Climate and Weather Extremes

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This chapter examines Florida's extreme weather hazards: 1) why they happen, 2) their relation to interannual to multidecadal climate variability, and 3) the potential of each hazard and spatial variability across the state. The weather hazards indicated are under these broad categories: precipitation (rainfall, flooding, droughts), thunderstorms (lightning, hail, convective wind, tornadoes), tropical weather (tropical storms and hurricanes), and temperatures (extreme highs and lows). The conclusions section mainly addresses the challenge of attributing extreme events to human-induced climate change.

Key Messages

- The state of Florida is prone to various types of weather extremes, with tropical cyclones being the most dangerous in terms of impact potential.
- Most types of extreme events exhibit a seasonal cycle making it more likely for them to occur at certain times of the year. Many of them are also sensitive to large-scale climate variation resulting in strong interannual to multidecadal variability. The most important climate indicator for extreme weather in Florida is the El Niño Southern Oscillation (ENSO).
- Strong spatial variability of extreme events and related hazards exists across the state, with certain areas more susceptible to particular weather hazards than others. Maps of observed frequencies of the different types of events in the past can help identify hot spots.
- Attribution of climatic extremes is challenging because of insufficient observational records (with strong variability) and limitations in models with regards to resolution and complexity of the processes involved in the genesis of extreme events. This is also the reason for large uncertainties in future projections of most types of extreme events.
- There is, however, agreement that changes in the mean, which are better represented in climate models, will also affect the extremes (e.g., increasing mean sea level will affect storm surge heights and frequency).

Keywords

Weather extremes; Seasonality; Climate variability; Frequencies; Attribution

Introduction

I lorida has a relatively dry cool season from October into May, a summer rainy season that lasts from June through September, and the overlapping hurricane season from June through November, which has varying impacts on the state from year to year. A narrower focus reveals that Florida has a distinct summer rainy thunderstorm season while the Florida Panhandle also has a distinct winter rainy season. The moisture-laden frontal systems bring

winter rain to the panhandle but the rain typically dwindles as cold fronts move southward across the peninsula.

Florida has been divided into seven climate division zones (Fig. 20.1; NCDC 2016) from the Panhandle and North Florida (climatic zones 1 and 2) to the Florida Keys (zone 7) on the south end. Most of the state is subtropical with only the southern tip (the southern part of zones 5 and 6 and zone 7) in the tropical environment yearround. Obviously the northern part of the state (zones 1-2) is cooler during the winter and, because this area is adjacent to the continental U.S., the warming influence of the ocean on land surface temperatures is comparatively



Figure 20.1. Florida Climate Division Zones.

less than over the peninsula. The central portion of the Florida Peninsula (zones 3 and 4 and northern zones 5 and 6) experiences mild winters and nearly daily summer thunderstorms as east and west coast sea breezes merge.

This chapter examines Florida's extreme weather hazards: 1) why they happen, 2) their relation to interannual to multidecadal climate variability, and 3) the potential of each hazard and spatial variability across the state. The weather hazards indicated are under these broad categories: precipitation (rainfall, flooding, droughts), thunderstorms (lightning, hail, convective wind, tornadoes), tropical weather (tropical storms and hurricanes), and temperatures (extreme highs and lows). The conclusions section of this chapter mainly addresses the challenge of attributing extreme events to human-induced climate change¹.

¹ The maps and descriptions of hazard potential areas that follow are based on either modeled deterministic probabilities, potentials derived from Geographic Information Systems (GIS) models or GISbased historical frequency assessments. These findings were part of a Florida Department of Emergency Management funded mitigation project undertaken by scholars at the University of South Carolina (FDEM 2015). Many of the hazards discussed cannot be modeled in a probabilistic fashion. Rather, future event "probabilities" must be derived from historical frequencies. As such, we define "hazard potential areas" as those places across the state subjected to historical hazard events and likely at risk for future events of the same type and magnitude. In each case, except for flooding and wildfire, historical event geographies and associated frequencies were created and overlaid with a 12-mile hexagonal grid to create a state-level view of disaster potential. This grid system provides a user-friendly view of event data at a scale appropriate for state-level comparisons.

Rainfall and Related Hazards

Seasonal rainfall varies greatly from the Florida Panhandle to the Florida Keys. Fig. 20.2 indicates that the monthly average rainfall over the panhandle area of northwest Florida is greatest during July but the cool season months of January, February and March also have considerable rain. This pattern changes as we move southward over the peninsula to the Everglades region, which encompasses the southern part of the peninsula, with the warm season months of June-September having the most rainfall and with decreasing amounts southward during the cool season.

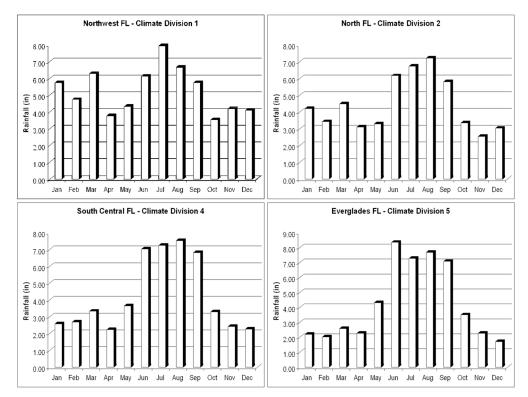


Figure 20.2. Average monthly precipitation for Florida Climate Divisions 1, 2, 4, and 5.

Floods

Flooding in Florida occurs in several different ways that include localized rainfall flooding, river flooding, and coastal flooding. Much of the flooding in Florida is associated with heavy rains that result from a stationary rainstorm, a series of repeat rainstorms, coastal convergence that produces a stationary area of rain, or a larger tropical weather system. Coastal flooding from storm surges occurs when strong winds from hurricanes or winter storms push shallow continental shelf waters onshore. In stronger storms, these inundating surges can be over 3.0 m

(10 ft). Often it is the combination of surge and rain that creates flooding in coastal areas (Wahl et al., 2015). In these scenarios, the surge covers drain pipes and the rainfall runoff backs up into the streets.

Flood Potential

Florida's low elevation above sea level and general lack of slope make flood hazards a threat for every county. Flood zones (Fig. 20.3), determined by the Federal Emergency Management Agency's (FEMA) National Flood Insurance Program, indicate areas at a 1% (100-year) annual probability of flooding. This "true risk" indication makes flood risk one of the easiest to quantify spatially. As such, flood risks and the mitigation of these risks are currently one of the only hazards accounted for in land-use planning, zoning, and building.

Flood hazard areas are fairly ubiquitous across much of the state but are highly conspicuous in South Florida, especially in the counties surrounding the Everglades, from Lake Okeechobee south to the Gulf of Mexico and east to the Atlantic Ocean. The entire Big Bend region of Florida, from Gulf County to Levy County and continuing into coastal Citrus and Hernando counties has a large amount of flood zone areas covering a majority of each of these counties.

The upland areas of St. Lucie and Martin counties have less land in flood zones. These, along with similar areas from inland Hernando County, north through Alachua and into Columbia and Suwanee counties, where pronounced ridges can be found, also have much more land area falling outside of federally-mandated flood zones.

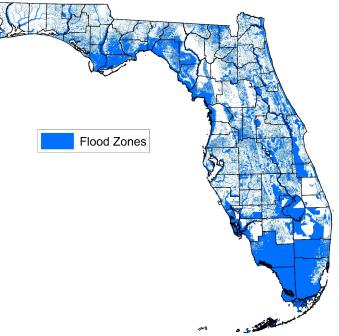


Figure 20.3. Flood potential.

Flash Flood Potential

It is not possible to predict exactly where rain will fall across the state in the future. However, the real threat to life from extreme rainfall events is not the rain itself, but instead flash flooding in areas with large expanses of impervious surfaces, greater slopes, and soil less capable of rapid water infiltration. These characteristics of the landscape, when analyzed geospatially, produce a visual depiction of flash flood potential (Fig. 20.4)².

Flash flood potential varies greatly across Florida, but a few places are known to have greater potential for this type of flooding. Among the areas with higher hazard potential are the northern panhandle areas where higher terrain supports rapid downslope movement of water, major metropolitan areas where impervious surfaces impede water infiltration, and low-lying areas around major waterways. The county with the highest overall flash flood potential is Charlotte County. Here, a greater total land area exhibits characteristics associated with higher flood potential. Homestead, in Miami-Dade County, has the highest flood potential at a single location while Gadsden County in North Central Florida has the highest average potential across the state.



Figure 20.4. Flash flood potential index (FFPI) based on Zogg et al. (2013).

² Modeled from Zogg (2013), this flash flood potential index (FFPI) is not a risk per se since it is not tied to certain precipitation events and the associated occurrence probabilities, but rather the numerical representation of areas that have a higher flash flooding threat from extreme rainfall amounts.

Floods and Climate Variability

Extreme precipitation and discharge events³ in Florida also show significant correlation with the Atlantic Multidecadal Oscillation (AMO), with increased values in AMO warm phases, in particular for precipitation events lasting >24 hours (associated with tropical cyclone landfalls) (Curtis 2008; Teegavarapu et al. 2013). There is, however, spatial variation in the AMO sensitivity. And in some areas in Southeast and Central Florida, as well as the Florida Panhandle, extreme precipitation events (and, in turn, extreme discharge events) appear to be less sensitive to AMO compared to the rest of the state. There is also a shift in the phasing: extreme precipitation events typically occur earlier in the year (June to August) during AMO cool periods, whereas they are observed later (August to October) during AMO warm periods.

Besides AMO, there are other large-scale climate indicators affecting precipitation patterns in Florida at interannual to decadal time scales, most notably the El Niño Southern Oscillation (ENSO): precipitation amounts during the Florida dry season (November to April) have been found to be larger in El Niño years compared to La Niña years (Teegavarapu et al. 2013). This is due to a general increase in storminess in the same season during El Niño years when the polar jet stream flows farther south allowing more frontal systems to reach Florida (e.g., Douglas and Englehart 1981). The Pacific Decadal Oscillation (PDO) has a similar influence on Florida climate as ENSO, but on longer decadal time scales (Misra et al. 2011).

Droughts

Florida is still vulnerable to periods of drought, even though the state has abundant precipitation by world standards. As might be expected, Florida droughts are most prevalent during the dry season when rain falls along fast-moving cold fronts and the amounts are minimal or nonexistent. The weather patterns that bring drought to the state are linked to areas of stationary high pressure to the west extending deep into the atmosphere. Droughts are subtle, though. These high pressure systems usually bring a northerly flow that produces nice sunny and dry weather. But after a while without rain, plants begin to wilt, streams and lakes get much lower, and the ground hardens. Sunny days become an unwelcome prospect for residents during drought conditions. Droughts are a part of Florida's climatic history, however with the increasing population, water shortages become a serious problem. According to the Florida Climate Center (2016), since 1900 every decade has produced at least one severe and widespread drought somewhere within Florida, with the most severe droughts occurring in 1906, 1927, 1945, 1950, 1955, 1961, 1968, 1980, 1984, 1998, and 2006.

³ Extreme hydrological events are typically defined as annual or monthly maxima or events that exceed some high threshold (usually expressed as percentile; e.g. the 99th percentile).

Drought Potential

Extended periods with lack of rain lead to hydrological (groundwater) and agricultural drought conditions. These types of droughts put pressure on water systems and can lead to conflict over the protection of water as a commodity. Using 16 years of data (2000-2015) from the U.S. Drought Monitor to calculate the average number of weeks in drought⁴ per year provides a view of the possible frequency of future droughts given similar circumstances (Fig. 20.5). These periods of extended dry weather will likely increase in an uncertain climate future.

Three key areas across the state have seen higher than average weeks in drought during the period of observation. First, the entire northern border area, from Jackson County east to Madison County, has the highest historical number of drought weeks per year. Second, the area from Jackson County east to Nassau County and southeast to Volusia County has at least a moderate drought frequency. Finally, the area north of Lake Okeechobee, including Glades, Highlands, and Okeechobee counties, northward along the border between Osceola and Brevard/Indian River counties and southeast into western Martin and Palm Beach counties also has a moderate drought frequency.

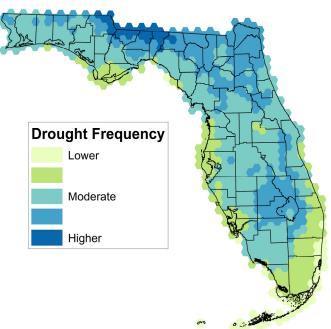


Figure 20.5. Drought frequency based on number of weeks in drought according to the U.S. Drought Monitor (2010-2015).⁵

⁴ Drought weeks are calculated where Standardized Precipitation Index (SPI) values are less than the - 2.0 (Extremely Dry) thresholds.

⁵ http://drought.unl.edu/MonitoringTools/ClimateDivisionSPI.aspx

Droughts and Climate Variability

Similar to extreme precipitation events and as we see later with hurricanes, Florida droughts are affected by large-scale climate variability, but with opposing effects. Observations and model simulations show that dry winters are weakly associated with La Niña patterns (Seager et al. 2009, Schubert et al. 2009). It has been found that during cold AMO phases there is reduced streamflow over Lake Okeechobee (Enfield et al. 2001) and fewer drought events over Florida (McCabe 2004). On the other hand, less precipitation and warmer temperatures have been observed during La Niña years, increasing the drought risk throughout Florida (Brolley et al. 2007).

Florida Wildfires

Wildfires are directly related to lack of rainfall and resulting drought conditions. More than 3,300 Florida wildfires occur annually according to the Florida Forest Service (2016). Fire is dependent on three ingredients: 1) heat as a source of ignition, 2) fuel, and 3) oxygen. As might be expected, the wildfire season begins after the summer thunderstorm season ends, around the beginning of October when the relative humidity is low even though temperatures can be warm during the "cool" season. These drier conditions more readily evaporate the moisture from dead branches and leaves; brush and grasses dry out. As the dry season progresses, fires become more likely, with the height of the fire season occurring during the spring before the summer rainy season starts. Fires are most often set by humans' carelessly tossed cigarettes, campfires, burn piles, and vehicles, or by arson. However, a third of the wildfires are started by lightning. Spring lightning storms that bring little rain may ignite a fire.

Florida also has some unique vegetation containing combustible oils that burn even while the plant is alive. Flammable plants native to Florida include galberry, wiregrass, saw palmetto, cabbage palm, and pine trees. In fact, half of Florida surface fires are fed by grass fuels with a third of the fires burning in patches of palmetto and galberry. Crown or tree canopy fires are a rare occurrence. Some fires ignite drier areas of swamp containing peat and logs and, once started, these areas often smolder for weeks at a time while emitting abundant and thick water vapor-laden smoke.

Smoky fires near roadways, especially when combined with fog, have led to some horrific roadway crashes over the years. In these conditions, visibility can go to zero in a matter of meters. This happens when smoldering organic material adds fine particulates and heated water vapor to the air and mixes with fog. The fine particulates emitted from the burning provide a nuclei for water vapor to form on as it condenses into fog. The thick mixture of smoke and fog creates deadly mix drifts over roadways, reducing visibilities to zero instantaneously.

During the early morning hours of 9 January 2008, visibility dropped to zero as smoke from a prescribed burn the previous day combined with fog and drifted across I-4 in Polk County in Central Florida. Seventy cars and trucks collided killing five people and injuring 38 (Collins et al. 2009). A similar traffic accident occurred on I-75 in Alachua County near Gainesville a few years later, on 29 January 2012, resulting in 11 deaths and injuring 46 others. In the wake of these accidents, the Florida Highway Patrol has become much more proactive in closing portions of highways when the possibility of smoke and fog could limit visibilities for drivers.

Wildfire Potential

Historically, Florida was a peninsula perpetually on fire with little to no assistance in controlling blazes. These fires would "clean the slate" and allow keystone species such as Gopher Tortoises to flourish. Advances in early fire identification and better fire suppression techniques have steadily reduced the number of brush/wildfires and allowed undergrowth to build. While the state no longer burns from coast to coast, small fires that would have normally burned themselves out can turn into conflagrations requiring massive containment efforts. To assist state and local fire planning and mitigation efforts, the Southern Wildfire Risk Assessment produced the Wildfire Susceptibility Index for Florida in 2010 (SWRA 2016). Fig. 20.6 uses this data to build an understanding of where "an acre or more" will burn if ignited. In contrast to many of the other frequency data pieces, this assessment produces a real estimate of potential for burning.

Patterns of wildfire susceptibility vary across the state, but a majority of the south central counties are at an elevated wildfire susceptibility and a swath of highest susceptibility trends north and south between northern Osceola County and Okeechobee County. Additionally, areas from Charlotte County northeast through Highlands County, east into Glades County, and north to central Marion County are characterized by at least a moderate wildfire susceptibility.

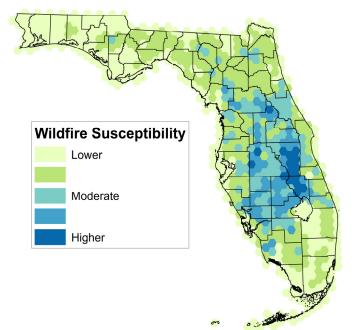


Figure 20.6. Wildfire susceptibility.

Wildfires and Climate Variability

Major wildfires often occur during drought conditions that are linked to La Niña. From 1981 to 2008, the most significant wildfires in Florida (Fig. 20.7; FreshfromFlorida.com 2017) burned 2,144,386 acres and most occurred either during La Niña or ENSO-neutral conditions. According to St. John's County Emergency Management (2017), the worst fires in Florida have occurred about every 20 years. The 1935 Big Scrub Fire in the Ocala National Forest, which occurred during a prolonged La Niña, was the fastest spreading fire in the history of the U.S., covering 35,000 acres in four hours. In 1956 during a strong La Niña, the Buckhead Fire burned 100,000 acres in Osceola National Forest in a single day. In the drought period of 1969 to 1976, during which a La Niña persisted except for several months when a brief El Niño episode brought more rain to South Florida during 1972-1973, fires in the Everglades gained national attention, with some fires reaching 50,000 acres. In 1985 during a La Niña, Florida had its first serious "wildland/urban interface" fire with the Palm Coast Fire, which burned 250 homes. This fire was important in introducing the state to the concept of the wildland/urban interface. In 1998 after a very strong El Niño that brought copious rainfall, which rapidly switched to a La Niña, fires ignited over much of the state and fire suppression organizations from 44 states responded. In July of 1998, Florida hosted the largest aerial suppression operation ever conducted in the United States. The 1998 fires received major media attention for almost two months, largely because of massive evacuations.

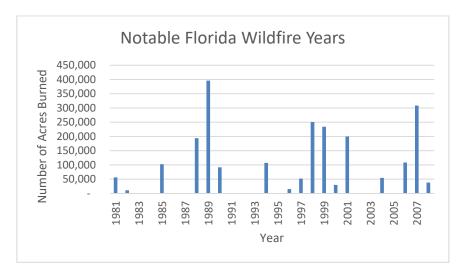


Figure 20.7. Notable Florida wildfire years and acreage burned.

Thunderstorms and Related Hazards

Thunderstorms develop from the abundant moisture in the form of water vapor over the state that is convectively lifted in an unstable atmosphere, then cools and condenses into growing cumulus clouds. As condensation occurs latent heat is released into the atmosphere, which adds to the instability and that increases rising motion in a towering cumulus cloud. The most notable convective cells develop within strong updrafts created by interactions with differential heating and wedged boundaries of slightly cooler air associated with sea breezes and outflows from existing convection. The stronger updrafts lift the water vapor in supercooled liquid form above the freezing level into an area of ice crystals. The mixed phase is an efficient process of cloud growth, as the supercooled vapor freezes onto the ice crystals and leads to a cumulonimbus (thunderstorm) cloud with the glaciated top. Severe weather typically develops in the colder area of the cloud.

Thunderstorms are steered by the average winds from the surface up to around 3 km. The position of the subtropical ridge, which is an extension of the Bermuda-Azores high pressure area, dictates the wind flow across the state as well as the timing and movement of convective clouds. When the ridge is north of Florida, the state experiences an easterly steering flow. When the ridge is south of Florida, the dominant steering flow is from the west. When the ridge is across the central peninsula, east winds flow over the south and west winds flow over the north. The speed of flow dictates the timing of sea breeze formation and movement inland. When the flow is from the east, sea breezes merge near the west coast. With westerly flow, sea breezes merge along the east coast. Under calm wind regimes, the east and west coast sea breezes merge in the central peninsula. Over the Florida Panhandle, the sea breeze propagates northward but is altered by east or west flow. Sea breeze convergence creates stronger updrafts and more vigorous thunderstorms.

The frequency of thunderstorms over certain parts of the state is also dictated by coastline shape. As sea breezes develop along the coasts and move inland, wind convergence can be focused by an area of land that juts into the water such as a cape. Apalachicola, Cape Canaveral, areas of Tampa Bay, and Fort Myers are areas of enhanced convergence. Landforms around Tampa Bay focus sea breeze convergence generating more frequent and persistent thunderstorms over 100 days per year, which is a greater number than any other part of the country. Other areas of Florida coastline that bend inland create the opposite effect with diverging wind inland from the area and less vigorous convection.

During the cool season, thunderstorms develop along frontal boundaries pushing into Florida where atmospheric moisture collects and is lifted in a more dynamic wind flow. We often see the jet stream near Florida, which creates stronger lift for thunderstorms. Winds that increase and flow from south to northwest with height can produce more persistent rotating thunderstorms. Additionally, during the cool season the mid-levels of the atmosphere are colder resulting in a

more unstable atmosphere and more energetic thunderstorms when surface temperatures are warm.

Thunderstorms are responsible for much of the damaging weather that impacts Florida. As a peninsula surrounded by warm water in the sub-tropics, Florida has a unique geography that creates a tap for the deep layer atmospheric moisture, which is a prime ingredient for thunderstorms. Coupled with instability to lift the moisture, the intense vertical motions within thunderstorms produce twisting tornadoes, downbursts of rain-cooled air, large pounding hail, and deadly lightning.

During the warm season, from June through September, thunderstorms rumble around the state daily. Florida has many land interfaces of forest, farmland, urban and suburban areas that are dotted with more than 7,700 inland lakes over 40,000 m² (10 acres) including Lake Okeechobee, and all this sandwiched in between the Gulf of Mexico and Atlantic Ocean. The diverse land surfaces absorb shortwave solar energy at different rates, leading to differential heating that becomes obvious when cumulus clouds form over hotspots during the summer late mornings. Heating over the land creates lower pressure and a natural wind flow from the surrounding ocean water areas inland. These sea breeze boundaries create an area of focused rising motion where clouds are more likely to develop. At night, the pattern reverses with wind flowing offshore as land breezes.

Lightning

Ice crystals that form the tops of thunderstorms attract positively-charged particles, the liquid water droplets down below attract negatively-charged particles. This changes when a thunderstorm cloud passes over the ground, as positively-charged particles are drawn to the surface of the Earth. When the voltage difference becomes too great, negatively-charged stepped leaders, which are small segments of energy, travel downward as positively-charged stepped leaders move up from the ground. As the stepped leaders meet, the channel becomes a conduit for electrical current moving from the ground to the cloud, which creates lightning. Lightning can also occur in clouds, from cloud to cloud, and from cloud to air. The temperature of lightning is estimated at 27760° C (50,000° F), which creates a rapid expansion of air outward that creates a brief vacuum then the air rushes back. This is what creates the thunder. The speed of sound is much slower than the speed of light, so for roughly every five seconds after the flash, the sound has traveled a mile. Although very bright, the lightning channel is extremely narrow, about the size of a pencil.

Roughly 90% of all lightning occurs over land areas nearest to the Equator, and the most prolific lightning locations across the globe are across the central African continent and near Lake Maracaibo in Venezuela. Florida leads the nation in lightning strikes and is known as the lightning capital of the United States, experiencing about 100 days with thunderstorms each year

across the central peninsula along the I-4 corridor. Florida also leads the nation in lightning deaths, averaging six per year.

Lightning Potential

Most of the lightning that strikes Florida occurs during the warm season across the central peninsula. During the warm season, tropical moisture and conditional instability lifted by diurnal sea breezes initiate convection that grows to 15 km (50 kft) until it encounters the stable stratosphere. Florida's coastal geography also shapes the sea breezes and areas with capes; areas of land extending seaward create coastal wind convergence, which amplifies the convection. It is these areas that have the most lightning. The synoptic scale wind flow determines where the lightning will be most prevalent from day to day. Over the panhandle, wind regimes have less impact on lightning than over the peninsula, where the east and west coast sea breezes collide and intensify the convection. Easterly winds promote sea breeze collisions and the strongest thunderstorms along the west coast of the peninsula. The converse is true with westerly winds. During the cool season, the most lightning occurs over the Florida Panhandle, where cold fronts carry more moisture and instability as they often lose it moving southward over the peninsula.

Mapping the average number of cloud-to-ground lightning flashes per year (1986-2012) from the National Central for Environmental Information provides a visual understanding of the historical frequency of this hazard (Fig. 20.8). Hillsborough County emerges as the leader in lightning frequency. This has to do with the shape of Tampa Bay, which forms the most prolific lightning storms with cloud-to-ground lightning strikes occurring about 25 times every 2.6 km² (one square mile) around Tampa and eastward along I-4 annually (Hodanish et al., 1997). Franklin County in the North Central Panhandle has the lowest lightning frequency. Seminole County, however, exhibits the highest average number of lightning flashes making it a location of concern for this type of hazard. Finally, Polk County, because of its size and location in relation to the "lightning belt" trending from Tampa to Orlando, has the highest overall number of strikes during the period of record. Other areas with higher historical lightning frequency include Pasco County north of Tampa.

Lightning and Climate Variability

A relationship between ENSO and global lightning activity has been found in both the intensity and position of lightning activity (Sátori et al., 2009). It has been observed that generally more lightning occurs in the tropical-extratropical land regions during warm El Niño episodes, especially in Southeast Asia. LaJoie and Laing (2008) specifically focused on the lightning activity along the U.S. Gulf Coast and noted that there is an ENSO influence, such that they observed the highest annual flash rates occurred in 1997 during the strongest El Niño event on record, while the lowest annual lightning flash rates occurred in 2000, which was more of a neutral/La Niña phase. This is consistent with what is observed, in general, globally.

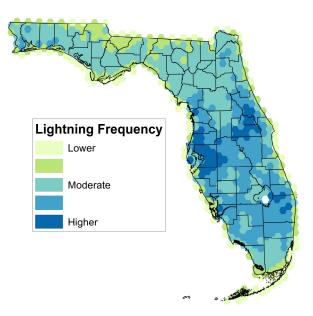


Figure 20.8. Historical cloud-to-ground lightning flash frequency (1986-2012).

Hail

Extreme updrafts produce supercooled liquid water vapor that freezes on frozen water droplets creating hail. Growth continues while the updraft is strong enough to suspend the hail. Hailstones sometimes aggregate into larger sizes or may be solely formed from frozen water layers. Hail falls when it moves out of the updraft, grows too large to be suspended, or when the updraft weakens. The largest hailstone recovered to date fell near Vivian South Dakota in 2010 and was over 200 mm (8 in) across with a mass of just under 1 kg (2.2 pounds).

According to the NOAA Storm Events database, 60% of the reports of Florida hail occur during the prolific summer thunderstorm season, with a peak in June; but, the largest hail falls during the cool season with a peak in March. During the cool season, the dynamics are stronger to produce supercell thunderstorms that produce large hail, and the atmosphere is colder and less melting occurs on the way down with lower freezing levels below 3 km. Supercell thunderstorms occur when atmospheric instability and wind shear are strong, thus organizing developing convection into a persistent rotating storm. During the warm season, wind shear is weak, the convective storms are short-lived, and the freezing levels are often above 4 km (13,000 feet). The typical maximum hail size reported during the warm season is around 50 mm (2.0 in). During the cool season the largest hail size reported has been twice that size, in the grapefruit category of 114 mm (4.5 in), and has only been reported in Florida three times in the past.

The number of Florida hail reports in the National Weather Service Storm Events database (Storm Events 2016) varies by decade and is biased by hail sizes reported (Table 20.1). The hail reports in the database begin during 1955 and averaged four reports per year during the 1950s.

During the 1960s, the reports averaged 14 per year because of increased sighting as population grew: up to 19 per year during the 1970s and 25 per year during the 1980s. During the 1990s, modernizations by the National Weather Service allowed for more robust inquiries into events and improved communication via cell phone and the Internet, which led to more than 130 reports per year in the 1990s and nearly 200 reports per year during the 2000s. The hail reports were biased primarily because of the popular and readily identified object, the golf ball (Table 20.1). When considering the reports of hail 32-51 mm (1.25-1.99 in) in size, golf ball-sized hail, 43-51 mm (1.7-1.99 in) was reported 629 times (69%) compared to 195 reports (31%) of smaller hail between 32-43 mm (1.25-1.69 in).

Size (mm)	Size (in)	Number of Events	Percentage	
101-114	4.0-4.5	4	0.10	Softball to Grapefruit
76-101	3.0-3.99	9	0.21	Tea Cup
51-76	2.0-2.99	90	2.15	Hen Egg to Baseball
43-51	1.7-1.99	629	15.01	Golf Ball
38-43	1.5-1.69	110	2.63	Ping Pong Ball
32-38	1.25-1.49	85	2.03	Half Dollar
25-32	1.0-1.24	1003	23.94	Quarter
20-25	0.8-0.99	606	14.46	Nickel
19	0.75	1654	39.47	Penny

Table 20.1. Reported hail sizes in Florida 1955-2015.

Hail Potential

Hail is another hazard that cannot be predicted well enough in advance to take any "real-time" precautionary measures against. Yet this hazard threat is capable of destroying roofs, windshields, and can cause major damage to crops across the state. Creating a geographic representation of historical hail events affords us a glimpse into where these events have interacted with human activity in the past. Using data from NOAA's Storm Prediction Center (1986-2015) to produce an average annual hail event surface (Fig. 20.9) provides us a "climatology" of events that can be utilized to identify areas of potential future human-hail interactions.

While human bias is evident in this depiction of hail events, with the major interstates and population centers popping out with higher frequency, we also see areas of higher threat in the less populated Polk County in Central Florida, in more rural western Duval County, and in areas along the northern I-4 corridor that have smaller populations. Orange County has the largest amount of land area historically impacted by hail events, followed by Hillsborough, Duval, and Polk counties. The highest historical frequency area is located from Sanford in Seminole County south to the northern edge of Orlando.

Hail and Climate Variability

Fig. 20.10 shows the number of reports of hail in Florida, one inch in diameter or greater, from 1995 (a time when reports were less likely to be biased due to National Weather Service staffing) to 2015. While ENSO is the most prominent indicator for Florida extreme weather, Fig. 20.10 does not provide evidence for a relation and hence we cannot identify robust relationships between hail and larger-scale climate variability, in general. For example, the lowest years (1995, 2000, 2002, 2010, 2013 and 2015) with under 60 reports across the state were varied with respect to the ENSO phase. The same is true for the years with the greatest number of reports (1998, 1999, and 2011), which had more than 100.

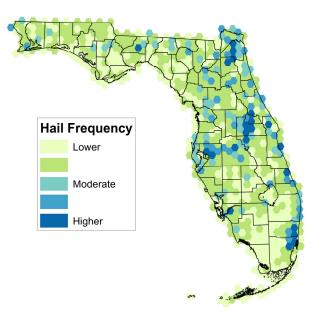


Figure 20.9. Historical hail event frequency (1986-2015).

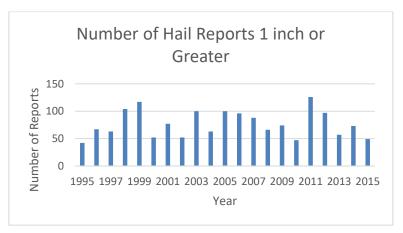


Figure 20.10. Number of hail reports one inch or greater.

Tornadoes

The strongest tornadoes that impact Florida develop along vigorous cold fronts during the cool season when instability, moisture, and wind shear is greatest. These strongest tornadoes usually develop from supercell convection organized by strong directional wind shear (changing wind direction with height). Under strong unidirectional wind shear, convective systems organized into lines near cold front boundaries will, at times form moderately strong tornadoes. The Fujita scale matches up tornado severity with numbers preceded by an "F". Since 2007, this scale was modified to the Enhanced Fujita scale preceded by an "EF". When the conditions are met for cool season tornadoes, they often occur in clusters over a several-hour time period. In the past, five tornado outbreaks with more than 10 fatalities have occurred in Florida and are described in Table 20.2. Grazulis (1993) defined a "tornado outbreak" as a group or family of six or more tornadoes spawned by the same weather system.

For the period 1991-2010, Florida leads the nation in the average annual number of EF0-EF5 tornadoes per 10,000 square miles, followed by Kansas and Maryland. State by state, Florida comes in third for the average total of tornadoes from 1991-2010, averaging 66 tornadoes per year; Texas, which has a large land area, averaged 155 and Kansas averaged 96. Florida comes in second for both the greatest number of tornadoes from 1980-1990, and the average number of days per year with tornadoes (28). That said, most of Florida's tornadoes are weak. When ranked by the strongest tornadoes (F3/EF3 and above) Florida ranks 25th with the frontrunners, which are all in areas with stronger instability and wind shear: Kansas at the top, followed by Arkansas, Texas, Tennessee, and Oklahoma.

Most of Florida's tornadoes are spawned during the warm season by single cell convection and are short-lived. These brief tornadoes typically cause damage to trees, aluminum awnings and carports, and only minor damage to well-constructed homes. Some of these tornadoes start as waterspouts and then move onshore causing damage along the shore.

Tropical cyclones typically produce fast 25 m s⁻¹ (56 mph) northward-moving tornadoes on the east side of the storm, up to EF2 on the Enhanced Fujita scale. The most significant tropical tornado outbreak on record occurred during Hurricane Agnes in June 1972, creating the fifth-deadliest tornado outbreak in Florida history.

Tornado Potential

Historical tornado frequencies across the state derived by the NOAA Storm Prediction Center statistics (SPC 2015) provide the basis for identifying possible future threats from these powerful hazards. In Fig. 20.11, hex grids illuminate the areas where tornadoes have been reported across the state from 1955-2015. Areas of high frequency can be seen across the state. And although some of the deadliest tornadoes have been in the interior of the state, the majority of tornado reports come from the more densely populated coastal areas. The western three panhandle counties (Escambia, Santa Rosa, and Okaloosa) have the highest frequency of tornadoes over the

period from 1955-2015. The Tampa Bay area is also characterized by higher numbers of tornadoes that often start as waterspouts and move onshore. The lower east coast area, from Miami north, also has a high frequency of reported tornadoes along with Orlando, the Space Coast area, and Jacksonville.

Tornadoes and Climate Variability

Interestingly, the number of tornadoes reported annually from 1995 to 2015 (Fig. 20.12) decreased over time. From 1995 through 2005, the average number of tornadoes reported each year in Florida was 76 with the greatest number of reports, over 100, during 1997, 1998, and 2004. From 2006 through 2015 the average annual number of tornadoes reported was 38 or about half that of the previous decade. The data at hand does not provide robust evidence for linking this decrease to climate variability.

Date	Event	Description
June 18-19 1972	Hurricane Agnes Tornadoes	Hurricane Agnes struck Florida with the fifth deadliest tornado outbreak in Florida history. Agnes travelled north, creating the costliest natural disaster in U.S. history at the time, with \$3.5 billion (1972 dollars) in storm damage. Rainfall from Agnes created extreme flooding in Pennsylvania, New York, Maryland, Virginia, and Washington D.C., killing 122 people. Researchers Hagemeyer and Spratt (2002) examined the deadly tornadoes slamming Florida that spawned from Hurricane Agnes. The storm produced 28 tornadoes over the southern half of the peninsula, from near Daytona Beach to Key West. Two of the tornadoes produced F3 damage, nine were ranked as F2, 11 were F1, and the other six were F0. One tornado cut a path 100 yards wide through Okeechobee City, killing six people and destroying 50 mobile homes. Another tornado near La Belle in Hendry County killed a woman in a trailer. The tornadoes injured 140 people, destroyed 15 homes and more than 200 mobile homes.
February 2, 2007	2007 Groundhog Day Tornadoes	The tornadoes took 21 lives and injured another 76 people. Within minutes, a mesocyclone that meteorologists had been watching gained strength and a tornado warning was issued. Minutes later soon-to-be victims of the Villages community, who were not woken by the siren sound of the warning on their NOAA weather radios, awoke to the horrendous sound of their homes being destroyed. The tornadoes demolished 200 homes and damaged over 1,100 in Sumter County. Those were the lucky victims – all they lost was their home. The tornado continued moving eastward rapidly at 60 mph with over 160 mph winds and ravaged the Lady Lake area, killing eight people and destroying more than 100 homes in Lake County before it lifted. A second tornado developed minutes later and obliterated the Lake Mack area, killing 13 people and destroying over 500 homes. A third tornado touched down just east of the second tornado before lifting along the East Coast at New Smyrna Beach. This tornado outbreak was the second-deadliest on record for Florida, with damages of \$218 million.

Table 20.2. Florida's Deadliest Tornadoes.

	1 1 1 2 2	
31 March 1962	March 1962 Tornado	A savage tornado ripped through Milton, Florida (about 30 miles northeast of Pensacola) claiming 17 lives and injuring 80. This was the highest death toll from a tornado in Florida up to that date. Along the seven-mile tornado path of destruction, three residential blocks were devastated. Homes were destroyed and trees left as stumps. The storm picked up a home with three residents inside and took them for the ride of their life. The tornado spun the house and gently dropped it a hundred yards away on the foundation of another home that was demolished by the twister leaving the residents unharmed. Relief workers, National Guardsmen, and sailors from nearby Whiting Field poured into the area to help the victims.
April 4, 1966	April 1966	Eleven people died and more than 3,300 people were injured
	Florida	during the 1966 tornado outbreak that left a more than 100-mile
	Tornado	(160-km) path of destruction across Central Florida. It occurred
	Outbreak	during the morning of April 4, 1966, beginning around 8:00 am. The strongest tornado, with an estimated intensity of F4, created a path of death and destruction from Clearwater on Central Florida's West Coast to Merritt Island near the Kennedy Space Center on the East Coast. At times, it was measured to be as wide as 300 yards. In addition to the deaths and injuries, more than 250 homes and businesses were destroyed. The tornado ripped through parts of the Forest Hills and Carrollwood areas, as well as the University of South Florida campus in Tampa. East of Tampa, in the town of Lakeland in Polk County, seven people lost their lives and a 55-foot radio tower was yanked from its concrete pilings and smashed to the ground. As the storm clouds continued moving eastward, citrus trees near Auburndale, were stripped bare and fruit was scattered on the ground. The second tornado moved ashore near the mouth of Tampa Bay and created destruction across over 100 miles to Cocoa Beach, where more than 20 frame homes, a shopping center, and 150 mobile homes were destroyed, and more than 100 were injured. This tornado outbreak is the fourth- deadliest documented in Florida.
23 February	Central Florida	Below is an account from the National Weather Service in
1998	Tornado	Melbourne, FL of the deadliest tornado outbreak in Florida, which
	Outbreak of	occurred in February 1998. "During the late night and early morning hours of 22.23
	February 1998	"During the late night and early morning hours of 22-23 February 1998 (Sunday - Monday), the most devastating tornado outbreak ever to occur in the state of Florida in terms of both loss of life and property damage, occurred from Kissimmee to Sanford to Daytona Beach. Forty-two people died as a result of the tornadoes and more than 260 others were injured. Over 3,000 structures were damaged, and more than 700 were completely destroyed. A total of seven confirmed tornadoes occurred that night. Four of the tornadoes were unusually long-lived and produced damage tracks of between 8 and 38 miles, resulting in the majority of damage and all of the fatalities. Uncommon for Florida tornadoes, the estimated wind speed for three of these twisters reached 200 mph which is on the high end of F3 intensity on the Fujita scale [and would be on the border between EF4 and EF5 intensity today]."

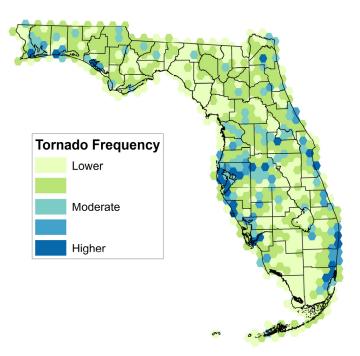


Figure 20.11. Historical tornado frequency (1955-2015).

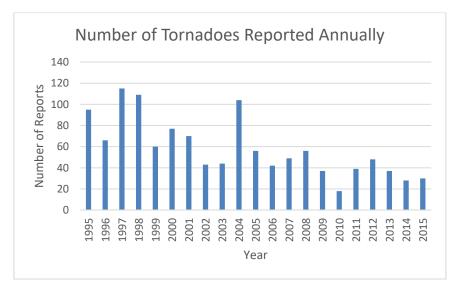


Figure 20.12. Number of tornadoes reported annually (1995-2015).

Damaging Thunderstorm Winds

Damaging thunderstorm winds are winds that cause damage to buildings or sturdy trees and are either estimated or measured at 50 knots or greater. Damaging thunderstorm winds across the state manifest in two ways. First, during the cool season when the atmospheric dynamics are stronger, thunderstorms develop near active cold fronts either in a linear or curved arrangement or as single strong super cells. These cool season thunderstorms are longer lasting than the summer thunderstorms that form within the very unstable tropical air mass and reach peak intensity and begin to dissipate within an hour.

Thunderstorm Wind Potential

Fig. 20.13 shows damaging thunderstorm wind frequencies over Florida derived from the NOAA Storm Prediction Center statistics (SPC 2015) from 1955-2015. Unlike tornado report frequencies, which have a coastal bias, the stronger thunderstorm winds are seen across interior areas of the state, as well. Some population bias is also indicated near major metropolitan areas.

Damaging Thunderstorm Winds and Climate Variability

Unlike tornado reports, which have decreased during the past decade, the reports of damaging thunderstorm winds have increased to more than 500 reports in 2011 and 2015 (Fig. 20.14). The decadal averages were 291 from 1995 through 2005 and 374 from 2006 through 2015. The data shows that the number of damaging wind reports appears to be linked to El Niño patterns with lesser annual reports linked to neutral or La Niña patterns.

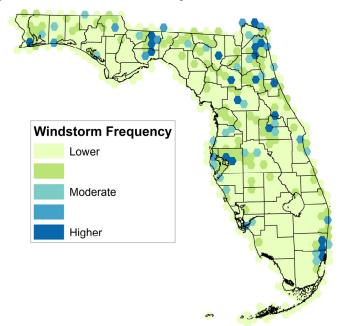


Figure 20.13. Historical damaging thunderstorm wind frequency (1955-2015).

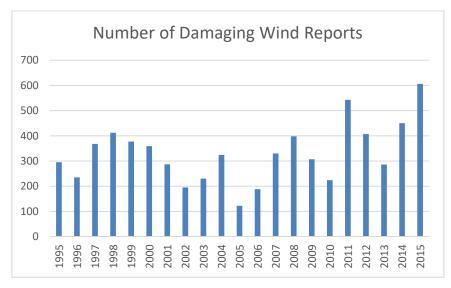


Figure 20.14. Number of damaging wind reports (1995 to 2015).

Tropical Weather

The term "hurricane" is used for North Atlantic Ocean and Northeast Pacific Ocean tropical cyclones. It comes from the Spanish word huracán, which was derived by Spanish explorers from references to hurakán (or 'god of the storm'), a word used by the Arawak people who inhabited the Greater Antilles and the Bahamas in the past. The Arawak may have taken it from the Mayan creator god, 'Hurakan', who blew the water.

Unlike mid-latitude low pressure systems with cold cores fueled by temperature contrasts between the poles and the tropics, hurricanes are warm core areas of low pressure fueled by warm ocean waters and tropical moisture that comes from the latent heat of vaporization being released by convection and condensation. Gray (1979) developed a set of six factors that he noted were necessary for tropical cyclone formation. Tropical cyclones are dependent on: 1) warm ocean waters above 27° C (80° F) over a deep layer (typically at least 60 m), 2) plentiful atmospheric moisture (i.e., high levels of mid-level relative humidity), 3) an unstable atmosphere that allows air to rise, 4) little or no vertical wind shear, which allows for strong vertical development, 5) sufficient Coriolis force to give the initial cyclonic spin, and 6) high relative vorticity.

Prior to the formation of a tropical cyclone, a disturbance is created through convergence of air. This convergence can form by more than one mechanism. For instance, it can be created along the Intertropical Convergence Zone where winds from the Southern Hemisphere cross the Equator and meet winds from the Northern Hemisphere. Another mechanism can be from African easterly waves that form off Africa. As air moves into these waves, convergence occurs. Regardless of the mechanism, the convergence causes air to rise and a disturbance is created.

These disturbances become "tropical depressions" when they are well organized and have a cyclonic circulation. If a tropical depression intensifies with a sustained wind speed of 17 m s^{-1} (39 mph), then it becomes a "tropical storm" and is given a name. When a sustained wind speed of 34 m s^{-1} (74 mph) occurs the system becomes a "hurricane." Hurricanes are ranked by intensity from Category 1 to 5, using the Saffir-Simpson scale (Table 20.3), with the categories corresponding to anticipated wind damage to sturdy structures. Major or intense hurricanes are those designated as a Category 3 hurricane or higher.

The official hurricane season begins June 1 and stretches to the end of November. Most of the early season storms and those that occur in November are typically weak because the ingredients are lacking and the storms often form in the Caribbean Sea and/or Gulf of Mexico where waters are warmer. As the deep Atlantic Ocean waters warm during the summer, many seedling storms that become hurricanes move westward from the continent of Africa's coast (around 20°N) and grow into tropical depressions. These systems are often known as Cabo Verde (Cape Verde) storms because they transit near or across the archipelago off the African Coast. In the Atlantic Basin, hurricane activity increases greatly during August, peaking around September 10 and beginning to decrease into October. When just considering the storms impacting Florida, roughly 33% occur in September, 25% during October, and 20% during August. As sun angles get lower and water temperatures over the Atlantic Ocean cool, October storms are more likely to form in the warmer waters near Florida and are often stronger than June storms.

During the warm season when southward cold air transport to balance temperatures in the northern hemisphere is minimal, tropical cyclones carry excess heat energy from the tropics toward the poles. Hurricanes bring multiple impacts for Florida residents including a battering storm surge, damaging winds, flooding rains, and tornadoes. Storm surge, which is the most deadly of these hazards, is a rapid rise in coastal waters as the storm moves near shore. Surges can be up to 9 m (30 ft) in a Category 5 hurricane in the shallow coastal waters along the Gulf Coast.

Category	Wind Speed (km h ⁻¹)	Wind Speed (mph)
1	119-153	74 – 95
2	154-177	96 - 110
3	178-208	111 – 129
4	209-251	130 - 156
5	≥252	≥157

Table 20.3. The Saffir-Simpson scale.

Date	Name	Description
September	The 1848	A 15-foot storm surge within Tampa Bay reshaped much of the
1848	Hurricane	area when a major hurricane struck in late September of 1848.
		Damage and loss of life were minimal because only a few people,
		mostly military, lived in the Tampa Bay region at the time.
		However, the surge had a huge impact on the barrier islands. The
		high surge, rough surf, and strong currents cut several gaps or
		passes through barrier islands including: Stump Pass at
		Englewood, Casey's Pass at Venice, New Pass at Palm Island
		(which became Longboat and Lido keys), and John's Pass
		between Madeira Beach and Treasure Island.
September	The Dry	This was one of the few historically-severe hurricanes that was
1919	Tortugas	not a Cape Verde storm. Instead, it was believed to have formed
	Hurricane (also	near Guadeloupe in the Lesser Antilles. The storm struck the
	known as the	Florida Keys on September 10, 1919 as a Category 4 hurricane.
	Florida Keys	As the storm progressed into the Gulf of Mexico, it attained one
	Hurricane) of	of its distinctive features – slow forward movement – before
	1919	finally making another landfall in southern Texas on the evening
		of September 14. Because of its slow speed and wide circulation,
		this hurricane had tremendous storm surge impacts across most of the U.S. Gulf Coast, even in areas far from where it tracked. The
		storm caused approximately 800 fatalities from the Bahamas to
		Texas. Many of the victims were on ships; less than 100 deaths
		occurred in the then sparsely-populated Florida.
October 1921	The 1921	The last hurricane to impact the Tampa Bay area directly was the
0000001721	Hurricane	unnamed storm of October 1921. The estimated Category 3 storm
	(unnamed)	made landfall just north of Tampa Bay, battered the city with
	(unnunieu)	winds exceeding 100 mph, and created a 10- to 12-foot storm
		surge in Tampa Bay. The storm caused \$1-10 million dollars in
		damage and was responsible for six deaths (Ballingrud 2002).
September	The 1928	The second-deadliest hurricane to strike U.S. soil, after the
1928	Okeechobee	Galveston Hurricane of 1900, was the 1928 Okeechobee
	Hurricane	hurricane. This storm was blamed for more than 4,000 deaths, of
		which over 2,500 were Floridians and most occurring near its
		landfall area of West Palm Beach to Lake Okeechobee on
		September 17, 1928. The storm earned its "Okeechobee" moniker
		because its winds pushed a tremendous amount of Lake
		Okeechobee's water into the adjacent lowlands, drowning many
		people who lived on the north and south sides of the lake. The
		track of this ferocious hurricane then turned northward, taking it
		lengthwise up the Florida Peninsula, which only added to its toll
~		on the Sunshine State.
September	The 1935 Labor	The deadly Category 5 Labor Day hurricane struck Florida's
1935	Day Hurricane	Upper Keys on September 2, 1935. It killed more than 400
		people. At landfall, this storm may have had the lowest central
		pressure (892 mb) in U.S. hurricane history and its localized
		storm surge of up to 20 ft was devastating. After striking the
		Upper Keys and moving across southern Florida into the Gulf of Mexico, the storm continued moving north but weakened just
		offshore of Florida's West Coast before making landfall again
		near Cedar Key on September 4 (Map 7.5). This was the first of
		three Category 5 hurricanes to hit the U.S. during the 1900s.
August 1992	Hurricane	Hurricane Andrew, whose southern Florida landfall at Elliott Key
1 iugust 1772	Andrew (1992)	and then in Homestead on August 24, 1992 as a Category 5,
	1 marcw (1772)	und then in fromestead on August 24, 1772 as a Calegoly 3,

		became the costliest natural disaster in Florida history, with over
		\$25 billion in damages (1992 dollars). Andrew left the most
		damage of any hurricane in U.S. history and its death toll of 44 Floridians was substantial.
September/	Hurricane Opal	Hurricane Opal was one of the most memorable storms of the
October 1995	(1995)	1995 hurricane season, causing more damage in Florida than
	(1))0)	elsewhere in the U.S. Opal was unusual in that it formed as a
		Cape Verde storm, but remained poorly organized until reaching
		just north of the Yucatan Peninsula where it was named a tropical
		storm on September 30, 1995. Opal then crossed the Yucatan
		from east to west, rapidly strengthening to Category 4 status over
		the Bay of Campeche before moving northeastward across the
		Gulf and slamming into the Florida Panhandle near Santa Rosa
		Island on October 4. Opal killed 50 people in Central America
		and 13 in the U.S. One of these deaths was in Florida during an
		F2 tornado that Opal spawned. Florida did bear a very large share
		of Opal's land and property damage, including major damage to
		Highway 98, which parallels the coast along Fort Walton Beach,
August 2004	The 2004	Destin, and other resort areas. A decade-long period of relative quiet for Florida ended with a
August 2004	Hurricanes:	vengeance in 2004 when four historically powerful storms made
	Charley,	landfall in or very near the state, and another weaker tropical
	Frances, Ivan,	storm (Bonnie) struck the Panhandle. According to the National
	and Jeanne	Weather Service, the sixth-, eighth-, and tenth-costliest hurricanes
		(Ivan, Charley, and Frances, respectively) in U.S. history affected
		Florida directly during that 2004 season.
		Charley, a Cape Verde storm, is known for its small
		geographic extent and multiple landfalls across the Caribbean and
		southeastern U.S. and also for setting a record (with Tropical
		Storm Bonnie) on August 13 (a Friday the 13 th , no less) as the
		only pair of named storms to hit a single state within a 24-hour period. Charley moved across the Dry Tortugas and then an
		unseasonably early atmospheric trough dipped southward across
		the Gulf, steering Charley northeastward. While being steered
		northeastward by the trough, Charley intensified rapidly before
		striking Cayo Costa along the southwest Florida coast with
		Category 4 winds. Charley continued inland over heavily-
		populated areas such as Orlando, Kissimmee, and New Smyrna
		Beach while still at hurricane strength. Charley re-emerged over
		the Atlantic Ocean making additional landfalls in South Carolina,
		and eventually merging with a frontal system as it moved over
		southern New England. Hurricane Frances, another Cape Verde storm that caused
		significant impacts, was a Category 2 at landfall near Hutchinson
		Island along Florida's southeast coast. Unlike Charley, Frances
		was a large, slowly-moving storm that caused more widespread
		damage but had less intense impacts. After wreaking havoc in the
		Bahamas as a Category 4 storm, Frances weakened prior to its
		Florida landfall and re-emerged in the Gulf of Mexico near
		Tampa before turning back to the northeast and striking land
		again near St. Marks.
		Hurricane Ivan made landfall west of Pensacola, on the
		Alabama coast. But Ivan's large extent, with an eye alone that
		extended for more than 40 miles, had its strongest impacts occur in parthyast Florida on the right side of the storm's landfall. Juan
		in northwest Florida on the right side of the storm's landfall. Ivan
L		had been a Category 5 storm as it entered the Gulf of Mexico and

	T	
		had weakened substantially to Category 3 strength just prior to its September 16 landfall in Gulf Shores, Alabama. However by September 20, Ivan had made a huge clockwise loop, re-emerging in the Atlantic before crossing the southern Florida Peninsula and making landfall near Miami. After its second landfall, Ivan crossed the Florida Peninsula, re-emerging in the Gulf of Mexico, and making its third and final mainland U.S. landfall as a tropical depression near the Louisiana-Texas border. One of the most distinctive features of Ivan was its strength at low latitudes. For area residents, the most memorable damage was to the I-10 Escambia Bay Bridge, where huge segments of roadway were moved off the foundation by the storm surge, taking many weeks to be repaired. Storm surge varied widely along Ivan's path, along the different types of coastline configurations and water depths in the storm's path; areas near the Bay Bridge experienced the worst surges, at over 13 ft. A non-Cape Verde storm, Jeanne, followed Ivan into Florida by less than a week. Hurricane Jeanne's Florida landfall occurred on September 26 near Hutchinson Island at almost the same location as Hurricane Francis' landfall, but Jeanne quickly dissipated after moving inland and trekking north-northwest up the western side of the Florida Peninsula. Like Ivan, Jeanne emerged in the Atlantic after crossing Georgia, the Carolinas, Virginia, and Maryland. However, unlike Ivan, Jeanne had already made its loop before reaching Florida and did not reappear for a second landfall. Jeanne's impacts were magnified by its timing – the rain from Jeanne had fallen on ground already waterlogged by Ivan, exacerbating flooding and crop damage. In terrain like Florida's, large trees are easily destabilized by such soggy conditions, particularly because the roots tend to be
August and	The 2005	shallow owing to the naturally-high water table. While Hurricane Katrina will always be remembered for its
August and October 2005	The 2005 Hurricanes: Katrina and Wilma	While Hurricane Katrina will always be remembered for its devastation in Louisiana, the storm also impacted Florida. In South Florida, Katrina caused 14 deaths, three of which were due to falling trees and another three due to drowning. Katrina dropped nearly 15 inches of rainfall imposed widespread damage and power outages, and a spawned tornado on Marathon Key on August 25, 2005. The pressure dropped to 985 mb and the intensity had increased abruptly just prior to that tornado's landfall. Hurricane Wilma holds the record low pressure in the Atlantic Ocean Basin, dropping almost 100 mb in one day to 882 mb. Wilma was one of the few intense hurricanes to have approached peninsular Florida from the west, after having clipped Mexico's Yucatan Peninsula. This northeastward turn occurred because Wilma's late-season lifespan made her more vulnerable than most storms to being steered by the eastern side of an upper- atmospheric trough. Wilma made landfall near Cape Romano, Florida, on October 24, 2005.

Tropical Storm and Hurricane Potential

Wind damage from tropical systems has ravaged every part of Florida at one time or another. Fortunately, since Hurricane Andrew (1993), we have not had a singular event cause catastrophic impacts. However, since that time many storms have produced moderate to severe damage. Understanding hurricane wind frequency in terms of return period or annual expected number of events enables planners and decision-makers to prepare for future threats. While hurricane paths are unpredictable, looking back over the past 25+ years provides valuable information pertaining to hurricane wind potential. Below, we calculate the average times per year an area can expect to experience tropical storm and hurricane force winds using Colorado State University's Extended Best Track dataset (Demuth et al. 2006).

Fig. 20.15 shows higher historical frequencies of tropical storm winds ($\geq 17 \text{ m s}^{-1} \text{ or} \geq 34 \text{ knots}$) reach much further inland, putting many more counties at a moderate to high potential. An area of elevated tropical storm wind frequency is present from Gainesville in Alachua County south to Key West and north again to Palm Beach. Coincidentally, the highest historical frequency of tropical storm winds occurs in Charlotte County. Here, more storm paths have crossed than any other place in the state during the period of observation.

Higher levels of hurricane wind frequency ($\geq 33 \text{ m s}^{-1} \text{ or } \geq 64 \text{ knots}$; Fig. 20.16) are shown over East Central Florida, from Osceola and Polk counties southeast to northern Palm Beach County, along with a swath trending northeast from western Monroe County through Broward County. Additionally, areas of southern Escambia and Santa Rosa as well as Brevard, Orange, Volusia, and Polk counties have at least a moderate potential for experiencing hurricane force winds. The pattern is slightly different when accounting for weaker but more frequent tropical storms, which are also capable of causing severe structural damage to homes and businesses.



Figure 20.15. Historical tropical storm wind frequency (1988-2014).



Figure 20.16. Historical hurricane wind frequency (1988-2014).

Hurricanes and Climate Variability

Hurricanes, and tropical cyclones in general, in the Gulf of Mexico and southeast of the U.S. are linked to larger-scale climate features and teleconnection patterns in multiple ways and at different time scales. Hurricanes can be responsible for multiple types of hazards such as extreme precipitation, tornadoes, or storm surges. The latter are the most dangerous and have the highest potential to cause catastrophic damage. Because of that, and due to the availability of long observational records from tide gauges, high coastal sea levels are often used as proxy to unravel the relationship between the variability in tropical cyclone activity at interannual to multidecadal time scales and climate variability/change. For Florida in particular, a strong relationship exists between extreme sea levels observed during the Atlantic tropical cyclone season and the Atlantic Multi-decadal Oscillation (AMO), which in turn is related to the size of the Atlantic Warm Pool that can favor the development of tropical cyclones; e.g., more landfalling cyclones were observed in AMO warm phases (Park et al., 2010a, 2010b). This leads to significant multi-decadal variations in extreme sea levels, as shown in Wahl et al. (2015, 2016), for the one in 100-year return water level (with a 1% probability of being exceeded in any given year) that is often used for design purposes by engineers or to define flood zones.

Another data source for this type of analysis is the "best-track" data (or HURDAT, which is short for HURricane DATabase) maintained by the National Hurricane Center. It contains information on a range of hurricane parameters (e.g., wind speed, central pressure, track), but it is considered more inhomogeneous due to rapid developments in observation techniques, for example, the use of aircrafts in the 1940s and satellites in the 1960s. The data show that ENSO also plays an important role in the variability of cyclone genesis at interannual time scales. Collins and Roache (2010) noted the presence of El Niño, when equatorial sea surface temperature is warm, inhibited tropical cyclone activity in the Atlantic for the 2009 season. On the other hand when equatorial sea surface temperature is cold (La Niña periods), hurricanes are more likely to affect the United States. The North Atlantic Oscillation (NAO), on the other hand, modulates the storm tracks and hence landfall locations; e.g., more hurricanes tend to affect the U.S. Gulf and southeast coast in years with below average NAO values (Elsner et al. 2001; Elsner 2003).

Florida's Record Maximum and Minimum Temperatures

Florida's all-time maximum temperature of 43° C (109° F) occurred on June 9, 1931 in Monticello (Jefferson County), just east of Tallahassee. Interestingly, the locations of Florida's all-time maximum and minimum temperatures are separated by only 64 km (40 mi). The all-time minimum temperature for Florida of -19° C (-2° F) occurred on February 13, 1899 in Tallahassee during an Arctic outbreak that impacted the entire eastern U.S. from February 10-13, 1899.

Historical Freezes in Florida

Several factors lead to freezes in Florida including: an air mass that becomes stationary in the frigid Arctic darkness, wind flow that then steers the air mass southeast through Canada, and preceding cold weather and snow cover along the path of the air mass over the central and eastern U.S. The following briefly summarizes Florida's historical freezes as noted by Citrus Mutual (2016).

Maximum and Minimum Temperature Potential

Identifying where temperature extremes occur enables us to understand where populations, crops, livestock, and infrastructure are most at risk. Utilizing 30 years (1985-2015) of daily temperature data from the National Climatic Data Center produces an average annual number of days where the daily low temperature has been below 32° (Fig. 20.17) or above 95° (Fig. 20.18). These visualizations enable planners and emergency managers to more completely identify where heat or cold protection might be needed or where crop losses may be expected.

Patterns of freezing temperatures follow a typical north-south trend where the panhandle has a higher frequency of freezing days compared to the southern part of the peninsula. This area abuts in the east to an area with a mixture of moderate to high freeze frequency: from Washington County in the panhandle, east to western Nassau, Duval and Clay counties, and south to northern Levy County.

Interestingly, the pattern of heat hazard days (above 95°) mimics cold days, for the most part, with a few notable exceptions (Fig. 20.18). The areas of highest heat hazard threat include Gadsden County south to the Gulf of Mexico, a small portion of Polk County in Central Florida, and a large portion of eastern Collier and northern Monroe counties. A large area extending from Jefferson County in the northeast to Baker and Clay counties, snaking south through Central Florida to Polk County, has at least a moderate frequency of heat hazard days.

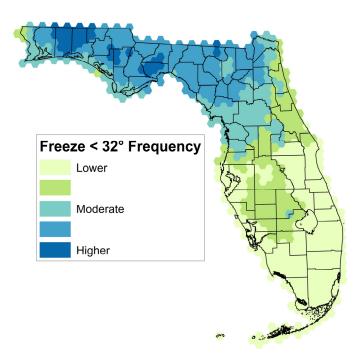


Figure 20.17. Frequency of temperatures below 32° F.

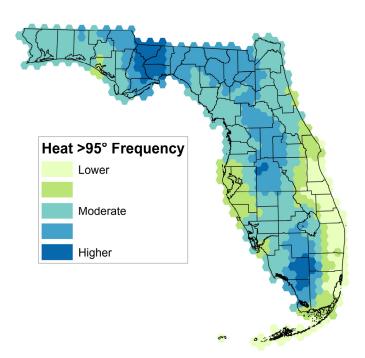


Figure 20.18. Frequency of temperatures above 95° F.

Temperatures and Climate Variability

Arctic outbreaks that create major freezes in Florida occur roughly every 10-20 years mainly during neutral ENSO or weak La Niña conditions, but they have also been observed in years with a positive ENSO index (Martsolf 2001; Gato-Maeda et al. 2008). A stronger connection exists between extreme freezes in Florida and the climate over the North Atlantic, as represented by the Arctic Oscillation (AO) or NAO (e.g. Wang et al. 2010). If those oscillations are negative, it means that there is higher than normal pressure over the North Atlantic and a lower than normal pressure in the equatorial Atlantic. This results in more storms affecting the northern part of Florida and increases the chances that polar air will be transported south. It has been shown, for example, that there is a 50% chance of a freeze when the AO index has extreme negative values, but close to a 0% chance in periods with extreme positive AO values (Hagemeyer 2007).

Heat waves and climate variability have been studied in Florida. Keellings and Waylen (2015) noted that the models indicate heat wave impacts are geographically opposing, resulting from warm or cool phases of ENSO. More intense heat wave events (in terms of increased magnitude, frequency, duration, and earlier timing) are brought to South Florida during the warm phase but at the same time there are diminishing events in the north. Alternatively, the cool phase ENSO amplifies heat wave events in North Florida while diminishing events in the south. Keellings and Waylen (2015) further noted that the warm phase of the AMO brings heat waves earlier in the summertime while also increasing their magnitude, frequency, and duration. This is consistent with other studies.

Outlooks into the Future

Attributing climate extremes and developing robust projections for the future remains a formidable challenge. And although models tend to agree (at least on the direction of expected changes) for near-term projections, the signals themselves are often small compared to the internal variability in the system. For longer time scales, different approaches and models may lead to more contrasting results, even in the direction of changes (IPCC 2012). One complication exists due to the fact that changes may be driven by competing factors. For example, while a warming of sea surface temperature favors the genesis of cyclones, an increase in the vertical wind shear in a warmer climate may have the opposite effect (although it may be minor) (Bruyère et al. 2012; Vecchi and Soden, 2007). However, a consensus has been reached among scientists, based on results derived with different methods, that the frequency of tropical cyclones will decrease in a warmer climate but that the intensity will increase (Bender et al. 2010; Knutsen et al. 2010), globally and in the Atlantic Basin. Uncertainties in regional projections of changes in tropical cyclone activity are even larger than those for global (average) projections (Christensen et al. 2013). For the southeastern U.S., Grinsted et al. (2013) used long tide gauge records as proxies for hurricane activity and applied a statistical downscaling approach that linked hurricane

storm surge activity to changes in global sea surface temperature. They reported that a 1° C increase in global sea surface temperature could lead to a significant increase (two- to seven-fold) in the frequency of Katrina-like hurricane events. Although uncertainties in projections of tropical cyclone activity remain large, it is very likely and expected that continuous and potentially accelerating global (and regional) mean sea level rise will increase the storm surge potential along major coastline stretches, including Florida's, by shifting the base water level for storm surges upwards (Hunter 2012; Hunter et al. 2013).

Future changes in precipitation extremes during the summer season are closely linked to changes in tropical cyclones (Misra et al. 2011), as the latter contributes significantly to the number of extreme rainfall events observed throughout the state. For a high greenhouse gas emission scenario (Representative Concentration Pathway (RCP) 8.5) and the target year 2050, Gao et al. (2012) found an increase of ~20% (302 mm/yr to 365 mm/yr) in the annual total of daily extreme precipitation, but smaller changes (~5% increase) in the frequency of daily extreme events.

In addition to an increase in the mean global temperature, climate models also point to an increase in extreme heat wave events (combined high temperature and humidity) in the state of Florida, where 10 cities with the greatest expected increase in the number of dangerous heat days (i.e., heat index that combines temperature and humidity exceeds 104°F) by 2050 are located; as many as 130 dangerous heat days could occur by 2050, compared to 25 under the present climate (Climate Central 2017). Later in the century (2080 to 2100), extreme heat events that currently have a 5% probability of occurrence in any given year are projected to have a 50% to 100% chance of occurrence (Melilo et al. 2014).

Romps et al. (2014) suggested that the lightning flash rate is proportional to the convective available potential energy (CAPE) times the precipitation rate and, when applied to 11 climate models, CONUS lightning strikes were predicted to increase $12 \pm 5\%$ per degree Celsius of warming. Using 2003-2012 cloud-to-ground lighting data across the U.S. from the National Lightning Detection Network (NLDN), Koshak et al. (2015) found a 12.8% downward trend in total cloud-to-ground lightning count for the 10-year period, although the authors found a slow upward trend in the number of positive-polarity flashes. This was during a time when temperatures were warming but moisture trended downward.

Conclusion

This chapter describes various types of climate-sensitive extreme weather events relevant to the state of Florida. For each type of extreme event, the atmospheric/oceanographic conditions for its formation are summarized, the spatial variability of the potential for the different hazard types is depicted, and the links to large-scale climate variability are discussed.

Potential future changes in (selected) climate extremes in Florida are also briefly discussed, highlighting that large uncertainties continue to exist in the projections of such events. For most types of hazards, especially when focusing on individual events, it is challenging to attribute changes to anthropogenic influences given the strong variability in extremes in combination with strong seasonal to multi-decadal fluctuations compared to the small underlying low-frequency signal (IPCC 2012). In general, there is more confidence in the attribution of observed changes in the mean climate, which can in turn affect the risk imposed by certain extreme events (e.g. mean sea level rise shifting the base water level for storm surges upwards). Two distinct methods can be used for the attribution. The first one relies on observational records to determine potential changes in the frequency or magnitude of extremes. For this kind of analysis, the record timescales need to be long enough to account for a robust separation of natural variability and longer-term trends associated with anthropogenic influences. This is often not the case and hampers attribution. The second approach uses models that can be run over long time periods, with and without assuming a world that is affected by human-caused climate change. This is done by ignoring or including the changing concentration of greenhouse gases and aerosols in the atmosphere and comparing the results from unforced (control) runs and forced runs. In this approach, uncertainties can be large because some extremes are more challenging to model than others and may not be captured very well in the simulations, (e.g., due to insufficient spatial resolution). Often, a combination of both methods is required (i.e., validation of the models' ability to reproduce observations) and, when combined with sound physical principles, leads to the most robust results (NASEM 2016).

Extreme weather will continue to impact Florida in the future. It is the rapid changes in climate that can have a devastating effect on life on Earth, as humans contribute to a warming climate. For Florida, this could mean prolonged drought at one end of the state and flooding rains at the other end. It could also be an increase in devastating tropical cyclones. As sea levels rise, human habitations in low-lying coastal areas will become repeatedly inundated with these extreme weather events, eventually resulting in mass migrations to higher ground.

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