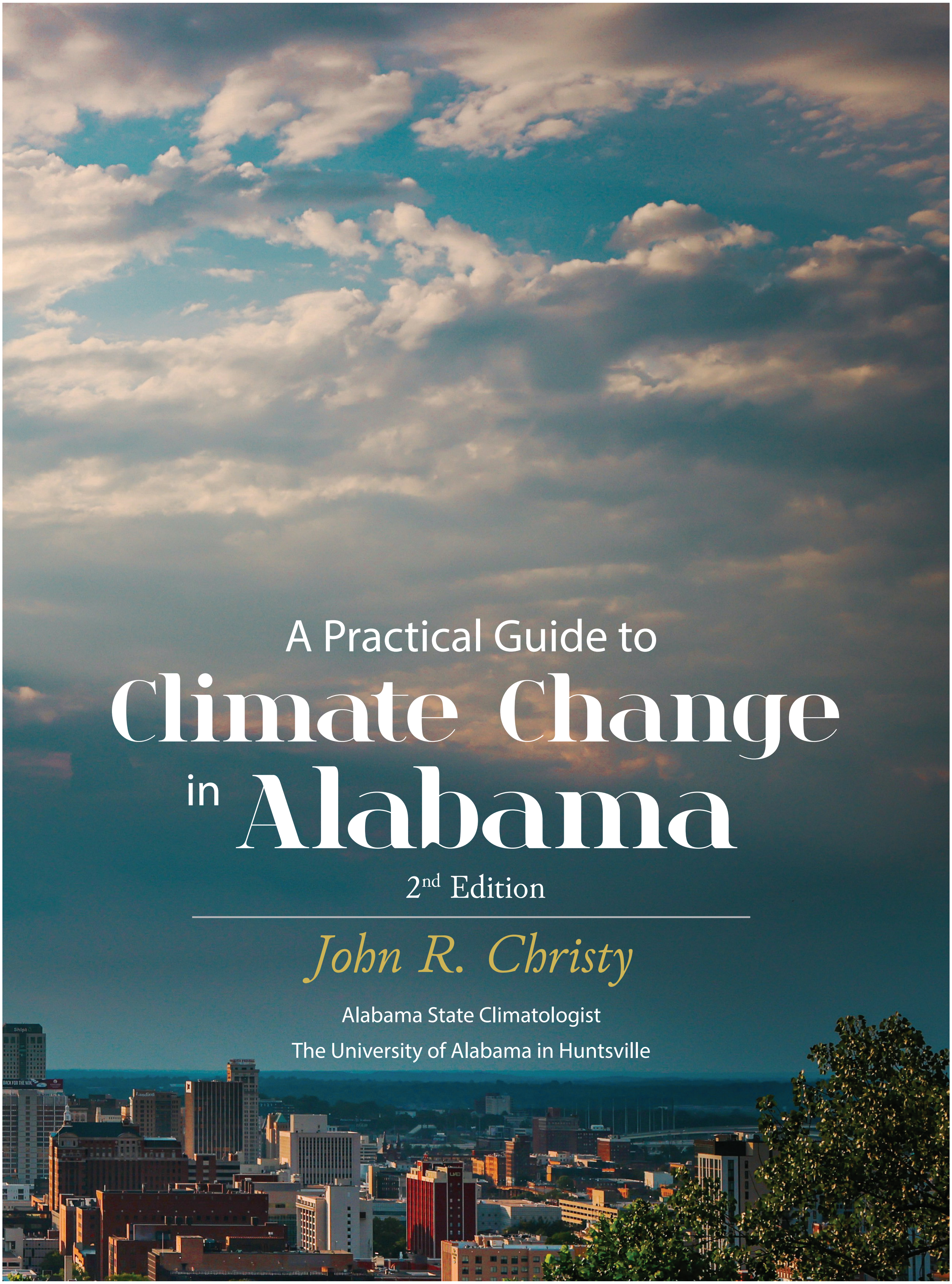

A Practical Guide to

Climate Change in Alabama

2nd Edition

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Book cover photography by Allan Francis
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Forward

In 2021, as Alabama's State Climatologist, I put together a booklet to address climate change as a general topic but with a major focus on Alabama. This was motivated by what was happening around the country as well-funded environmental groups were actively influencing state legislators and administrations by supplying reports of what I believe were biased representations of "climate change". These reports were provided to entice these states to enact legislation to "deal" with this alleged problem. Those efforts are continuing and becoming more intense so updating the 1st edition is a needed undertaking.

Since the 1st edition, we have experienced over two more years of weather to talk about, but we've also gathered new data, and data from earlier times, so that there is more information to show. This allows us to look at longer periods to better-judge today's climate against the events of the past 140 years or so and this is reflected in the updated charts. Much of the material will be taken from the 1st Edition, but there will be new topics as well. To help me with this effort was Abigale Barre who gathered most of the early data for analysis. Additionally, Jennifer Geary again has provided wonderful images of Alabama to bring a sense of our state's beauty to the reader – a beauty which our climate will continue to support.

Summary

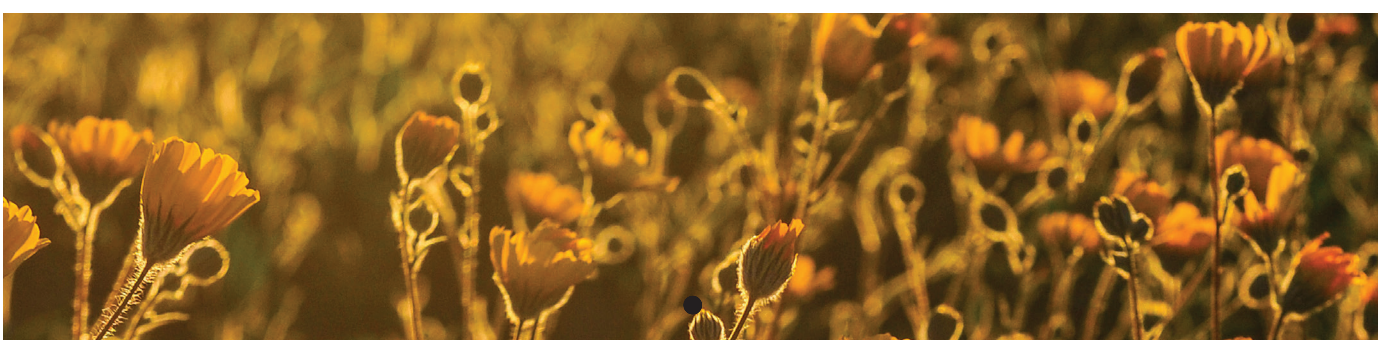
As noted in the 1st edition of A Practical Guide to Climate Change in Alabama, any climate variable will show some type of change between different periods whether they be weeks, months, years or millennia. However, knowing "why" such changes occur is often unsolvable because our climate system is an expression of two interacting, chaotic and turbulent fluids – the atmosphere and the ocean. Together, they can create an infinite variety of weather and climate patterns which lead to extreme events all on their own. This naturally turbulent character makes it difficult to accurately predict its evolution beyond a week or so. When something unusual happens, it is a quick and easy answer to say "climate change (i.e., humans)" but when one asks the accuser to "prove it", well, they can't because we are not able to quantify nature's enormous contribution to these variations.

Further, and unfortunate for us, determining the precise impact of extra greenhouse gases (GHGs) on the climate over the next 100 years is basically guesswork because the GHG influence is less than one percent of the total energy flows within and between these two components. The most sophisticated climate models indicate large disagreements amongst themselves about the influence of GHGs, varying by ± 35% around their average just in the temperature response to GHGs alone. Thus, identifying the isolated influence of extra GHGs requires essentially perfect observations and enormously clever detective work. Even so, one cannot "prove" human-sourced GHGs fundamentally caused a specific (or a series of) disastrous extreme events because Mother Nature's capability to do so on her own is vast and still poorly understood.

Be that as it may, upon examining several important Alabama climate variables such as extreme summer heat (including Mobile's 2023 heat wave), yearly rainfall, heavy rain events, droughts, snowstorms, hurricanes, and tornadoes, we find no significant changes associated with the increasing concentrations of GHGs and the modest warming effect they likely exert.

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 2 inches per decade.

The latest theoretical climate model simulations have been unable to replicate the types of changes in climate variables that Alabama (and other regions) have experienced since the late 19th century and so offer little guidance for the future. However, and this is important, 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.

Now, there is a rhetorical point to bring to our attention early. Prior to the turn of this century, "Climate Change" referred to any type of change in the climate system relative to some reference base. It was very common for scientists to discuss all sources of climate change, and then to try and separate out what bit humans might have influenced in the recent decades. In this sense, Climate Change would appropriately deal with Ice Age fluctuations of the last 1.7 million years, the global heat during the Mesozoic (dinosaur era) or the cold temperatures 600 to 170 years ago in the Little Ice Age.

Around 2000 however, bureaucracies, such as the United Nations which officially examine the climate change issue, decided to "change" the meaning of "Climate Change." They now promote "Climate Change" as referring only to the human impact on climate. I think the average person could see this was an attempt to implant the idea that humans, basically, caused every change that was observed (and mercilessly exaggerated in the media - social and otherwise) and that Mother Nature was now unemployed. So, keep this in mind when you listen to the phrase "Climate Change" and the likely nuance intended. Fortunately, some agencies still regard Mother Nature as important.

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 through transportation, industry, electrification, etc., lifting billions of real people out of poverty. A good example is India which in 2023 landed a spacecraft on the Moon in addition to pulling hundreds of millions of its citizens out of poverty thanks to the energy contained in carbon.   Indeed, India's Power Minister, R. K. Singh stated prior to the 2023 international climate conference (COP-28) in Dubai, "There is going to be pressure on nations at COP-28 to reduce coal usage. We are not going to do this … we are not going to compromise on availability of power for our growth."

The use of carbon-based energy has largely removed the threats created by weather events from which we are now protected with deaths from these events down about 98% in the last 100 years. An excellent discussion of the benefits of carbon is found in Alex Epstien's book *Fossil Future* (2022). As noted however, my own booklet here will not delve into the social issues that attend the use and/or restriction of carbon-based fuels and products.

The main human-generated GHG is carbon dioxide (CO2) - a by-product of combustion of carbon-based fuels such as coal, oil and natural gas, though other processes like cement production add to the total.

Fortunately, CO2 is non-toxic in any foreseeable atmospheric concentration and is even a boon to the biosphere which ingests CO2 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 CO2 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 CO2 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 CO2 has had a positive impact on food production worldwide. This benefit is likely to continue into the future as CO2 levels creep upward but never achieving the level of enrichment seen when the biosphere initially developed millions of years ago.

Of concern then is that potential changes in the climate due to extra CO2 (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 response to increasing CO2 is important to examine.

The policy dilemma is fairly clear – on the one hand, there is no question that carbon-based energy and products, due to their affordability, reliability, power-density, effectiveness, and accessibility, enhance and extend 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 dependable 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 energy issue.

With so much attention drawn to this topic of "climate change", I, as the Alabama State Climatologist, prepared this update as a non-technical report to inform the reader about climate change in general and in particular for Alabama and what this may mean for our state. In this second edition I've updated several charts, added a few more and changed things around a bit, but the overall presentation and results are much the same.

I 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 2nd edition will not be written in a scientific style where, normally, each statement is 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. As noted in the Forward, many of these reports are published with the aid of environmental advocacy organizations and/or politically motivated agencies 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. There will certainly be need of a 3rd edition in the years to come, but my authorship is unlikely as retirement beckons.

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. Unfortunately, we do not have an instrument that can measure the isolated impact of CO2 on the climate, especially whatever indirect effects it might exert on the weather.

With that in mind, we do have theoretical climate models from which we can run experiments to see what differences the models reveal between a world with and without the extra CO2. However, models are models – they are crude representations of the real thing and as will be shown, can't reproduce what's already happened very well and their predictions vary widely.

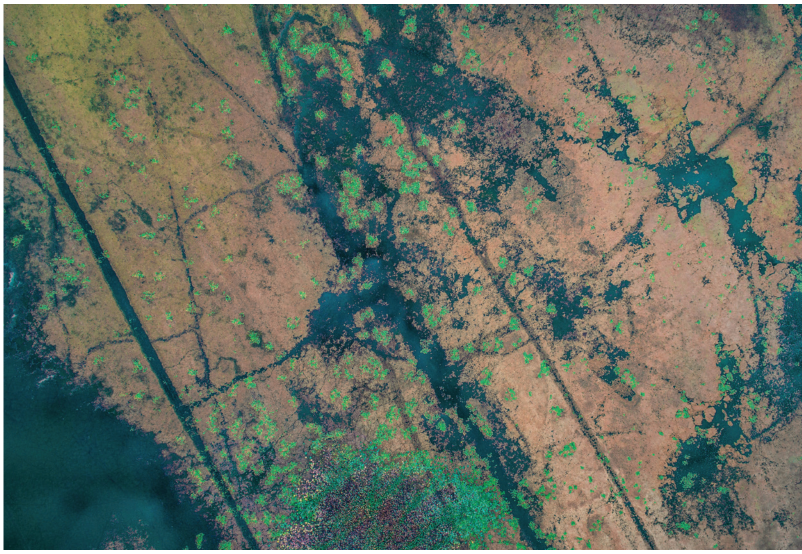
While some parts of the climate's various energy flow processes in models are based on direct, fundamental physical concepts (e.g. fluid motion, radiative transfer, basic thermodynamics), the actual partitioning of energy flows is tied to many uncertainties as they try to estimate major effects of complicated processes like turbulence, land surface energy exchanges and clouds which are generally too small to directly represent. These uncertainties are seen in part by the various conclusions the models show for certain, important factors. 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). What is even more problematic is that we do not know what he actual aerosol response was.

This kind of uncomfortable information exposes the serious ambiguities that inhabit current modeling experiments and reveals that different modeling groups chose their own ways to estimate the "physics" of the climate system. Think about it. If climate modeling were "settled science" then why do the different models have major differences in their formulation and results?

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 changes 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 Alabama Climatologist's 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 in the last 150 years 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, as mentioned above, 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 CO2) a murky, and some would say, almost impossible problem. Unfortunately, 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 survive and thrive. But again, we see from the long history of climate that the collection of plants and animals which have inhabited Alabama has experienced dramatic changes as the climate has varied through enormous cycles, often surpassing the survival limits of whatever local flora and fauna had been established but which are now extinct.

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 1883 to 2023, we would likely be surprised at how the climate-extremes change from one period to the next. 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 140 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, wettest fortnight, coldest month, etc. There are dozens and dozens of options that may be determined. However, based on very simple statistics, we would expect fully half of these extremes to be exceeded in the next 140 years due only to the influence of Mother Nature. Extreme events will continue to occur no matter what the extra GHGs do.

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 processes. The point here is to be cautious about those who attempt to stir up excitement about "record" events because we only have a tiny slice of time - that "blink-of-an-eye" - over which we have actual observations.

There is this further note as well. Extremes are often disconnected from the background average, so it may not be a surprise to see changes in extremes that don't match changes in overall averages.

There may be a period of record heat in a year that otherwise was cold, somewhat like the 1991 NY Mets achieving a remarkable 10-game win streak in a year they finished under 0.500.

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 140 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 in a variable 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?", I 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 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, I 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.

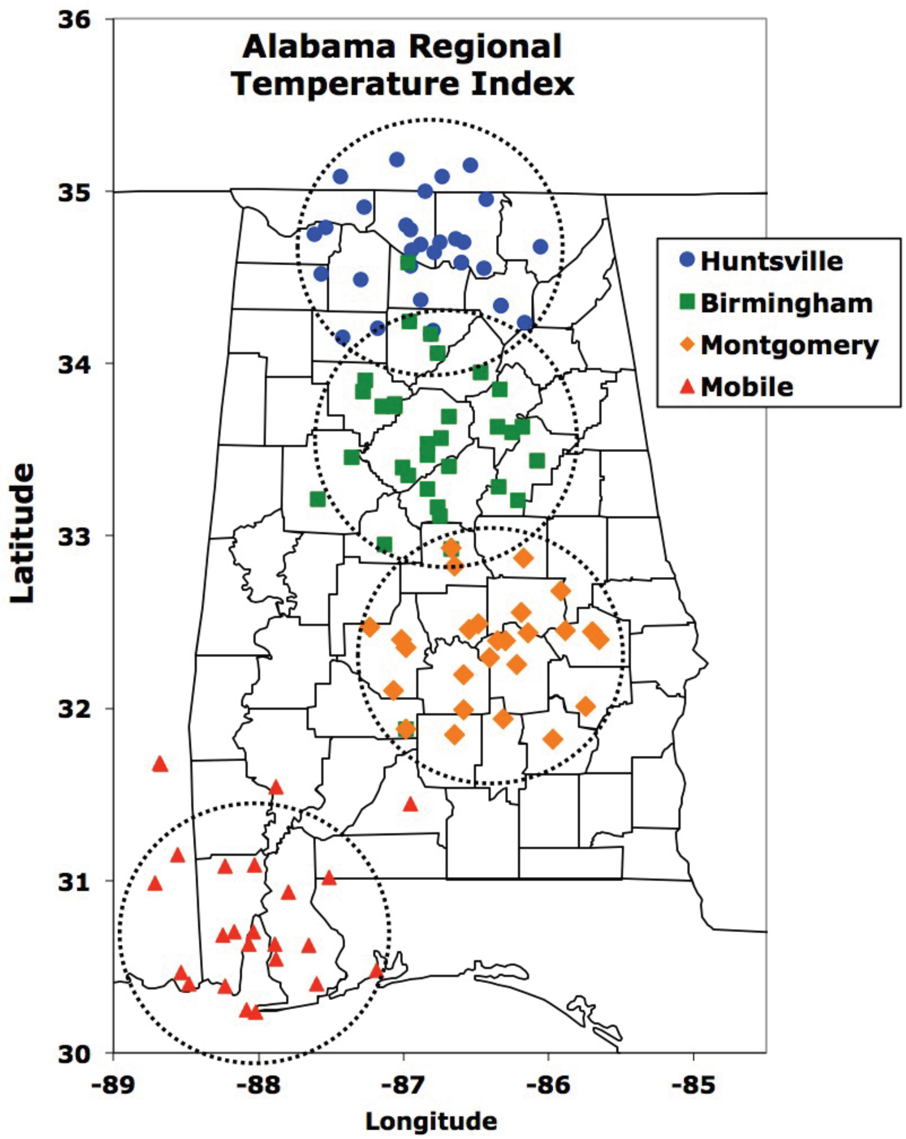


Figure 1. Four regions for which long-term summer high temperatures were constructed. The location of the stations used in the construction for each region are indicated by the symbols.

In Christy and McNider 2016, (Dr. Richard McNider was Alabama's State Climatologist before I took over in 2000) 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 2023.

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.

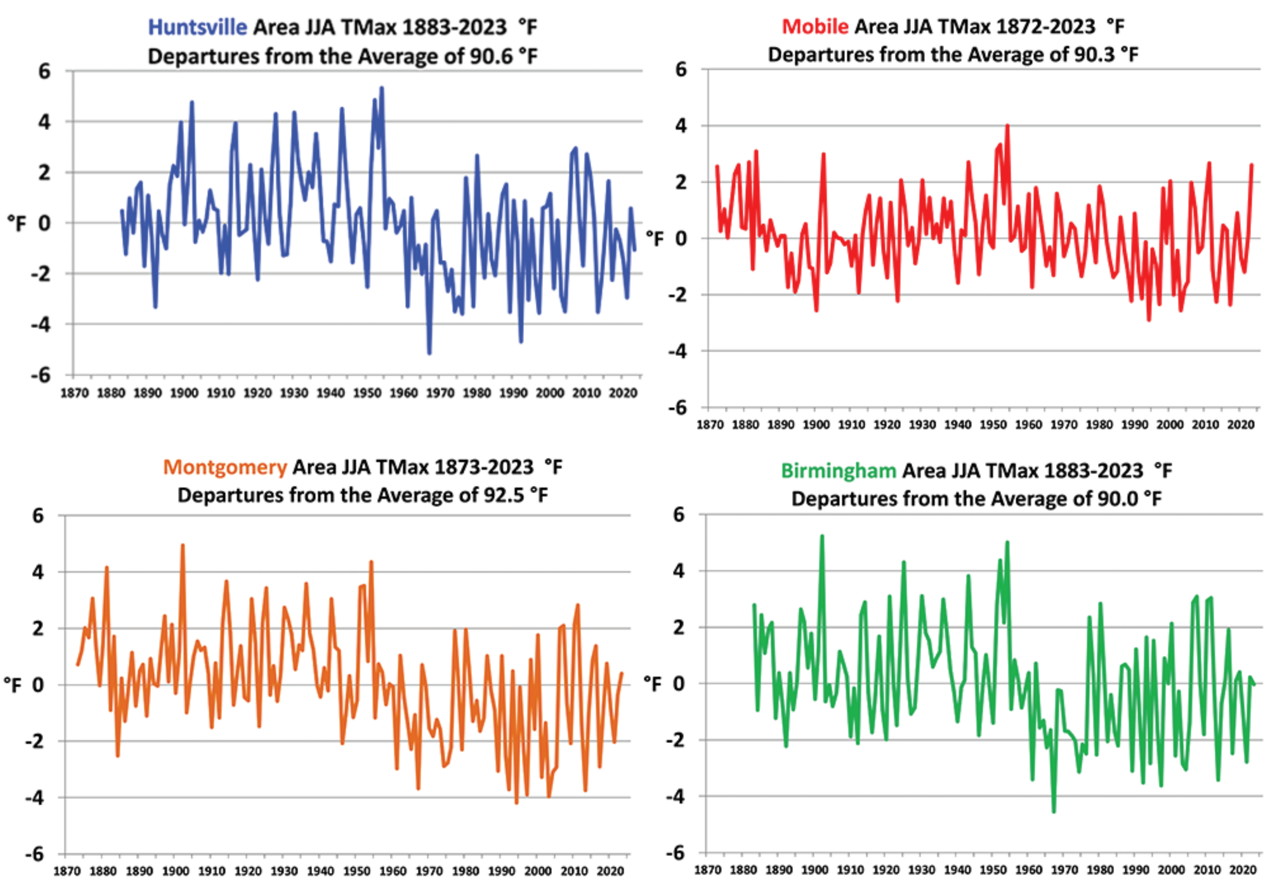


Figure 2. Summer (June, July, August) average daily high temperature departures from average (stated in titles) for four metro regions in Alabama ending with the summer of 2023.

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. Notice too that the regions can vary. In 2023 Mobile was much hotter than 2022 (I'll talk about Mobile's hot summer later) while Huntsville was actually cooler.

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 2023 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 was discussed in the 1st edition where we also found 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 GHGs) 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.

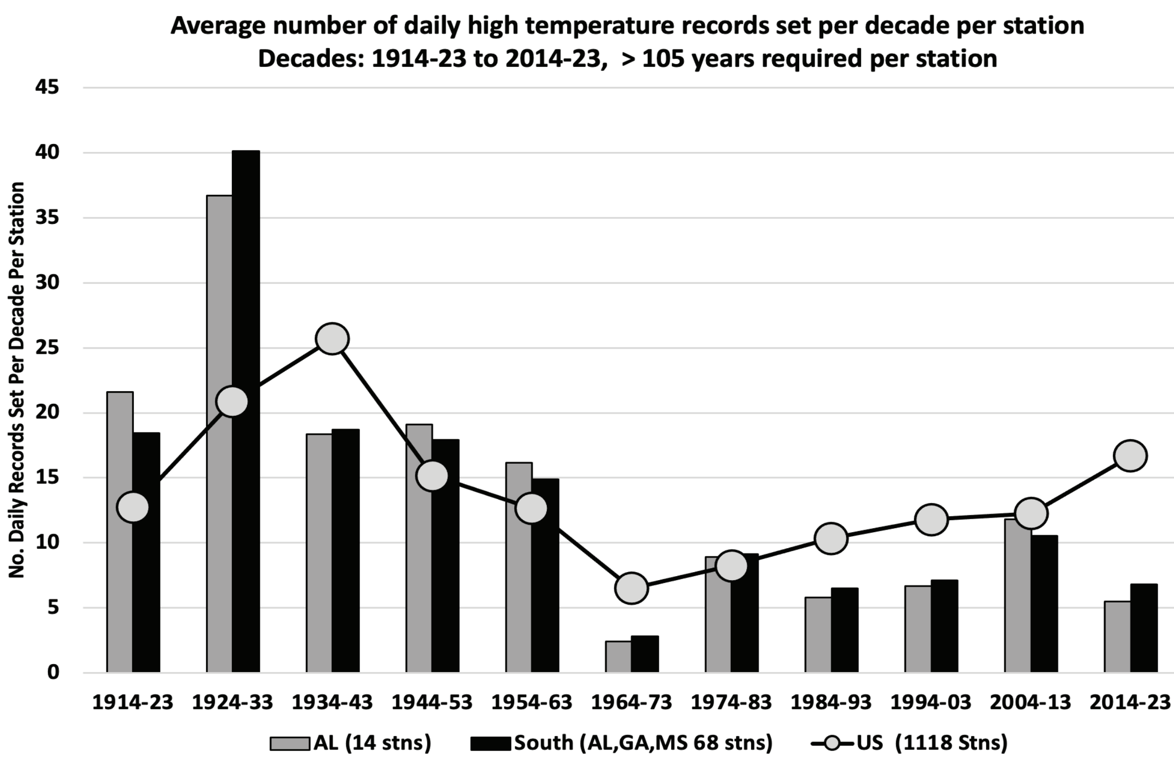


Figure 3. Total number per decade of daily high temperature records during May to September set per station for Alabama, the Southeast (AL, GA, FL, MS, NC, SC, TN) and the conterminous US. The number in parentheses is the number of stations used in each region. A station was required to have > 105 years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

Changes in Temperature Extremes

Figure 3 may reveal a surprising result to many. For Alabama, as well as the Deep South (AL, GA, MS) 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. The expected value of 14 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 an 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 that generate daily *high* temperature records.

In the 1st edition I discussed the different result for the daily *low* temperatures in which it was found that the 1960s to 1980s experienced the most record *lows*, but after that, the number declined rapidly. 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 figure above, we have a confident expression of "what" has happened regarding "changes" in daily hot 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.

In the 1st Edition I discussed in some detail six possible reasons as to "why" this difference of the long-term changes between *high* and *low* temperatures has occurred. Those reasons were changes-over-time in; (1) atmospheric moisture, (2) land cover, (3) weather-pattern variability, (4) urbanization (related to #2), (5) rainfall, and (6) GHGs. Alabama has seen a slight increase in rainfall, and thus moisture availability, which acts to cool the days and warm the nights through more humidity and cloud cover. Also, many stations that were once rural are now measuring temperatures within or close-to urbanized areas, and this leads to warmer nights. The effect of extra GHGs is likely having a small effect on nighttime *lows*, though we don't see the same for the daytime *highs*. Overall a combination of the reasons given above lead to warming nighttime *lows* while having some impact on lowering daytime *highs*, likely through increases in rain and cloudiness.

Keeping in mind all of the factors above that influence temperature we shall examine some metrics with regards to extremely hot temperatures. First, we shall simply count the number of very hot days to see how their numbers are changing.

Figure 5 shows the number of days on which the average station in each region reached or exceeded 95 °F (a 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 South when there has been little rain in the previous weeks, a condition that occurred more often before 1955 in the South than after.

In the conterminous US (Fig. 4, circles) the decade of 1934-43 included the major Dust Bowl years that were associated with weather conditions that produced the greatest number of hot days, about 260 per station per decade or 26 events per year for the average station across all 48 states. The previous decade was also characterized by many heat waves, including those in 1925 and 1930. [Over the entire 110-year period the average US station warmed to 95°F or above about 21 times per year.]

For Alabama, the hot and dry summers of 1925-1931 provided the most 95+ °F days and hence the largest number in that decade (black bar). The latest decade in Alabama experienced a dearth of hot days, barely exceeding the number in the cool 1960s.

Of interest here is that when a sufficient number of Alabama stations began reporting in 1883, at least one station reported a temperature of 100°F or higher 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. However, the impact of a dry period can be miserable, seen most recently in SW Alabama in August 2023 as very little rain had fallen in the previous weeks and many 100°F daily temperatures were recorded in the area (see later). The bottom line of these weather extremes is that they do not show an increase for Alabama, the South or even for the conterminous US as a whole.

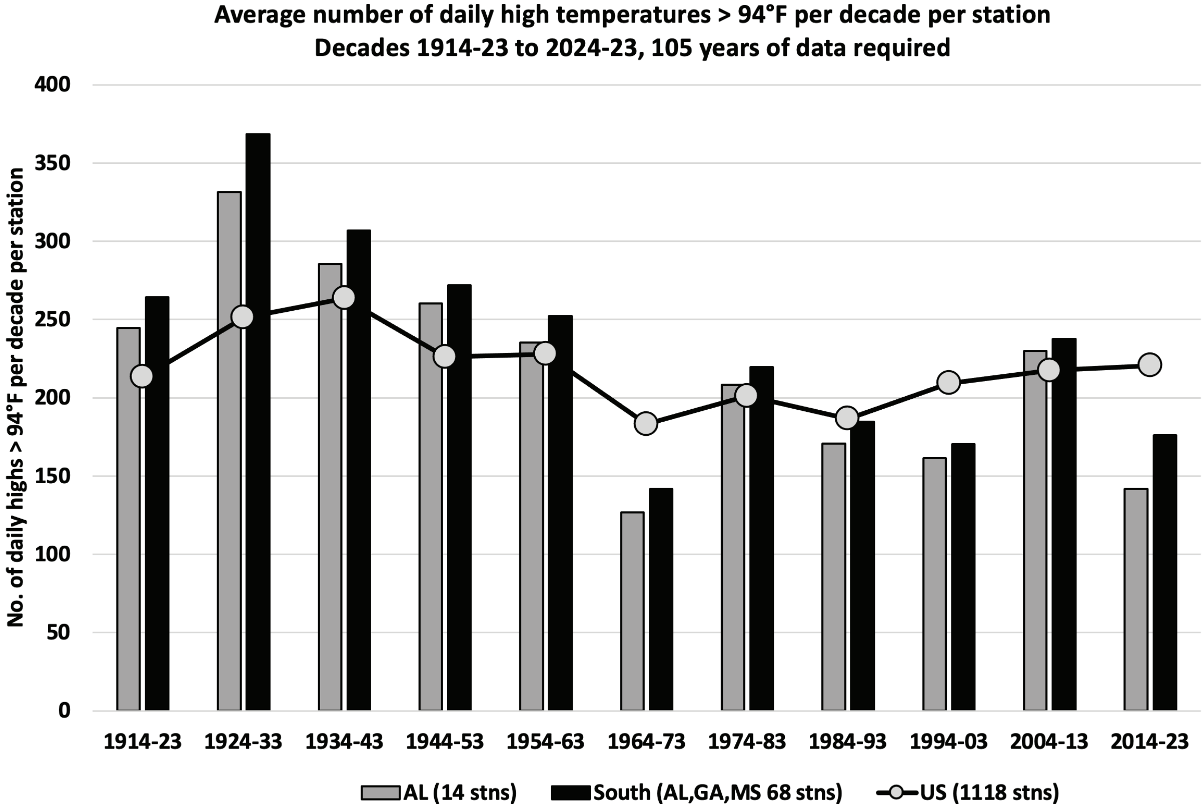


Figure 4. Number of hot days (highs > 95 °F) per station in AL, the South and the conterminous US. The value represents the total events per decade at the average station in each region.

How low do *Lows* go and how high do *Highs* rise?

We will look at the real extremes in temperature here. The coldest recording by a station in Alabama occurred on 30 January 1966. On that day, Ms. Lucile Hereford of New Market was serving as the town's postmistress and volunteer weather observer. I spoke with her around 1990 about that day. She said the ground was covered with snow, about a foot, when she trudged out to the instrument shelter at 5 p.m. for the daily reading and was quite surprised at what she saw. She asked an acquaintance who was passing by on that bitter afternoon to take a look. He thought the *low* reading was -28°F, but Ms. Hereford reckoned it was closer to -27°F, and that was the value reported. Yes, in Alabama it plunged to 27 below.

Interestingly, Ms. Hereford's handwritten value looked a bit like -17°F to the officials at the Weather Bureau, and for years -17 °F was listed as the official reading (Fig. 5). Later, a reporter investigating the weather that day discovered from Ms. Hereford that the "1" was really a "2" and so the reading was officially changed to -27°F which stands today as the coldest reading ever observed in Alabama. As it turned out, that was also the coldest reading for the entire conterminous US on that day.

Figure 6 (p. 7, left panel) is a map of the state's temperatures on that day and shows that about half of the state was below zero and that the second coldest station was Russellville at -24°F. In between Russellville and New Market are the lakes of the Tennessee River which kept stations nearby (Decatur, Muscle Shoals, etc.) a bit warmer.

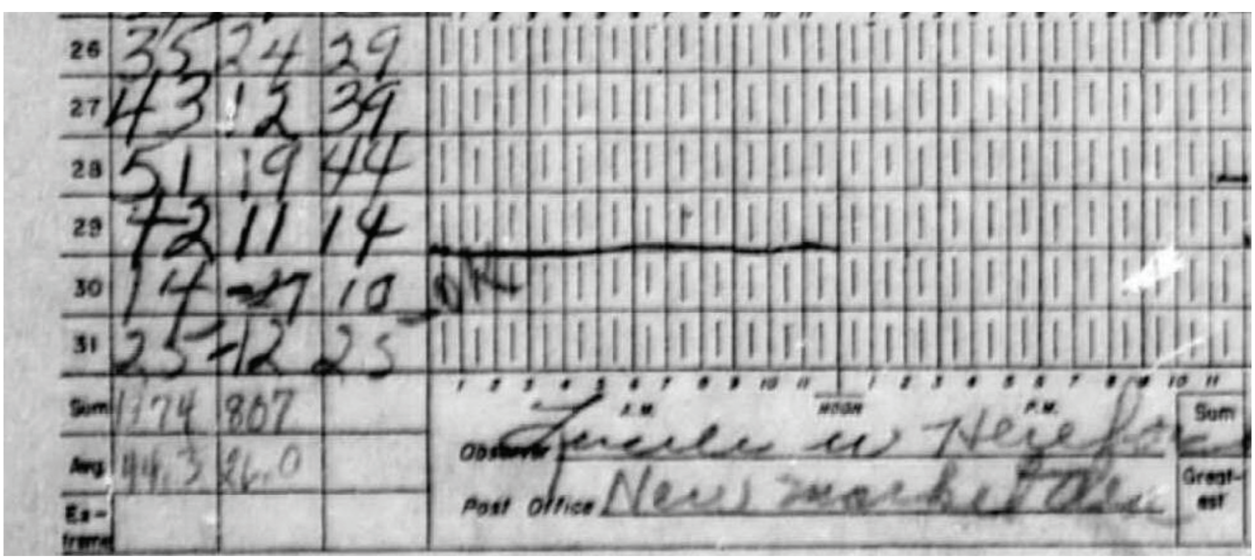


Figure 5 . Temperature entries for 26-31 January 1966 by Lucile Hereford of New Market. Note the smudge on the minimum temperature value for the 30th which led to a misreading as a "-17" rather than a "-27".

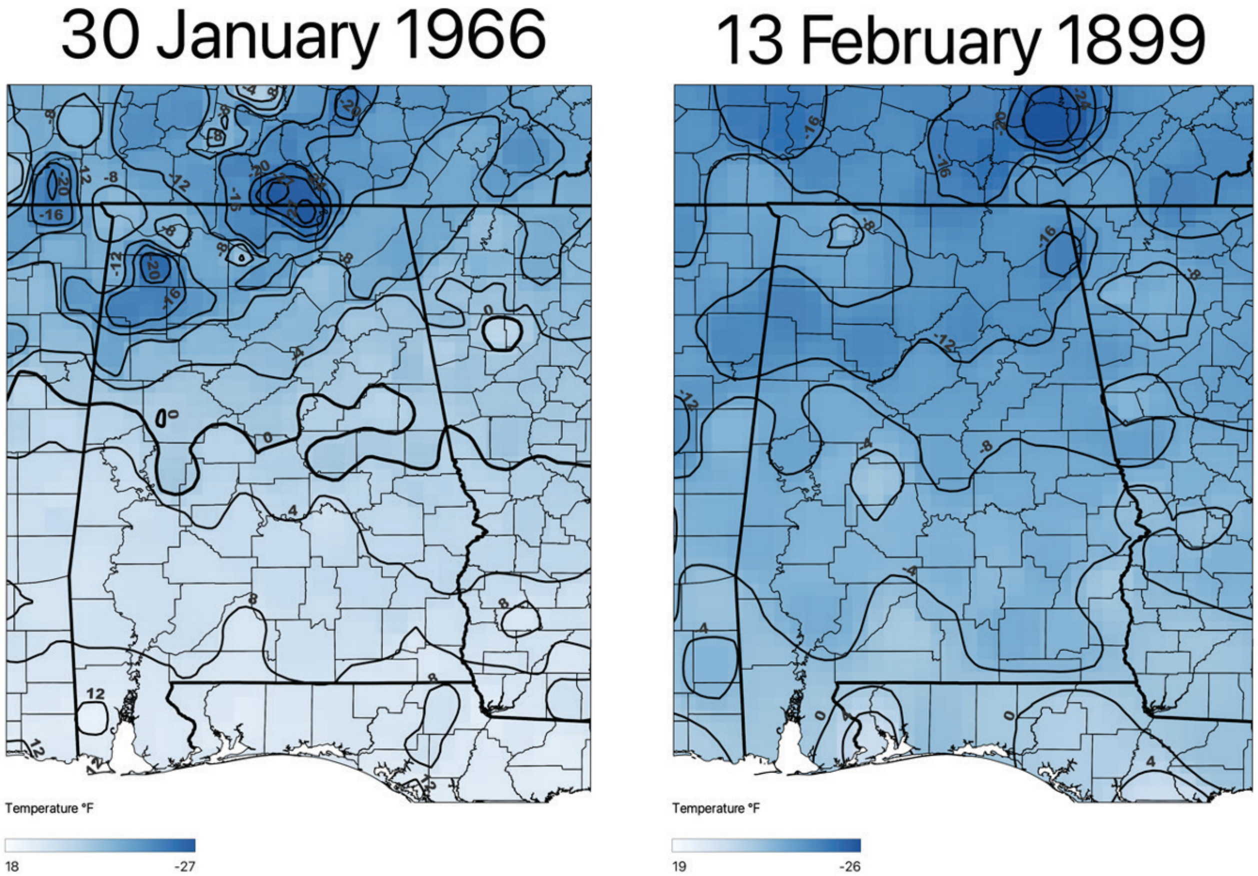


Figure 6. Temperature distribution of the daily lows across Alabama and adjacent states for 30 January 1966 (left) and 13 February 1899 (right). The two coldest readings were -27°F at New Market and -24°F at Russellville on the left. Note that the temperatures along the Tennessee River lakes (i.e., Decatur, Muscle Shoals, left) are warmer as they are near water bodies that kept the temperature from falling as much.

So, the coldest reading measured in Alabama was -27°F on 30 January 1966 in New Market. However, there is another way to define the "coldest day" and that is by the geographic average of all stations in the state, and for that we must go back over 120 years. For perspective, the statewide average temperature on 30 Jan 1966 was +0.2°F.

A bitter cold airmass invaded the entire South from Texas to South Carolina in mid-February 1899 and earned the title "The Great Arctic Outbreak of 1899" and the "St. Valentine's Day Blizzard" along the East coast. It was so cold, ice floes were spotted on the Mississippi River moving into the Gulf and Tallahassee recorded Florida's coldest temperature, their only sub-zero observation, at -2 °F. Though no Alabama stations dipped below -17 °F, the extent of the below-zero weather was much greater than in 1966, extending all the way to the Gulf with Mobile plunging to -1 °F, the only below-zero reading recorded there in over 150 years of data. The average statewide low temperature was -7.5 °F, almost 8 °F colder than 30 January 1966, thus also earning a title of Alabama's Coldest Day (Fig. 6)

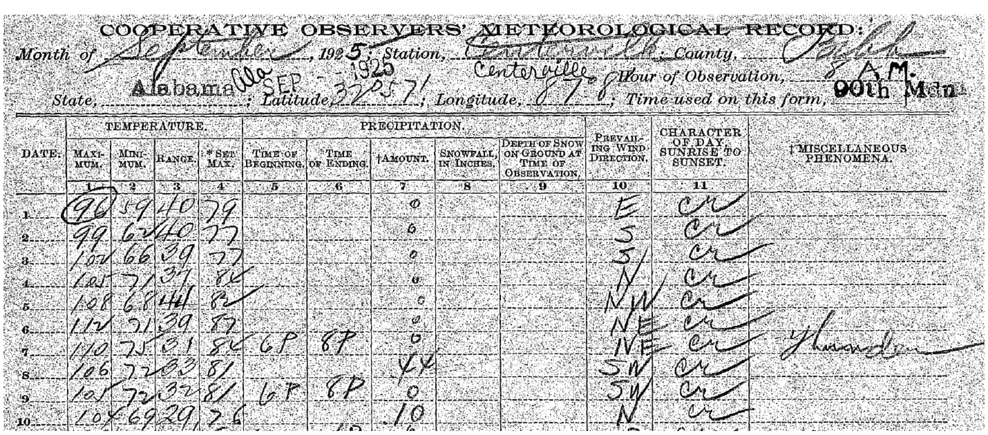
On the other end of the temperature scale, the state's hottest reading arrived in 1925 after a long dry spell in the state. In fact, August 1925 still reigns (no pun intended) as the driest August on record. On the morning of 6 September, volunteer observer Josiah M. Kennedy walked out to the thermometer shelter in his yard just southeast of Centreville to see that the previous day's temperature had topped out at 112 °F, the hottest ever measured in the state (Fig. 7).

July of 1930 was also hot in Alabama. On the 29th, Thomas W. Carter of Madison dutifully went to his backyard on Church Street, where the official station was located, and recorded a value of 111 °F which occurred just before a light shower cooled things off. This still holds the claim as the second hottest reading for the state.

The magnitude of the yearly hottest and coldest readings at any Alabama station are given in Figs. 8 and 9. Reliable coverage for the hottest observations began in 1883 when many summertime Cotton Region stations were established. For the coldest readings I start in 1884, though it was not until 1888 that there was what I consider enough coverage. (Prior to 1888, several stations reported the 0700 temperature as TMin because they did not have a true TMin thermometer).

On average, the difference between the hottest day and coldest night in Alabama in a given year is slightly more than 100 °F. The average hottest is 104.0 °F and the average coldest is +2.8 °F. The difference in the variation of TMax vs. TMin is remarkable, with the range of the annual hottest temperatures being only 14 °F (98 to 112 °F) and that of the coldest 43 °F (-27 to +16 °F).

Now, back to the main story of historical temperatures, as noted above, one cannot see a signature of the response to extra GHGs in these results. The expectation is that one should see a rising trend of 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 1914 to 1954 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).



COOPERATIVE OBSERVERS' METEOROLOGICAL RECORD:

Month of September, 1925; Station, Centreville; County, Bibb

State, Alabama; Latitude, 32°57'; Longitude, 87°8'; Hour of Observation, 8 A.M.; Time used on this form, 90th Mdn

SEP 1925

DATE.	TEMPERATURE. Maximum. 1	Minimum. 2	Range. 3	* Set Max. 4	PRECIPITATION. Time of Beginning. 5	Time of Ending. 6	† Amount. 7	Snowfall, in Inches. 8	Depth of Snow on Ground at Time of Observation. 9	Prevailing Wind Direction. 10	Character of Day, Sunrise to Sunset. 11	† Miscellaneous Phenomena.
1	96	59	40	79			0			E	cr	
2	99	62	40	77			0			S	cr	
3	104	66	39	77			0			S	cr	
4	105	71	37	84			0			N	cr	
5	108	68	41	82			0			NW	cr	
6	112	71	39	87			0			NE	cr	
7	110	75	31	84	6P	8P	0			NE	cr	Thunder
8	106	72	33	81			44			SW	cr	
9	105	72	32	81	6P	8P	0			SW	cr	
10	104	69	29	76			.10			N	cr	

Fig. 7. The first ten days of observations during September 1925 from Centreville recorded by Josiah Kennedy. The 112 °F appears on the morning of the 6th.

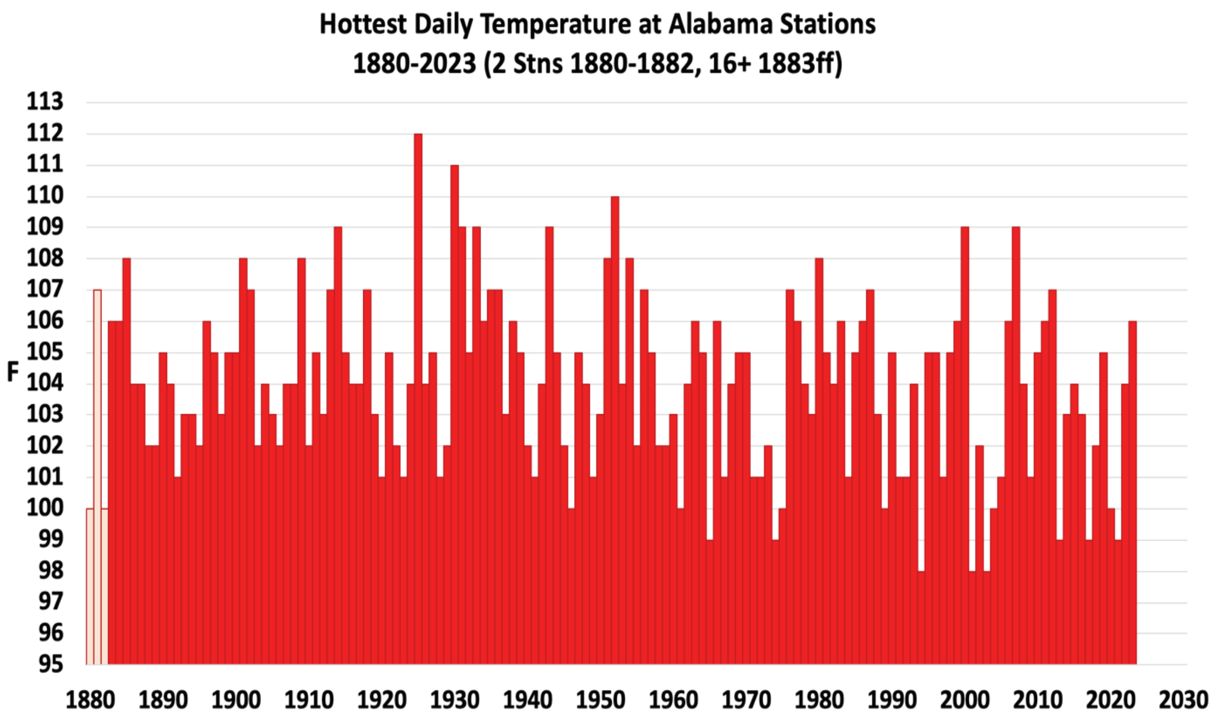


Figure 8. Hottest reading each year for Alabama stations for 1880 to 2023. Only three stations were observing in 1880-1882, so these are lightly-colored.

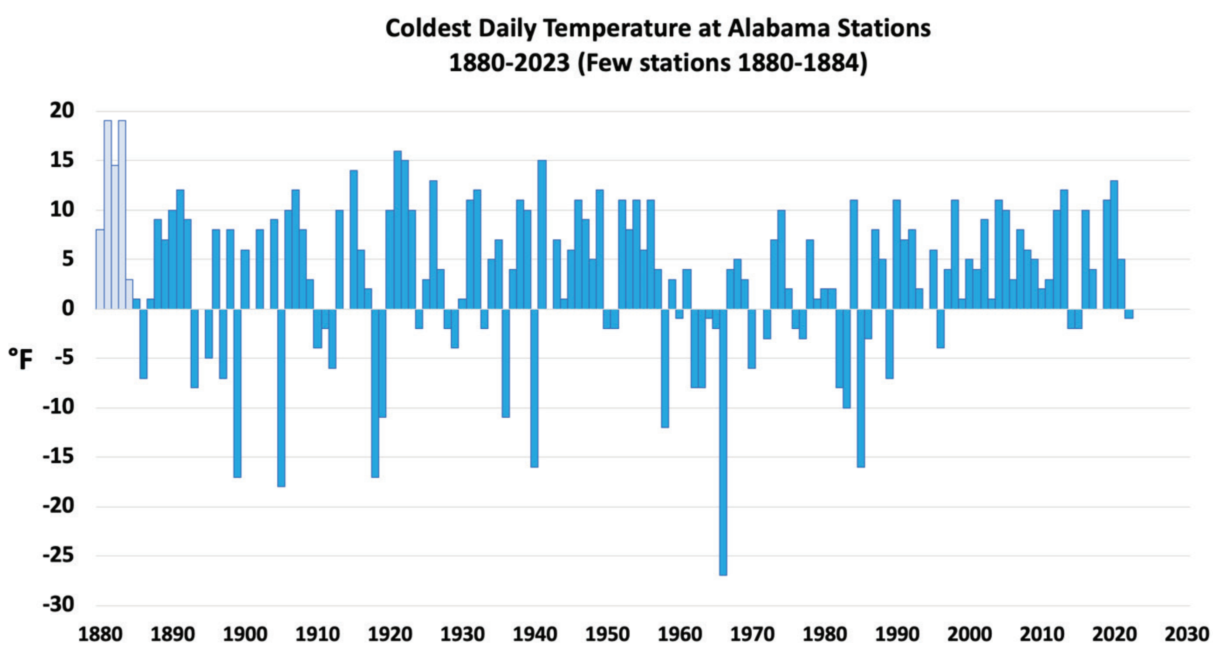


Figure 9. As in Fig. 8 but for the coldest reading of any station. Only a handful of stations reported in 1880-1884, so these are lightly-colored.

Alabama's Hot Spot in 2023 : Mobile

It is always exciting in the Alabama State Climate Office to witness a new "All Time Record" somewhere in the state. On 26 August 2023 the Mobile Regional Airport west of the city (FAA call sign "MOB") exceeded their earlier highest temperature record reaching 106 °F while Mobile Downtown (International) Airport ("BFM") tied their highest at 104 °F. The official digitized NOAA data for these stations begins in 1948 and show that the 104 °F at BFM was apparently a new record too.

However, I descended into the deepest recesses of the NOAA document archive and retrieved data for MOB back to 1942 (when civilian operations were moved there from BFM on Dec. 1 1941). I was also able to extend BFM data back to 1933 when Civil Aviation and later Weather Bureau personnel set up observations for aviation. This search discovered that on 5 Aug 1947 BFM also topped out at 104 °F. So, with the additional data, the headline story didn't change much – MOB experienced the hottest day in 82 years and BFM tied their hottest.

In 2023, only one other Alabama station tied MOB with a reading of 106 °F, Evergreen Middleton Field AP. The story there is not as remarkable because the long-term Evergreen city station, which closed in 2018, had seen 106 °F or above six times since 1884, including 107 °F in 1925 and 1930. As noted, Alabama's all time high of 112 °F was measured in Centreville in 1925.

A detailed history of the weather observations at the Mobile airport stations is too complicated to go into here, but suffice it to say that we have had continuous summer observations specifically at MOB since 1942 from National Weather Service personnel (82 years) and at BFM since 1933, taken mostly by military service members from December 1941 to 1967 at which time the Air Force closed operations. There was a long gap at BFM until observations resumed in late 1996 when an official station was installed to support the downtown airport's growing air traffic. But it is very unlikely that a potential hot temperature record occurred during the gap. Finally, a station west of town, but not as far as MOB, Spring Hill took observations between 1906 and 1950.

The value of the hottest temperature each year at these four Mobile-area stations described above is shown in Fig. 10. The highest value of 106 °F in 2023 is 1°F above the 105 °F measured at MOB in 2000. Spring Hill (1921), BFM (1947, 2023) and MOB (1952) have all reached 104 °F.

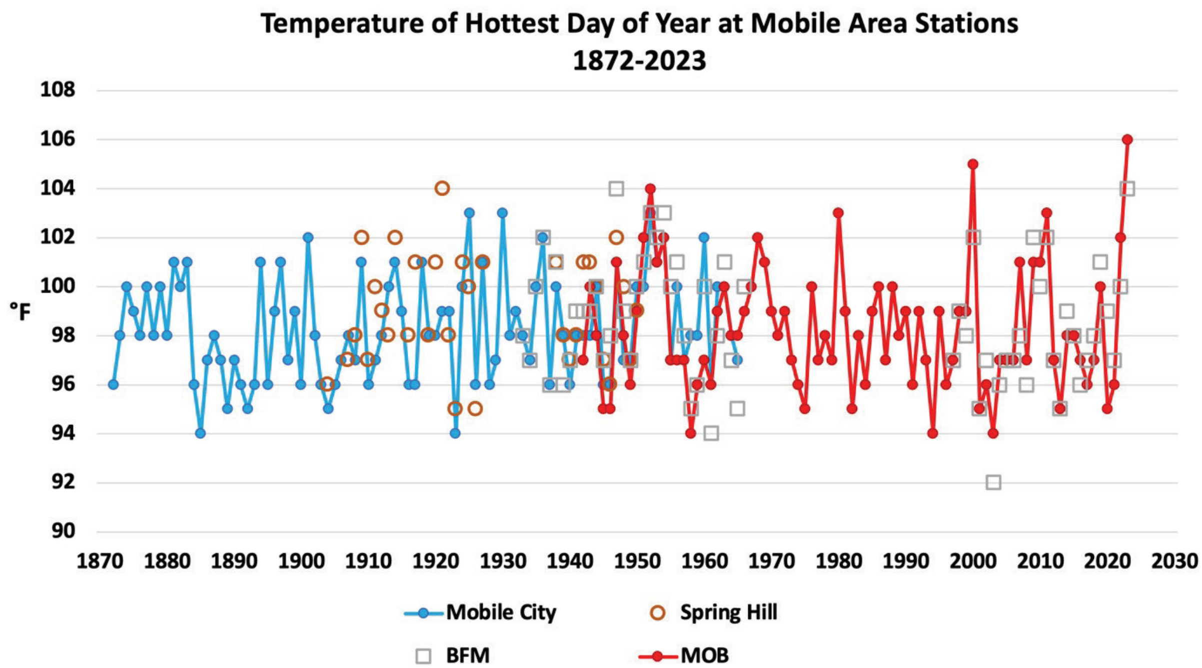


Figure 10. Value of temperature on hottest day of each year in the Mobile area. Stations are Mobile City, Spring Hill, Brookley Field (BFM) and Mobile Regional Airport (MOB).

Broadly speaking, the 2023 heat wave was a major phenomenon from central Texas through Louisiana and at times through southern Mississippi. Louisiana in particular was hard-hit with 39% of its long-term stations achieving their record high temperatures since 1914. The average station in LA exceeding 99 °F 20 times in May-Sep 2023, well ahead of the two years tied for 2nd place (1924 and 2011) when the average station had 15.2 days greater than 99 °F. In late August the eastern nose of this heated region extended into south Alabama, producing the very hot temperatures in Mobile.

Another interesting feature of 2023 was the relatively light easterly winds across the Florida peninsula. Normally these winds act to stir up the ocean water so that cooler, deeper water mixes with the warm surface water, lowering the surface temperature. In 2023, the winds were lighter than normal, so there was less mixing and the surface layer waters in the eastern Gulf were much warmer than usual, helping to keep things warm over land, at least near the coast, and perhaps even energizing hurricane Idalia.

In any case, it was extremely hot on 26 Aug 2023 in Mobile which spurs two questions, (1) were these temperatures really the hottest in, say, 150 years during which time we've had a fair bit of increasing infrastructure and population? and (2) is this part of a long-term pattern of warming? Extreme temperatures result from a combination of the general pattern of the background climate, the day-to-day variations of weather and local effects due to issues such as the amount built-up infrastructure near the station and the way the instruments are mounted, so we shall keep this in mind.

The hottest ever in Mobile?

Regarding question 1, unfortunately we do not have observations from these airports for earlier years when other searing summers baked the area, 1883, 1902, 1925 and 1930 for example. In fact, when looking at the stations surrounding Mobile with records going back at least 100 years, none achieved a record in 2023, though two Mississippi stations tied theirs. Those not hitting records include Fairhope, Bay Minette, Pensacola FL and in MS, Columbia, Laurel, Hattiesburg and Poplarville. Biloxi and Waynesboro MS matched their records set in several earlier years. This information casts some doubt on whether 2023 was hotter than years before airport observations began.

I should note here that there was an official US Army Signal Corps and later US Weather Bureau station in downtown Mobile (City Office) from 1871 to 1953 with continuing observations through 1965 taken by volunteers. The WBAN ID was 93855 and COOP ID 015483. Precise temperatures were taken with official instrumentation, but the exposures of the instruments varied considerably as the station was moved from building to building several times. Thus, it is not straightforward to compare these readings taken next-to or on-top-of buildings with those of the more open landscape associated with airport observations.

The longest continuous stretch at one location of the City Office was 1913 to 1936 from the roof of the City Bank Bldg, 12-14 St. Joseph St at an elevation of 119 ft above the ground. At such a height, daytime temperatures tend to be cooler than measured near ground level, partly due to increased ventilation. And, being only 3 blocks from the Mobile River and Bay provides a different climate setting than the inland station at the Mobile Regional Airport.

After the Weather Bureau closed the City Office, downtown measurements were moved to ground level in May 1953 and provided by a volunteer observer. Even so, we know that in the scorchers of 1925, 1930 and 1952, the City Office measured values of 103 °F, the hottest measured within the city. What would the temperature have been 12 miles west at ground-level in the drier area where MOB was eventually established? We will likely never know the answer with high confidence.

So, to answer question #1, the evidence above suggests that the heat wave of 2023 was indeed remarkable, but in terms of the broader area, was likely just on par with a few earlier extreme heat waves. We can say with some certainty, however, that in the immediate vicinity of MOB the hottest temperature in 82 years occurred in 2023 as long as we assume that the increasing urban infrastructure around that station had little impact on the reading.

Is there a pattern of warming?

Question 2 is actually easier to answer than question 1. A pattern of general warming, if it were apparent, should be detectible across the Mobile area and throughout the summer at many stations. The answer is seen in Fig. 2 above for Mobile.

The result indicates some general rises and falls, but the long-term trend is actually slightly downward (-0.5 °F per century, which is essentially zero). Thus, taking all of the information from the past 152 years, we can say there has not been a long-term pattern of summer warming in the Mobile area. In fact, eight of the ten coolest summers have occurred since 1988. For the summer as a whole, 1954, 69 years ago, tops the scale with an average daily high temperature being about 4 °F warmer than usual, coming in at 94.3 °F.

Finally, and ironically, for the state as a whole, the number of warm-season, daily high temperature records set in 2023 was actually below the long-term average.

This section may change as new information is discovered, but at this point we can say that the hottest temperature in the last 82 years at the Mobile Regional Airport of 106 °F occurred in late August 2023. When looking at temperatures from a few earlier episodes, the 2023 heat wave was roughly equal to what the area had seen in, for example, 1925 and 1930. In terms of the broader question of detecting a pattern of summer warming over the past 150 years, the evidence indicates there have been hot and cold summers, but that there has been an insignificant downward trend in the temperature values.

Temperature Changes in the Future

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. 11. 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 2023 and starting in any year on or before 1950 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 2014-2023 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 which we are testing) for Alabama failed to reproduce the actual long-term temperature variations. This was the same result published for earlier versions of these mod-

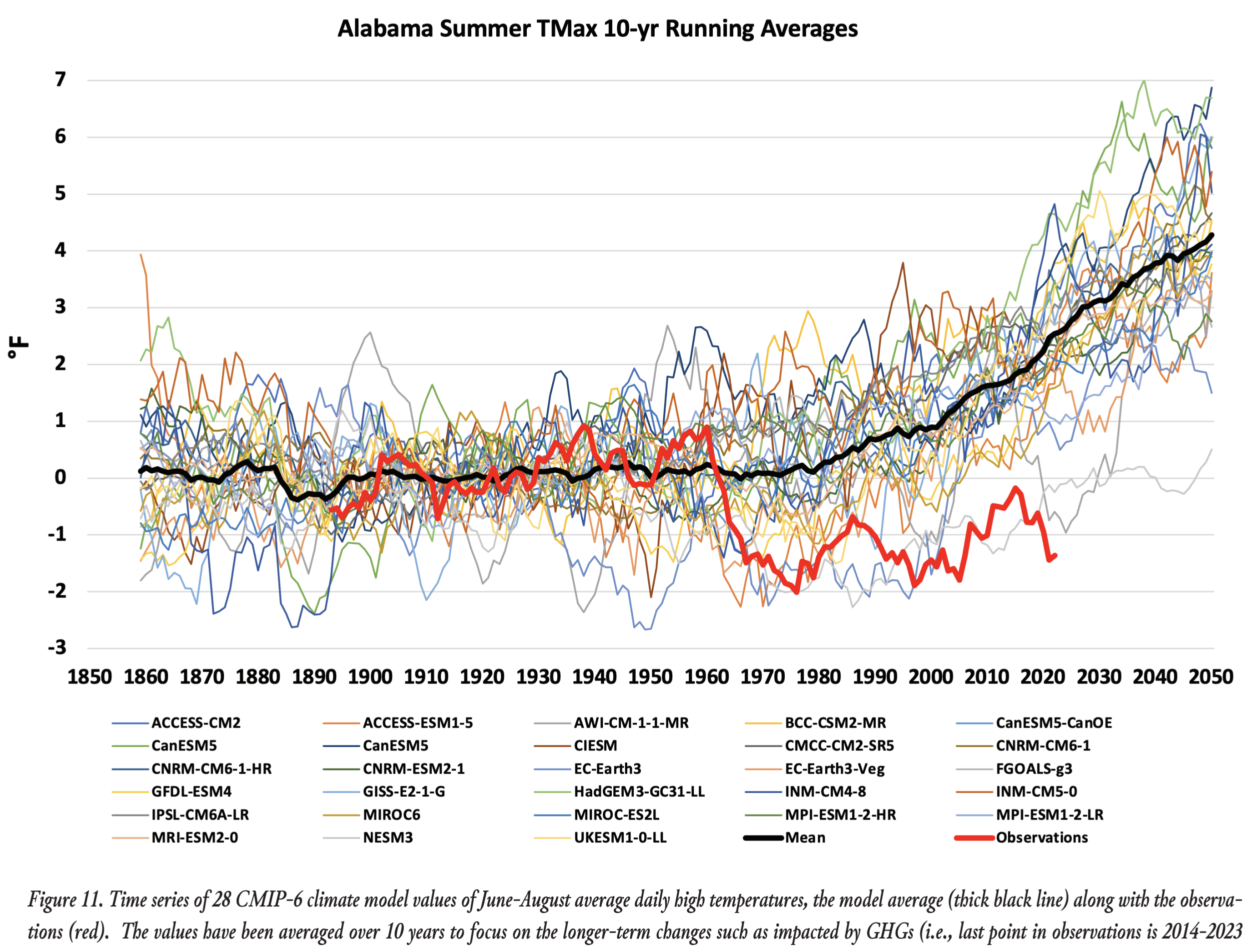


Figure 11. Time series of 28 CMIP-6 climate model values of June-August average daily high temperatures, the model average (thick black line) along with the observations (red). The values have been averaged over 10 years to focus on the longer-term changes such as impacted by GHGs (i.e., last point in observations is 2014-2023 average). All of the time series are in reference to their 1886-1935 average.

els (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).

To demonstrate that models have problems elsewhere too, my UAH colleague Dr. Roy Spencer occasionally provides information to grain growers in the Midwest, the nation's most productive area for this food source. He looked at the observations over the last 50 years of temperature change (1973-2022), and not surprisingly found a small upward trend of +0.13 °C/decade (+0.23 °F/decade) partly because of the cool summers in the late 1970s. He then checked the attempts (i.e. hypotheses) of 36 of the latest climate models to see how well they were able to reproduce this observed trend. https://www.drroyspencer.com/2023/06/epic-fail-in-americas-heartland-climate-models-greatly-overestimate-corn-belt-warming/. Figure 12 indicates, as was the case of the Alabama temperatures, the models were all running too hot - from 50% to 700% too hot. As hypotheses, a classically-trained scientist would conclude that these models have been falsified, invalidated or "not fit-for-purpose."

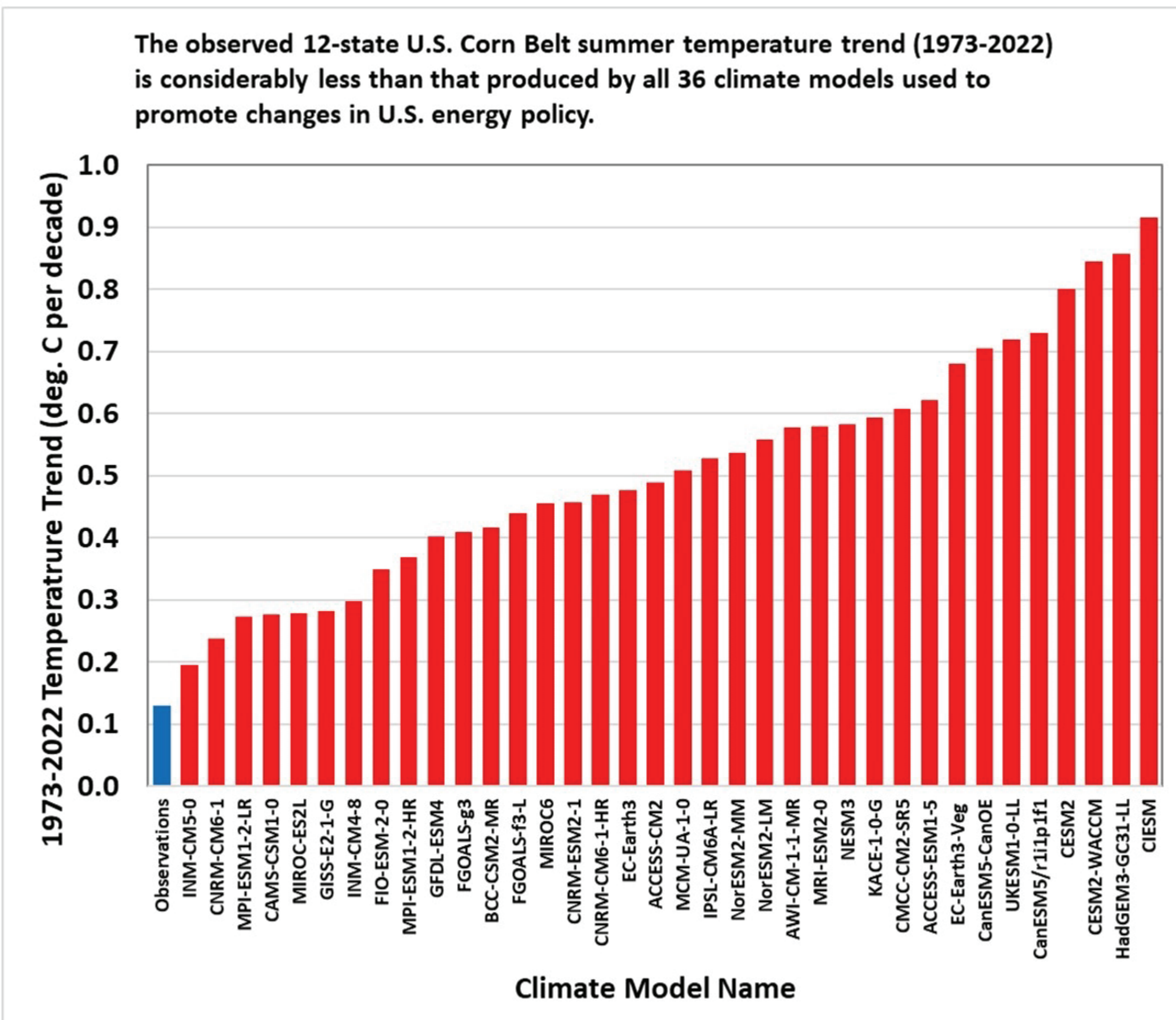
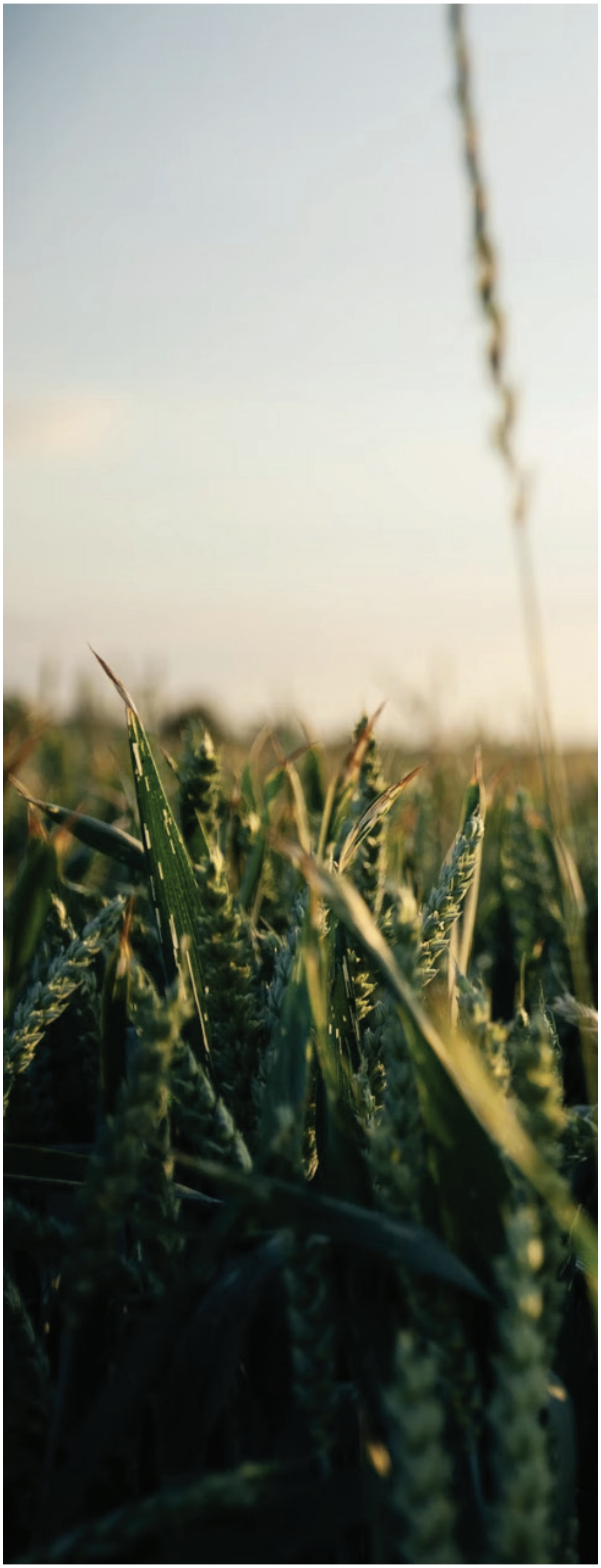


Figure 12. Summer (growing season) temperature trend for the 12-state U.S. Corn Belt for 1973-2022. The observed value is in blue and the model hypotheses are in red. [(www.drroyspencer.com)](www.drroyspencer.com)



With the failure of these hypotheses (models) to reproduce the long-term changes in the climate that have occurred in Alabama (and the Midwest), 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 forced 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 45,000 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.

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 categories 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" 140 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. Unfortunately, such changes are not predictable with confidence at this time.

Again, my colleague Dr. Roy Spencer has studied this area of research and with a little assistance from me published a scientific paper in 2023 in which he calculated the amount of heat energy gained in the last 50+ years in the ocean and land (*Spencer and Christy, 2023*). The basic goal was to determine how sensitive the climate system is to the extra GHGs, expressed as a temperature value that would theoretically occur after CO2 has doubled from the 19th century and the climate settles down. He assumed that all of the increase in the heat content of the land and ocean was due entirely to the extra GHGs. The most widely promoted range of values is 2.5 – 4.0 °C from the United Nation's Intergovernmental Panel on Climate Change. Our value was based on the actual observations of the climate system over the past 50+ years, being 1.86 °C, which is quite a bit below that of the U.N.'s "authoritative" result and suggests the actual climate is not very sensitive to increasing GHGs.

A lesson from history 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 all of the possibilities in the "blink-of-an-eye" 140 years to know what magnitude of extremes may happen soon.

Changes in Precipitation

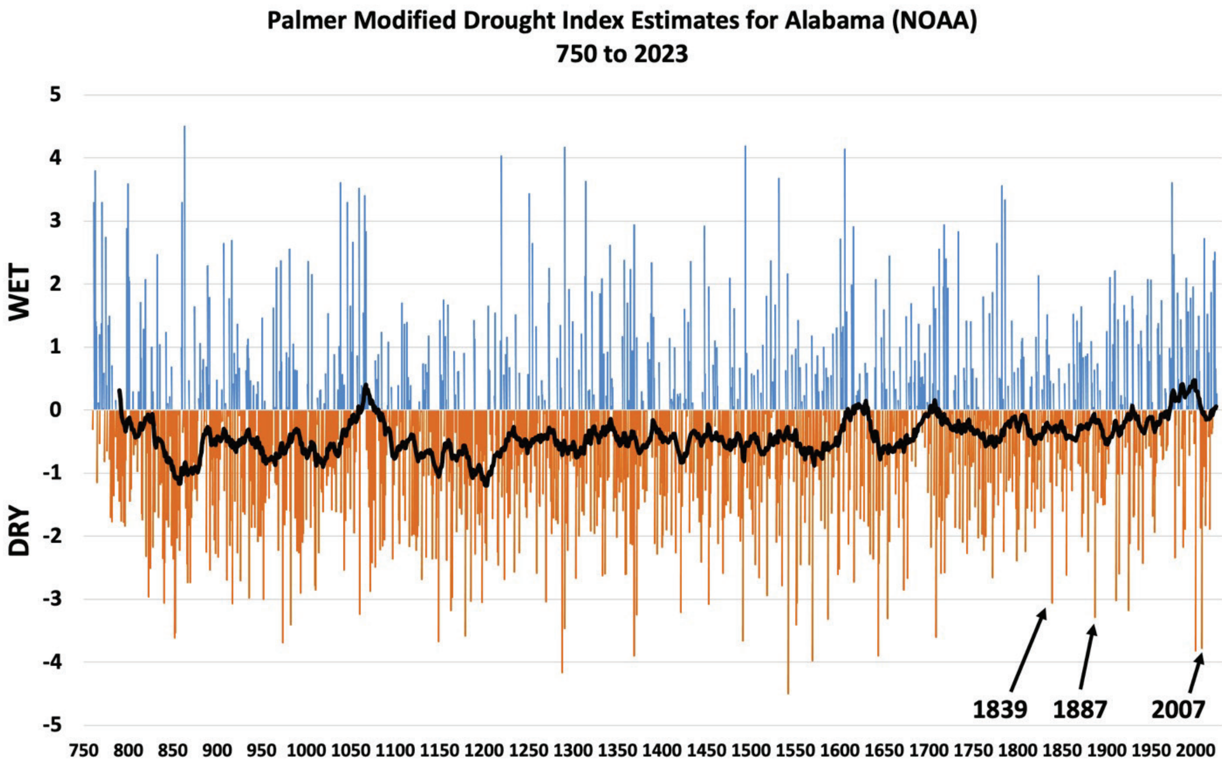


Figure 13. Annual values and running, 30-year trailing average (black line, e.g. the value at 1970 is the average of 1941 to 1970) of the NOAA Living Blended Drought Atlas (Gille et al. 2017). The values generally represent the condition in mid-summer based on the precipitation in the just-concluding growing season.

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 which 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.

The long-term (1200+ years) estimates of drought and wetness suggest the current situation in Alabama is wetter than what was typical of past several centuries (Fig. 13). 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 -3.78) was exceptional for the state.

One point to be drawn from this is 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 or 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 and also mentioned the effects of the dryness in 1887.

[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.

[1887] Crops of all kinds suffered on account of the drought and hot weather.

These are examples of climate extremes 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. Don't forget as well that since federal and corporate reservoirs were built in the first half of the 20th century, river flows now are maintained at a higher level in the summer than before. This means that the drought of 2007, though more severe, did not present the same dire consequences as occurred in the 19th century. In other words, as civilization has progressed and hardened itself against the vagaries of weather, the impacts of extreme climate events have had less and less impact on the human economy.

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. 13. 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. 14.

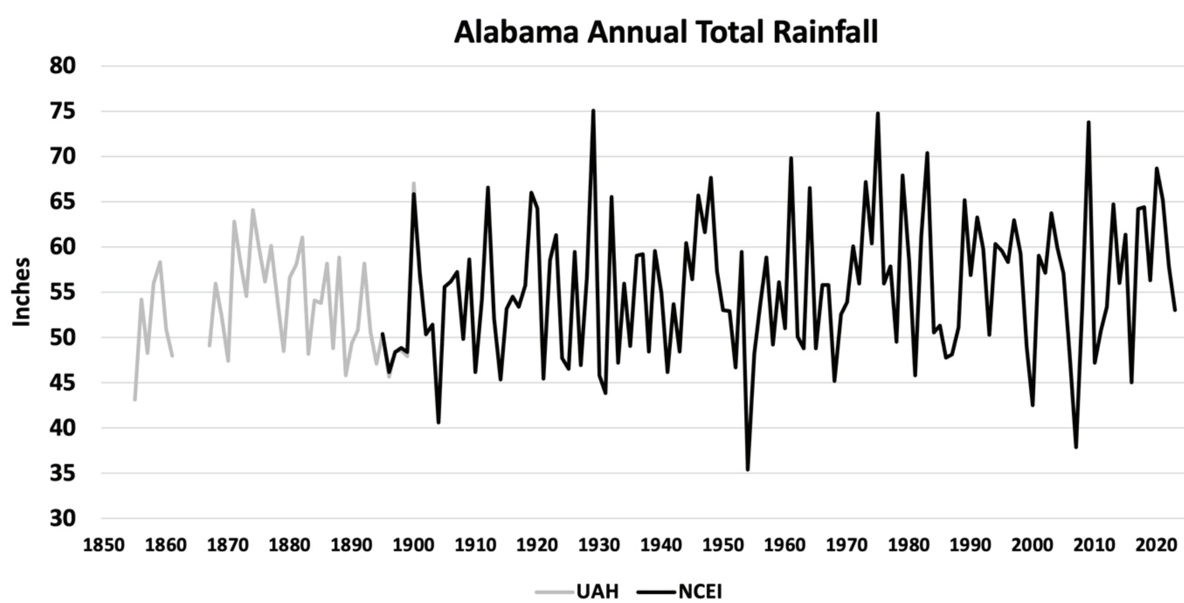


Figure 14. Annual total of geographically-averaged precipitation over the state. UAH assembled data prior to 1901 (gray) to begin the time series in 1855 to supplement NOAA/NCEI data starting in 1895 and ending in 2023. There are seven years of overlapping data between UAH and NOAA/NCEI which produced a correlation of > +0.99 between the two datasets.

Looking carefully at the instrumental record of annual Alabama precipitation amounts (Fig. 14), one finds a slight upward trend of about +2.5 in/century. For the nation as a whole since 1895 NOAA calculates the trend as similarly positive at +1.8 in/century. However, if starting in other years, for example looking at the last 60 years (starting in 1964) Alabama's 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. 15). 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.

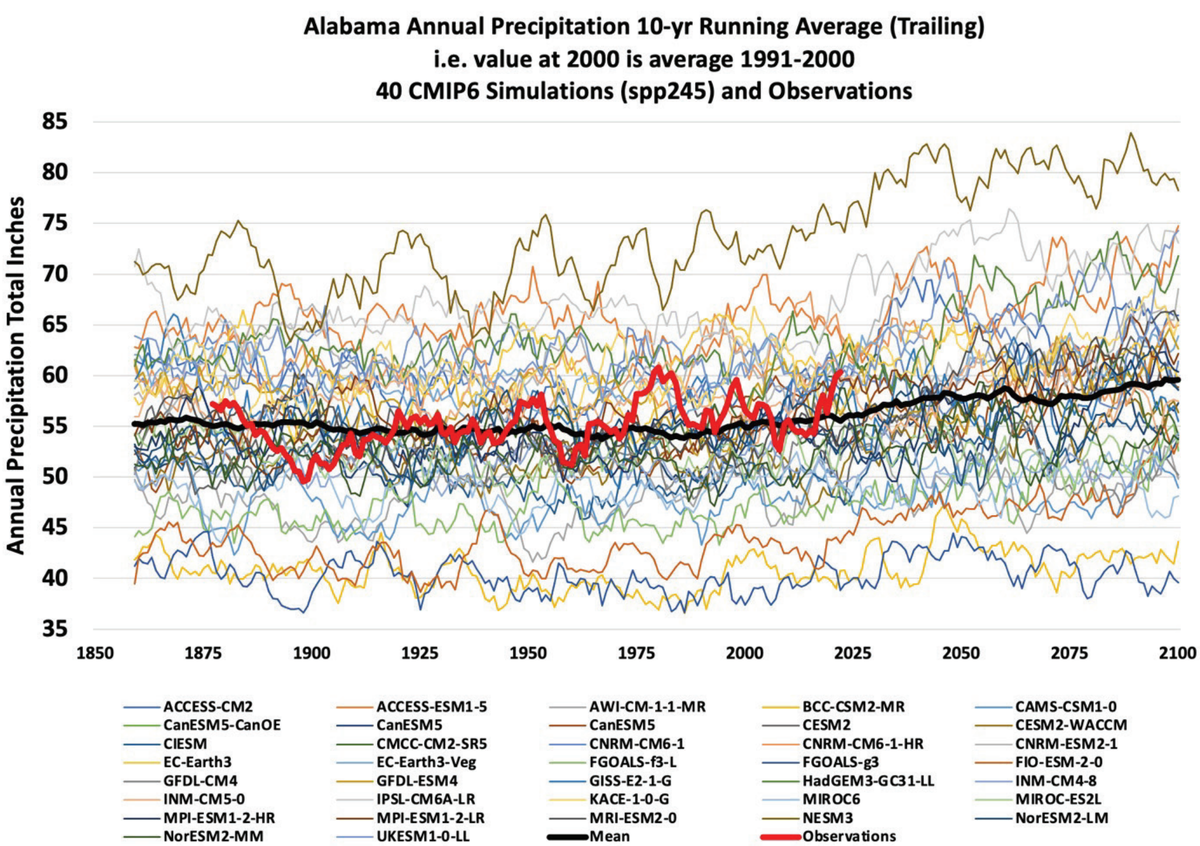


Figure 15. Ten-year running means of annual statewide precipitation for Alabama as depicted by 40 simulations from CMIP6 output, their average (thick black line) and observations (thick red line). The simulations use observed forcing through 2014 and estimated forcing to 2100 using scenario ssp245.

Changes in Precipitation Events

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).

Since the previous edition I have built a dataset of daily precipitation values beginning in 1872 for 23 stations in the humid Southeast from Austin TX northeastward to Washington DC. This dataset represents 150 years of continuous data and Mobile and Montgomery are included. This dataset is able to answer many questions about the frequency and intensity of multi-day precipitation events.

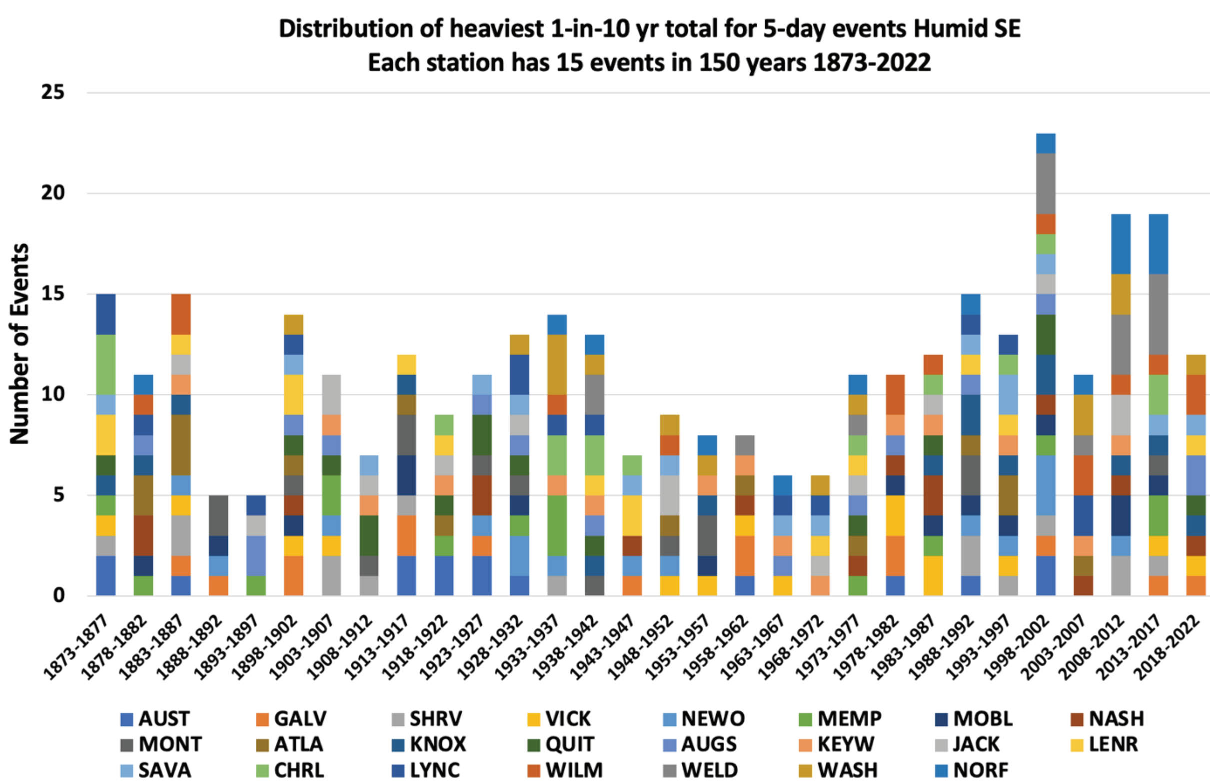


Figure 16. Distribution in time (by 5-year periods) of the 15 heaviest 5-day rainfall events for 23 stations in the humid Southeast from Austin TX northeastward to Washington DC.

Figure 16 displays the occurrence of the heaviest 5-day rainfall events for each station. I determined the 15 heaviest events for each station, i.e., 1-in-10-year event rate, and plotted them by 5-year periods beginning with 1873-77 through 2018-2022. One can see variability, with three recent periods (1998-2002, 2008-2012 and 2013-2017) higher than the others, giving the appearance of an upward trend, or an increasing occurrence of heavy events. Upon more careful examination, it was discovered that the upward trend was dependent entirely on the four eastern-most stations (Wilmington NC, Weldon NC, Washington DC and Norfolk VA) with the trend of the other 19 stations being zero. In other words, in the past 25 years there have been some unusually heavy storms in the far eastern sector of this region that is not representative of the larger-scale pattern.

This is another example that shows how choosing different time periods or regions 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 or region. 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

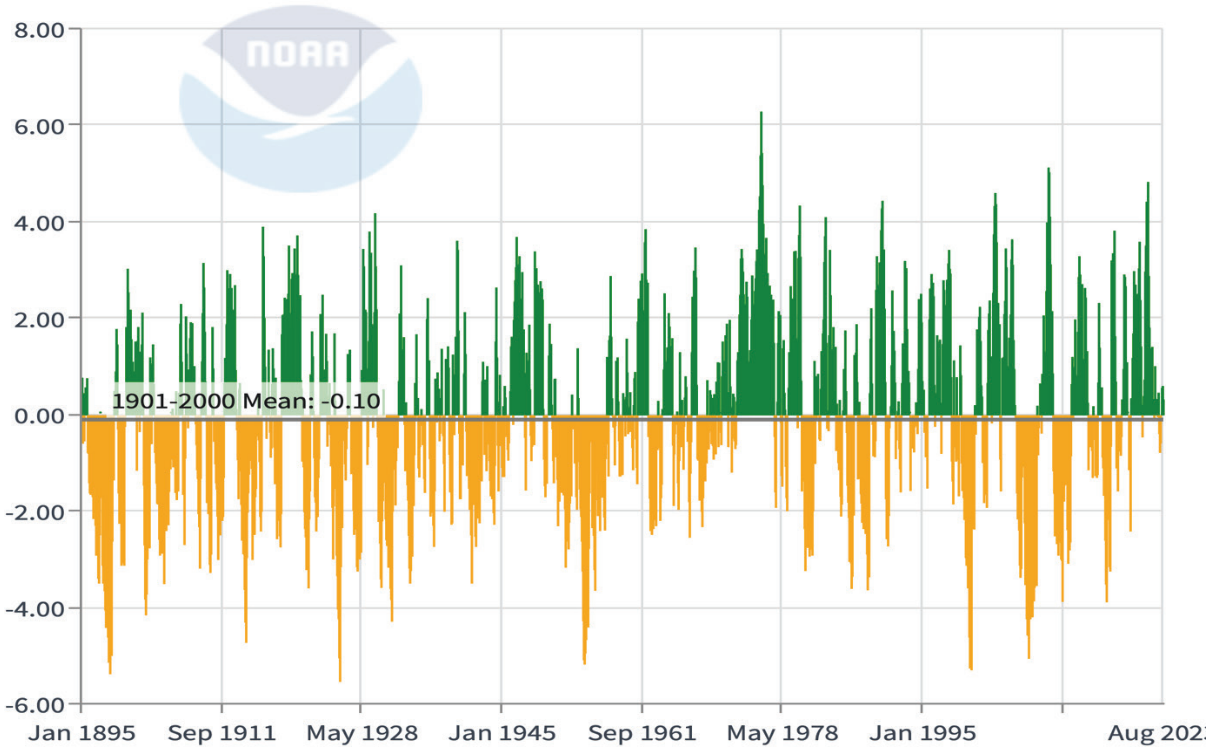


Figure 17. Monthly Palmer Modified Drought Index for Alabama (NOAA/NCEI).

NOAA/NCEI provides several types of metrics that quantify the length and severity of droughts and in Fig. 17 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. 13) 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 precedented 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.

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.

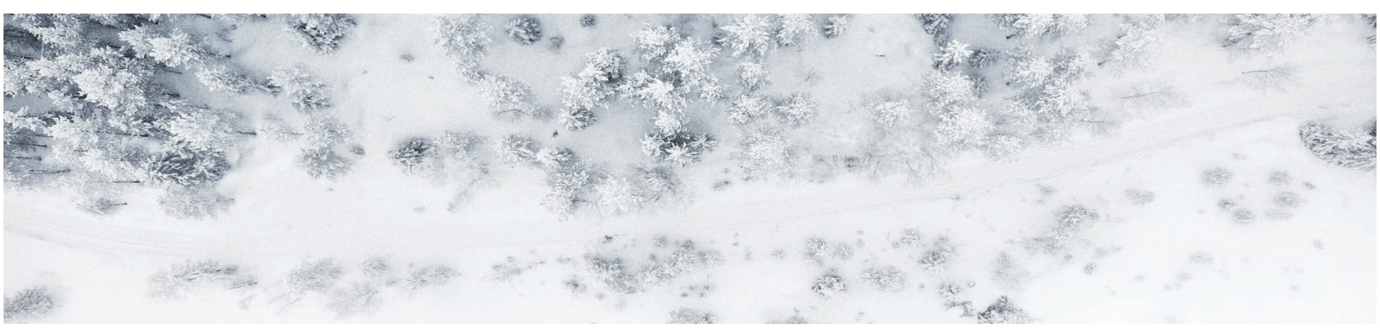
Snow falls every year somewhere in the state, though in 1925, 1929, 1949 and 2005 only traces were recorded at the available stations. Snow can fall anywhere in the state too, for example, Mobile recorded 5 inches in Jan 1881 and 6 in 1895 and at least 1 inch several times since.

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 infamous March 1993 "Storm of the Century" which saw snow fall from Mobile to Bridgeport. Finally, the still-remembered 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. That was also the year Alabama played Mississippi in the Sugar Bowl in New Orleans where visible on the sidelines were piles of shoveled snow. 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 (Nov to Apr) and the station with the most was selected for each year. 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 127 years with measurable snow, these stations accounted for 94 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.

Unfortunately, in the past couple of decades many of the traditional "Cooperative" observer-stations have ceased to report snowfall for various reasons, including closure. Some of the newer airport stations, which use electronic equipment for weather monitoring, sometimes report snowfall irregularly since snow must be measured by a person. However, a volunteer network known as the Community Collaborative Rain, Hail and Snow (CoCoRaHS) network (https://cocorahs.org – you too can join!) has been established and today over 200 Alabama citizen-scientists send in daily precipitation reports which include snowfall. Since this is a somewhat different network of stations, I've now included them as a separate bar in the chart and the correlation with the COOP values is quite high, 0.92.



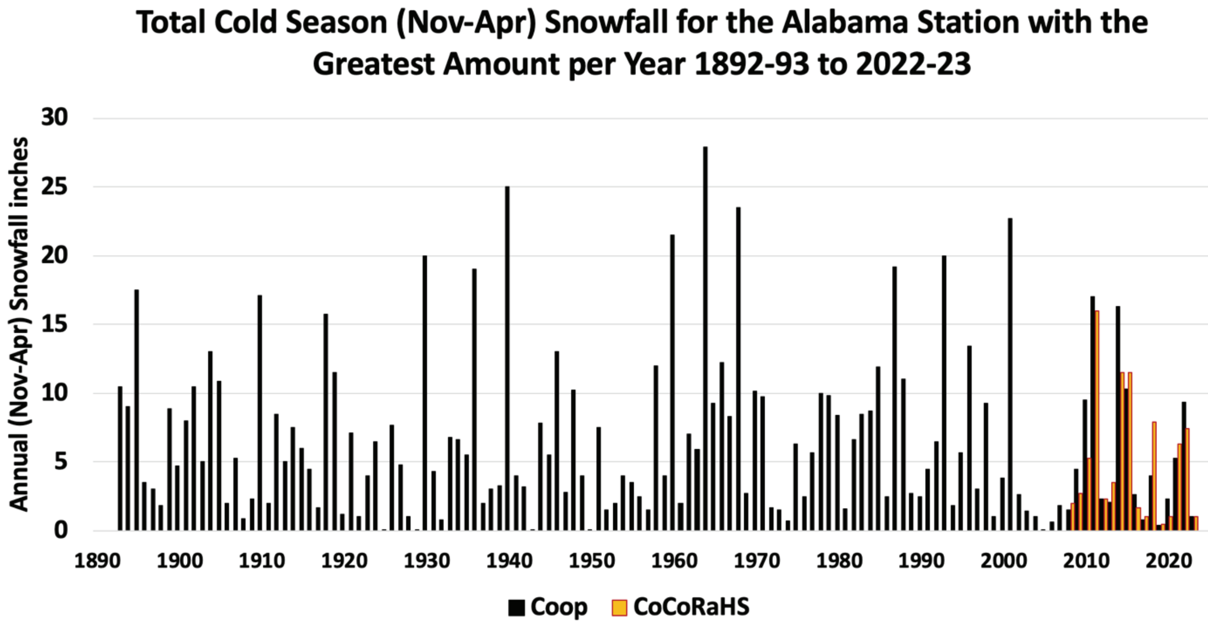


Figure 18. The amount of snowfall measured at the station in the northern third of Alabama with the most snow each year from 1893-2023. The value for each year is the 6-month total beginning with Nov of the year prior through Apr of the year designated. Reports from the volunteer CoCoRaHS network, which began in 2008, are included in yellow. Out of 127 years with measurable snowfall (four years had only a trace), Valley Head accounted for 43 of the snowiest values followed by Florence/Muscle Shoals with 25.

The information in Fig. 18 indicates no meaningful trend in this metric of heavy snowfall. Be aware that robust statistical analyses are difficult with snowfall because there are few stations that actually measure this hit-or-miss phenomenon, and snowfall events are often confined to small areas where stations don't exist. In any case, this evidence, minimal as it is, does not suggest a lessening of snowfall as GHGs have increased.

Changes in sea level

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 extra snow remained on land during summer, piling up from winter to winter, not being able to melt 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. 19 below, changes in sea level have a fairly

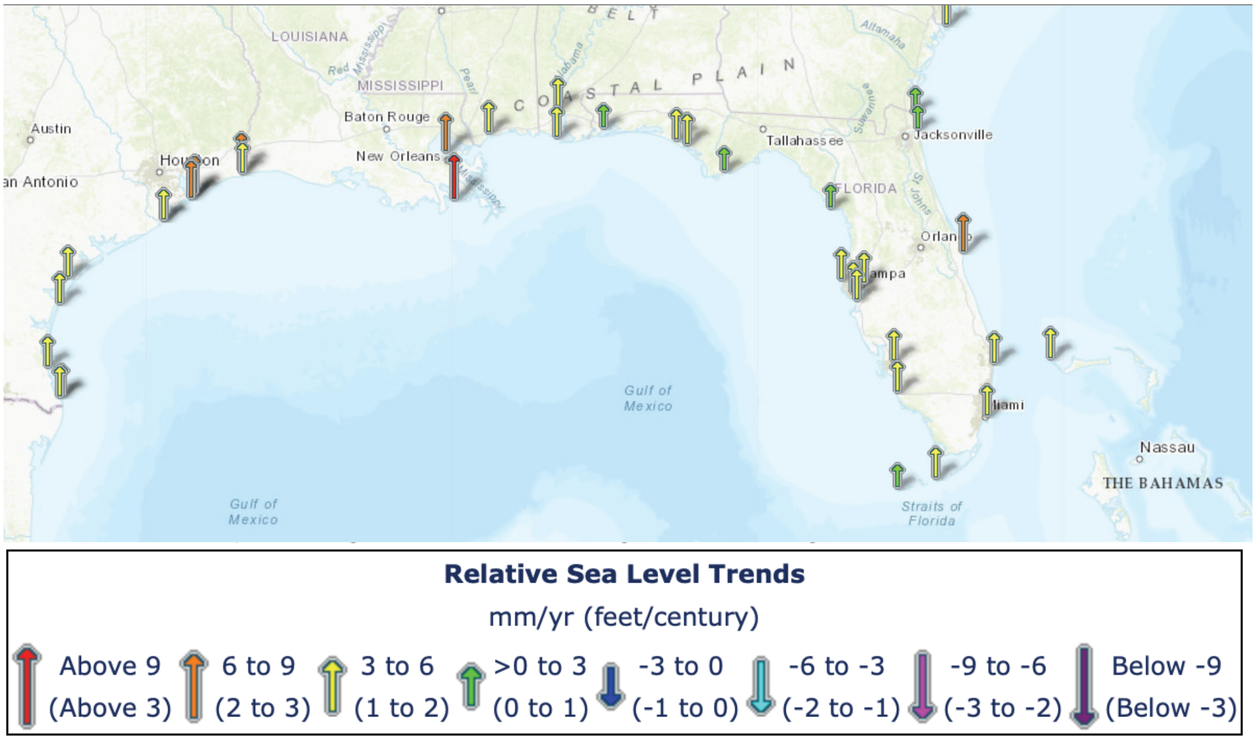


Figure 19. Relative change in sea level at various tide gauge stations along the southeastern US coastline (NOAA). These values essentially provide the net change when considering changes in land elevation as well as sea elevation.

wide range in our local region, for example compare trends (the length of the arrows) between Louisiana (red) and Florida (green). 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 less, 1-2 inches per decade.

Notice too that the sea level varies quite a bit from year to year (Fig. 20), with a large rise of over 7 inches in just ten years at Dauphin Island between a low point in 2007 to the high point in 2017. The rise in the previous four decades was only about three inches. After 2017 the level dropped a couple of inches by 2018, then bounced back up in 2020. So, variations of a few inches, up and down, are common over the course of a decade. I should note that there are some locations, southern Alaska for example, where the relative sea level is actually "falling" due to the tectonic uplift of the land relative to the sea. Looking at the past 50 years, the rise at the Alabama coast has been about the height of a football (Fig. 20).

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 7,000 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 of the 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 1½ inch per decade (or even 2) 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 or 2 inches per decade, but a rise of 10 ft in six hours that comes with a major hurricane. This is the real threat.

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 (see below for hurricanes crossing anywhere in Alabama). 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 $kn^2 \times 10^{-4}$).

Figure 21 indicates the northern hemisphere 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 almost 900 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. The last 30 years have seen a slight decline since the peak in 1992, but this multi-decadal variation is common in the signal of North Atlantic hurricanes.

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. 22). 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 (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 $kn^2 \times 10^{-}$) 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.

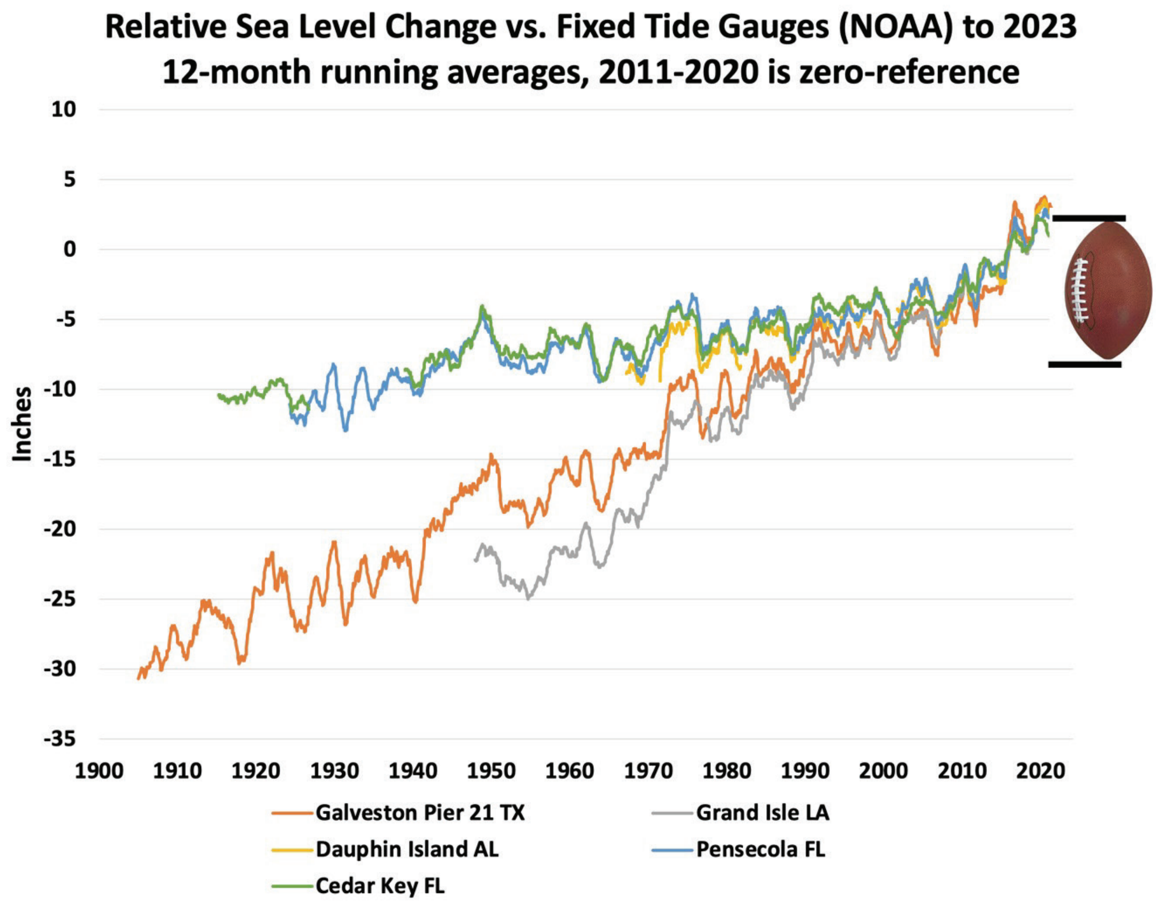


Figure 20. Changes in sea level relative to the coast at five stations along the Gulf Coast. The football indicates the change in relative sea levels for along the Alabama Coast in the past 50 years.

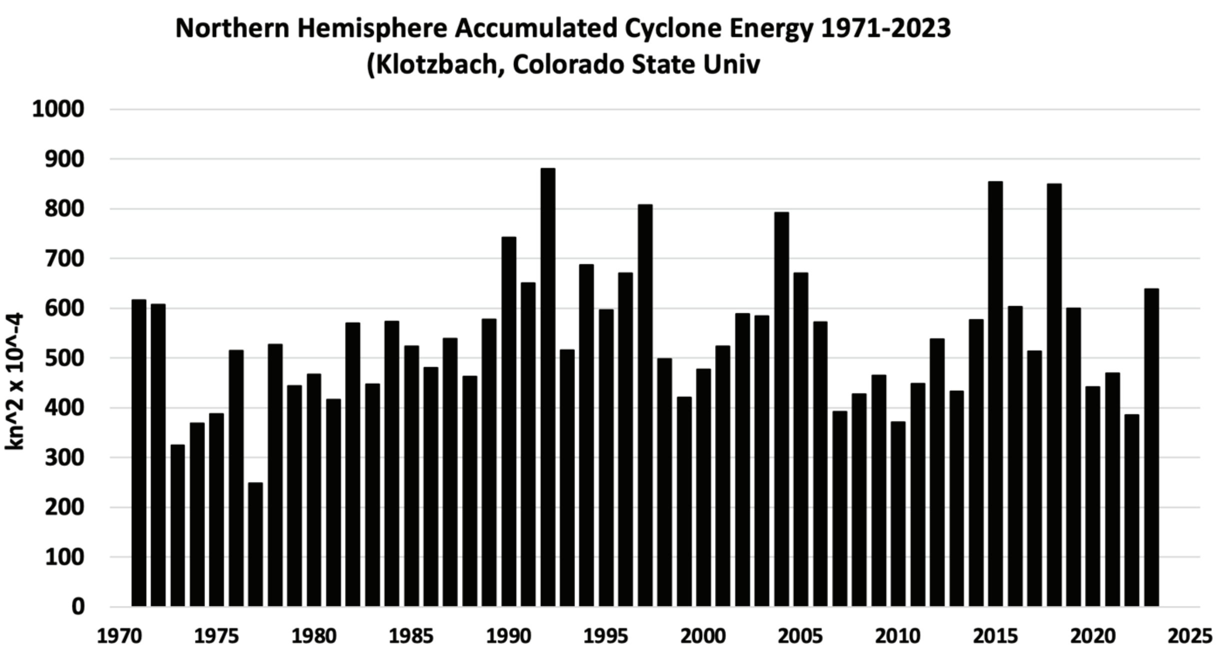


Figure 21. Northern Hemisphere ACE calculated from observations by Klotzbach (Co. St. Univ). Because hurricanes originate and often spend their entire life over the oceans, until satellite images were available in the 1970s, there was little information over the vast southern and central ocean basins.

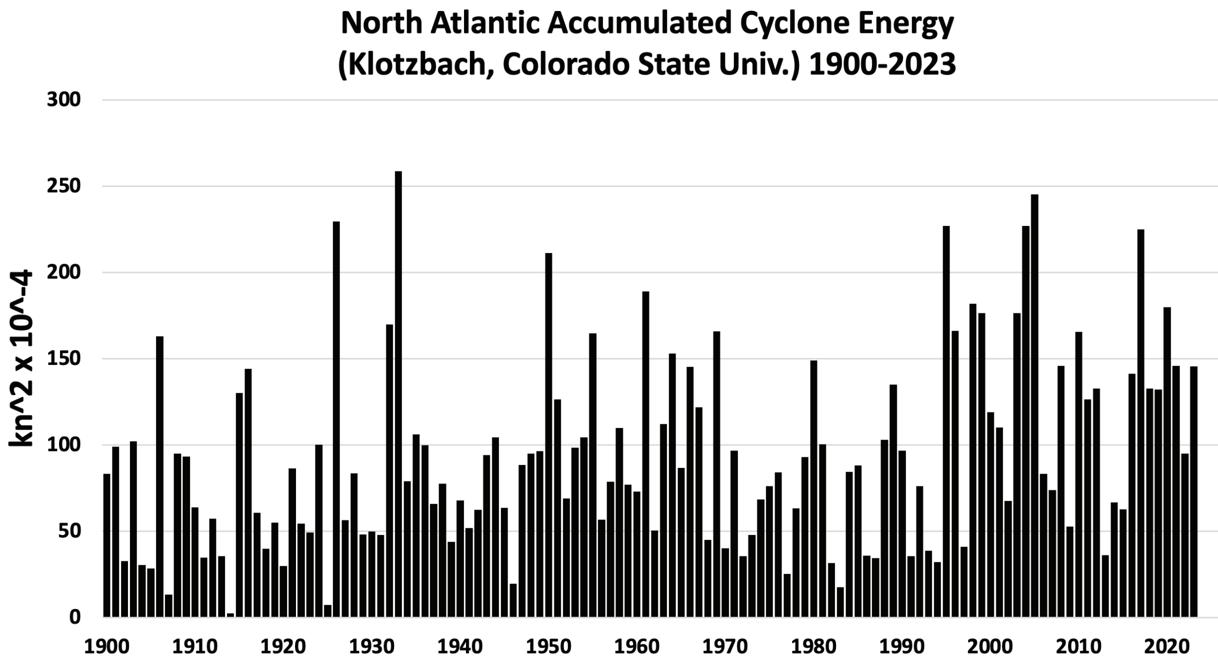


Figure 22. Annual Accumulated Cyclone Energy for the North Atlantic Basin.

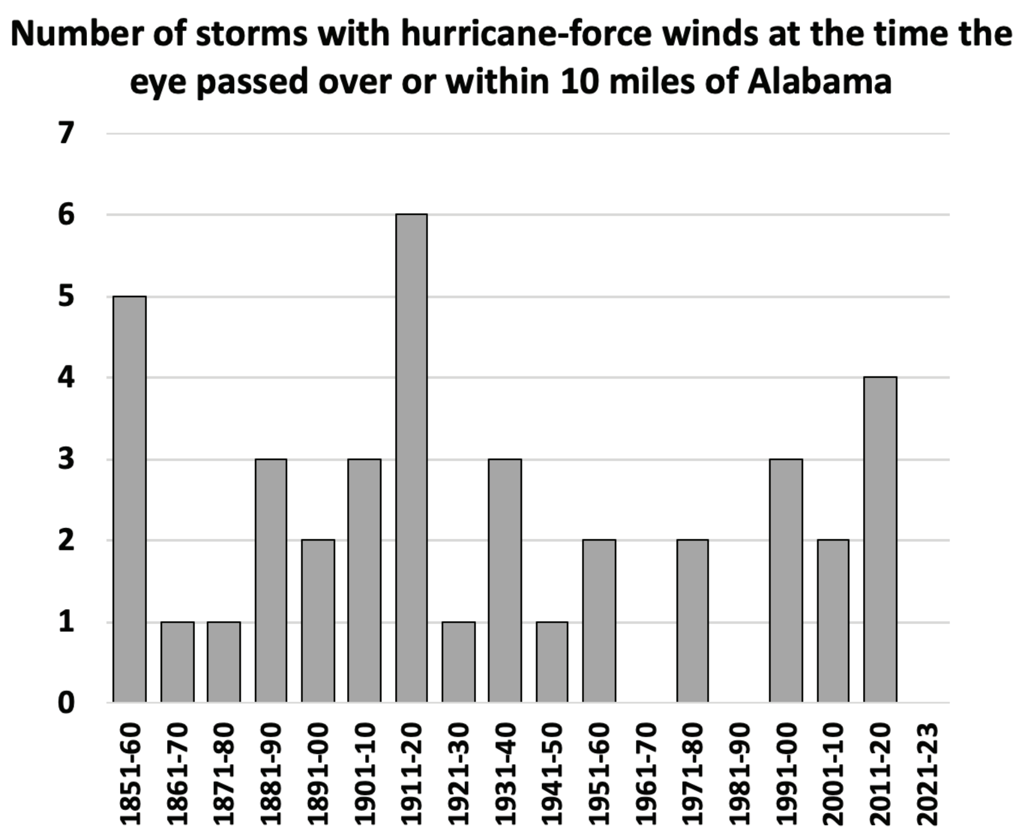


Figure 23. Number of storms per decade with hurricane-force winds at the time the eye passed over or within 10 miles of Alabama

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.

The number of storms whose eye passed over or within 10 miles of Alabama while having hurricane force winds is displayed in Fig.23 as determined by the National Hurricane Center's annual tracking maps. Hurricane incidences are truly a hit-or-miss phenomenon. From 1957 to 1974, Alabama did not experience a single hurricane-force event, while the single years of 1916, 1995 and 2020 each had two. The decade of the 19-teens experienced six hurricanes while the 1960's and 1980's had none. The overall average is 2.3 per decade, or about one every four years.

These random events may be minimized in one's mind, but 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 similar strikes from past decades. The Gulf Coast, including Mobile and Baldwin Counties, is enhancing its status as a target-rich environment for such disasters.

Changes in Tornadoes

Talking about tornadoes in Alabama is not easy because nearly all of us have our own stories or know of others who've had terrible experiences with these storms which strike Alabama every 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. 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 by NOAA 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 change in a climate variable.

Nationwide there has been a fairly noticeable decline in the frequency of major tornadoes since 1954 (Fig. 24). In the first 35-year period (1954-1988) the country was struck by an average of 53 events per year. In the last 35 years (1989-2023) 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).

In terms of climate variability, a record of only 70 years of a chaotic phenomenon like tornadoes is quite brief. In looking at this period, however, there is a suggestion that there has been an eastward shift in the main tornado tracks from the southern Plains that move them closer to Alabama (Dixon et al., 2011, Coleman and Dixon, 2014). There is even a term "Dixie Alley" coined to note that especially long-track and strong (EF4-EF5) tornadoes have struck the region from northern Louisiana and eastern Arkansas eastward to Georgia and northward to central Tennessee. Alabama and Mississippi, especially their northern sections, are in the center of "Dixie Alley." The total number of tornadoes is still greater to our west, but the strong tornadoes combined with heavy forests (trees become missiles) and a relatively populated rural countryside with vulnerable housing provides opportunity for tragic consequences.

In the past 74 years almost ten deaths on average result from tornadic events each year in Alabama. The outbreak of 27 Apr 2011 left 252 fatalities, second only to 1932 when 299 Alabamians died.

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.

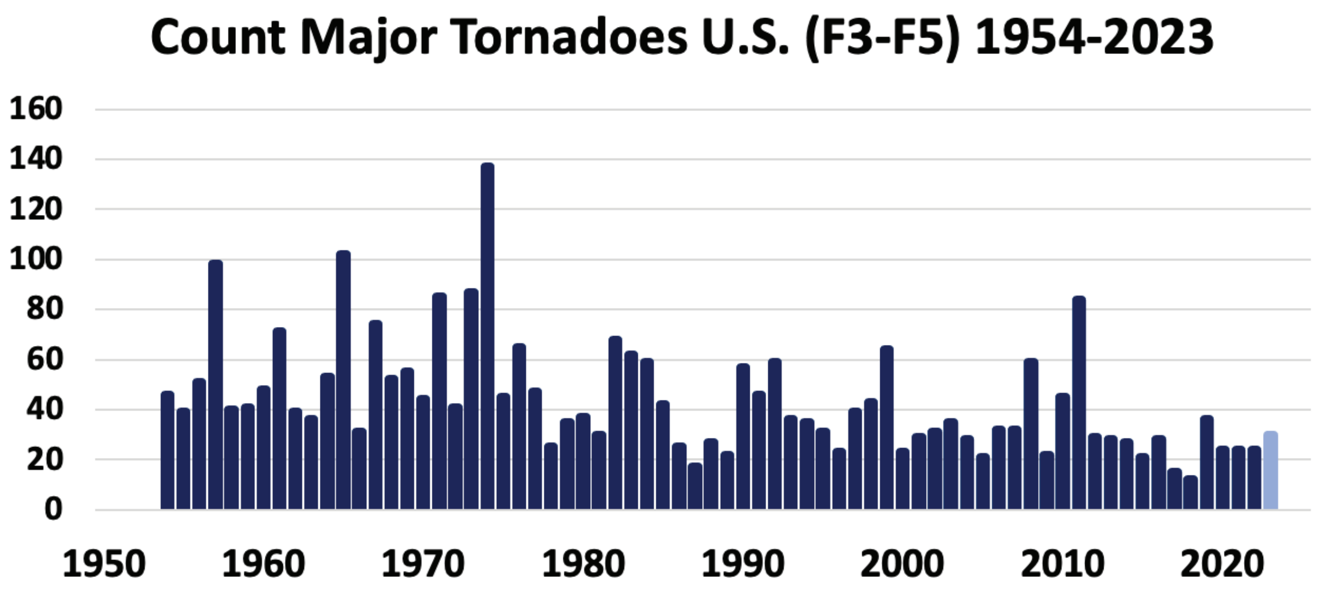


Figure 24. Number of major tornadoes (EF3-EF5) in the conterminous U.S. per year (NOAA).

Global Atmospheric Temperature

In 1990, Dr. Roy Spencer (then at NASA, now at UAH) and I built a dataset of global atmospheric temperatures from polar orbiting satellites. This was the first climate dataset of deep-layer or bulk monthly measurements derived from microwave sounding units onboard weather satellites. The "bulk" atmosphere here is roughly the temperature of the air from the surface to about 40,000 ft, or you can think of it as the temperature of the column of air below you when you are at the highest altitude of a transcontinental flight. There are many advantages to such a measurement such as no contamination from urban development and the fact the instrument sees the globe in a systematic way as it orbits from pole to pole 14 times a day as the earth spins eastward underneath the spacecraft.

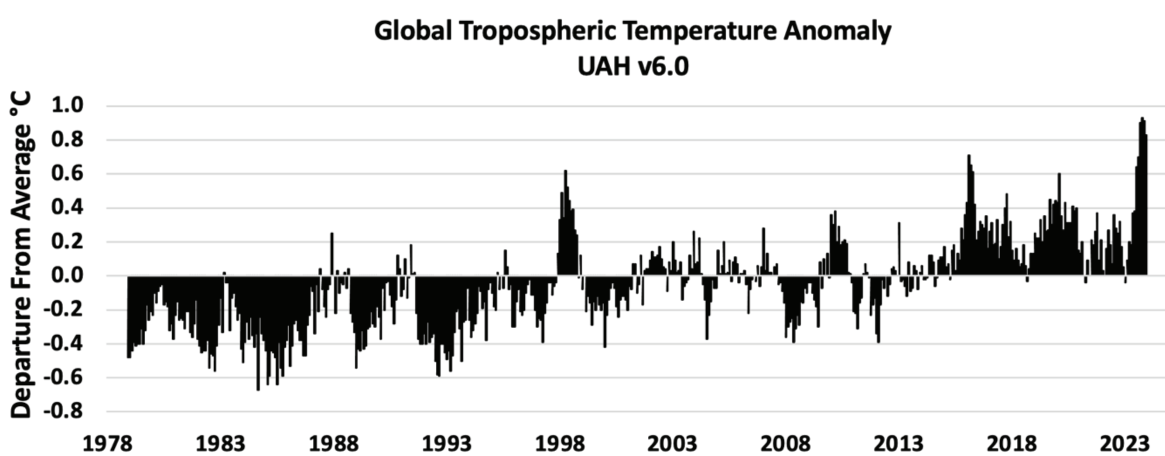


Figure 25. Global monthly tropospheric temperature anomalies as measured by microwave sounding units on polar orbiting satellites produced at UAH. The reference period is 1991-2020.

In Fig. 25 we show the month-by-month global temperature anomaly which we make available every month and about which one can see a lot of variability. What usually catches one's eye are the sharp warming spikes, especially in 1997-98, 2015-16 and 2023. These occur because of El Niño events in which the tropical Pacific Ocean waters warm well above average and this in turn warms the atmosphere. Not as easily seen are the cold spells following volcanic eruptions of 1982 (El Chichon) and 1991 (Mt. Pinatubo).

The sharp upward rise in 2023 is due to the major El Niño which made calendar-year 2023 the warmest of the 45-year record. Along with these peaks is an underlying trend of +0.15 °C/decade. If we remove the temporary impacts of volcanoes and El Niños however, the underlying trend is about +0.1 °C/decade, the methodology of which is described in detail in Christy and McNider 2017. It is very possible that this underlying warming is due largely to the extra GHGs. Because these changes are small (tenths of a degree), this is why the much larger variations of extreme weather events don't seem to be affected, at least through 2023.

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. And don't forget that GHG concentrations were much higher in the distant past.

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 influence 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 I made earlier (that the evolution of climate over the last 140 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). I guess they didn't check the data for Alabama.

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 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 weather variables, no further comment is needed as we have already 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 26 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.

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.

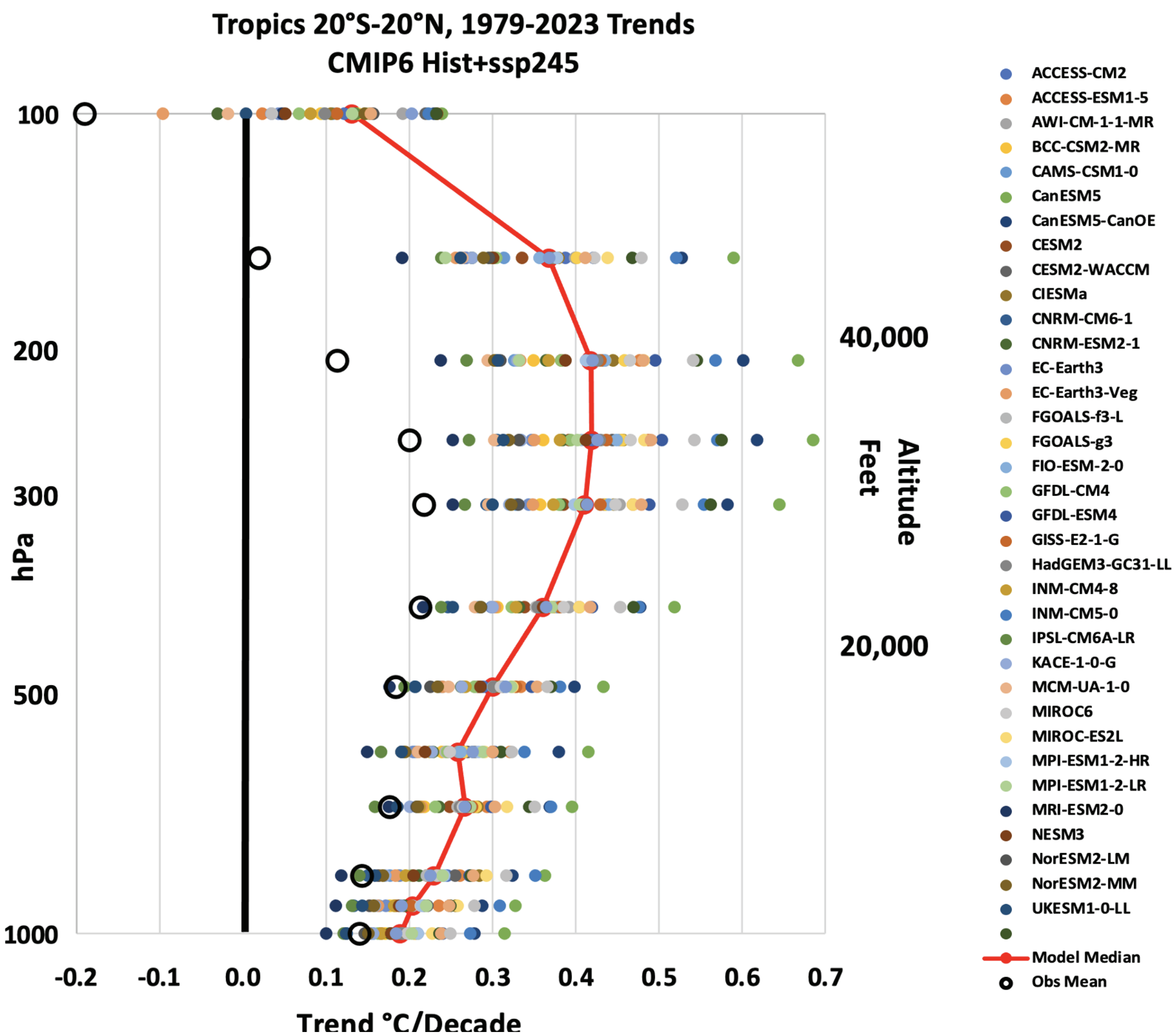


Figure 26. Tropical temperature trends from the surface to about 50,000 ft in the atmosphere for 1979-2020. Open circles are the observations and solid circles the model output for the same region and time period. The red line represents the median result from the models. The model names are in the list on the right.

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 economic impact of the policy 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, the proper limits of its credibility and the very limited nature of our understanding. 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.

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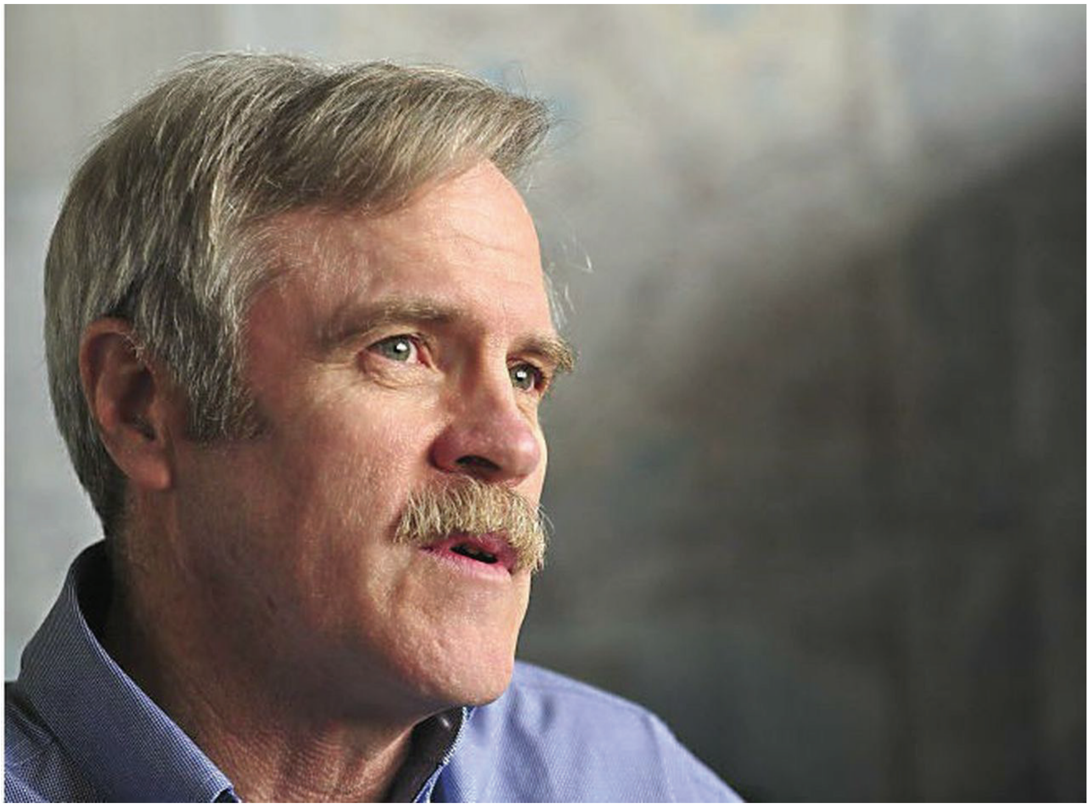
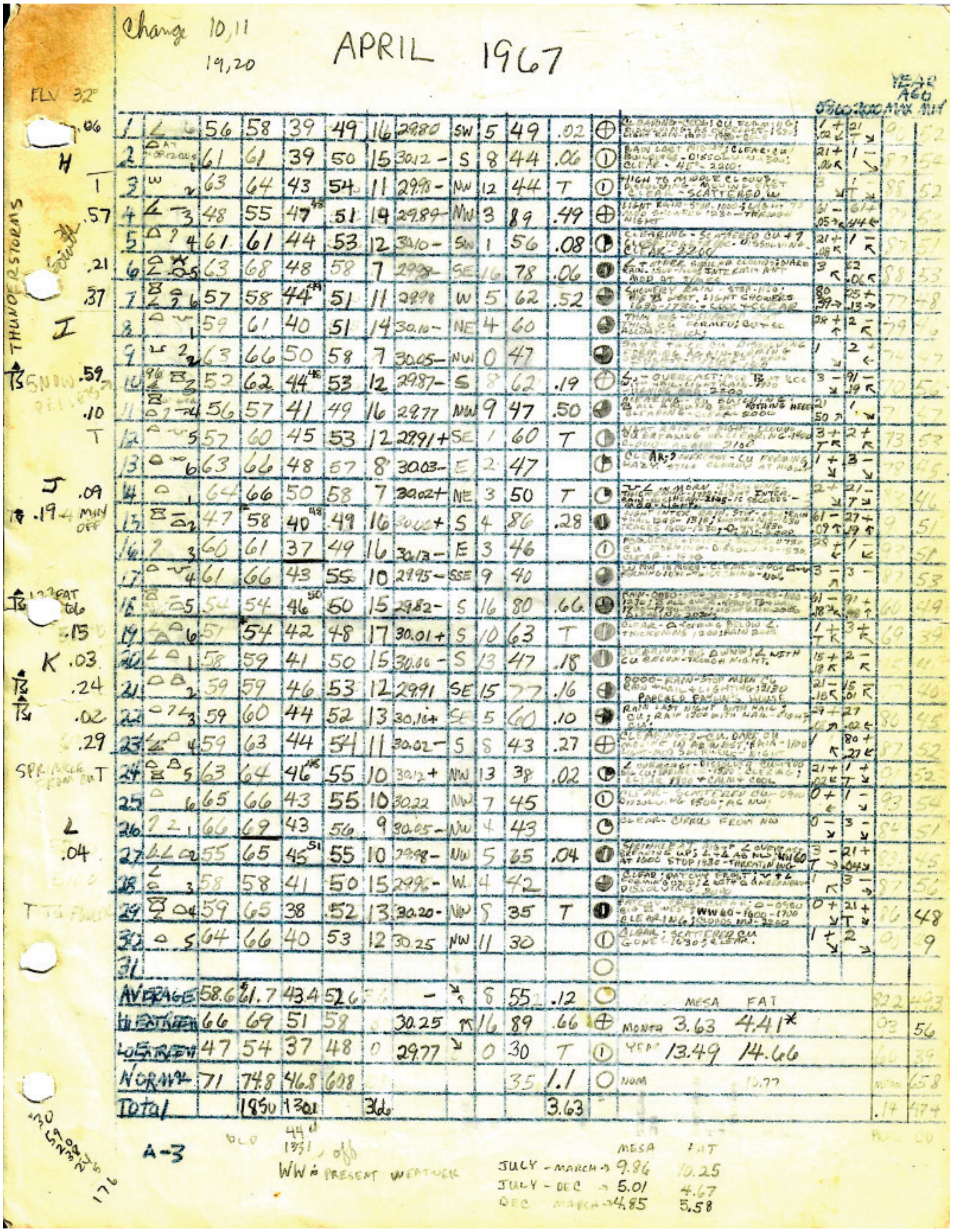


Dr. John R. Christy is the Distinguished Professor of Atmospheric and Earth Sciences, Director of the Earth System Science Center and Alabama's State Climatologist at the University of Alabama in Huntsville (UAH). He was awarded NASA's Exceptional Scientific Achievement Medal, the American Meteorological Society's Special Award for satellite research and the rank of Fellow of this Society. He has published over 100 scientific papers, appeared as an expert witness on climate in U.S. Federal Court, and has testified before the U.S. Congress 20 times. The greater Fresno area served as his home from birth to graduation from Fresno State (B.A. Mathematics.) After teaching Physics and Chemistry in Kenya, East Africa, he earned a Master of Divinity from Golden Gate Baptist Theological Seminary, then served as a bi-vocational pastor while also teaching math at nearby colleges. He headed back to the classroom for M.S. and PhD degrees in Atmospheric Sciences from the University of Illinois which then prepared him for his career at UAH.



Change 10,11
19,20

APRIL 1967

ELV 32°

Day										
1	56	58	39	49	16	29.80	SW	5	49	.02
2	61	61	39	50	15	30.12 -	S	8	44	.06
3	63	64	43	54	11	29.98 -	NW	12	44	T
4	48	55	47	51	14	29.89 -	NW	3	89	.49
5	61	61	44	53	12	30.10 -	SW	1	56	.08
6	63	68	48	58	7	29.98 -	SE	16	78	.06
7	57	58	44	51	11	29.98	W	5	62	.52
8	59	61	40	51	14	30.10 -	NE	4	60	
9	63	66	50	58	7	30.05 -	NW	0	47	
10	52	62	44	53	12	29.87 -	S	8	62	.19
11	56	57	41	49	16	29.77	NW	9	47	.50
12	57	60	45	53	12	29.91 +	SE	1	60	T
13	63	66	48	57	8	30.03 -	E	2	47	
14	64	66	50	58	7	30.02 +	NE	3	50	T
15	47	58	40	49	16	30.02 +	S	4	86	.28
16	66	61	37	49	16	30.13 -	E	3	46	
17	61	66	43	55	10	29.95 -	SSE	9	40	
18	54	54	46	50	15	29.82 -	S	16	80	.66
19	51	54	42	48	17	30.01 +	S	10	63	T
20	58	59	41	50	15	30.00 -	S	13	47	.18
21	59	59	46	53	12	29.91	SE	15	77	.16
22	59	60	44	52	13	30.16+	SE	5	60	.10
23	59	63	44	54	11	30.02 -	S	8	43	.27
24	63	64	46	55	10	30.12 +	NW	13	38	.02
25	65	66	43	55	10	30.22	NW	7	45	
26	66	69	43	56	9	30.05 -	NW	4	43	
27	55	65	45	55	10	29.98 -	NW	5	65	.04
28	58	58	41	50	15	29.96 -	W	4	42	
29	59	65	38	52	13	30.20 -	NW	5	35	T
30	64	66	40	53	12	30.25	NW	11	30	
31										
AVERAGE	58.6	61.7	43.4	52.6		-		8	55	.12
HI EXTREME	66	69	51	58		30.25		16	89	.66
LO EXTREME	47	54	37	48	0	29.77		0	30	T
NORMAL	71	74.8	46.8	60.8					35	1.1
Total		1850	1301		366					3.63

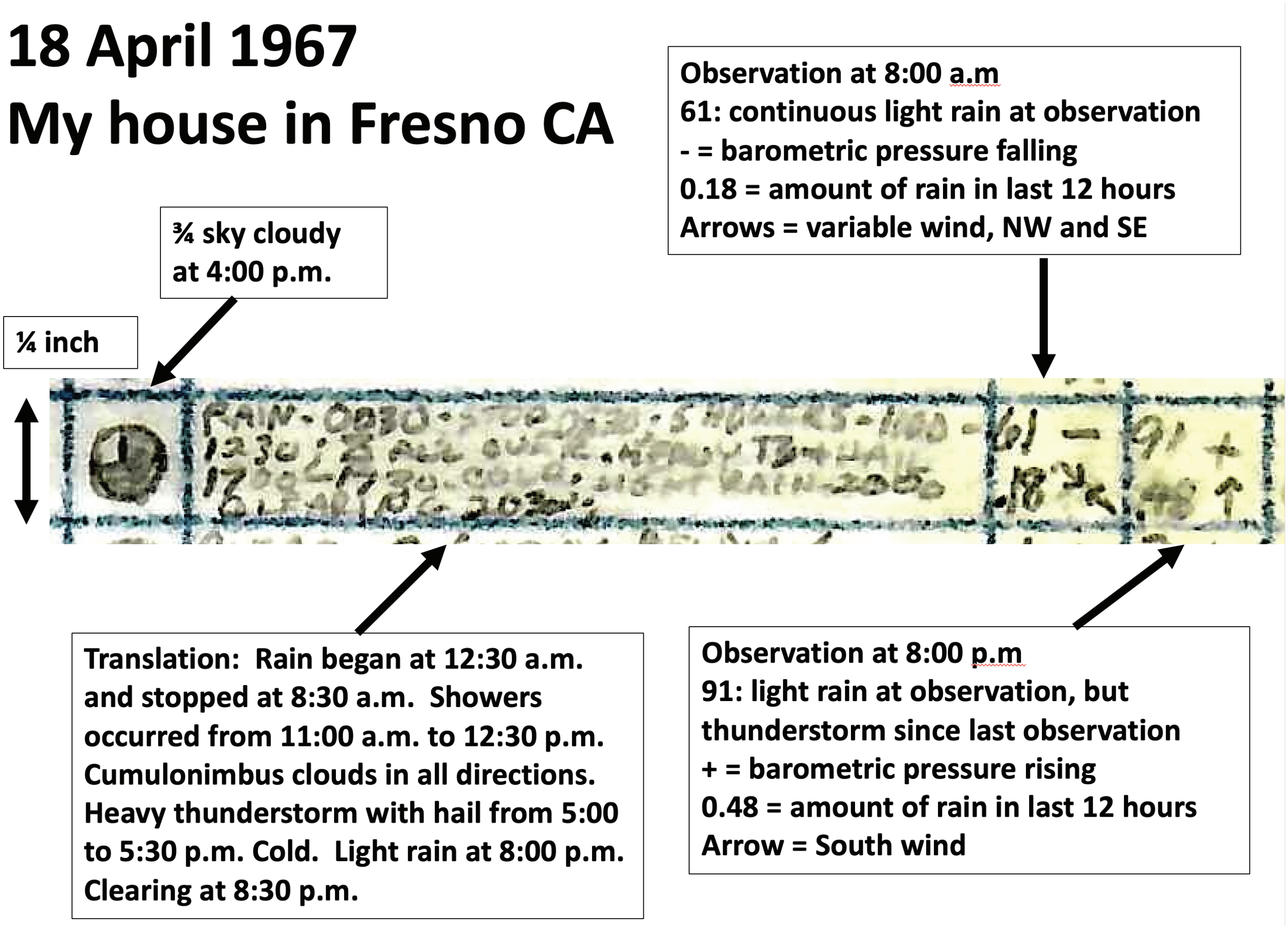
MESA FAT
MONTH 3.63 4.41*
YEAR 13.49 14.66

A-3

WW = PRESENT WEATHER

	MESA	FAT
JULY - MARCH →	9.86	10.25
JULY - DEC →	5.01	4.67
DEC - MARCH →	4.85	5.58

Dr. Christy has been fascinated with weather and climate his entire life. Here is an example of his teenage weather observations taken in April 1967. No computers back then, just hand-ruled paper and a mechanical pencil.



In this close up of one day from the previous image, you can see how much information he put into a space that was only 1/4 inch tall.