few spots and since water seeks a uniform level, that should be enough information for the entire globe. However, global sea level changes happen to be extremely complex to measure because the values vary considerably in space and time. As shown from NOAA's tide gauge measurements along the Gulf Coast in Fig. 13 above, changes in sea level have a fairly wide range in our local region, for example compare trends (the length of the arrows) between Louisiana and Florida. This figure introduces some of the complexity involved with determining "sea level" and how fast it is changing.

One factor that impacts relative sea level change is the vertical motion of the land at the sea shore. Louisiana tide gauges show the relative sea level rising there around 3 ½ inches per decade since 1960. This rate-of-rise is largely due not to the sea rising but to the land sinking (subsiding) from extraction of water and energy products and to the diminishing sediment deposition caused by the channelization of the delta river system. On the other hand, at Dauphin Island AL and the Florida Panhandle, which are largely unaffected by subsidence, the rate of relative rise is about five times less, ¾ inch per decade. There are even other locations, southern Alaska for example, where the relative sea level is actually "falling" due to the tectonic uplift of the land. Looking at the past 60 years, the difference between the lowest and highest 12-month average of sea levels relative to the Alabama coast has been about the height of a football (Fig. 14).

Since the mid-nineteenth century, the average height of the global ocean has been rising relative to the average height of the global coastline. Most is due to the net melting of ice on land (as occurred between 15,000 and 8,000 years ago), but about 30% is due to the thermal expansion as the upper layer of the ocean has warmed. Since 1970, NOAA estimates the grand-average sea level has risen about 5 inches. For many reasons, for example the way ocean basins expand as they fill like a child's flexible pool, the actual relative rise at the coastline for non-subsiding land is less, but 1 inch per decade (or even 1 ½ in) is a reasonable number to use for planning over the next 50 years. However, the real threat at the coastline is not a rise of 1 inch per decade, but a rise of 10-15 ft in six hours that comes with a major hurricane. This is the real threat.

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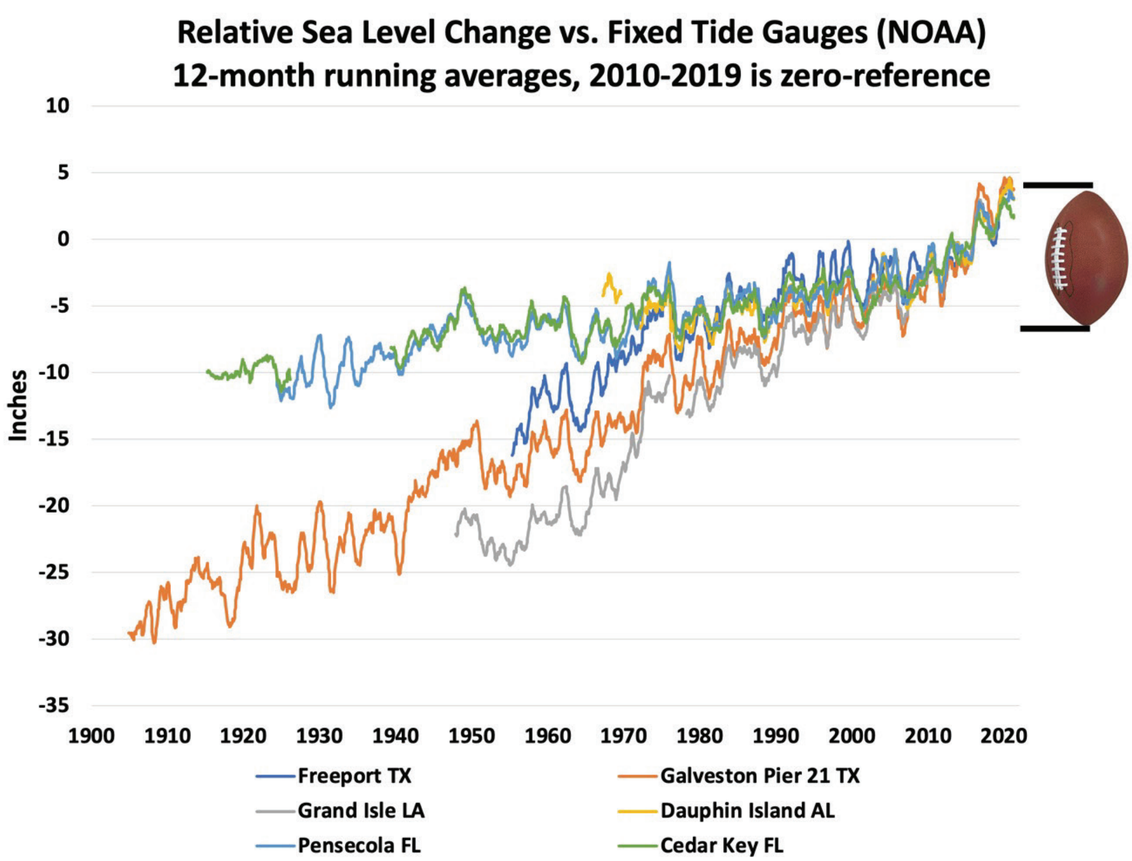
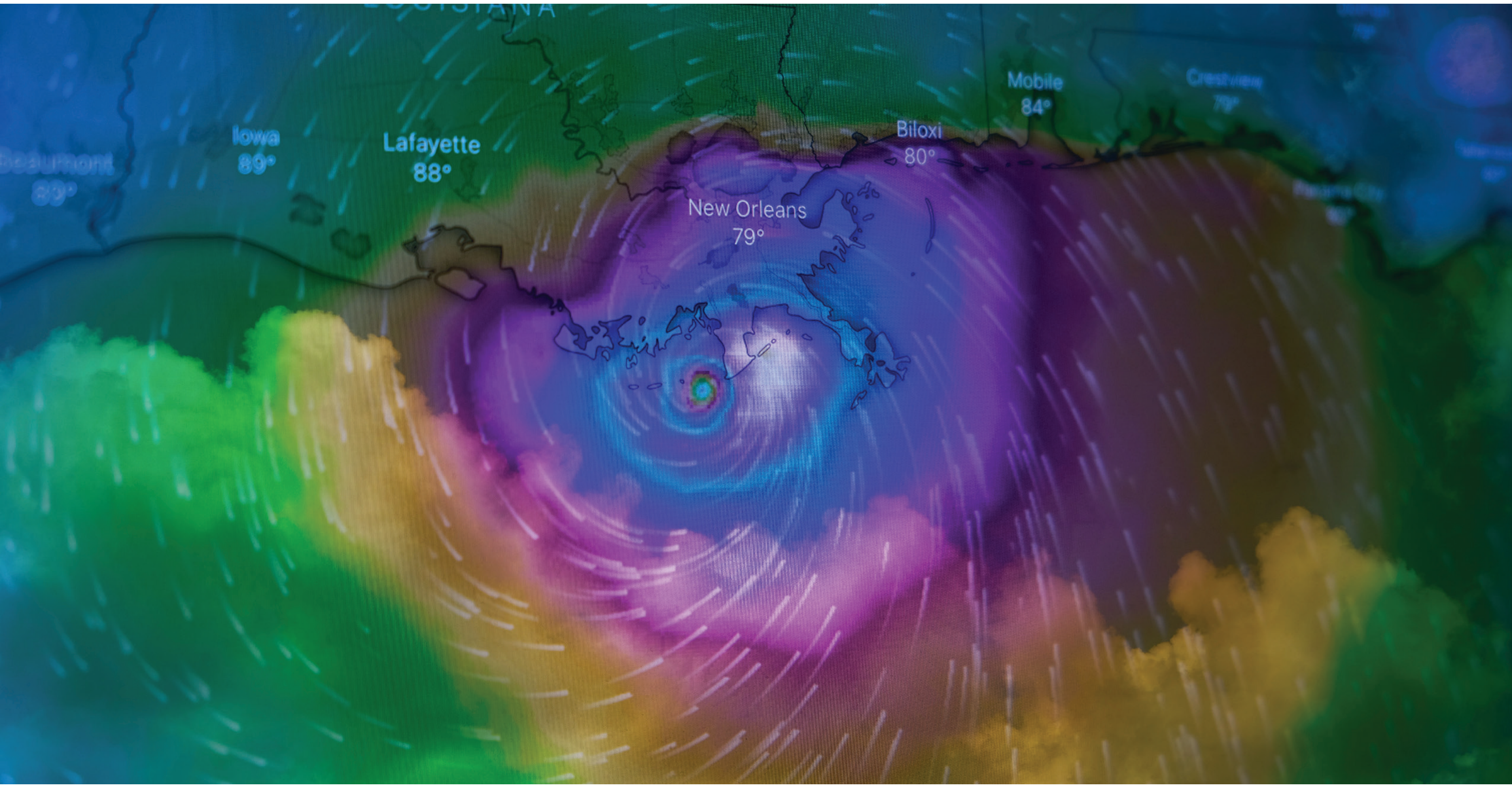


Figure 14. Changes in sea level relative to the coast at six stations along the Gulf Coast. The football indicates the lowest and highest sea levels for any 12-month period along the Alabama Coast in the past 50 years.

Changes in Hurricanes



Alabama's two coastal counties (Baldwin and Mobile) are subject to direct hurricane strikes about once every 10 years, though impacts of hurricanes coming ashore in Louisiana, Mississippi and Florida have been important as well. The three strongest hurricanes to make direct hits on Alabama since 1850 were Category 3 hurricanes (winds 111-129 mph): "Miami" 1926, Frederick 1979, and Ivan 2004 (again, NOAA HURDAT archives are exceedingly valuable here). Though rare, a hurricane may maintain minimal status as far inland as Montgomery. Analysis of hurricane records both for the Atlantic basin, which affect Alabama, and for the world as a whole (the Pacific has more hurricanes than the Atlantic) indicate there have been decadal variations but no significant long-term trend in frequency or intensity (Vecchi et al. 2021).

One metric that combines the strength and duration of hurricanes is the Accumulated Cyclone Energy or ACE. This is a useful metric as it is more descriptive than a simple count of hurricanes or checking the highest wind speed that a hurricane momentarily attains. ACE utilizes the observations of each hurricane along its life cycle to document the total energy contained in the storm. The ACE for each hurricane is calculated and then all such storms are summed for the year. The units are usually the square of the velocity (knots) which is divided by 10,000 to keep the numbers manageable (units of kn^2 x 10^{-4}).

Figure 15 indicates the global ACE for each year since 1972 when the first weather satellites were deployed and able to detect likely hurricanes on a global basis. The range is quite remarkable from less than 400 to 1200 in individual years. However, there is no detectible trend within this variability that would indicate a change due to extra GHGs. Indeed, the year with the highest ACE was 1992, the year with the coolest northern hemisphere summer, suggesting very little relationship between large-scale temperature values and ACE.

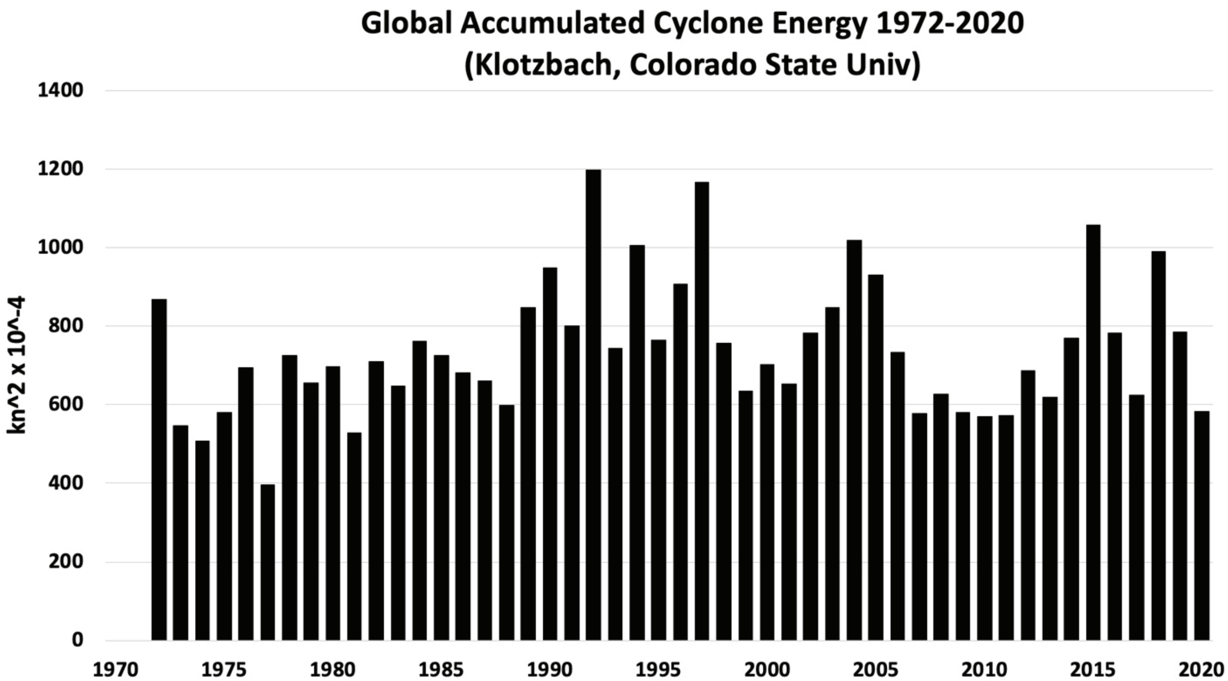


Figure 15. Global ACE calculated from observations by Klotzbach (Co. St. Univ). Because hurricanes originate and often spend their entire life over the oceans, until satellite images were available in 1972, there was little information over the vast southern and central ocean basins.

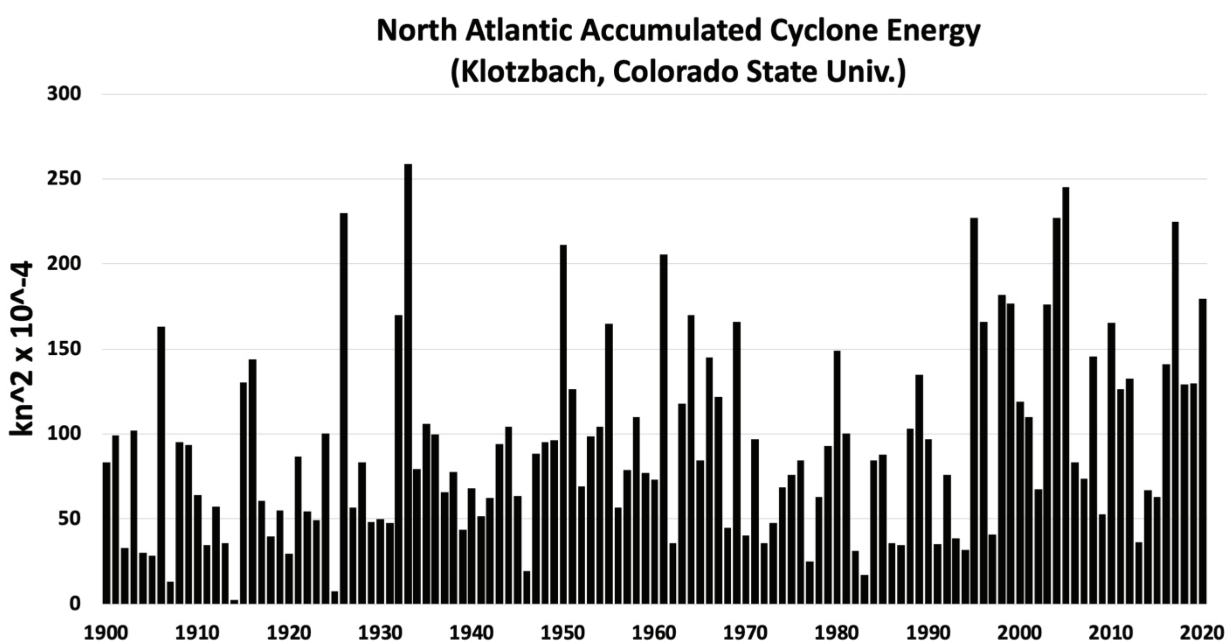


Figure 16. Annual Accumulated Cyclone Energy for the North Atlantic Basin.

With many ship reports in the North Atlantic Ocean since the mid-19th century, a reasonable reconstruction of ACE is possible for this basin which impacts Alabama (Fig. 16). The early years are likely underestimated (Vecchi 2021), but the basic time distribution has high credibility, especially after the 1920s. Note that 2020 was reported to have had more North Atlantic named-storms (30) than any other year, yet its ACE doesn't even put 2020 in the top ten.

Today, tropical cyclones that briefly reach the status of "Tropical Storm" and thus earning a name (sustained winds of 39 mph) are captured by an intensely vigilant satellite network even though they may last only a few hours (often called "shorties"). These would have been overlooked in the pre-satellite era, so counting simple numbers of named tropical storms and hurricanes does not lend itself to consistency over time – a key point for climate studies. Note that ACE in 2020 was 180 $kn^2 \times 10^{-4}$ with 30 named storms while the "record" ACE year of 1933 (259 $kn^2 \times 10^{-4}$) produced only 20 named storms.

The North Atlantic Basin ACE reveals decadal features that relate to a pattern known as the Atlantic Multi-Decadal Oscillation which switches every 20 to 40 years. The AMO essentially represents the warm and cool phases of the sea water temperatures of the North Atlantic. Since 1995 the AMO has been in the warm (active) phase for North Atlantic hurricanes as it was during 1880-1900 and 1945-1970. Inactive phases occupied the periods in-between. A simple extrapolation of this index would suggest a lessening of hurricane ACE in the Atlantic starting around 2030 or so.

Though flooding from rain and damage from wind can be extensive, the main destructive force of a hurricane is the storm surge - the abnormal rise of sea level which is pushed inland by the storm. The current small, continuing rise in sea level will add to the potential reach of these surges. In the past 60 years, NOAA indicates storm surges of as much as 15 to 28 ft (Ike 2008, Katrina 2005, Opal 1995, Camille 1969) have flooded their respective strike-areas of the Gulf Coast.

The three major hurricanes to directly hit Alabama generated surges along Alabama's coastline of 14 ft ("Miami" 1926), 12-15 ft (Frederick 1979), 9 ft (Ivan 2004, though 13 ft in Florida). Other major hurricanes that made landfall in adjacent states but had significant impact on Alabama occurred in 1852 (12 ft Mobile), 1860 (~ 7 ft Mobile), 1893, 1916 (11.6 ft Mobile), 1969 (9.2 ft Dauphin Is.), 1985 (8.4 ft Dauphin Is.), and 2005 (14 ft Bayou La Batre). The storm surge that caused the worst U.S. fatality event (~8,000 deaths, Galveston TX 1900) was less than 15 ft. Sobering statistics from NOAA indicate that for the Gulf Coast counties, 67% of interstates, 57% of arterial roads, and 29 airports are vulnerable to a rare but possible 23 ft storm surge. Here again is the dilemma of governments who spend tax dollars for infrastructure resilience – how much to spend to protect the citizens from a very rare event? What regulations should be enforced to reduce catastrophic losses?

While no significant change in hurricane frequency and intensity has been observed, and anticipated changes due to GHGs are uncertain (some speculate a slight increase in the strongest hurricanes but not in overall numbers), hurricanes and tropical storms will cause major and even catastrophic damage in the future. The value and density of the built-up infrastructure on the coastline continue to increase and thus these storms will cause damages that exceed any similar strikes from past decades. The Gulf Coast, including Mobile and Baldwin Counties, is increasing its status as a target-rich environment for such disasters.

Orange Beach, Alabama
Image by Steven Van Elk via Unsplash.com

Changes in Tornadoes

Alabama is struck by tornadoes each year. The National Weather Service assigns four Offices to watch over separate parts of Alabama but the group in Birmingham has responsibility for over half of the state and often keeps tabs of state-wide statistics gathered by all the offices, some of which are given here. (Huntsville, Mobile and Tallahassee have responsibilities for parts of adjoining states too.) Using data from the last two decades only, when sophisticated radar has been available to observe virtually every tornadic event, a best guess is that on average 60 to 65 tornadoes touch down in Alabama each year. This comes to about 1 per year per county but because there is a tendency for more tornadoes to occur in the north, northern counties average a bit more than one per year and southern counties a bit less than one per year. April 2011 was particularly active pushing up the annual total to 145, including 62 on the 27th alone. By contrast, the quietest year of the last 20 was 2013 when only 23 were counted.

Most tornadoes are relatively weak and in the past were largely unrecorded, which is why, for example, the annual average of Alabama tornado touchdowns in the 1960s is listed as only 15. Since the major tornados (EF3 to EF5 or wind gusts > 135 mph) always leave a considerable scar on the landscape it has been customary to examine the occurrences of these as the best indication of changing frequency over time. Again, consistency-of-measurement throughout the time period is critical for studying the change in a climate variable.

Nationwide there has been a fairly noticeable decline in the frequency of major tornadoes since 1954 (Fig. 17). In the first 33-year period (1954-1986) the country was struck by an average of 56 events per year. In the last 34 years (1987-2020) the number dropped significantly to 34 per year. This is a further example of the idea that short-lived, extreme phenomena are not closely related to a slow and tiny change in the climate system's energy-flow due to extra GHGs.

Some have speculated that more tornadoes are occurring in short-term "outbreaks" (e.g. 27 April 2011) which means there are longer periods that are tornado-free since the total number is not rising

(Brooks et al. 2014, Tippett et al. 2016). There has been speculation too that if one response to increasing GHGs is a relaxation of the temperature difference between the Gulf and Canada, then there would be a less favorable environment for tornadoes (Trapp et al. 2007) but which might actually enhance the frequency of severe thunderstorms (Diffenbaugh et al. 2013). One other idea is that the spatial distribution of tornadoes may be drifting a bit eastward since the 1950s from the "tornado alley" of the southern plains toward Alabama and there is some information to support that hypothesis (Gensini and Brooks, 2018), though no confident indication as to "why" or if it will continue or reverse.

Keep in mind that the effort to understand changes in tornado frequency over the next century depends on climate model hypotheses which have been demonstrated above to have failed in characterizing the climate variations and trends of Alabama. Remember too that climate models have such coarse spatial resolution that they do not simulate thunderstorms or tornadoes, but attempt to capture the changing, larger-scale environment in which they occur – and which for Alabama was not well done. Thus, one may only offer conjectures about tornadic tendencies looking ahead. With that in mind one can note that it is likely, just as with hurricane fluctuations, that the occurrence of tornadoes is subject to multi-decadal variability as part of the natural dynamics of the climate system. In this case, one would expect that an increase in major U.S. tornado events is entirely plausible and may move the annual counts back to their pre-1987 levels in the next few decades with or without extra GHGs.

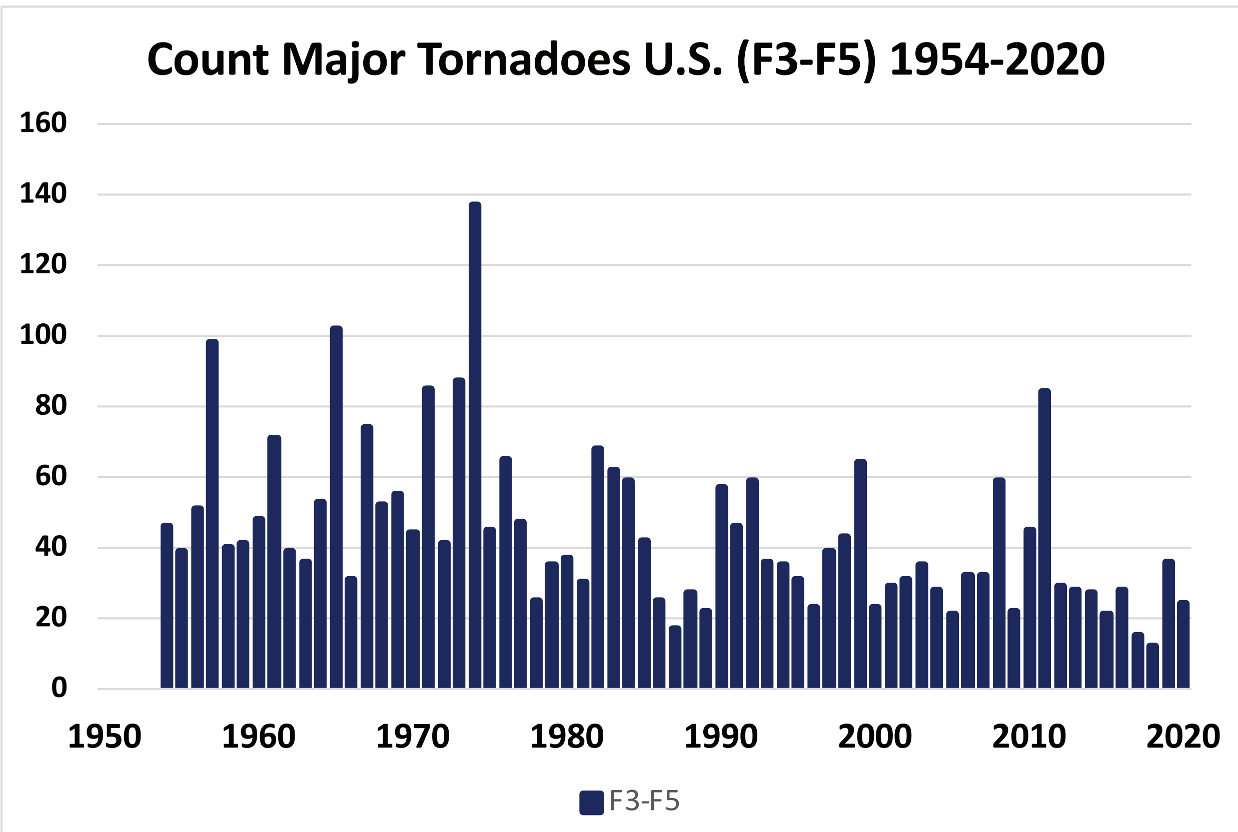


Figure 17. Number of major tornadoes (EF3-EF5) in the conterminous U.S. per year (NOAA).

Final Thoughts

This report has taken a tour through the climate metrics that are of interest to Alabamians, displaying how they have varied and changed over time. As indicated, there hasn't been a detectable impact on these metrics from the extra GHGs. These GHGs, for the foreseeable future, will continue to accumulate in the atmosphere as a result of energy production that sustains human life – we just haven't been able to detect with confidence their impact on climate in Alabama.

The evidence indicates that for a region the size of Alabama and the way weather changes all the time already, the extra GHG-effect is still so small it is lost in the noise of natural variability. And, there is this possibility - since the forcing that the extra GHGs exert is such a tiny part of the entire system one can imagine that other major processes might take fuller advantage of their ability to cool-off the climate and, at least in part, counteract the warming influences of extra GHGs. The direction that the climate takes from here for the world and especially for Alabama is still a murky issue.

In contrast to the statement earlier that the evolution of climate over the last 135 years in Alabama could be simply that of natural variability, the latest United Nations document (IPCC, 2021), Assessment Report No. 6 or AR6, on climate change states, "Human-induced climate change is already affecting many weather and climate extremes in every region across the globe. Evidence of observed changes in extremes such as heatwaves, heavy precipitation, droughts, and tropical cyclones, and, in particular their attribution to human influence, has strengthened since AR5 [the previous report in 2013]." (Summary for Policymakers or SPM statement A.3).

That the AR6 found "changes" should not be a surprise, as we have seen, because any climate metric will show some type of change over any period. Note that the AR6 often reports on "change" since 1950 – a relatively short 70-year period which, for the US, skips some of the most extreme weather events that have been observed such as those of the heat waves and droughts of the 1930s. Even so, the report has little to say about the Southeastern US.

In support of the dramatic-sounding AR6 claim are three maps of (1) hot extremes, (2) heavy precipitation and (3) short-term drought (IPCC 2021, Fig. SPM.3) for inhabited areas around the globe that show changes since 1950. An opinion as to whether human emissions may have been a major factor in the observed change is also offered. For the eastern US, the AR6 indicates there is no real evidence of change in any of these three climate phenomena that would support a human cause. This non-result was also true for hurricanes, tornadoes, hail, lightning and high winds.

Regarding sea level rise, globally, the AR6 estimates about 1 ½ in per decade to 2100 for a reasonable scenario of emissions (but the rate will vary greatly depending on what is happening at specific coastlines like Louisiana). All of these conclusions agree with the information discussed in this report. [As to the AR6 forecasts for the coming century on the non-sea level variables, no further comment is needed as we have seen how inadequately the models depicted the history of Alabama's climate since the 19th century.]

In the last few years there has been a continued push by environmental advocacy groups (and the media) to tie specific events, especially extreme events, such as flooding, hurricanes etc., to large-scale global warming. However, the amount of actual warming in the deep atmosphere, where these weather events are generated, is not rising at a rapid pace. In fact, observations continue to show considerably less warming than all theoretical global climate models used in AR6 available as of its release in 2021. For example, Figure 18 compares the tropical temperature trends at various altitudes for the models (hypotheses) used in AR6 and actual observations, demonstrating the overheating which characterizes the models (for more details see Christy and McNider 2017, McKitrick and Christy 2020 and Mitchell et al. 2020). Note that the coldest model just matches observations at lower elevations, but above 25,000 ft (where important thermodynamic processes occur that determine the global surface temperature) all of these models warm the atmosphere too much, generally by factors greater than two.

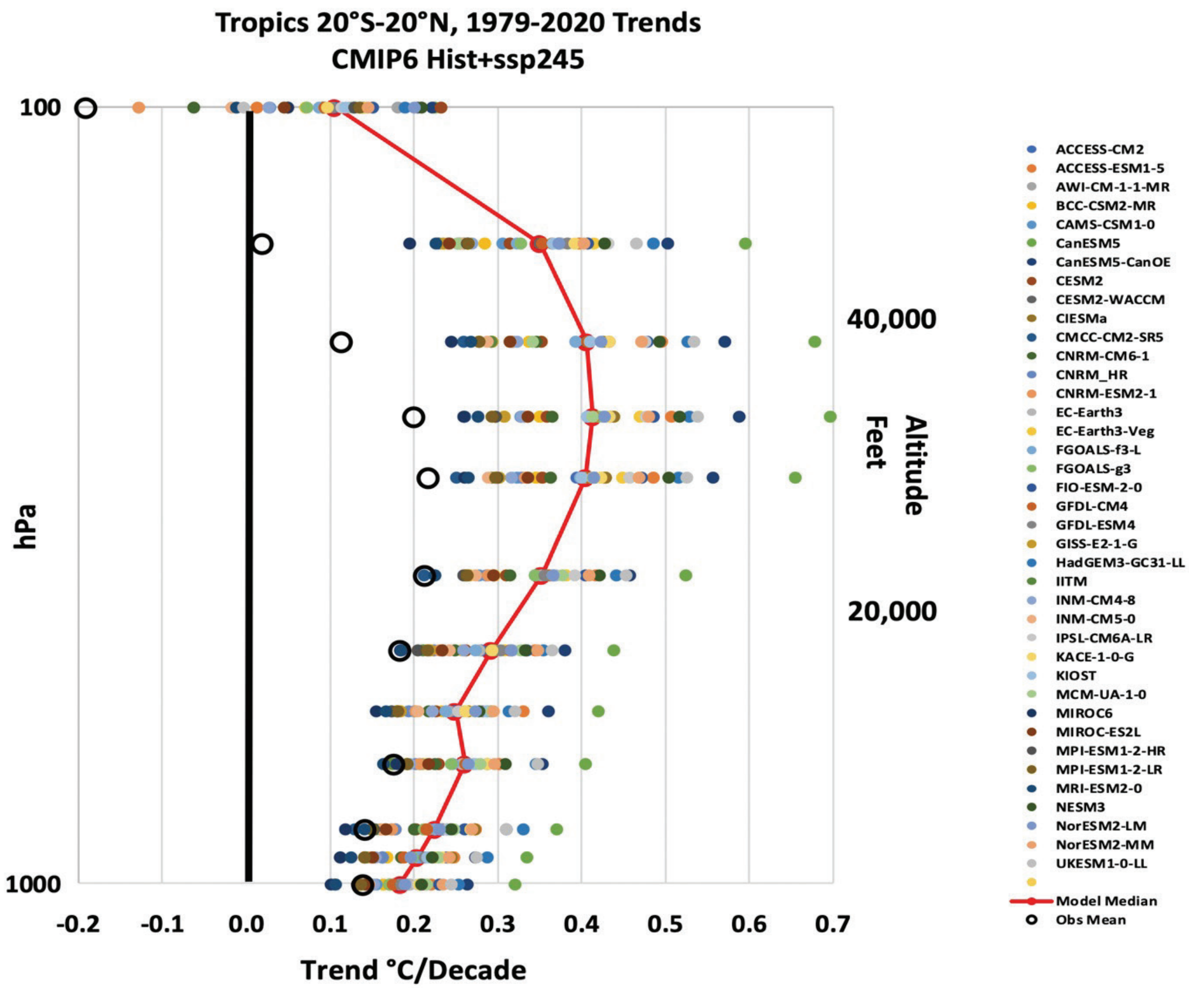


Figure 18. Tropical temperature trends from the surface to about 50,000 ft in the atmosphere for 1979-2020. Open circles are the observations and solid circles the model output for the same region and time period. The red line represents the median result from the models. The model names are in the list on the right.

The AR6 admits this discrepancy (IPCC 2021, e.g. Fig. 3.10), and in oblique ways, indicates that models seem to have a problem. So, since the much warmer atmosphere in models is not a characteristic of the real atmosphere, the claims of future heavier storms or worse hurricanes or more droughts (changes which have not yet occurred as shown earlier) carry little credibility for now.

Energy policy questions are beyond the scope of this report. The application of what is contained herein suggests that, at least for Alabama, the full impact of extra GHGs is so small that whatever energy policy is adopted to reduce an already small effect by an additional fractional amount will have an influence that would be undetectable and un-attributable compared with whatever the climate is going to do anyway. Thus, the impact of the policy on the economy is a critically important issue to be examined by those with that expertise. The bottom line of this report is that Alabama has experienced tremendous extremes in weather variables and we should do our best to prepare for these extremes because they are virtually certain to occur again, and with a high probability that they will be "worse," with or without the influence of extra GHGs.

One high school physics instructor used to say that whenever we make scientific pronouncements we should begin with, "At our present level of ignorance, we think we know …" Such an attitude of humility helps us to look at the climate information we have with a better sense of its potential utility and the proper limits of its credibility. The backbone of this report is the observations of climate that tell us something about how things have changed over time.

Keeping an eye on these facts will allow us to test various claims for their credibility and help prevent us from taking unnecessary and often expensive policy pathways.

This report will remain available electronically and as new information is discovered, we shall provide updates and then the reader will be able to see how "science" is a constantly evolving process that can change the way we view the world as new information is discovered. In addition, as particular issues are brought to our attention from our Alabama constituency, we will be able to address those through this document.

> At our present level of ignorance, we think we know …

Madison County Lake, Alabama
Image by June via Unsplash.com

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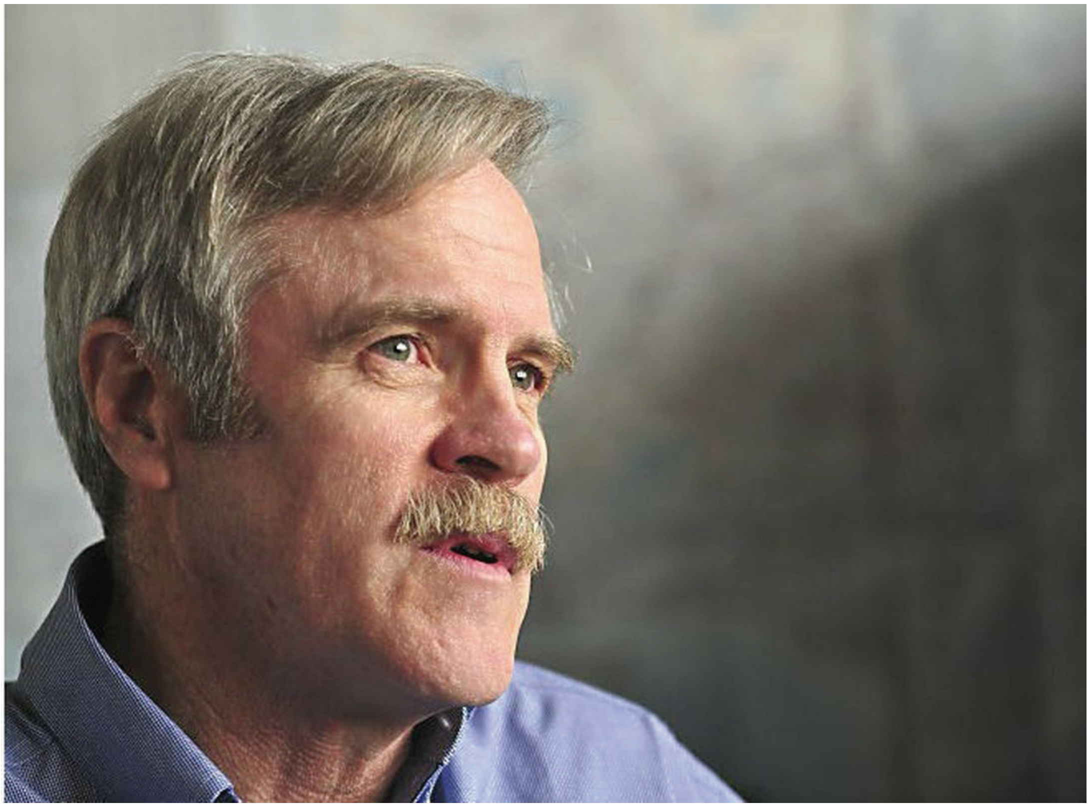

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