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CLIMATE VARIABILITY

IMPACTS IN THE SOUTHEASTERN UNITED STATES

The goal of this education module is to summarize our current understanding of climate variability and its impacts on the Southeast. This article analyzes the various natural climate cycles that impact weather and climate in the Southeast which will leave the reader with an understanding of the relevant climate cycles for the Southeast as well as their individual and collective impacts on various resources, namely water and food.

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What is Climate Variability?

Most people confuse the terms climate change and climate variability. **Climate change** is the long-term (e.g., decades, centuries, or longer) changes in climate that most scientists believe are largely caused by humans, while **climate variability** is arises from naturally occurring oscillations within the earth's system as it tries to reach a stable energy state (see the figure on the following page).

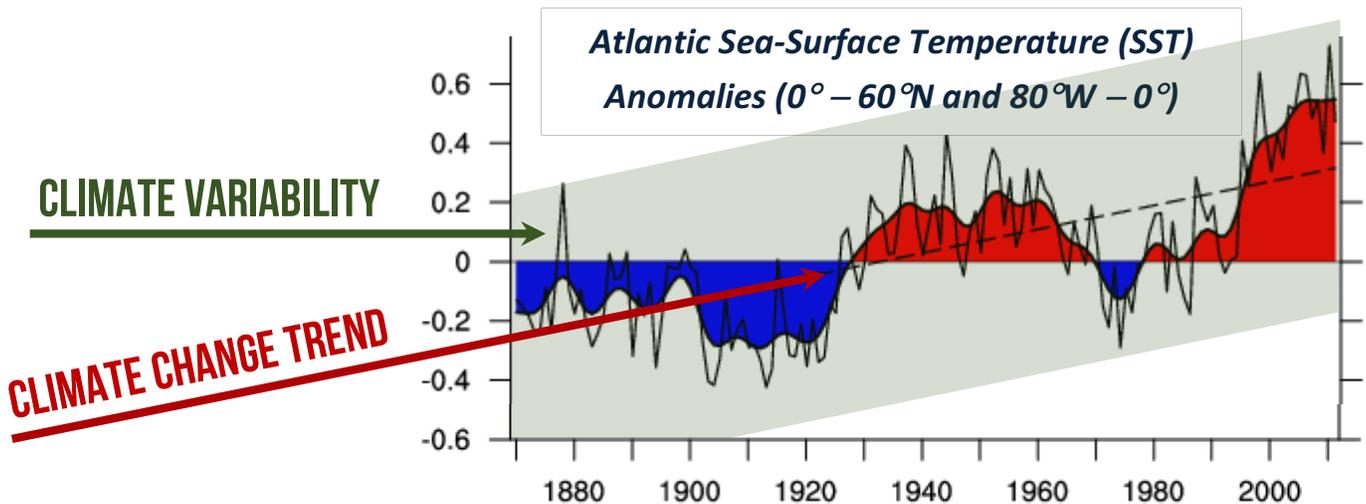
The variability within the climate system stems from uneven heating of the atmosphere and oceans followed by a redistribution of energy around the globe. This process leads to

pattern changes in precipitation, temperature, pressure, and other climate components. For example, naturally occurring seasonal climate variability is caused by the tilt of the earth as it orbits the sun. This tilt leads to uneven heating of the northern and southern hemispheres and provides the mechanism for the four seasons—winter, spring, summer, and fall. Energy in the form of heat is then redistributed throughout the climate system primarily by atmosphere-ocean mechanisms like winds and currents. These physical relationships are the reason we experience characteristically different weather and climate events in each season.

One way that scientists monitor and predict variability is by using sea-surface temperature (SST) and sea-level pressure (SLP) values in different parts of the globe. Using statistical methods and climate models, scientists have successfully linked SST and SLP fluctuations to

climate patterns in various regions of the globe (not necessarily near SST or SLP measurement locations). For example, fluctuation in SSTs in the Pacific and Atlantic oceans have been linked to droughts in parts of the southeastern United States. These fluctuations occur in specific locations around the world and have been classified into different oscillations (discussed

below). Most oscillations have periodicities—the time it takes for a single cycle to complete—on the order of seasons to decades or even longer. It is not relevant to discuss those cycles that are longer than the lifetime of a typical person, so we will focus on those cycles with periodicities less than 100 years.



Atlantic Sea-Surface Temperature (SST) anomalies from 1870 to 2011 demonstrate the difference between climate variability and climate change. Variability (oscillations of the climate cycles) can be seen occurring about the climate change trend line (dashed black). The pattern is more clear from the smoothed (121-month moving average) SST anomalies (thick black) as opposed to the noisy (highly variable) monthly anomalies (thin black). The faded green shading indicates what would be considered natural variability about the climate change trend line. In a changing climate, variability occurs about the climate change trend line as opposed to the climate normal (average for the entire period). Image adapted from Trenberth and Shea (2005).

Relevant Variability Cycles

There are numerous climate cycles occurring simultaneously throughout the earth. These cycles collectively impact climate around the globe, but some have a larger impact on specific regions than others. In this module we are concerned primarily with the climate in the Southeast, so we discuss cycles known to be most relevant to this region. There are at least four climate cycles known to impact the climate of the Southeast including the El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO), and North Atlantic Oscillation (NAO). The figure on the following page shows the geographic location of each of these cycles.

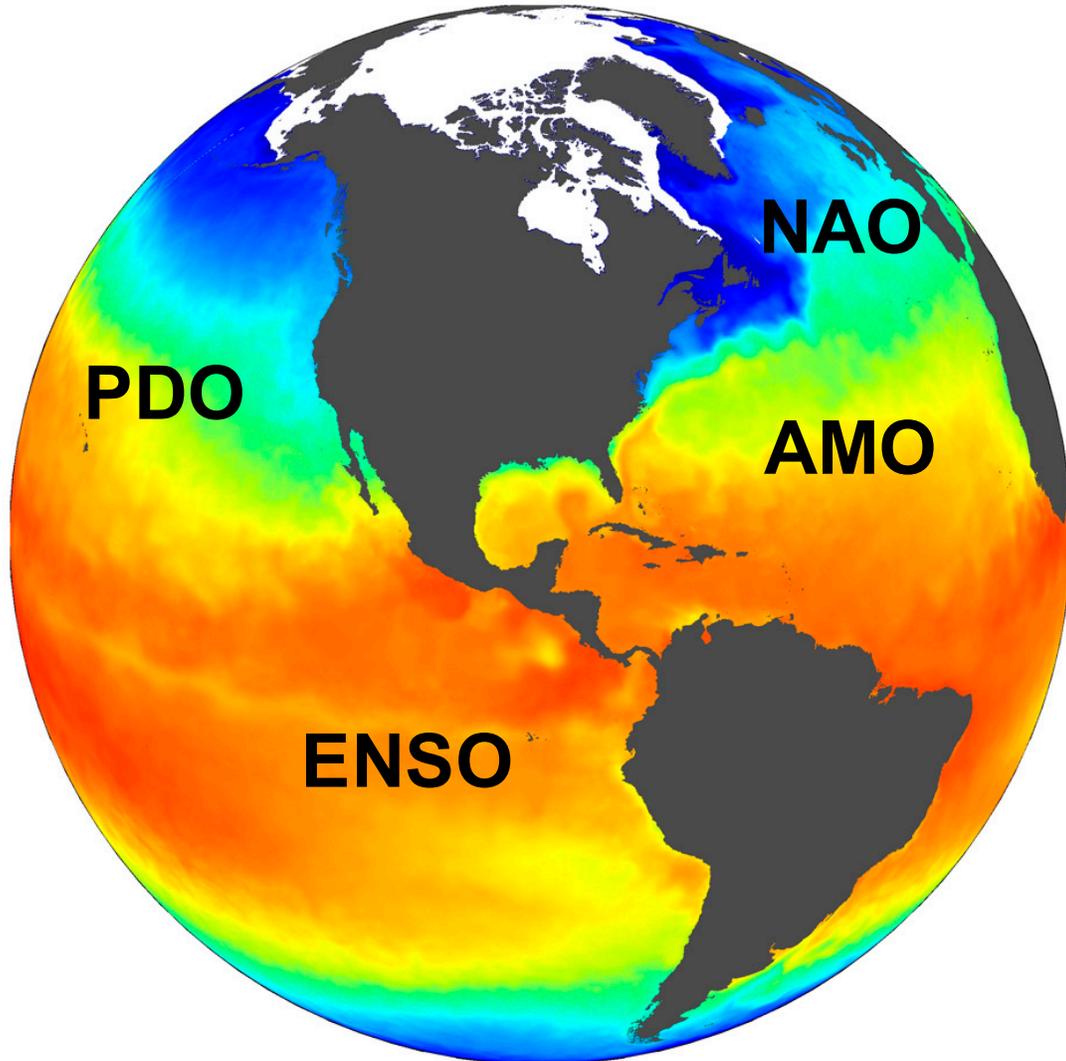
The El Niño Southern Oscillation (ENSO)

The most publicized and well-known climate cycle is ENSO. ENSO is the periodic fluctuation in SSTs and the air pressure of the overlying atmosphere in the central-eastern equatorial Pacific region (west of Peru). Warming and cooling of SSTs within this region is responsible for extreme weather events such as hurricanes, droughts, and floods around the world including the southeastern United States. ENSO has a predictable periodicity of 2 to 7 years, but its magnitude and climatic effect varies drastically around the world.

Based on SST anomalies (departures from normal), ENSO is divided into three phases: El Niño, La Niña and Neutral. El Niño is the large

scale warming of SSTs in the equatorial Pacific region. The opposite of El Niño within the ENSO cycle is La Niña, which refers to large-scale cooling of SSTs in the same equatorial Pacific region. In many regions around the world, especially in the tropics, La Niña produces climate variations that are opposite of those

produced by El Niño. The neutral phase occurs when SSTs are near normal in the equatorial Pacific. The recurring ENSO phases are never identical to prior occurrences because they depend on the intensity of SST anomaly, the time of the year when it develops, and its interaction with other climate oscillations.



The geographic source location of four climate cycles known to impact the climate of North America and especially the southeastern United States. Relevant cycles include the El Niño Southern Oscillation (ENSO), Atlantic Multidecadal Oscillation (AMO), Pacific Decadal Oscillation (PDO), and North Atlantic Oscillation (NAO). Relative ocean sea-surface temperatures (SSTs), indicated by warm and cool colors, were included for reference. Figure adapted from NOAA Climate.gov.

The Pacific Decadal Oscillation (PDO)

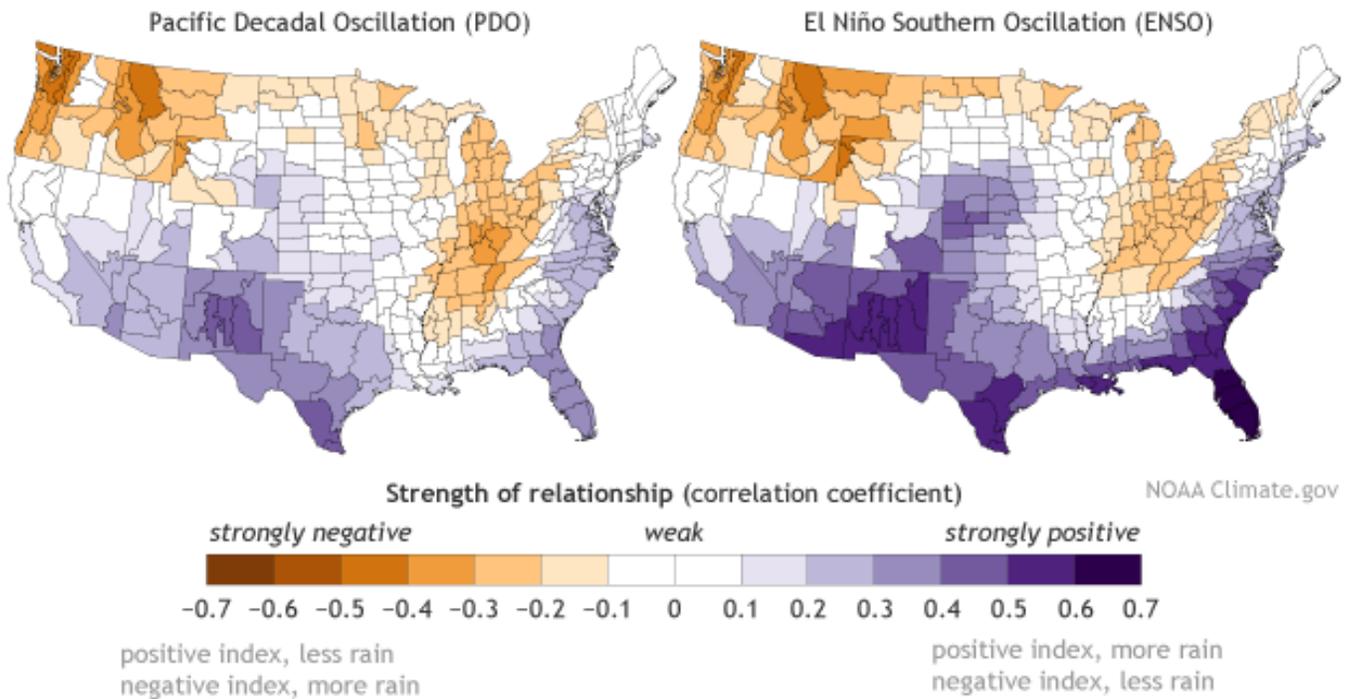
PDO has a similar geographic location to ENSO, and its positive and negative phases produce results similar to the corresponding phases of ENSO. However, their cycle durations are very different. A single phase of the PDO cycle can

last about 15 to 25 years, while ENSO phases usually last only 1 to 3 years.

The PDO climate oscillation primarily occurs in the northern Pacific Ocean. The area used to determine the PDO phase forms a horseshoe off the West Coast of North America extending

from Alaska to the northern border of ENSO (near Central America). Since PDO is located near the ENSO climate cycle, the two oscillations can affect each other as well as

regional climate patterns. Some studies have found that both PDO and ENSO can influence precipitation patterns in the US (figure below).



The relationship between Pacific Decadal Oscillation (PDO) and El Niño Southern Oscillation (ENSO) and precipitation anomalies in the United States. ENSO has a stronger relationship (positive or negative) than PDO in most areas, but both tend to influence U.S. climate similarly, provided that they are in the same phase. Figure from NOAA Climate.gov.

Atlantic Multi-decadal Oscillation (AMO) and North Atlantic Oscillation (NAO)

Just like ENSO and PDO are located nearby in the Pacific Ocean, AMO and NAO neighbor each other in the Atlantic Ocean. NAO is similar to PDO in that it has a similar periodicity (around 15 to 20 years for a single phase). NAO has a significant impact on regional climate across the eastern U.S., Europe, and Siberia as well as climate in the Arctic and subtropical Atlantic Ocean (Hurrell et al. 2003). Some oscillations are bimodal, which means that they oscillate on two (maybe more) timescales. Both NAO and PDO have been associated with bimodal cycles.

AMO has the longest periodicity in our list of climate cycles with single phases lasting up to 40 years or even longer. Due to its long cycle duration and the relatively short observation

period, AMO has not been studied as intensively as the other climate cycles. Still, we have discovered a number of climate patterns driven by the AMO climate cycle. For example, that the positive phase of AMO can increase both the number of tropical storms becoming hurricanes and their power as they make landfall in the Southeast. A strong correlation also exists between the phases of AMO and seasonal precipitation patterns (including drought) in the contiguous U.S.

Phase Determination

In each of the climate cycles discussed above, there are associated phases. These consist of a positive (warm) phase and a negative (cool) phase, and in the case of ENSO, a third (neutral) phase. These phases represent when

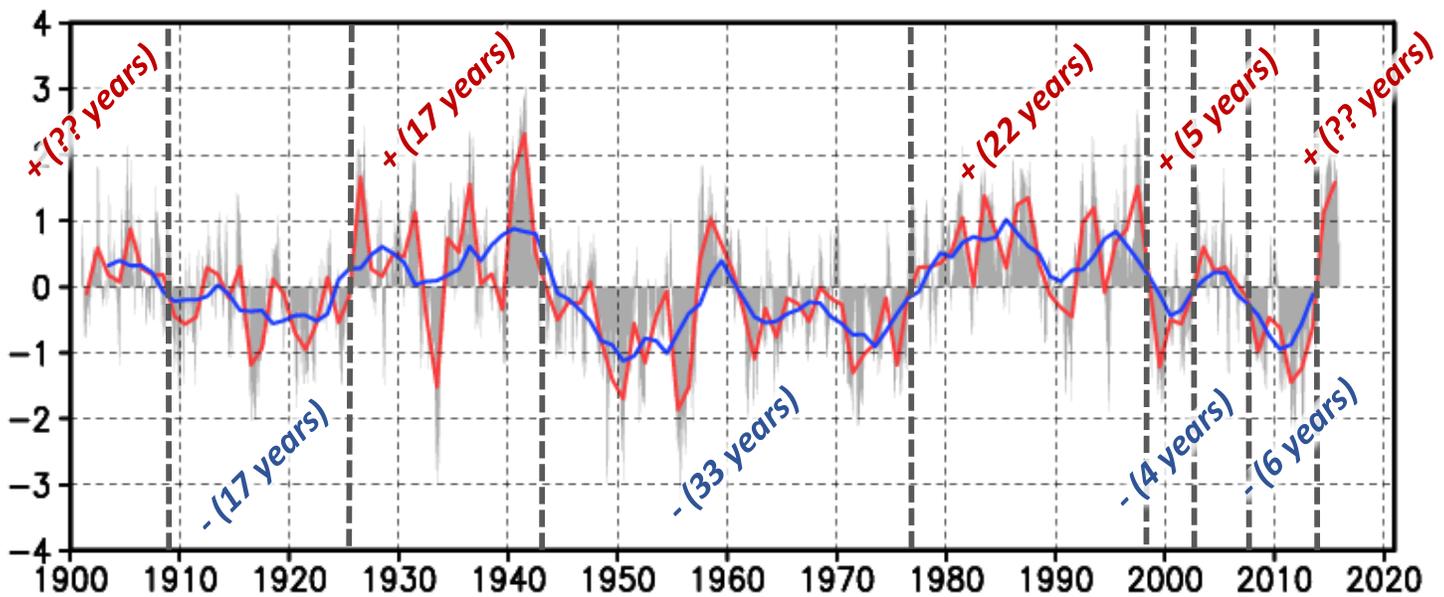
a climate cycle is in either of its extremes and when certain climate patterns are more likely to occur. The exact method for determining cycle phases can differ, but they all follow a general process. This process involves the use of climate indices.

Climate indices are monitoring tools that can describe and identify significant patterns and phases within each climate oscillation. Most climate indices are represented as a time series (meaning that they change with time) where the value of the index represents a climate condition. Usually, indices represent SST or SLP anomalies for a given area, and indices may be time-averaged (smoothed over time) to more

clearly indicate the climate cycle phase. Spatially-averaged SST/SLP anomalies in different regions of the ocean have been used to describe each of the relevant climate cycles discussed in this module including ENSO, PDO, NAO, and AMO. Observed phases of the four cycles are recorded in the following table. Compare this table to a figure on the following page that shows a time series of the PDO index in the Pacific Ocean, which is used to determine the phase (positive or negative) of that oscillation. Notice that monthly data is much more 'noisy' than the running averages, which better communicate the PDO phase.

Positive (warm) and negative (cool) phases for four climate variability cycles relevant to the weather and climate of the southeast United States. Observations are for the time period from 1950 to 2016 (Adapted from Singh et al. 2015).

	<----- Shorter Cycles ----->		----- Longer Cycles ----->	
	ENSO	PDO	NAO	AMO
Warm / Positive Phase	1953, 1957,	1977 - 1998,	1950 - 1951,	1950 - 1963,
	1963, 1965,	2003 - 2007,	1973 - 1976,	1995 - 2016,
	1969, 1972,	2014 - 2016,	1981 - 2016,	...
	1977, 1982,	
	1987, 1991,			
	1993, 1997,			
	2002, 2004,			
	2009, 2015,			
...				
Cool / Negative Phase	1950, 1954,	1950 - 1976,	1952 - 1972,	1964 - 1994,
	1955, 1956,	1999 - 2002,	1977 - 1980,	...
	1964, 1970,	2008 - 2013,	...	
	1971, 1973,	...		
	1974, 1975,			
	1981, 1988,			
	1998, 1999,			
	2000, 2007,			
	2008, 2010,			
	2011, 2012,			
...				



A time series of the PDO index. The gray bars represent monthly SST values with running annual mean values (red line) and five-year running mean values (blue line). Positive and negative phases are indicated with an appropriate sign, phase duration, and text color. Figure adapted from the Japan Meteorological Agency (JMA).

Direct Climate Impacts

When assessing the impacts of climate cycles on the earth system, there are generally two types of impacts: direct and indirect. Direct impacts are usually those which are most easily assessed—the connections are usually clear, they tend to be immediate, and are located near to the cause. Indirect impacts are those that may not be an immediate result of the cause. These impacts can even be a result of a direct impact. For example, variability cycles and their SST and SLP fluctuations may cause climate patterns in other regions such as increased precipitation. Increased precipitation may lead to increased streamflow, and that will lead to subsequent impacts. The increased precipitation in this example is considered a direct impact, and the increased streamflow (and subsequent impacts) are indirect impacts.

We discuss climate cycles having the most significant impact on the Southeast, but some cycles may be left out if their impact is small or not well-known. The cycle which has the most direct impact on the Southeast and which has

been studied most is the El Niño Southern Oscillation (ENSO) cycle.

The ENSO cycle predominantly impacts precipitation and temperature during the winter season in the Southeast. During the winter season El Niño (warm phase) is responsible for above-normal precipitation, while La Niña (cool phase) generally results in drought. Almost all of Florida, Georgia, Alabama, South Carolina, Mississippi and Texas exhibit above-normal winter temperatures during La Niña while the process reverses during El Niño (figure on the following page).

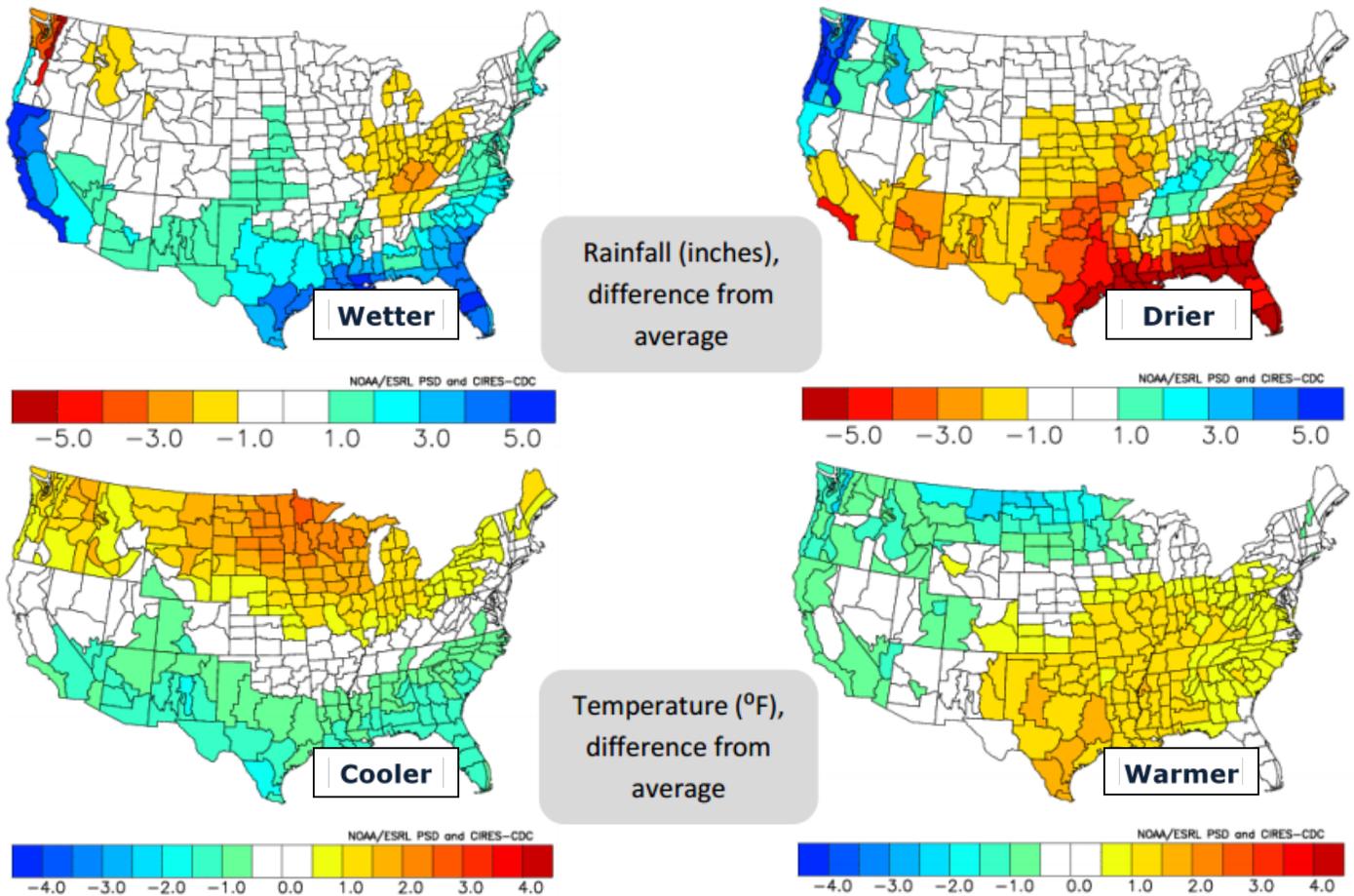
ENSO does not act alone on the climate in the Southeast. Precipitation anomalies caused by ENSO can either be enhanced or reduced when ENSO phases are associated with other decadal and multi-decadal cycles. When La Niña acts with other long-term cycles it can cause severe droughts in the Southeast. For example, Enfield et al. (2001) found that winter precipitation patterns associated with ENSO had different responses depending on the phase of AMO. In Florida, El Niño precipitation anomalies have been found to be enhanced

when associated with positive phases of the PDO cycle (Kurtzman and Scanlon, 2007). The positive phase of PDO modulates the impacts of the ENSO cycle, making it stronger, while the negative phase weakens ENSO cycle. A similar relationship was found between AMO and ENSO phases. Individually, the positive AMO phase exhibited more precipitation in parts of Florida and coastal regions of the Southeast, but the

positive AMO phase was highly correlated with the ENSO index and winter precipitation in the Southeast (Curtis, 2008). This means that AMO phases (and other cycle phases like PDO) can and do modulate (strengthen or neutralize) the effects of ENSO. It is safe to presume that all the climate cycles modulate each other, and that is precisely why determining their effects (individually vs. collectively) can be difficult.

El Niño (Warm ENSO Phase)

La Niña (Cool ENSO Phase)



Precipitation and temperature anomalies during warm and cool phases of ENSO. El Niño is generally associated with cooler, wetter climate and La Niña with warmer, drier climate for the months November to March. ENSO generally impacts these months most because that is the time of year when the Pacific Ocean is warmest (thus exporting the most heat energy). Slight changes in temperature gradients (a few degrees Fahrenheit) can drastically change the direction of this energy redistribution therefore changing climate patterns. Figure from NOAA NWS.

Other Indirect Impacts

Although the direct impacts that climate cycles have on regional climate are important, what is

probably more important to stakeholders and the general population are the indirect impacts, which are influenced by the regional climate. These include impacts on important resources

such as food, water, and energy. ENSO, PDO, NAO, and AMO all impact these resources in their own unique way and collectively as a giant web of climate interactions.

How do we know that these specific climate cycles, which are often halfway across the globe, impact local climate in the Southeast? Even though scientists have not fully understood the direct relationships between climate variability cycles and local climate, they have explored various teleconnections—causal relationships—through statistical and climate modelling. Through these modelling efforts, scientists have discovered that in the Southeast, influences from climate variability can be either beneficial, harmful, or both. For instance, El Niño has been linked to lower Atlantic hurricane activity and above-average precipitation in the Southeast. However, the increased rainfall could lead to flooding and El Niño has also been linked to increased severe weather (from a stronger, extended Pacific jet stream). For some regions the benefits may outweigh the harm or vice versa. Ultimately, we should recognize the potential impacts of the various climate events (ENSO, PDO, NAO, and AMO) and plan accordingly.

Impact Assessment Strategies

There are two major assessment strategies which can be categorized as either 'individual analyses' or 'coupled analyses'. An individual analysis is performed in order to understand the impacts of a single cycle on a system. However, in reality these cycles do not occur in isolation of each other, but simultaneously. For example, AMO is a multidecadal cycle occurring in the Atlantic Ocean and a single AMO phase usually lasts about 30 years. Within that time, several cycles of ENSO would have occurred in the equatorial Pacific Ocean. These cycles interfere with each other in the global scheme of things, which means that local climate and impacts can vary vastly from one climate phase to another. To evaluate complex relationships

such as these, scientists use a coupled analysis. An example of a coupled analysis is included in the following section.

Streamflow and Baseflow

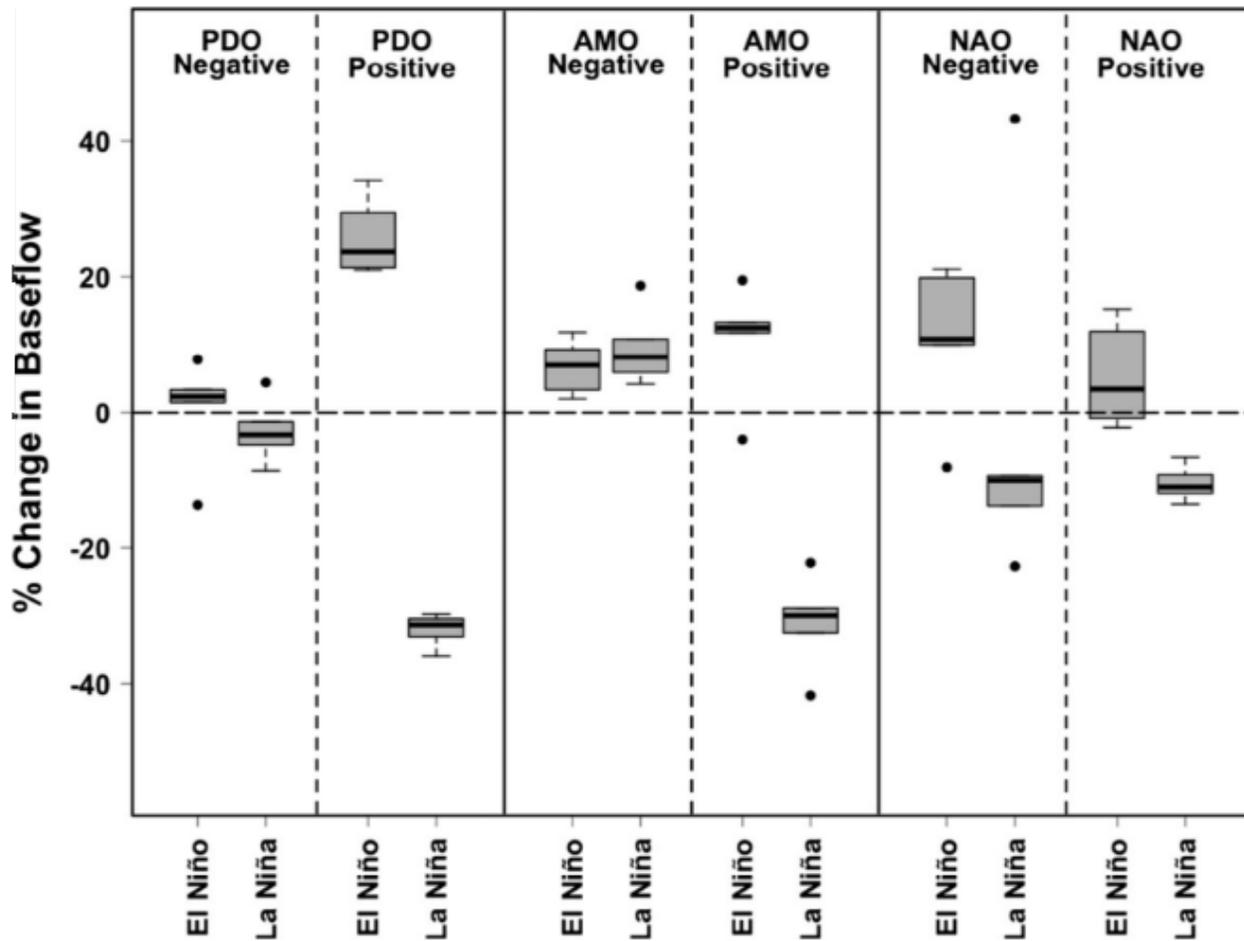
Since there is such a strong correlation between precipitation and temperature with ENSO, PDO, and AMO in the Southeast, we would expect that these climate cycles would be strong enough to impact parts of the hydrologic cycle, which is closely related to climate. Studies conducted by Tootle et al. (2005) showed that major climatic oscillations influence streamflow levels in the Southeast. The figure on the following page is from a study (Singh et al. 2015) that used a coupled analysis of climate cycles to determine their combined effects on baseflow in the Flint River.

Baseflow levels in the Flint River Basin are generally above normal during El Niño and below normal during La Niña. When combined with ENSO, both AMO and PDO have significant impacts on baseflow there. The positive phase of each of these enhance the effect of ENSO, whereas NAO does not appear to make a significant difference. In addition, the negative phase of PDO and AMO significantly reduce the impact of ENSO on baseflow in this region. Baseflow levels were above normal during both the ENSO phases when associated with the AMO negative phase. Thus, the cool phase of AMO negates the effect of La Niña on baseflow in the region (suggesting that La Niña might not always be responsible for droughts in the Southeast). Therefore, we must examine all the climate cycles to achieve a full understanding of climate variability impacts on both the regional climate and the precious resources of the Southeast.

We would expect that other areas in the Southeast would be impacted similarly, but the nature and degree to which those systems are affected by climate variability will differ based on how unique, local climate patterns respond to these climate cycles. It becomes much more

difficult to make widespread generalizations of impacts from these climate cycles on resources such as water, food, and energy. This is due to the complex relationships that obscure impacts from climate variability—hence, impacts on resources are typically called indirect impacts.

Despite the obscurity of these relationships and the potential for different outcomes (especially in climate-sensitive areas of the Southeast like Florida), the Flint River Basin in Georgia responds as a typical southeastern river would to the climate cycles discussed.



Box and whisker plots showing the percentage change in baseflow levels in the Flint River Basin for a coupled climate variability analysis. Note the extreme differences of ENSO (El Niño and La Niña) during the positive PDO and positive AMO phases. Also note that the phase of NAO does not modulate (modify or change) ENSO impacts on baseflow in this basin (Singh et al. 2015).

Groundwater

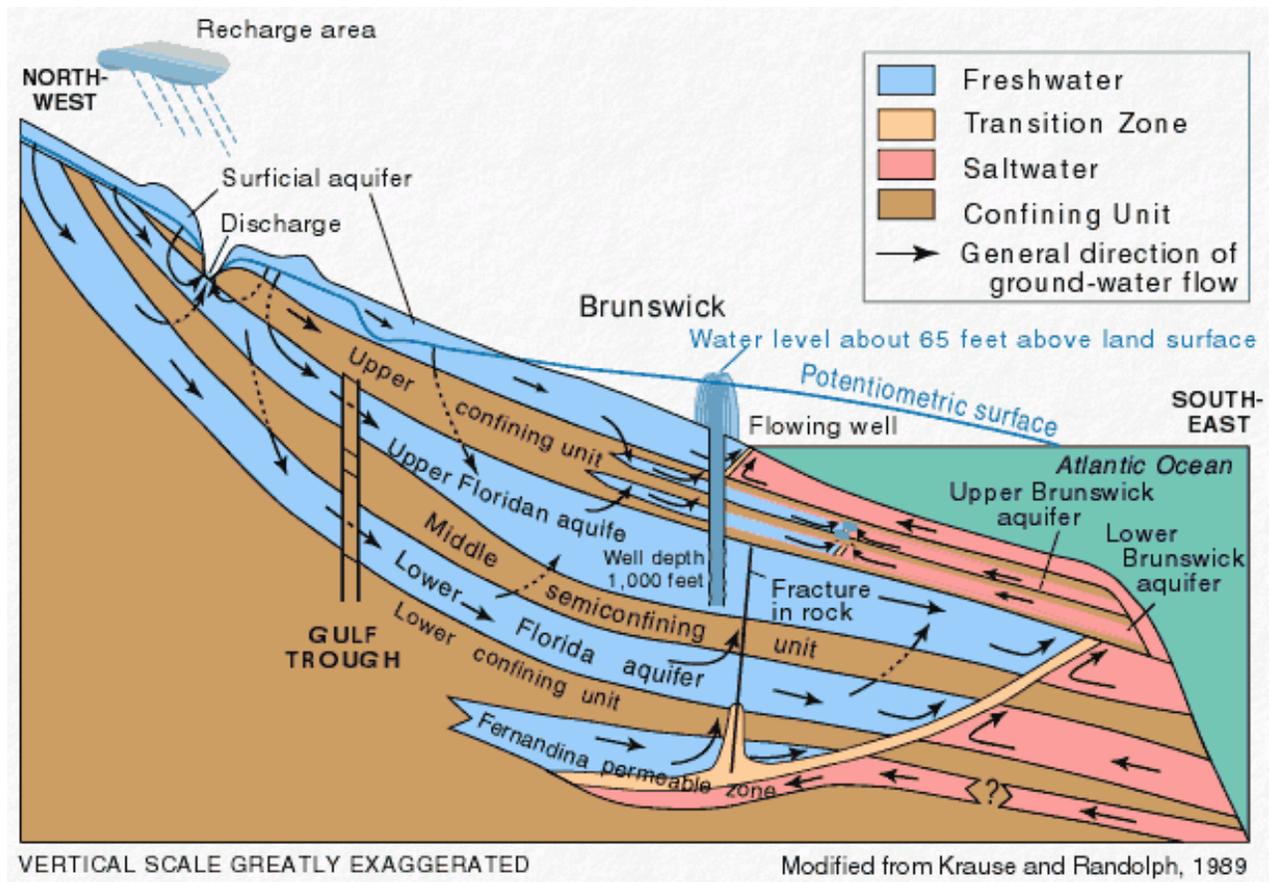
Another major resource impacted by climate variability is groundwater. Groundwater does not interact directly with precipitation. Instead, it relies on low-intensity precipitation that can infiltrate into the soil and slowly recharge the relevant aquifer(s). An aquifer refers to a body (rock, soil, or another subsurface feature) that permits water movement underground. Climate cycles that impact groundwater will either

enhance or disrupt the amount of precipitation infiltrating into any given aquifer, and recharge areas may be more sensitive to these influences.

One major groundwater system located in the Southeast is the Floridan Aquifer system. Aquifers can be confined or unconfined based on the presence of confining layers above or below the aquifer. Confining layers impede but do not stop water flow between the surface and

individual aquifers. The Floridan Aquifer system consists of two major aquifer units including the

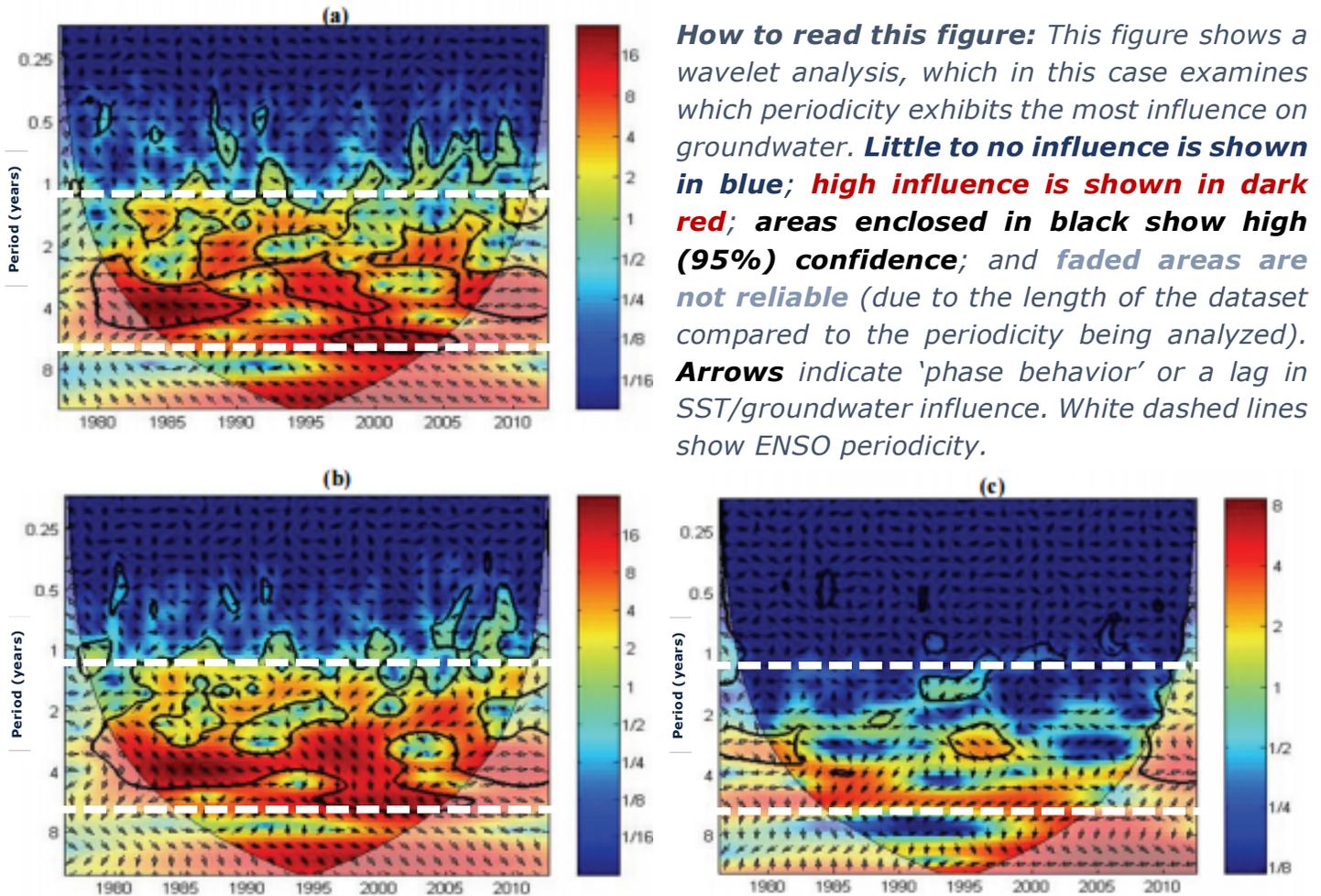
Upper Floridan Aquifer (UFA) and the Lower Floridan Aquifer (LFA) (see the figure below).



A conceptual model of the Floridan Aquifer system. This figure shows the various confining layers, aquifers, and subsurface interactions responsible for groundwater exchanges in the region. The surficial aquifer responds more quickly to climate events at the surface, whereas deeper layers may take much longer or will perhaps not even respond to climate events. Figure from web at: <<https://water.usgs.gov/edu/gwartesian.html>>.

The UFA is the unit through which most of the irrigation and municipal water supply demands are met in the region. In order to ensure future supply for agricultural irrigation and municipal water it is imperative that we determine which climate cycles are influencing groundwater most and how they are impacting the resource. Unfortunately, climate impacts on groundwater can be difficult to assess due to short data records, which are insufficient for determining connections to the longer climate cycles such as PDO, NAO, and AMO. These climate cycles have single phases lasting 15 years or longer, but most groundwater datasets only began recording in the 1950's or later.

Therefore, much of the analysis pertaining to groundwater has focused on connections to ENSO, which is a much shorter climate cycle. ENSO teleconnections (causal relationships) in the UFA have been detected using advanced statistical analyses. One study by Mitra et al. (2014) showed that groundwater levels in the shallow and moderately deep overburden areas are significantly influenced by ENSO (overburden refers to the amount of material lying over the various wells). However, groundwater levels under deep overburden areas do not exhibit strong teleconnections with ENSO (figure below). The ENSO periodicity is indicated by white dashed lines.



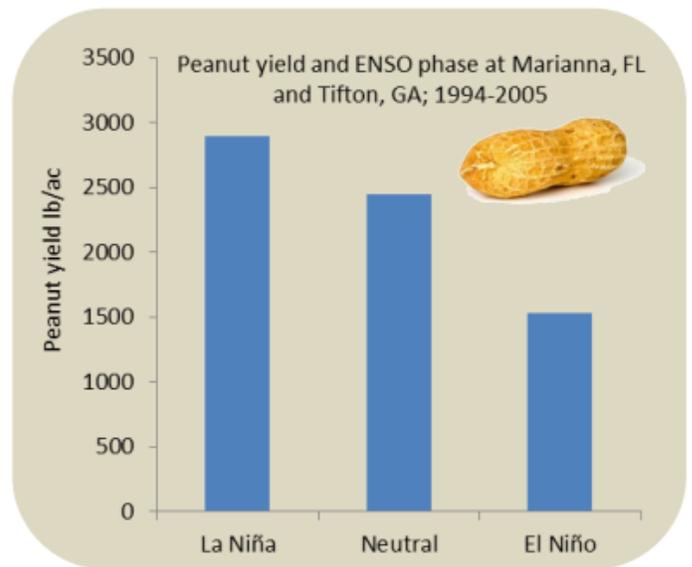
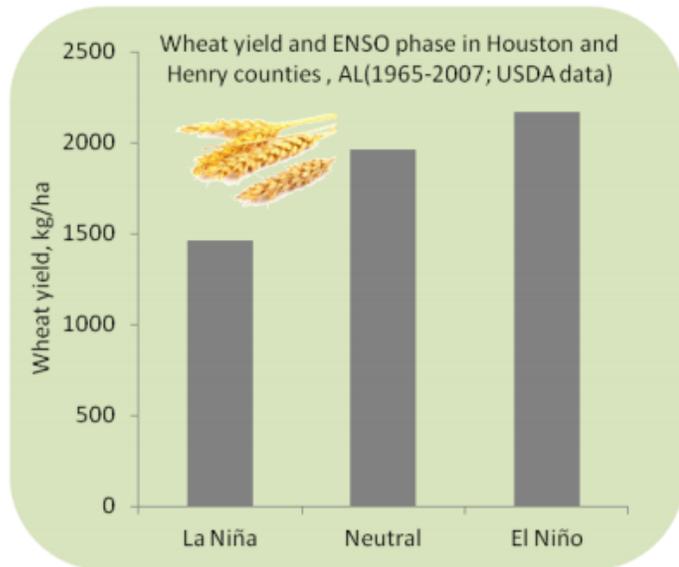
Wavelet teleconnections between ENSO and groundwater levels in the UFA under (a) shallow (b) moderately deep and (c) deep overburden conditions. The figures show correlation between ENSO SSTs and groundwater levels in the different depth wells over the entire period of the data (1975 to 2014). Both (a) and (b) exhibit strong influence of ENSO on groundwater in the respective overburden conditions (shown in red). Figure adapted from Mitra et al. (2014).

Agricultural Crop Production

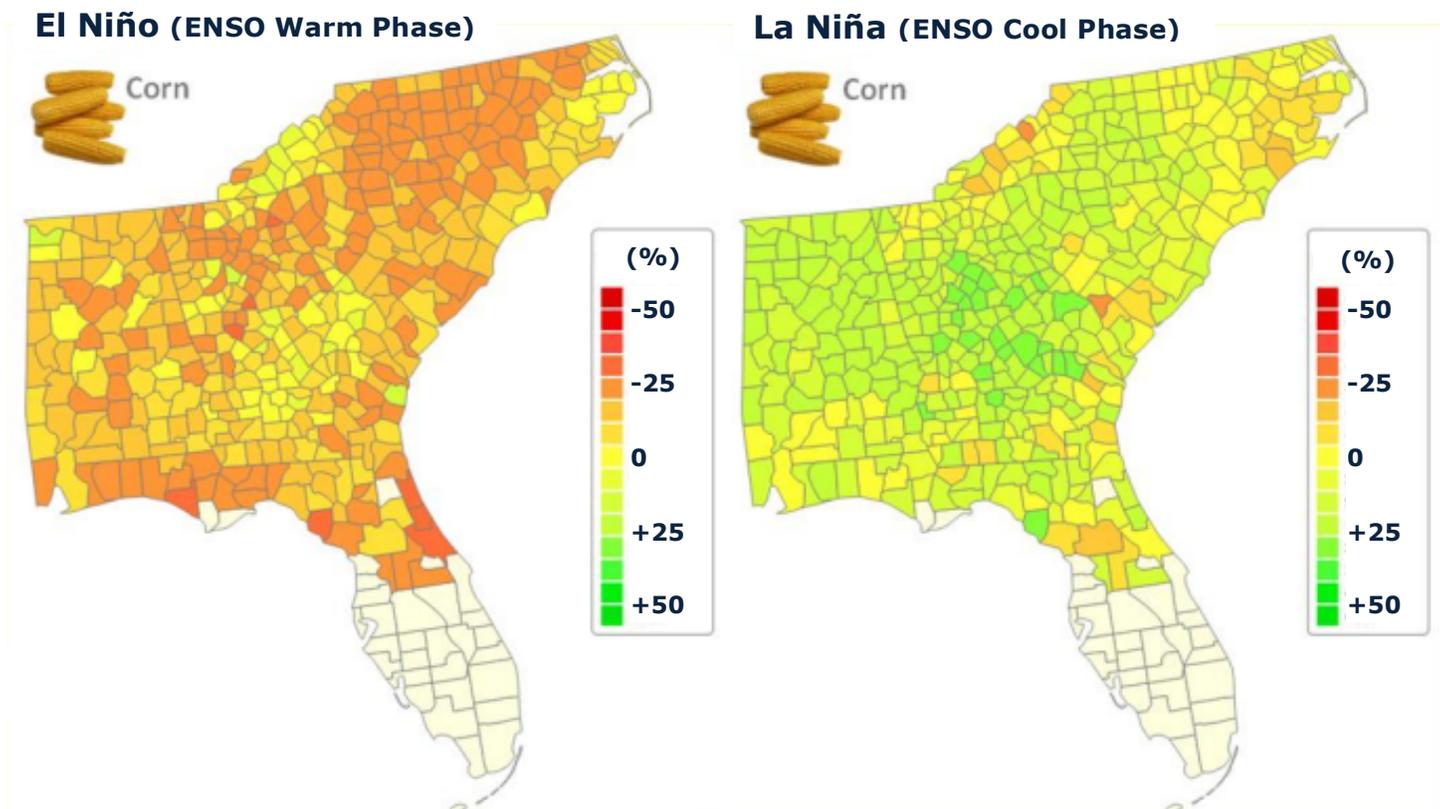
A third resource which is significantly impacted by climate variability is crop production. Similar to groundwater, the impacts of longer term climate variability on crops may not be well understood due to relatively short observation periods. In time, our understanding of indirect impacts will increase with longer observation periods and higher quality datasets. Despite how young our understanding of longer climate cycles may be, we still can summarize the effects of ENSO on agriculture.

When it comes to any impact assessment, but especially agriculture, it is important to

recognize spatial variation. El Niño may impact one part of the Southeast one way but may have the opposite effect in another. This is even more true of agriculture than water resources because of the unique responses of various row crops to climate variability. Too much rain or higher temperatures can have a negative effect on some crops, while benefitting others. It is critical not to draw general conclusions about climate variability impacts across different agricultural crops since they can exhibit opposite reactions to climate cycles. See the figures on the following page for an example of crops respond differently to ENSO.



El Niño Southern Oscillation (ENSO) impacts on winter wheat and peanut production in select counties in the Southeast. Results for other counties may vary due to unique local climate impacts and agricultural practices, but impacts will be more or less the same across the Southeast for these crops. See the figure on the following page for an example of the typical spatial variability associated with agricultural impacts from ENSO. Figures from agroclimate.org.



Percentage differences (from mean) in county-level corn yield for El Niño and La Niña phases (varying county records from 1920 to 2011). Although some counties reported slightly different results, there is a general spatial trend, with some areas that are more sensitive and some more resilient to ENSO effects. However, it is clear from the figure that El Niño is associated with lower corn yields and La Niña is associated with higher corn yields. Figure from agroclimate.org.

In short, the impact of ENSO on crop production is varied. Some crops benefit from a warmer Pacific Ocean and others are harmed by the same warming. The spatial variability of these impacts limits what can be generalized

for any given region, but many of the impacts on the Southeast are consistent throughout the entire region. A summary of El Niño and La Niña impacts on agriculture is provided below.

Agricultural Impacts of El Niño:

- 20% lower corn yield (from an increased cloud cover)
- Higher wheat yields in southern Alabama and Georgia
- Reduced peanut yields (from increased Tomato Spotted Wilt virus)
- Reduced risks of Hessian Fly and Aphid reproduction (late winter crop planting)
- Higher chill accumulation and increased fungal/bacterial diseases for winter crops
- El Niño years are good for winter pasture due to wetter conditions
- **Highlights:** longer, colder winter; more cloud cover and rainfall; more disease; slower growth; lower risk of drought; more leaching; more flooding; delayed planting and harvesting due to rain.

Agricultural Impacts of La Niña:

- Higher irrigated corn yields (assuming drought has not depleted water supply)
- Yield reduction might ensue in the years following La Niña
- Wheat yield in northern Alabama is generally higher than average
- Increased yield in tomatoes and green peppers during La Niña years
- Decreased fungal and bacterial diseases and reduced fungicide applications from the drier weather
- **Highlights:** warmer winter; less cloud cover and rainfall; less disease; higher growth (from more growing days and less cloud cover); higher risk of drought and severe drought; higher irrigation needs; and short frost season.

Summary

This module focuses on the natural variations within the climate system. These variations, which are expressed through many individual climate cycles, are regularly recurring cycles that redistribute heat energy throughout the earth. It is currently not clear whether climate change will interfere with how these cycles presently operate. However, these cycles will continue to impact regional climate and various resources across the entire planet as well as in the Southeast. ***This module does not assess anthropogenic (man-caused) impacts or feedback loops (impacts that worsen or reduce other impacts) in regard to climate variability.*** These impacts do exist, however, and they can cause more harm than the natural impacts themselves. For example, drought induced by climate variability in the Southeast

is worsened by increased irrigation and municipal water demands (such as lawn care). This reduces groundwater levels which in turn pull more water from streams to compensate for losses. The years 2007 and 2011-2012 are recent examples of La Niña-induced droughts. Such events have happened frequently enough that the Army Corps of Engineers has included ENSO climate forecasts in their Water Control Manual for managing the numerous reservoirs in the Apalachicola-Chattahoochee-Flint (ACF) River Basin.

We wish to emphasize a few final thoughts regarding climate variability in the Southeast. First, understanding the precise meaning of climate variability, the impacts it has on climate and resources in the Southeast, and the potential to forecast climate cycles (and their impacts) is invaluable. Stakeholders and policy-makers should understand that it is not difficult

to incorporate climate forecasts into decisions, which is becoming simpler and more reliable with each passing year. Second, all climate cycles, especially the four mentioned in this module, are being studied intensively for their impacts on the country as a whole and the southeastern region. Shorter cycles are already forecasted and those forecasts can be integrated into decision-making now, while longer cycles (namely AMO) will certainly be studied and forecasted in the near future. Lastly, climate variability differs from climate change. The news media narrative tends to portray climate change as only harmful to society, but this is simply misleading, and climate variability is wrongly lumped together with climate change. ***Climate variability presents both benefits and harm, but it is best described as 'different.' With proper planning and suitable response—informed by a healthy understanding of climate forecasts and likely impacts—the benefits of climate variability can be fully realized and harm can be mostly avoided.***

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