CHAPTER 16

Terrestrial and Ocean Climate of the 20th Century

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The Florida peninsula, with its close proximity to the equator surrounded by robust surface and deep water ocean currents, has a unique climate. Generally, its climate is mild with variations on numerous time scales, punctuated by periodic extreme weather events. In this chapter, we review the mechanisms by which some well-known natural variations impact the regional climate and modulate the occurrence of extreme weather over Florida and its neighboring oceans. In addition, we explore the role of land cover and land use changes on the regional climate over the same area. It is made apparent from the review that remote variations of climate have an equally important impact on the regional climate of Florida as the local changes to land cover and land use.

Key Messages

- Florida is a unique region to the east of the Rocky Mountains with a very distinct monsoonal type of wet season in the summer that distinguishes it from the rest of the seasons.
- Florida's climate is as much affected by remote climate variations as local variability over land and its neighboring water bodies. Florida's climate is affected by more global scale natural variations like ENSO, AMO, PDO. Similarly, there is a discernible impact of local land cover and land use change on surface temperatures in Florida.
- There are important interactions of the observed climate across time and spatial scales to consider. For example, the sea breeze over the Florida Panhandle is shown to be affected by the subtle variations of the Bermuda High. Similarly, ENSO forcing on Florida's winter climate is affected by decadal variations such as the PDO and the AMO.

Keywords

Seasonal cycle; Diurnal variations; Sea breeze; ENSO; Tropical cyclones; Hurricanes; AWP; AMO; PDO; PIZA

Introduction

The atypical peninsular geography and relatively close proximity to the equator give Florida, a land of flowers in a latitude of deserts, a unique and desirable climate. This is a leading factor for the state's growing population and tourism. Florida has a relatively mild climate throughout the year, significant freshwater resources that are replenished naturally by seasonal rains, and picturesque coastlines that have led to rapid growth in human settlement and urbanization along the coast. However, amidst its rather serene climate, Florida often experiences a considerable number of weather and climate anomalies that pose a threat to the region and those living in it. This chapter will focus on this variability around the mean climate in the region, where variations span a range of time scales, from days to decades to centuries. Our understanding of these variations is largely limited by the availability of reliable observations of certain critical meteorological and oceanographic variables. We have, therefore, restricted discussions in this chapter to variations that could be reasonably resolved in the past 100 years. However, it is a challenge to isolate natural variability of climate when artificially-introduced variations from changes in location of observation, instrumentation, and method of measurement are not accounted for (Misra and Michael 2012). In addition, complex interactions in natural climate variation across space and time, as well as anthropogenic climate change, make understanding the manifestation of specific climate anomalies and weather events difficult. Some of these issues will be closely examined in this chapter.

The Seasonal Cycle

The distinct seasonality of Florida manifests in its hydroclimate, with a clear and apparent rainy season coinciding with the June-July-August (JJA) season (Fig. 16.1). In fact, Fig. 16.1 suggests that by volume of rain (mean seasonal rain multiplied by the surface area over which it falls), the state of Florida receives the highest in the Continental United States (CONUS). Much of this rainfall seasonality is sustained by diurnal variations (Fig. 16.2; wherein rain maximizes in certain times of the day). This diurnal variability is typical of marine environments in lower latitudes, where day and night temperature differences between land and ocean cause sufficient density variations in the atmospheric layer to drive an atmospheric circulation (e.g., sea breeze) that would spawn thunderstorm activity during certain times of the day. But more fundamentally, with a warmer atmosphere in the summer season there is a higher moisture-holding capacity that gives rise to more diurnal variations in precipitation if there is a sufficient moisture supply to the atmospheric column to condense. This is partly because of the Clausius-Clayperon equation, which relates the saturation vapor pressure (a measure of the maximum moisture-holding capacity in a given volume of air to temperature) and implies water-holding capacity of the atmosphere increases by about 7% for every Kelvin rise in temperature (Trenberth et al. 2003).

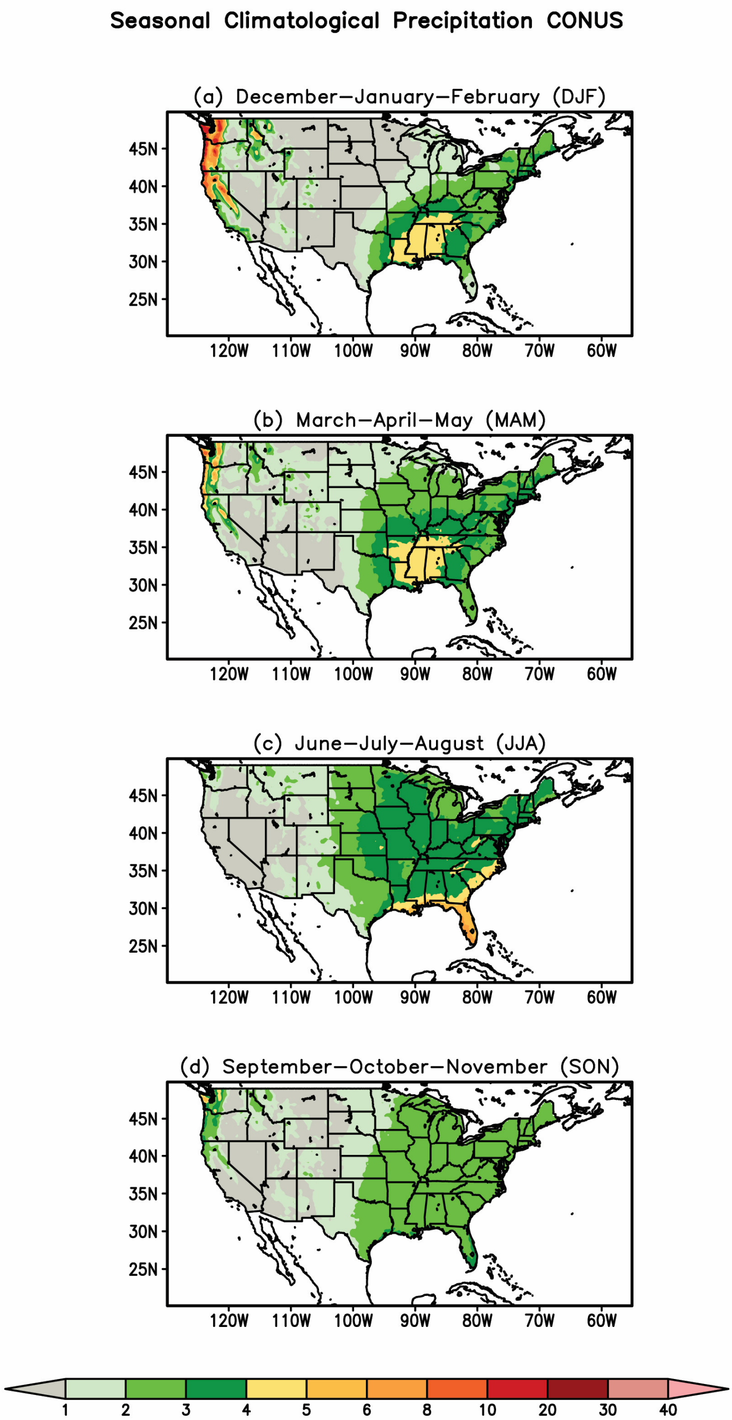


Figure 16.1. Climatological seasonal mean precipitation over the Continental United States (CONUS) for a) December-January-February (DJF), b) March-April-May (MAM), c) June-July-August (JJA), and d) September-October-November (SON) seasons from the National Centers for Environmental Prediction (NCEP) Climate Prediction Center (Higgins et al. 2000). The units are in mm/day.

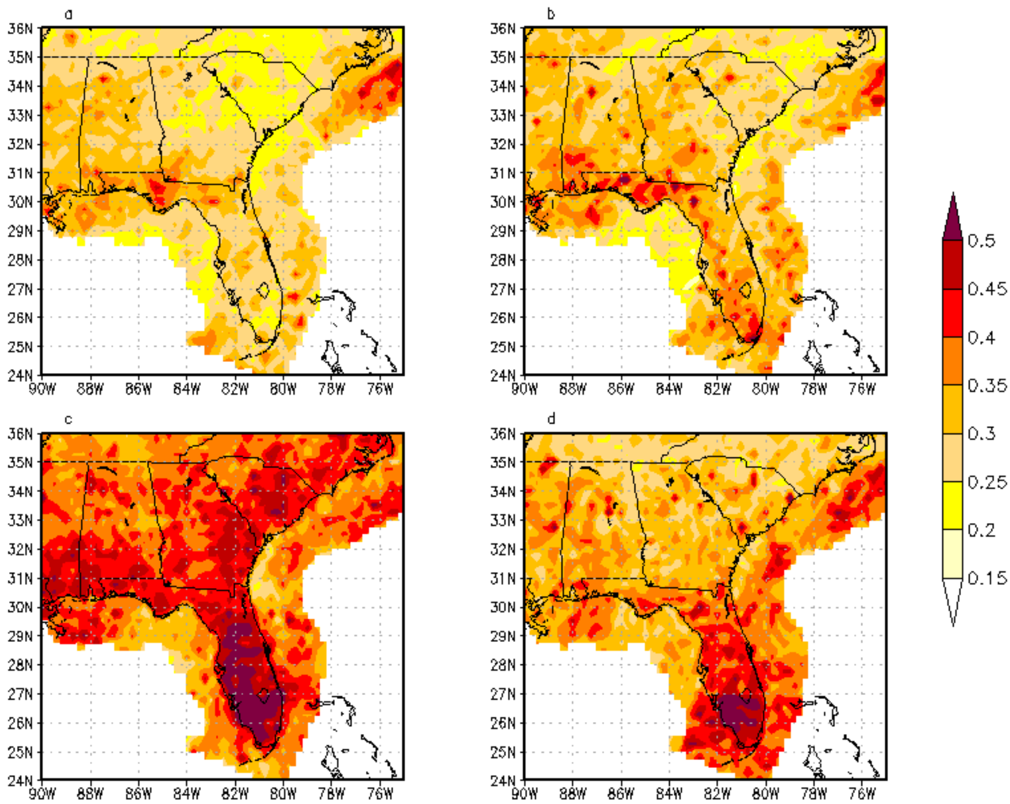


Figure 16.2. The fraction of diurnal variability that explains the total seasonal variability in a) DJF, b) MAM, c) JJA, and d) SON seasons from NCEP Stage IV hourly data (Lin and Mitchell, 2005). From Bastola and Misra (2013).

Seasonality in the temporal correlations between precipitation and surface temperature over Florida reveal that they change from positive correlations in the winter to negative correlations in the summer (Trenberth and Shea 2005; Misra and Dirmeyer 2009). In the winter time, surface evaporation that leads to cooling of the surface temperature is not an important contributor of moisture for local precipitation (Misra and Dirmeyer 2009). Therefore, positive correlations between surface precipitation and temperature are a likely indicator of warm moist advection ahead of the cold front that favors precipitation and warms the surface (Trenberth and Shea 2005). However, in the summer season, surface evaporation becomes an important source of moisture for local precipitation that leads to negative correlations with precipitation, as evaporation tends to cool the surface temperature.

Some of this seasonality in the hydroclimate of Florida is also caused by the seasonal vacillation of the North Atlantic Subtropical High (NASH; Davies et al. 1996; Misra et al. 2011; Li et al. 2013). The NASH, also known as the Azores or Bermuda High, displays a distinct high pressure anticyclone in the lower troposphere during the summer over the subtropical Atlantic basin that changes to two distinct high pressure systems over eastern North America and northwestern Africa by the winter season. These seasonal migrations of the NASH modulate the large-scale moisture advection (Li et al. 2013; Chan and Misra 2010), low-level divergence (Misra et al., 2011), and atmospheric stability (Selman et al. 2013), which impacts seasonal precipitation over Florida.

Diurnal Variability

In this section we delve further into the drivers of diurnal variability of precipitation and temperature in Florida, and discuss their delicate interplay. In order to analyze these variables, we extracted the diurnal harmonic from the NCEP's STAGE-IV radar-based precipitation data (STAGEIV; Lin and Mitchell 2005) and surface temperature from the North American Land Data Assimilation System-1 (NLDAS-1; Cosgrove et al. 2003).

We see (Fig. 16.3) that in the winter and fall months the amplitude of diurnal variability of precipitation is much lower than in the spring and summer months. In the winter and fall seasons, it is the passage of transient (synoptic) frontal systems that dictates precipitation variability. This is also reflected by the spatially varied timing of diurnal maximum precipitation in these seasons. However, as spring and summer set in, the timing of diurnal maximum precipitation becomes quite uniform, centering around 2000 UTC. This is, in fact, slightly offset from the timing of the diurnal maximum temperature, depicted as the black vectors in Fig. 16.4.

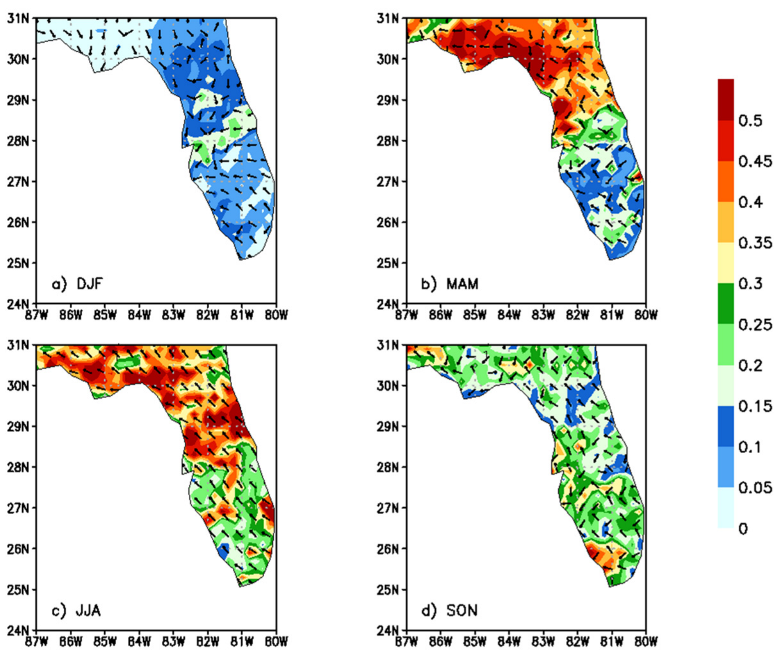


Figure 16.3. The seasonal average of diurnal amplitude (mm/day) and phase or timing (overlaid vectors) of precipitation (shaded) from NCEP STAGEIV (Len and Mitchell 2005). Vectors indicate the UTC time of maximum diurnal precipitation and are arranged as if on a 24-hour clock face (e.g., vectors pointing north represent 0000 UTC, east 0600 UTC, south 1200 UTC and west 1800 UTC).

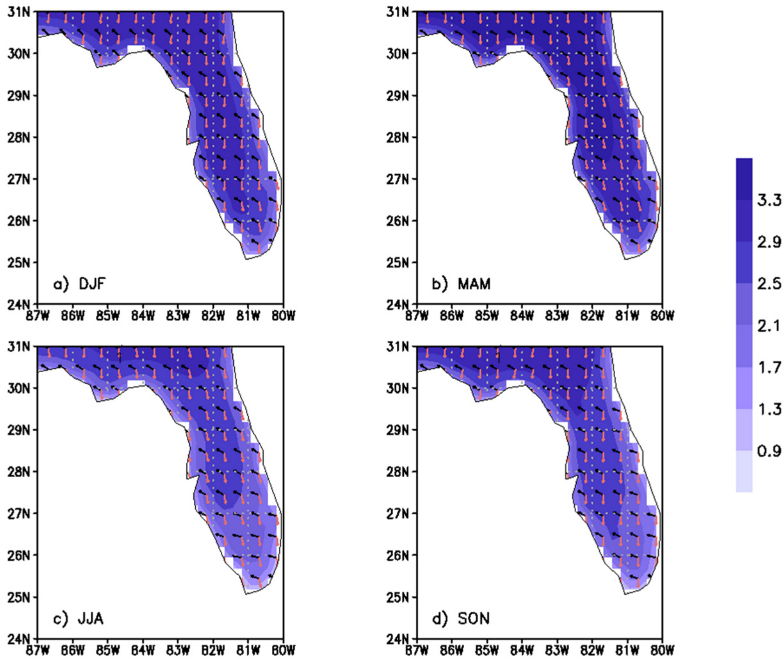


Figure 16.4. Same as Fig. 16.3 but for surface temperature from the North American Land Data Assimilation System-1 (NLDAS-1; Cosgrove et al. 2003). The seasonal average of diurnal amplitude (shaded) and the phase or timing (overlaid vectors) of T_{max} and T_{min} in black and pink vectors respectively.

Shown in Fig. 16.4 is the diurnal amplitude of surface temperatures with the timing of maximum temperature (black) and minimum temperature (pink) overlaid. In general, we find that the diurnal amplitude of daily temperatures is quite uniform in Florida — generally on the order of 2 °C in the interior of the state and 1 °C near the coastlines. The relatively smaller amplitude of diurnal variations of surface temperature in South Florida compared to the rest of the state during the summer season is a result of the cooling induced by precipitation from persistent sea breeze circulations (Case et al. 2005). Likewise, the larger diurnal amplitude of surface temperature near the coasts in the winter months relative to other seasons is a result of the absence of sea breeze circulations.

One of the most influential features of Florida's delicate ecosystem is related to the presence of daytime sea breezes and nocturnal land breezes that most commonly occur in the summer season. This relatively shallow atmospheric circulation is a direct consequence of the differential heating of air over land and ocean, which builds up a strong temperature contrast especially in the summer season. This differential heating between land and ocean is a result of the differential in the heat capacity (the amount of heat energy required to raise the temperature by a °C per unit mass) of land, which is typically far less than that of ocean. This causes a horizontal pressure gradient leading to the so-called sea breeze circulation. Cloud and thunderstorm development usually occurs in the ascending part of the circulation and typically matures in the afternoon after the downwelling shortwave flux results in maximum heating of land. At nighttime, this circulation is reversed, establishing the land breeze, again owing to the differential rate of cooling between land and ocean that leads to a thermal contrast opposite to that of sea breeze. Numerous sub-regional features, such as local land use (Pielke et al. 1999), coastal orientation (Baker et al. 2001), and even changes in the local maritime environment (Van der Molen et al. 2006) dictate the inland propagation of the sea breeze.

There is usually a convergence of a double sea breeze front over peninsular Florida, one translating westward from the Atlantic Coast and the other moving eastward from the Gulf Coast (Byers and Rodebush 1948; Blanchard and Lopez 1985; Gibson and Vonder Haar 1990). The sea breeze circulation, being relatively shallow in depth, is sensitive to the prevailing wind speed and direction (Nicholls et al. 1991). For example, Misra et al. (2011) showed that the sea breeze over the Florida Panhandle is associated with the variability of the Bermuda High pressure system. They showed that by way of the Sverdrup vorticity balance, the large-scale meridional flow of the high pressure system along the Florida Panhandle will cause modulation of the large-scale divergence in the region, which then modulates the strength of the late afternoon sea breeze. In seasons when the Bermuda High is stronger, it promotes stronger upper level divergence over the Florida Panhandle coast (Fig. 16.5a), which makes the sea breeze along this coast stronger than usual. Similarly, in summer seasons when the Bermuda High is weaker and retracted further east, the large-scale conditions become less favorable for sea breeze along the Florida Panhandle (Fig. 16.5b).

ENSO Variability

El Niño-Southern Oscillation (ENSO) variations in the equatorial Pacific have a global impact on seasonal anomalies and extreme weather through atmospheric teleconnections. This remote teleconnectivity of ENSO variations is a result of atmospheric (stationary Rossby) waves emanating from the anomalous release of diabatic heating with associated changes in large-scale atmospheric circulation and upper ocean heat content redistribution in the equatorial Pacific. One such teleconnection that affects the winter and early spring climate of the Southeastern US (SEUS), including Florida, is the shift in the subtropical jet stream related to upper air geopotential height in response to the shift in the atmospheric convection from the western to central equatorial Pacific (Fig. 16.6). This 200 hPa height pattern (Fig. 16.6) consists of alternating high and low pressure centers along a great circle route featuring stronger (weaker) Aleutian low, high (low) pressure over Canada, and low (high) pressure over the SEUS. Typically, this results in cold and wet (warm and dry) winters in warm (cold) eastern equatorial Pacific (ENSO) years over the SEUS (Ropelewski and Halpert 1986, 1987). The episodic weather events during these anomalous winters can be inferred from such upper air circulation patterns (Fig. 16.6). For example, the warm ENSO associated with wet and cold winters in the

SEUS are related to increased frequency of frontal and cyclone activity steered along the southern part of the US by the zonally-oriented and equatorward displaced subtropical jet stream (Eichler and Higgins 2006). In contrast, during La Niña winters the subtropical jet stream is more meridionally-oriented and shifted poleward, bringing a wetter winter to Canada (Smith et al. 1998).

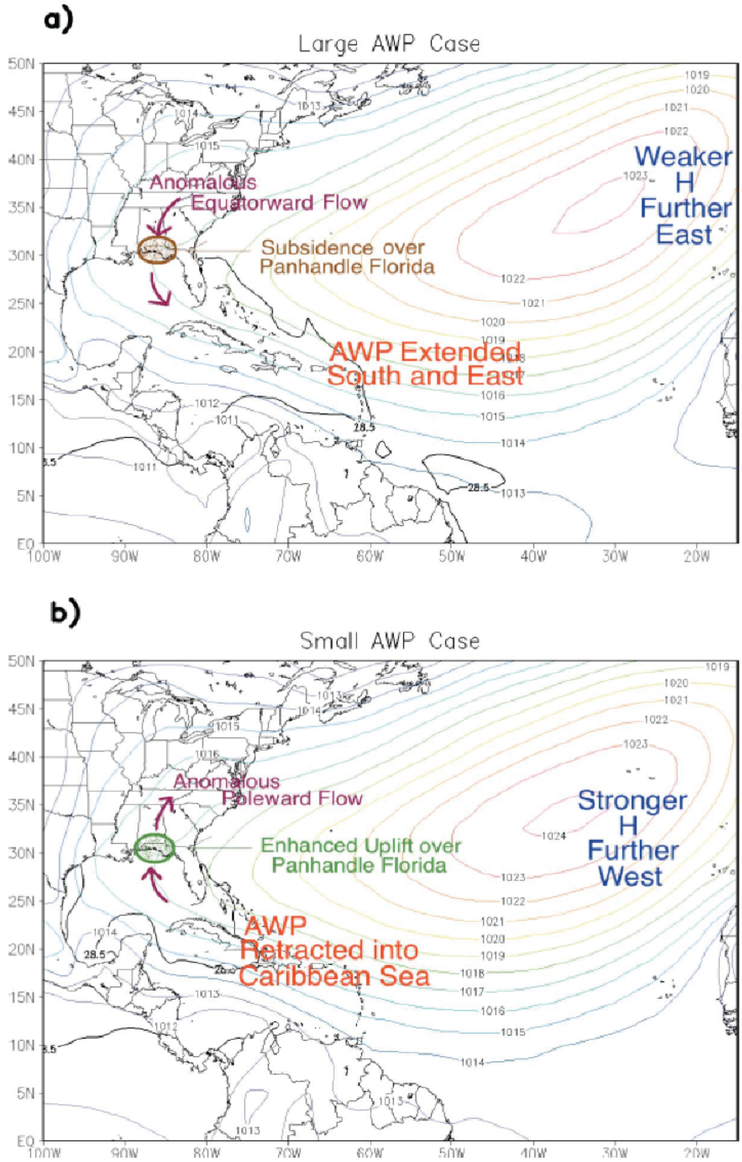


Figure 16.5. Schematic of the anomalous conditions over the Florida Panhandle generated by the modulation of the North Atlantic Subtropical High (NASH) in the a) large and b) small Atlantic Warm Pool (AWP) years. The composite mean sea level pressure (hPa) from NCEP-R2 reanalysis (Kanamitsu et al. 2002) is contoured for the five a) large and the b) small AWP years. From Misra et al. (2011).

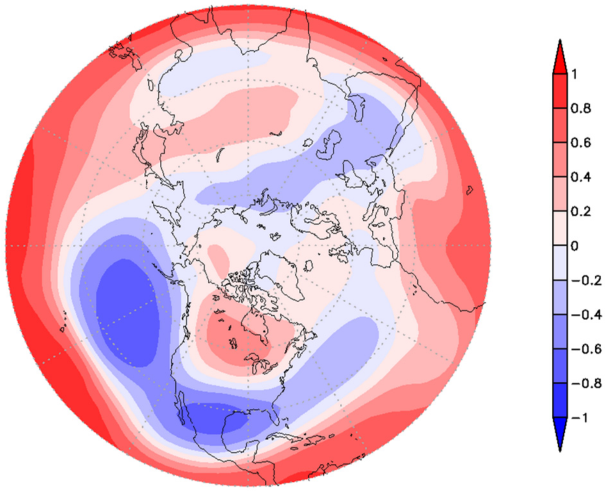


Figure 16.6. The contemporaneous correlation of the mean December-January-February Niño3.4 SST index with corresponding seasonal mean 500 hPa geopotential heights from NCEP-DOE reanalysis (Kanamitsu et al. 2002).

The winter weather in the SEUS, especially the surface temperatures, are also strongly influenced by other variations such as the Arctic Oscillation (AO; Thompson and Wallace 1998), the North Atlantic Oscillation (NAO; Stephenson et al. 2003) and the Pacific North American pattern (Higgins et al. 2002; Hagemeyer 2006). These variations can occasionally mask the ENSO influence. For example, the winter of 2009-2010 was an El Niño event in the equatorial Pacific that set record low temperatures across Florida. This was a result of both the canonical El Niño forcing from the Pacific and a very strong negative NAO. However, the winter of 2010-2011, despite being a La Niña event in the equatorial Pacific, continued to be dominated by the negative NAO influence resulting in very cold surface temperatures in the SEUS, contrary to the ENSO forcing. These extremely cold temperature episodes during the winter in Florida are devastating to the local agriculture, especially citrus (Miller 1991; Attaway 1997). In a related study, Stefanova et al. (2013) showed that both ENSO and the AO have a significant influence on the skewness and kurtosis of the surface temperature in the SEUS. The authors indicated that negative skewness of the surface temperature over Florida is exacerbated in La Niña or positive AO winters. But the converse of the El Niño or the negative AO forcing on the reduction of negative skewness of surface temperature is found to be less impactful.

However, it is important to recognize that the influence of ENSO variations are not restricted to the boreal winter and spring seasons. They are also found to influence the seasonal Atlantic tropical cyclone activity during the boreal summer and fall seasons (Gray 1984; Shapiro 1987). It is widely recognized that tropical cyclogenesis and development occur when these necessary conditions are satisfied: a) warm ocean waters (≥ 26 °C), b) an atmosphere that is potentially unstable for convection to occur, c) relatively moist lower troposphere, d) a minimum distance of about 500 km away from the equator for Coriolis force to be effective, and e) relatively low values of vertical shear between 850 and 200 hPa. That said, these conditions alone are not sufficient to lead to tropical cyclogenesis, as many disturbances that occur in such favorable conditions do not develop into tropical cyclones (Velasco and Fritsch 1987; Emanuel 1993). The Atlantic Basin feels the impact of ENSO remotely through changes to its vertical shear in the so-called main development region (MDR) of Atlantic tropical cyclones (10 °N to 20 °N and from northwest Africa to Central America; Gray 1984; Shapiro 1987; Goldenberg and Shapiro 1996). During El Niño (La Niña) years, the vertical shear increases (decreases) in the MDR owing primarily to an increase (decrease) in the upper level westerlies (Landsea 2000). In a related observational study, Bove et al. (1998) indicated the probability of two or more landfalling hurricanes in the US to be 28%, 48%, and 66% during El Niño, neutral, and La Niña years, respectively (Fig. 16.7a).

Atlantic tropical cyclones are critical to the hydroclimate of Florida (Knight and Davis 2009; Maxwell et al. 2012, 2013; Prat and Nelson 2013 a, b). Knight and Davis (2009) ascertained from observations that peninsular Florida, especially south peninsular Florida, has the highest density of landfalling tropical cyclones in the continental US besides the Carolina coasts. Using the Tropical Rainfall Measuring Mission (TRMM) 3B42 rainfall analysis product, Prat and Nelson (2013a, b) found that tropical cyclones contributed 10-15% of the annual rainfall in Florida. More importantly, they found there is an increase in the probability of landfalling hurricanes (especially category 1 and 2) in Florida during neutral and cold ENSO years relative to warm ENSO years (Fig. 16.7b).

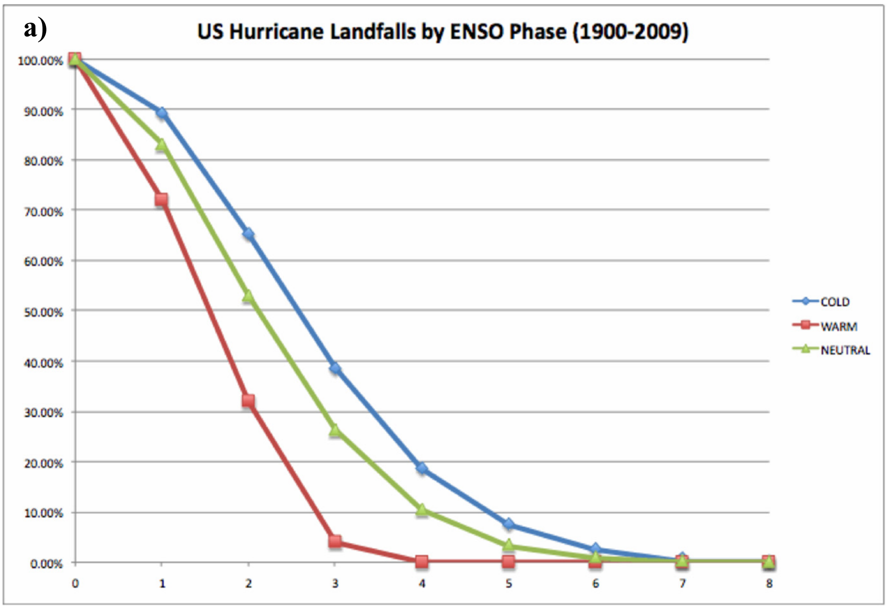
There is, however, a temporal variability of the ENSO teleconnection as a result of other low frequency variations such as the Pacific Decadal Oscillation (PDO; Manatua et al. 1997), the Atlantic Multi-decadal Oscillation (AMO; Kerr 2000), and the non-stationarity of ENSO itself (Trenberth and Shea 1987; Allan et al. 1996). Since the strength of these atmospheric teleconnections are linearly dependent on the equatorial Pacific SST anomalies (Kumar and Hoerling 1998), it is reasonable to expect these teleconnections to be modulated by variations in the amplitude of ENSO SST anomalies (Diaz et al. 2001). Using observations, several studies have shown that the positive (negative) phase of AMO weakens (enhances) the ENSO teleconnection with the SEUS rainfall (Enfield et al. 2001; Mo 2010; Misra et al. 2012; Nag et al. 2015). Similarly, Diaz et al. (2001) indicated ENSO teleconnections with North America have intensified post-1976. Several things might explain such a change. The first is that the character of ENSO variations changed in the mid-1970s due to the stochasticity of the coupled ocean-atmosphere system of the equatorial Pacific; ENSO began occurring later in spring and extending far less to the west from the eastern equatorial Pacific in comparison to earlier decades (Diaz et al. 2001). Second, the PDO SST variations in the North Pacific could be influencing the ENSO teleconnection, with cold (warm) SST anomalies in the North Pacific enhancing (weakening) the teleconnection (Gershunov and Barnett 1998). Third, the multi-decadal variation of the equatorial Pacific SST could also result in such modulation of the teleconnection (Diaz et al. 2001).

In a related study, Mo (2010) found contrasting ENSO teleconnections for the early period of 1915-1960 and the more recent period of 1962-2006. The study further finds that in recent decades the ENSO teleconnection in the SEUS has become weaker and attributed this to two different kinds of ENSO identified by their characteristic evolution and manifestation of SST anomalies (Ashok et al. 2007; Yu and Kao 2007). These two types of ENSO are: the central Pacific ENSO and the eastern Pacific ENSO. The central (eastern) Pacific ENSO has a maximum SST anomaly in the central (eastern) Pacific, which Mo (2010) determined to have different teleconnection patterns with surface meteorology over North America. The frequency of central Pacific ENSOs has increased in recent decades, which produces a wave train that is consistent with the west-east contrast in surface temperature, as opposed to the wave train created by eastern Pacific ENSOs in past decades that produced north-south contrast over North America (Mo 2010).

Atlantic Warm Pool Variability

The Atlantic Warm Pool (AWP) is a seasonal feature that is defined by the appearance of SSTs warmer than or equal to 28.5 °C in the Gulf of Mexico, Caribbean Sea, and the parts of the subtropical northwestern Atlantic Ocean (Wang and Enfield 2001). The AWP constitutes the dominant part of the Western Hemisphere Warm Pool (WHWP), which is preceded by a similar appearance of warm SSTs ≥ 28.5°C in the northeast tropical Pacific Ocean. However, Misra et al. (2016) found that the AWP variations are unrelated to variations of the warm pool in the tropical northeast Pacific. The AWP has a seasonal peak in terms of its areal coverage in the August-September-October season that coincides with the seasonal peak of the Atlantic tropical cyclone activity (Wang et al. 2007). Surface heat budget studies of AWP have indicated that the radiative fluxes dominate in the Gulf of Mexico, while in the Caribbean Sea upwelling and advective cooling also play a significant role in regulating SSTs (Lee et al. 2007; Misra et al. 2013).

The seasonal peak of the AWP-induced heating forces a Gill-type atmospheric response (to off-equator diabatic heating) in the form of extratropical stationary waves (Lee et al. 2007). These waves produce rainfall variability over the continental US (Fig. 16.8a), while modulating the subtropical highs in the North Atlantic Ocean (Fig. 16.8b) and in the southeastern Pacific (cf Fig. 8 in Wang et al. 2010). In other words, Fig. 16.8a suggests that in large (small) AWP years the June-October seasonal rainfall over the Mississippi and Ohio valleys is reduced (increased) accompanied by a reduced (increased) strength in the NASH (Fig. 16.8b). Furthermore, AWP variations and their teleconnections to North American hydroclimate are also observed to be largely independent of the ENSO variations in the equatorial Pacific (Wang et al. 2006, 2008; Misra et al. 2013).



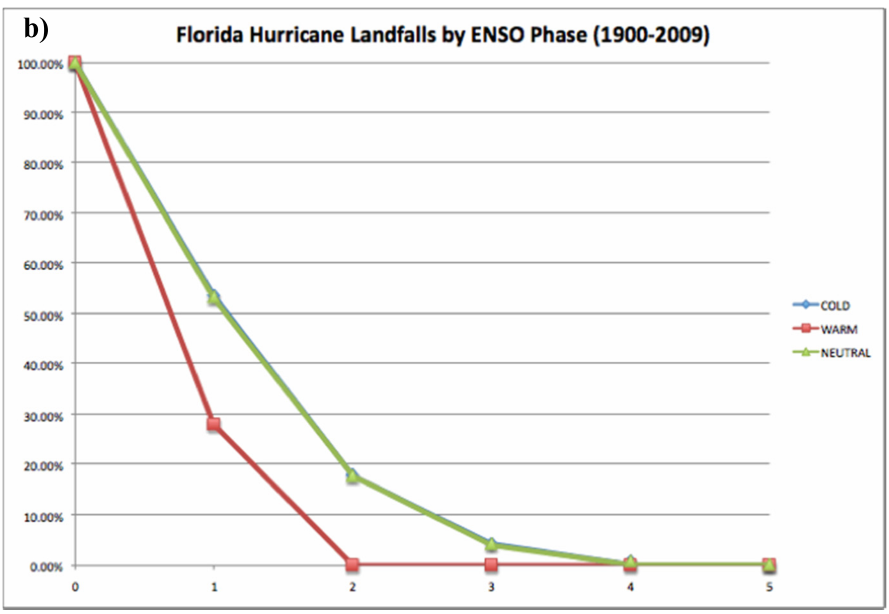


Fig. 16.7. Inverse cumulative frequency distribution of a) US and b) Florida landfalling hurricanes for the period 1900-2009 using HURDAT (http://www.aoml.noaa.gov/hrd/hurdat/Data_Storm.html).

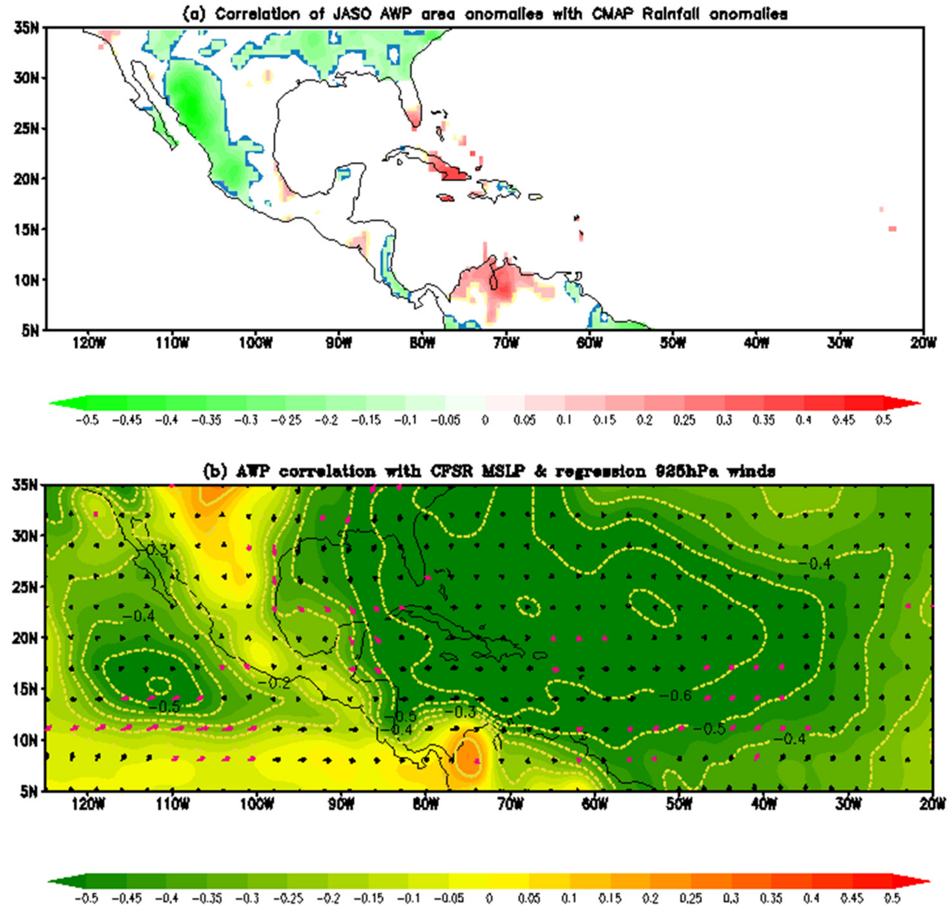


Figure 16.8. Correlation of the June-October AWP area anomalies (SST from Reynolds et al. 2007) with corresponding a) rainfall anomalies (shaded; rainfall from Chen et al. 2002) and b) mean sea level pressure (MSLP) anomalies (shaded; MSLP from Saha et al. 2010) and regression of June-September AWP area anomalies on corresponding 925 hPa wind anomalies (winds from Saha et al. 2010). The significant values at 95% confidence interval according to t-test are contoured and vectors are shown in red.

Misra and DiNapoli (2013) observed that Florida has a distinct seasonal cycle of rainfall that gives rise to a monsoonal type of climate, and they objectively defined the onset and demise of the Florida wet season for a particular grid point over peninsular Florida as the day after the cumulative rainfall anomaly ($C'_m(i)$) reaches a minimum and maximum for the year, respectively. The cumulative rainfall anomaly is given by:

$$C'_m(i) = \sum_{n=1}^{i}\left[D_m(n) - \bar{\bar{C}}\right], \quad (1)$$

where

$$\bar{\bar{C}} = \frac{1}{MN}\sum_{m=1}^{M}\sum_{n=1}^{N} D(m,n). \quad (2)$$

$D_m(n)$ is the daily rainfall for day n of year m, and $\overline{\overline{C}}$ is the climatology of the annual mean rainfall over N (=365/366) days for M years. This definition breaks down when the unique rainy season begins to disappear moving north of Jacksonville (Misra and DiNapoli 2013). Misra and DiNapoli (2013) showed that the onset and demise of the wet season are profoundly modulated by ENSO and AWP variations. They demonstrated that warm (cold) ENSO events in the winter are followed by early (later) onset of the rainy season in peninsular Florida. Similarly, Misra and DiNapoli (2013) indicate that large (small) AWP events associated with weakening (strengthening) of the NASH, leads to later (early) demise of the wet season thereby resulting in longer (shorter) length of the wet season in parts of peninsular Florida. This teleconnection is consistent with the positive correlation of June-October seasonal rainfall with AWP area variations observed over South Florida in Fig. 16.8a.

The Atlantic Multi-decadal Oscillation (AMO)

A roughly 60- to 80-year periodicity is observed in SSTs in and around the Atlantic Ocean basin after removal of the warming signature of the last 150 years and this is known as the AMO (Figure 16.9). The AMO is characterized by alternating multi-decade phases of persistently above and below average SSTs in the Atlantic between 0 and 70 °N. The range in SSTs between the warm (+) and cool (-) phases is ~0.4 °C (Delworth and Mann 2000; Enfield et al. 2001; Kerr 2000; Schlesinger and Ramankutty 1994). Historically, warm phases have been documented from 1860-1900 and 1925-1965, and cool phases from 1905-1925 and 1965-1995. Analysis of North Atlantic climate time series from tree rings further suggest that an "organizational phase" exists between warm and cool phase shifts during which SST variability is dampened on multi-annual to decadal time scales (Gray et al. 2004). Persistence of multi-decadal variability consistent with the AMO in paleo proxy records prior to the anthropogenic period suggests that the oscillation is natural in origin (Gray et al. 2004; Saenger et al. 2009; Waite 2011).

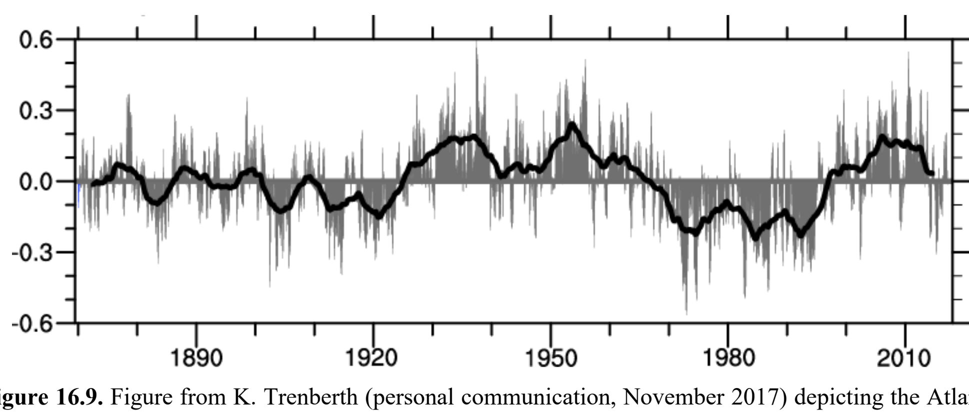


Figure 16.9. Figure from K. Trenberth (personal communication, November 2017) depicting the Atlantic Multi-decadal Oscillation (AMO) Index from HadISST data over the period from 1871 to 2016, updated from Trenberth and Shea (2006). The AMO Index is derived by subtracting the global-mean SSTA time series from the North Atlantic average time series (Trenberth and Shea 2006).

While the impact of the AMO on SSTs is implicit in the nature of the oscillation itself, the AMO has also been shown to affect many aspects of the climate system throughout the Atlantic sector. Of particular relevance to Florida are linkages between the AMO and changes in air temperature, precipitation, and storm occurrences that have significant implications for hazard mitigation, resource management, and sustainability across the state.

Multi-decadal changes in air temperatures have also been associated with variability in evaporation and precipitation budgets of the continents bordering the Atlantic. During warm phases of the AMO, the majority of the United States receives below average rainfall; this is particularly true in the midwest and southwest where droughts tend to be more frequent and severe. One notable example is the 1930s Dust Bowl event, which occurred during a warm phase of the AMO. On the other hand, cool phases of the AMO tend to result in these same areas experiencing above average rainfall. While North Florida conforms to this relationship, Central and South Florida are marked exceptions to this rule as they receive above average rainfall during AMO (+) phases and below average rainfall, resulting in increased drought and wildfires, during AMO (-) phases. Evidence of this relationship can be observed in Lake Okeechobee where inflow can vary up to 40% between phases, resulting in significant implications for water management practices (Enfield et al. 2001; Kelly and Gore 2008). As previously stated, inter-annual winter rainfall associated with ENSO variations is also impacted by the AMO phase. Studies have shown that water transparency in Florida lakes, which has been linked to precipitation and the resulting runoff of dissolved organic material, is also sensitive to the AMO. Gaiser et al. (2009) found that observations and hindcasts of lake transparency demonstrate multi-decadal trends, with transparency being greatest in AMO cool phases associated with below average rainfall, and vice versa. Given the increasing frequency and severity of algae bloom events in Florida waterways and coastal communities, these multi-decadal drivers should be considered in future mitigation measures.

Compilations of AMO indices, proxy reconstructions, and observations indicate that the number of landfalls of major hurricanes in the Gulf of Mexico and along the eastern seaboard of the US is significantly higher during warm, or positive, phases of the AMO than during cool phases (Figure 16.10). These phenomena are most likely connected through the AMO's impact on SST and vertical wind shear ($|Vz|$) in the MDR of the Atlantic Ocean. Studies suggest that circulation anomalies in the Atlantic Ocean's MDR reduce $|Vz|$ during warm phases of the AMO, allowing storms to grow and intensify, while increased shear in this region during cool AMO phases inhibits growth and organization (Bell and Chelliah 2006; Nyberg et al. 2007).

Research also suggests that the AMO is linked to Atlantic tropical cyclone activity through the AWP. Multi-decadal trends are evident in the warm pool region, where AMO warm (cool) phases are associated with repeated large (small) AWPs (Wang et al. 2008). The AWP region is comprised of the Gulf of Mexico, the Caribbean Sea, and the western tropical North Atlantic, and lies in the path of the development region for Atlantic hurricanes. Thus, it may also play a role in connecting them to the AMO. The growth of anomalously large AWPs in association with warm phases of the AMO would reduce $|Vz|$ in the region of cyclogenesis and increase the moist static instability of the troposphere, favoring the formation of hurricanes (Wang et al. 2008). Recently, there has been a relative increase in storm intensity and landfall. Goldenberg et al. (2001) provided a well-supported synthesis of the mechanisms argued to be contributing to this increase, proposing a feedback mechanism whereby faster thermohaline circulation (THC) results in warmer North Atlantic SSTs and cooler South Atlantic SSTs that enhances Sahel rainfall and decreases $|V_Z|$ in the MDR. However, it is important to note that anthropogenically-induced warming may also amplify these feedbacks with hurricane development in the Atlantic sector. Currently, it is difficult to discern the relative contributions of this versus phase changes of the AMO.

Despite being one of the dominant climatic controls for the Atlantic sector, the precise forcing and stability of the AMO remains poorly understood. Coupled ocean-atmosphere models and paleo reconstructions suggest that the multi-decadal mode is linked to variability in the exchange of water and heat associated with the Atlantic Meridional Overturning Circulation (AMOC). This driver also offers the best mechanism to explain connections between the AMO and other climatic oscillations on decadal to multi-decadal timescales, as well as associations beyond the Atlantic. However, recent modeling investigations by Clement et al. (2015) suggest that the AMO may be a response to stochastic forcing by mid-latitude atmospheric circulation and thermal coupling in the tropics, where changes in ocean circulation (e.g. AMOC) may be dominantly responding to, rather than forcing, the AMO. Furthermore, both models and observations suggest that changes in heat flux to the surface, as produced by low-level clouds and atmospheric dust, contribute to the tropical manifestation of the AMO (Brown et al. 2016; Yuan et al. 2016).

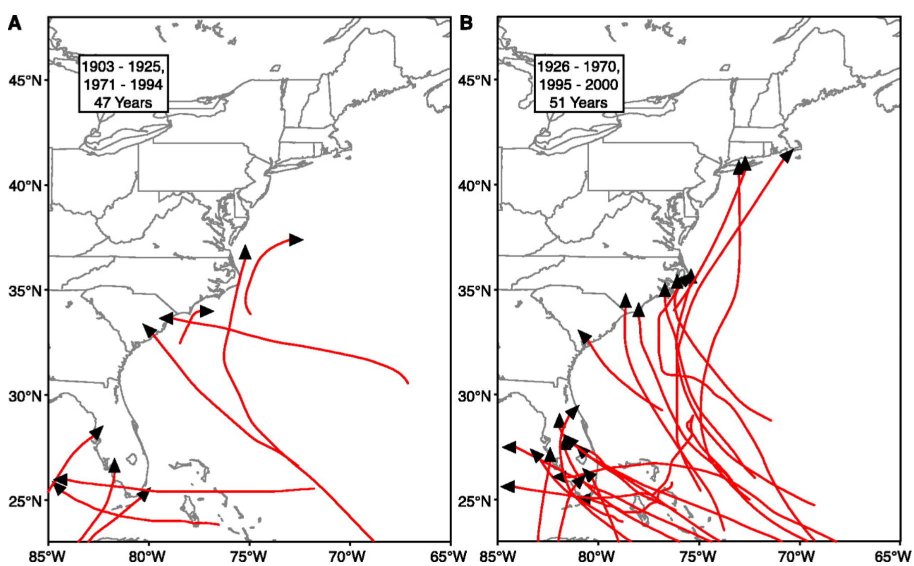


Figure 16.10. Panels from Goldenberg et al. (2001) contrasting US East Coast major hurricane landfalls between (A) cool and (B) warm phases of the AMO. Reprinted with permission from AAAS.

Unfortunately, understanding the mechanisms associated with the AMO is limited in large part by the relatively short duration of the instrumental period, which only covers the last 110 to 150 years. In response, considerable effort is being put into generating long-term paleo proxy reconstructions of multi-decadal change. And the impacts of anthropogenic warming on the long-term stability of the AMO also remain unclear. Modeling simulates long-lived, low frequency persistent variability through time; however, several proxy reconstructions indicate instabilities in the oscillation that, when coupled with anthropogenic uncertainties, hinder predictability. For the time being, the multi-decadal variability in temperature associated with the AMO acts to alternately obscure (during cool phases) and enhance (during warm phases) anthropogenic warming in the North Atlantic region.

Land-Atmosphere Interactions

Land-atmosphere interactions manifest over many different time scales, some of which have already been discussed in relation to diurnal variations. The SEUS is one of the few regions on earth that shows a cooling trend during the 20th century (Trenberth et al. 2007; Ji et al., 2014), often termed the “warming hole.” The cooling trend in the SEUS has been attributed to several factors including changes in SST (Robinson et al. 2002), land-atmosphere feedback (Pan et al. 2004), and internal dynamics or chaos (Kunkel et al. 2006). This cooling trend is found to be strongest in the late spring–early summer period, which is coincident with the seasonal increase in rainfall (Portmann et al. 2009). In other words, rainfall tempers the surface warming during the season thus conforming to the well-known near linear relationship of trends in temperature and diurnal temperature ranges to precipitation amounts (Trenberth and Shea 2005; Zhou et al. 2004; Dai et al. 1999; Madden and Williams 1978). However, Portmann et al. (2009) suggested the additional influences, including increasing strength in the direct and indirect impact of rising concentration of aerosols and rapid changes in vegetation could also be causing the region’s temperatures to cool. But Ji et al. (2014) showed that the spatial extent and magnitude of the “warming hole” in the SEUS has diminished gradually over recent decades.

Land use/land cover changes can also affect climate through variations in the partitioning of the available energy between sensible and latent heat and the breakup of precipitation between runoff, canopy storage, and evapotranspiration, which can alter the consequent atmospheric feedback (Zhao et al. 2001; Feddema et al. 2005; Kalnay and Cai 2003). Irrigation, a form of land use, raises evaporation during the day and changes the Bowen ratio by way of wetting the soil, which leads to apparent cooling of the surface temperature (Kueppers et al. 2007; Sacks et al. 2009; Misra et al. 2012). On the other hand, irrigation can lead to surface warming of the nighttime minimum temperature (T_{min}) under weak wind conditions (typically at night, when the boundary layer is decoupled from the rest of the atmosphere), as wet soil has a raised heat capacity and conductivity compared to dry soil (Elsner et al. 1996). The urban heat island effect can also have a significant impact on warming trends (Oke 1973; Karl et al. 1988a; Karl and Jones 1989; Misra et al. 2012). The heat capacity and conductivity of building and paving materials allow for more heat to be absorbed during the day in urban areas than in rural areas. The heat then becomes available at night to partially compensate for the radiational cooling from the outgoing long-wave radiation loss. Another cause of increased urban heating is from the trapping of the reflected solar radiation by the narrow arrangement of buildings (often referred as the reduced sky view factor), which is ultimately absorbed by the walls of the buildings in the urban areas. Additional factors such as increased atmospheric pollutants, production of waste heat from air-conditioning, refrigeration systems and industrial processes, and obstruction of rural air flows by the windward face of built-up surfaces can also contribute to the urban heat island effect. As a result of these factors, a higher T_{min} is usually observed in the urban areas relative to the rural areas (Karl et al. 1988b).

Misra et al. (2012) found considerable spatial heterogeneity in the observed linear trends of monthly mean maximum (T_{max}) and minimum temperatures (T_{min}) from station observations in the SEUS (specifically Florida, Alabama, Georgia, South Carolina, and North Carolina). In a majority of these station sites, the warming trends in T_{min} were found to be stronger in urban areas relative to rural areas (Fig. 16.11). This was determined by examining the scatter of the T_{min} with the Population Interaction Zone for Agriculture (PIZA; USDA-ERS 2005), which is an index that represents the residential, commercial, and industrial urban activities affecting agriculture. The PIZA values range from 1 to 4, with lower (higher) values being representative of rural (urban) areas.

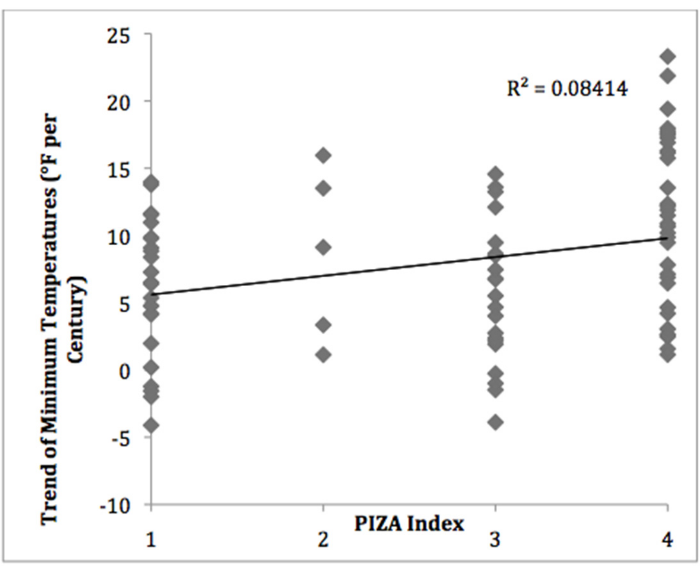
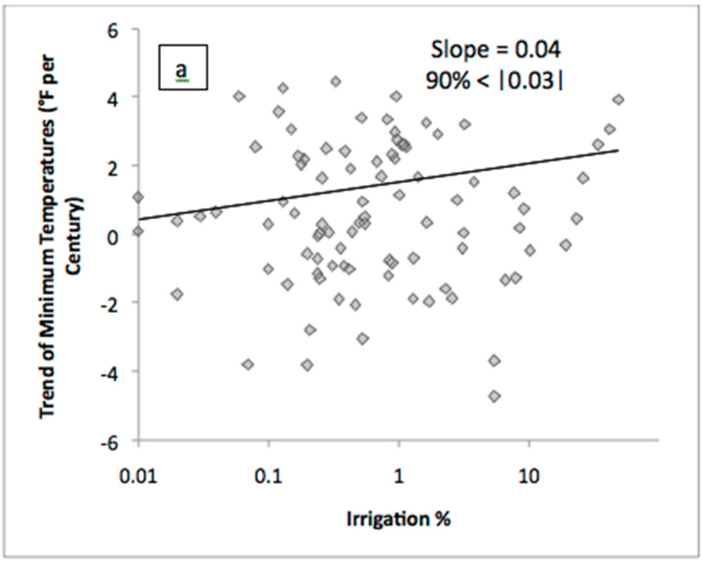


Figure 16.11. The scatter plot of the linear trends (in ^{0}F/century) over the southeast US (which includes Florida, Alabama, Georgia, South Carolina, and North Carolina) of T_{min}. Adapted from Misra et al. (2012).

The linear trends of T_{min} in urban areas of the SEUS is approximately 7 °F/century compared to about 5.5 °F/century in rural areas. It should be noted that trends in T_{max} had an insignificant relationship with PIZA (Misra et al. 2012). However, it was shown that during the summer season, T_{max} has weaker warming (or stronger cooling) trends with irrigation, while trends in the summer season T_{min} show stronger warming trends (Fig. 16.12). The corresponding figures for other seasons show an insignificant relationship (Misra et al. 2012). The relationships implied in Fig. 16.12 are consistent with theory, which suggests that by way of evaporation, irrigation cools T_{max} that is measured during the day. On the other hand, theory also suggests that irrigation would raise the heat capacity and conductivity of the otherwise dry soil, which under weak wind conditions (anticipated at night) would lead to warming of the T_{min}. Furthermore, Misra et al. (2012) revealed that linear trends in T_{max} in the boreal summer season show a cooling trend of about 0.5 °F/century with irrigation, while the same observing stations on an average display warming trends in T_{min} of about 3.5 °F/century. The seasonality and the physical consistency of these relationships with urbanity and irrigation would suggest their non-negligible influence on the spatial heterogeneity of the surface temperature trends over the southeastern United States.

Secular Changes

As noted in the previous section, the so-called warming hole of the SEUS has diminished over recent decades, suggesting an overall warming of the surface temperature (Ji et al. 2014). On the other hand, an insignificant linear trend can be observed in the monthly mean precipitation of SEUS in the 20th century (Portmann et al. 2008; NOAA 2012). However, there is a growing body of evidence to suggest that the frequency of extreme precipitation events in the SEUS has increased in recent decades (Kunkel et al. 2013; Wuebbles et al. 2014). While the reason for the observed rising trend in extreme precipitation events is not known for certain, the increasing atmospheric water vapor content in a warming climate is considered to be the most probable cause (Karl and Trenberth 2003; Kunkel et al. 2013). In a related study, Knight and Davis (2009) indicated that extreme precipitation from tropical cyclones has been increasing by approximately 5-10% per decade in the SEUS. They attributed this increase to storm wetness (precipitation per storm) and storm frequency over their period of analysis (1972-2007). However, analysis of longer time periods of tropical cyclone data has revealed conflicting conclusions, with some suggesting increases in Atlantic tropical cyclone frequency over time (Holland and Webster 2007; Mann and Emanuel 2007) while others suggest the opposite (Vecchi and Knutson 2008; Chang and Guo 2007). The former studies, using the strong statistical relationship of tropical Atlantic SST variations to changes in Atlantic tropical cyclone frequency, arrived at the conclusions of rising tropical cyclone frequency from the observation of similar rising trend in Atlantic SSTs attributed to anthropogenic forcing (Holland and Webster 2007; Mann and Emanuel 2007). But when accounting for lower reporting of short-lived tropical cyclones in the pre-satellite era (prior to 1966) leads to a long-term trend of Atlantic tropical cyclones that is statistically insignificant (Vecchi and Knutson 2008; Landsea et al. 2009). Although there may be no significant trend in the Atlantic TC frequency, sea level rise has exacerbated the damage from flooding of modern storms relative to historical storms of comparable strength (Zhang et al. 1997, 1999).



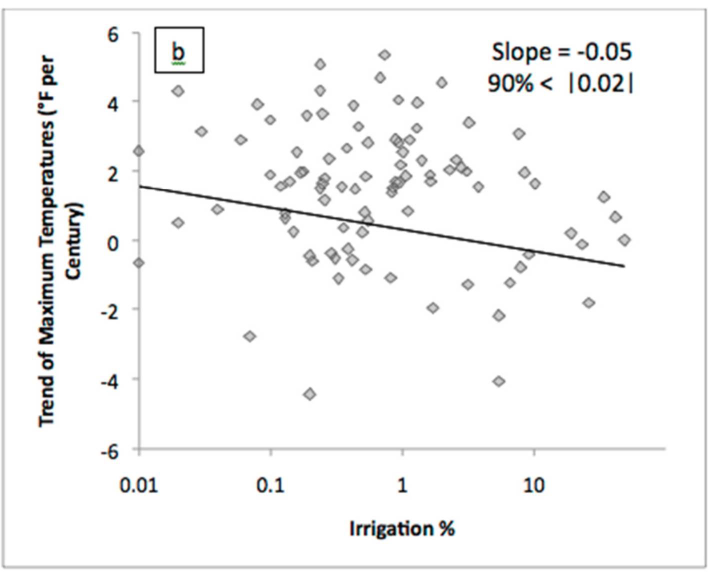


Figure 16.12. The scatter plot of the linear trends (^{0}F/century) in JJA over the southeast US (which includes Florida, Alabama, Georgia, South Carolina, and North Carolina) of a) T_{min} and b) T_{max} with the irrigation data. The slope and its 90% confidence level obtained from a Monte Carlo approach are shown on the top right corner. From Misra et al. (2012).

Conclusion

With its mild climate and its 1,350 miles of picturesque coastline, Florida is one of the most desirable places for populations to live and migrate to. However, Florida's geographic position also leaves it exposed to significant climate variability, including periodic weather extremes. Florida is a unique region east of the Rocky Mountains with a very distinct monsoonal type wet season in the summer that distinguishes it from the other seasons. Similarly, given its proximity to tropical latitudes, Florida also has significant diurnal variations of rainfall especially in late spring and summer season. Finally, Florida has a high density of landfalling Atlantic tropical cyclones in the Continental US that contributes significantly to the hydroclimate of the region.

This chapter establishes that Florida's climate is as much affected by remote climate variations as local variability over land and its neighboring oceans. There is a discernible impact of local land cover and land use change on surface temperature and irrigation across the SEUS, including Florida, with urban areas showing a warming trend comparatively stronger than that in the rural areas. Similarly, SEUS regions with sustained irrigation over time have been shown to have a cooling (warming) trend in the maximum (minimum) temperatures. Likewise, variations of the SST in the neighboring oceans (e.g. variations in the size of the Atlantic Warm Pool [AWP] residing over Gulf of Mexico, Caribbean Sea and parts of northwestern subtropical Atlantic Ocean) affect the local climate, from sea breezes in the Florida Panhandle to variations in the Atlantic tropical cyclone activity.

This chapter's discussion also highlights the scale interactions of the observed climate across time and spatial scales. For example, the Florida Panhandle sea breeze is shown to be affected by the subtle variations of the Bermuda High. Similarly, ENSO forcing on Florida's winter climate is affected by decadal variations such as the PDO and the AMO. The manifestation of decadal-scale variations such as the PDO and AMO at the local scale (e.g., influence on Lake Okeechobee inflow, AWP variations) raises hope for regional decadal predictability for Florida. This attempt at decadal predictability could go a long way toward mitigating the vulnerability of the state to climate anomalies.

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