Catastrophic Weather Perils in the United States | Climate Drivers

Table of Contents

INTRODUCTION

The last 10 years have seen a variety of weather perils cause significant insured losses in the United States. From the wild fires of 2003, hurricanes of 2004 and 2005, to the severe thunderstorm events in 2011, extreme weather has the appearance of being the norm. The industry has experienced over $200B in combined losses from catastrophic weather events in the US since 2002.

While the weather is often seen as a random, chaotic thing, there are relatively predictable patterns (so called "climate states") in the weather which can be used to inform our expectations of extreme weather events. An oft quoted adage is that "climate is what you expect; weather is what you actually observe." A more useful way to think about the relationship between weather and climate is that the climate is the mean state of the atmosphere (either locally or globally) which changes over time, and weather is the variation around that mean.

This paper will examine the climate states that drive, to greater or lesser extents, the extreme weather events experienced in the United States, specifically: hurricanes, severe thunderstorm, and wild fire[1]. The aim is not to provide a complete description for extreme weather but a helpful guide to understanding some of the influences on catastrophic weather events.

ATLANTIC HURRICANES

Formation

For hurricanes to form, several atmospheric and oceanic conditions need to be present:

- **Warm Sea Surface Temperatures.** Oceanic heat is the energy source for hurricanes. Temperatures in excess of 26.5°C are required for tropical cyclones to form ("cyclogenesis"). This is the primary reason why hurricane formation is generally restricted to the period from June to the end of November – beyond this, the waters of the Atlantic are too cold to support cyclogenesis.
- **Low Wind Shear.** Wind shear acts to disrupt the structure of a tropical cyclone.
- **High Atmospheric Moisture.** Water vapor in the atmosphere surrounding a tropical cyclone mediates the transfer of energy from the ocean to the tropical cyclone; dry air reduces the ability of the tropical cyclone to draw energy from the ocean. Typically, hurricanes pick up ("entrain") dry air from over the land as they approach landfall, which is one reason why hurricanes often weaken in the 12-24 hours prior to landfall.
- **Good Outflow.** Tropical cyclones draw in warm, wet air at the ocean's surface, use the energy contained to sustain or intensify the storm, and expel cold, dry air from the top of the storm. If the cold, dry air is not allowed to escape effectively, then the strength of the storm can be significantly reduced.
- **Low Atmospheric Dust.** Dust in the atmosphere (in the Atlantic, "dust" usually means sand and soil lifted into the atmosphere from sub-Saharan Africa) acts to reduce the amount of sunlight reaching the ocean and the lower atmosphere by reflecting the sun's radiation back to space. When there is high dust content, the ocean and the lower atmosphere cool, meaning there is less energy for a tropical cyclone to use.

Wind Shear

The changing of wind speed and direction with height in the atmosphere.

Water Vapor

Water in the atmosphere in the gaseous state.

An analogy can be drawn between a hurricane and an automobile engine. The sea surface temperature represents the fuel going into the engine – the more fuel (heat), the more power the engine produces (stronger storm). The wind shear represents the timing of the engine – if the timing of the engine is off (high wind shear), the engine cannot produce full power (weaker storm). The water vapor represents the oil lubricating the engine – if the engine is not well lubricated (low water vapor content), then the engine is not as efficient as it can be (storm weakens). The outflow represents the engine's exhaust – an efficient exhaust (good outflow) allows the engine to develop full power (stronger storm). Finally, the dust represents contaminants in the fuel – if there are more contaminants (higher dust), the fuel cannot burn as effectively (weaker storm). We note that of the five necessary conditions for hurricanes to form listed previously, only two of them (sea surface temperature and wind shear) have strong correlations to climate variability. These will be discussed below.

Climate Impacts

Atlantic Sea Surface Temperatures

The tropical Atlantic has seen changes in its sea surface temperature (SST), relative to the average. Figure 1 below shows the SST anomaly (deviation from the average) since 1982 for the region of the Atlantic around 10°N. What can be clearly seen in Figure 1 is that the tropical Atlantic has warmed since the late 1990s with the strongest warming (largest positive anomalies) seen in the period since 2004.

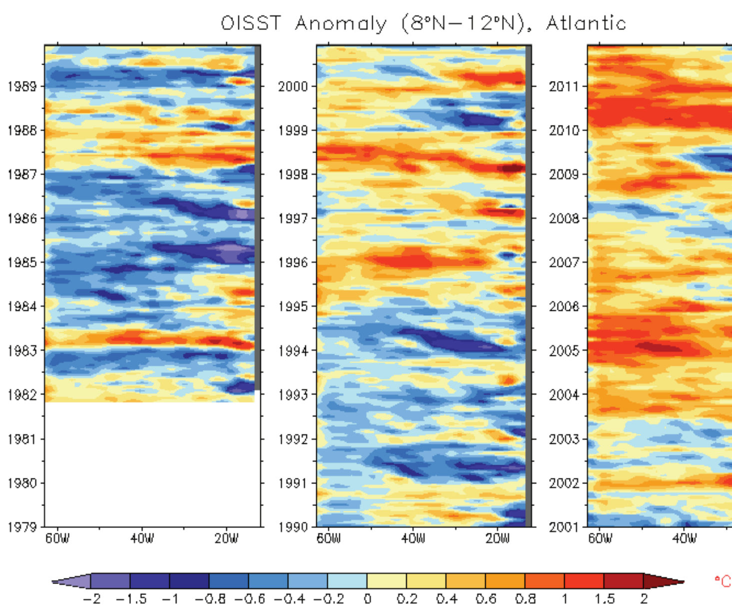

FIGURE 1: Tropical Atlantic Sea Surface Temperature Anomaly
(SOURCE: NOAA Climate Prediction Center)

The wide consensus of scientific opinion is that this warming is a function of a natural variability in the Earth's climate system, known as the Atlantic Multidecadal Oscillation (AMO). The AMO was first identified in 1994[2] and is thought to be related to small changes in the deep currents flowing through the Atlantic (the Thermohaline Circulation). AMO cycles have been observed for the last 150 years, with varying degrees of accuracy and reliability, and the length of each warm or cool period is observed to be in the range 20-40 years. We note, however, two important points:

1. The AMO has a purported length (from the opening of a cold phase to the closing of a warm phase) of around 70 years, however, the 150 years of observations we have are not enough for traditional statistical techniques to definitively confirm whether the AMO exists as a real oscillation in the climate system. The inference that the AMO is real is based mostly on computer modeling of the Earth's oceans (models produce an oscillation very much like the AMO) and also on longer time series of SSTs based on proxy methods. The jury remains partially out on whether the AMO actually exists.
2. There is no demonstrated predictability for the AMO; computer models are unable to provide any definitive guidance as to when the current warm phase of the AMO may end. The supposition is that the current warm phase, if the AMO is real, will peak around 2020.

The main issue clouding the firm attribution of changes in Atlantic SSTs to the AMO is anthropogenic (i.e., caused by human activity) climate change. That the Earth has warmed over the last 50 to 100 years is beyond doubt, and this warming has likely warmed the Earth's oceans. This has introduced a signal into the data used to classify the AMO. In 2006, Kerry Emanuel (MIT) and Michael Mann (Penn State) postulated that the recent warming of the Atlantic could be explained without recourse to the AMO at all; Emanuel and Mann posited that the changes in Atlantic SSTs are caused by a combination of global warming and aerosol cooling[3]. The debate, AMO versus global warming/ aerosols, has yet to be resolved. However one point is clear: whichever theory is proved to be correct, the tropical Atlantic is warm and will remain so for at least the next 10-20 years.

Regardless of the reason for warm SSTs in the Atlantic, warm SSTs are indeed well correlated with Atlantic hurricane activity. Figure 2 below shows the North Atlantic Tropical SST Index (NTA[4]) and the anomaly of named storms[5]. As can be seen, tropical cyclone activity is generally higher than the average (Named Storm Anomaly is positive) when Atlantic tropical SSTs are warmer than average (NTA values are positive).

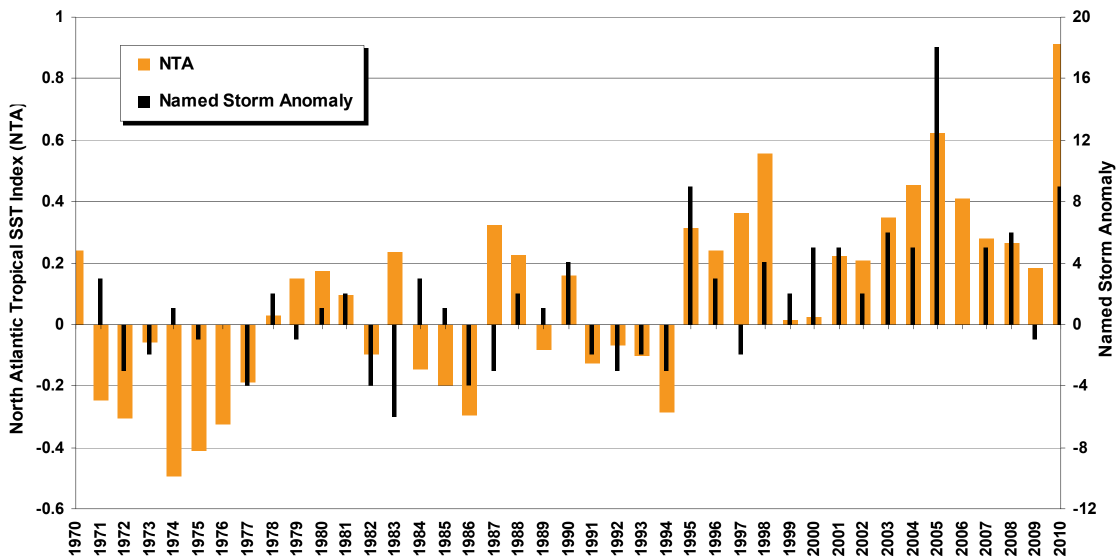

FIGURE 2: Tropical Atlantic SST Anomalies vs. Named Storm Anomalies
(SOURCE: NOAA Climate Prediction Center)

El Niño Southern Oscillation (ENSO)

The El Niño Southern Oscillation (ENSO) is a well researched, if not entirely well understood, natural oscillation in the Earth's climate system, and it has a major effect on wind shear over the tropical Atlantic. It is generally characterized as a cycle of warming and cooling of the equatorial Pacific Ocean although this cycle also encompasses changes in rainfall, surface air pressure, and atmospheric circulation across the Pacific and into the Atlantic. ENSO has three primary states:

1. **Neutral.** This is the average state with no overall impact on climate.
2. **El Niño.** This is the state of ENSO denoted by warm equatorial SSTs (often called the warm phase of ENSO). El Niño, "the little boy" in Spanish, or "the Christ child," derives its name from the warming that occurs off the coast of South America typically around Christmas as part of the warming phase.

Historical Impacts

A recent study has suggested that a strong El Niño between 1789-1793 caused a series of poor crop yields across Europe which is seen as one of the causes of the French Revolution.

El Niño has a wide variety of impacts around the globe:

- In the US, winters in the Northwest and Upper Midwest are warmer and drier than average with reduced snow, while winter in California and much of the Southern US is cooler and wetter than average. Summers in the Northwest and Upper Midwest are wetter than average.
- Most of Asia bordering on the Pacific is warmer than average during an El Niño winter with much of Indonesia and Australia drier and cooler than average during an El Niño summer (southern hemisphere).

3. **La Niña.** This is the state of ENSO denoted by cool equatorial SSTs (often called the ENSO cool phase). La Niña, "the girl" in Spanish[6], is the opposite of El Niño.

- In the US, the Northwest and Midwest are wetter during La Niña winters, and the Southern US is drier and warmer than average.
- Indonesia is wetter during La Niña winters, while summers across Australasia are wetter and warmer than average (for summers in the southern hemisphere).

Figure 3 shows the SST patterns indicative of El Niño and La Niña.

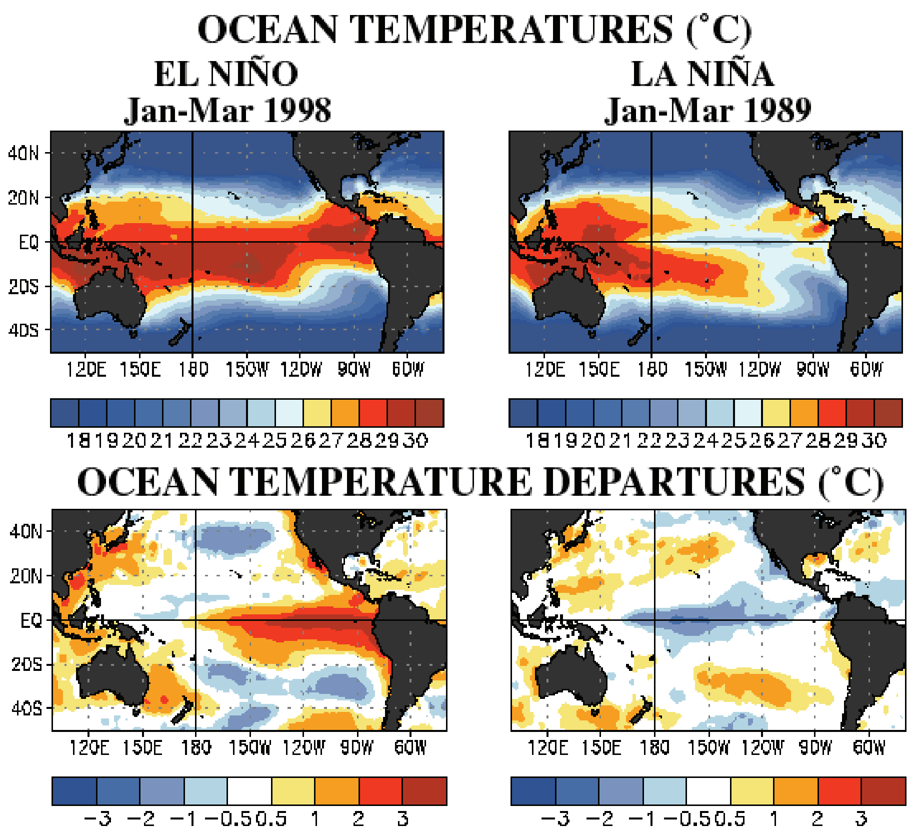

FIGURE 3: El Niño and La Niña SST Patterns

(SOURCE: NOAA Climate Prediction Center)

Each ENSO phase can persist for one or even two years (with the average around 9-12 months), and a typical cycle repeats every 3-5 years. The cause of ENSO is an area of very active academic research. The basic theory is that ENSO is caused by the interaction of two different sets of waves traveling across the equatorial Pacific[7]. However, the actual mechanism is poorly understood and hard to model. For this reason, models of ENSO generally do not perform well, and we have limited ability to predict ENSO. Peculiarly, there exists a "Spring Barrier" to ENSO prediction making ENSO forecasts much less reliable through the northern hemisphere spring; it is not clear why this should be.

ENSO is a major factor for hurricane activity. The ENSO cycle, as one of its effects, changes the level of wind shear over the tropical Atlantic:

During El Niño (warm phase), the upper levels of the atmosphere see increased westerly winds and increased easterly winds at lower levels. These changes in winds aloft increase the amount of vertical wind shear over the tropical Atlantic leading to less hurricane activity. Hurricanes that do form during El Niño tend to be weaker and shorter-lived.

During La Niña (cold phase), the situation is reversed – increased easterly winds at upper levels, increased westerly winds at lower levels. This situation acts to reduce vertical wind shear over the tropical Atlantic creating the potential for increased hurricane activity.

The impact of ENSO on hurricane activity is seen in Table 1 below. It shows plainly that hurricane activity is suppressed during El Niño (warm phase). It is less clear that there is much distinction between La Niña (cold phase) and Neutral; while La Niña does show more activity than Neutral, the difference is not large and is not statistically significant (at the 90% confidence level). Looking at two different time periods (1951-2000 and 1951-2010), the same pattern is evident although the average incidence of named storms increases when the period 2000-2010 is added to the sample. This is to be expected given the large increase in hurricane activity seen during this period. The averages of La Niña and Neutral become closer when the years 2000-2010 are included, which is mainly a function of adding in the 2005 hurricane season when 28 named storms formed during a Neutral year.

PERIOD	ALL YEARS	COLD PHASE	NEUTRAL PHASE	WARM PHASE
1951-2000	10.0	10.8	10.2	8.6
1951-2010	10.9	11.6	11.5	8.9

TABLE 1:
Average Named Storm Count Per Year By ENSO State
(SOURCE: Named Storm Data From NOAA CPC; ENSO Years From FSU COAPS)

Given the activity data, a more discriminating rule of thumb for the current period of hurricane activity becomes clear: hurricane activity will likely be above average unless an ENSO warm phase (El Niño) is present. ENSO cool phase (La Niña) and ENSO Neutral both lead to increased activity or, at least, neither suppresses hurricane activity.

A final quirk in the ENSO story has come to light only in the last few years – the existence of the Modoki El Niño. Modoki is Japanese for “similar, but different” and a Modoki El Niño has a warm pool of water form in the central Pacific rather than along the eastern and central Pacific[8]. The cause of this shift in the structure of El Niño is not understood although some studies have posited a link between global climate change and the existence of Modoki El Niño. The effects of Modoki El Niño on hurricane activity may be significant; there is some evidence that landfalling hurricanes occur more frequently during a Modoki El Niño. As seen above, a traditional El Niño suppresses hurricane activity, whereas a Modoki El Niño might actually increase hurricane activity. However, few Modoki El Niño cycles have been seen and the correlation between Modoki El Niño, and hurricane activity lacks statistical weight at this time. Little work has been done so far to see if La Niña is also potentially changing.

North Atlantic Oscillation (NAO)

The North Atlantic Oscillation (NAO) is a pattern of natural variability affecting the North Atlantic region. There are two dominant high and low pressure systems that generally exist over the North Atlantic – the Icelandic Low (an area of low pressure that generally sits centered around Iceland) and the Azores High (an area of high pressure, generally centered around the Azores). East-west oscillations in the Icelandic Low and Azores High give rise to the NAO.

The positions of the Icelandic Low and Azores High control the strength and direction of westerly winds in the northern Atlantic and, as a consequence, the direction of storm tracks across the Atlantic. First discovered in the 1920s, the NAO is primarily an atmospheric phenomenon with little or no coupling to oceanic variability (contrast with ENSO which is an oceanic variability that is linked, or coupled, strongly to the atmosphere). The NAO varies over time but tends to stick in one state for intervals of several years. Notwithstanding this, the NAO has little predictability. The NAO is closely related to other climate modes of the Northern Hemisphere, most closely to the Arctic Oscillation (AO)[9]; indeed, there is an ongoing debate in the academic world as to whether the NAO and the AO are simply different expressions of the same phenomena.

The NAO has a well-defined index which is taken as the difference in pressure between Reykjavik, Iceland, and Ponta Delgada in the Azores[10]. The NAO has two phases:

1. **Positive (NAO+).** During the positive phase, the Icelandic Low is deeper than average, and the Azores High has a higher pressure than average. This leads to the NAO Index having a higher than average value. NAO+ years show more frequent, and stronger, winter storms crossing the Atlantic by a more northerly track. Winters in Europe are typically warm and wet, with cold, dry winters in Canada and mild, wet winters along the Eastern US.
2. **Negative (NAO-).** During the negative phase, both the Icelandic Low and the Azores High are weaker than average, giving an NAO Index lower than average. NAO- years have fewer and weaker storms crossing the Atlantic; those that do form take a more west-east track. This brings warm, wet air to the Mediterranean and cold, dry conditions to northern Europe. The Eastern US sees colder and snowier winters.

While the NAO has its major effects during northern hemisphere winters, by controlling the position of the Azores High, the NAO also influences the direction of hurricanes. Note that the NAO does not influence hurricane activity but does play a major role in where hurricanes go when they form.

- **NAO+:** A positive NAO is associated with a stronger, more easterly oriented Azores High[11] which generally allows hurricanes to take a more northerly track. During NAO+ years, hurricanes are more likely to either approach the East Coast of the US or recurve away from the US entirely.
- **NAO-:** A negative NAO is associated with a weaker but more westerly oriented Azores High. This prevents hurricanes from taking a northerly track, forcing them to travel east-west. This results in hurricanes being more likely to impact the southeastern US and the Gulf of Mexico.

Quasi-Biennial Oscillation (QBO)

The Quasi-Biennial Oscillation (QBO) is a regular reversing of the winds at high altitude near the Equator. The period of the QBO is approximately 28 months with a longest observed period of 36 months and a shortest of 20 months. When the QBO is in the so called “westerly” phase, the high altitude winds flow against the prevailing trade winds, producing low wind shear in the region close to the Equator. During the corresponding easterly phase, the high altitude winds flow with the prevailing trade winds and increase wind shear near the Equator; the easterly phase is typically twice as strong as the westerly phase.

The QBO was first discovered in the 1950s, although a theoretical explanation for it was not found until the 1970s. The theory, in essence, states that wind reversal is driven by gravity waves from the troposphere traveling upwards and dissipating in the stratosphere.

Given that the QBO is seen to moderate tropical Atlantic wind shear, it is natural to expect that the QBO would have some impact on hurricane activity. Indeed, up until the mid-1990s this was the case. In work detailed by the Australian Bureau of Meteorological Research[12], during the period 1950 to 1990, an average of 11.5 named storms formed during the westerly phase as compared to 8.5 during the easterly phase, with almost twice as many hurricane days (days with active hurricanes) during the westerly phase relative to the easterly phase. However, recent work[13] has shown that the relationship between the QBO and hurricane activity has broken down and is no longer present; no reason for this change has been definitively found.

One impact from the QBO on hurricanes have been found to persist, however. During the westerly phase (i.e., when there is low wind shear near the Equator), hurricanes are more likely to form near the Equator. These storms are of the classic Cape Verde-type (i.e., long-lived storms forming in the deep tropical Atlantic near the Cape Verde islands). Conversely, during the easterly phase (i.e., high wind shear near the Equator), hurricanes are more likely to form away from the Equator. Looking at the 2005 and 2006 hurricane seasons, this reasoning is borne out:

- In 2005, which was a QBO easterly year, the average latitude and longitude of hurricane formation was 20.6N, 66.9W. 2005 was the most active year on record, but very few of the storms that year were of the Cape Verde-type; the majority formed closer to land.
- In 2006, which was a QBO westerly year, the average latitude and longitude of hurricane formation was 18.8N, 52.6W. 2006 saw much lower activity but, of the storms that did form, the preponderance were Cape Verde storms and they remained harmlessly at sea.

One result of storms forming deeper (i.e., further south and east) in the Atlantic is that it gives them longer to be influenced by steering currents (such as the NAO) and the likelihood is that storms forming in the deep Atlantic will rarely approach land. The QBO, then, can be used as climate diagnostic after all – during QBO easterly years, storms will form closer to land increasing the likelihood of a landfall; during QBO westerly years, storms will form in the deep Atlantic and are less likely to make a landfall.

Summary

Hurricane Activity

ATLANTIC SSTs	ENSO	LIKELIHOOD
Warm	Cool Phase (La Niña) or Neutral	Increased Activity
Cool	Warm Phase (El Niño)	Decreased Activity

Hurricane Steering

NAO	LIKELIHOOD
Positive	East Coast US Landfall or a Miss
Negative	Southeastern US Landfall or Gulf of Mexico

QBO	LIKELIHOOD
Westerly	Less Likely to Make Landfall; Greater Influence of NAO
Easterly	More Likely to Form Near Land, Make Landfall; Less Influence of NAO

SEVERE THUNDERSTORMS

Formation

Severe thunderstorms comprise four different types of atmospheric peril:

1. **Tornadoes.** These can be described as small areas of intense low pressure around which winds can reach in excess of 280mph. The diameter of tornadoes range from 300 to 2,000 feet. As tornadoes are local events for which actual wind measurements are scarce, they are typically classified on the Fujita (or Enhanced Fujita) Scale which assigns an approximate range of wind speed based on a subjective analysis of the damage caused by the tornado.
2. **Hail Storms.** These are simply intense thunderstorms that have enough internal convection for water and ice particles to grow to diameters of upwards of an inch. Such hailstones, especially when accompanied by strong winds, can cause significant property and crop damage.

3. **Straight-Line Wind.** These storms are a significant, damage-causing component of thunderstorms. These storms, often called "downbursts" or "microbursts", are simply areas of rapidly descending rain and wind from inside a severe thunderstorm cell. Wind speeds in some of the stronger downbursts can reach 100 or 150 mph.

4. **Derecho.** This is another common type of straight-line wind which is created by the merging of many thunderstorm cells into a cluster or solid line extending for many miles.

Severe thunderstorms can occur throughout the world, anywhere warm moist air is lifted. The rise may be initiated by any or all of the following:

- Unequal heating of the surface
- Effect of terrain
- Lifting of air along a frontal zone
- Diverging upper level winds

The Great Plains region of the US is most prone to the development of the kind of thunderstorms that produce hail, tornadoes, and other damaging winds. The Great Plains are susceptible because of cool and dry upper-tropospheric air from the Rocky Mountains mixing with warm and moist surface air from the Gulf of Mexico over a region of relatively flat topography. Severe thunderstorms can also be created during hurricanes. Almost all hurricanes affecting the US spawn at least one tornado.

Climate Impacts

El Niño Southern Oscillation (ENSO)

As discussed earlier, ENSO has the potential to influence weather across much of the United States. It is natural, therefore, to assume that ENSO has the potential to influence severe storm activity.

Unfortunately, there is little academic work on this subject and what does exist is often contradictory. One major issue is that tornado data are not reliable further back in time than the mid-1970s. From the mid-1970s onwards, weather radars were in wide use across the United States, meaning that most, if not all, of the tornadoes that formed were observed. Prior to this, however, tornadoes were only entered into the record if they were actually observed by a person or there was physical proof (i.e., damage) that one had occurred. Consequently, the tornado record prior to the mid-1970s suffers from a significant under-reporting bias. Given this data issue, correlations of severe storm activity with ENSO have had to rely on small sample sizes and lack statistical credibility.

From the data we do have available, there are indications that during El Niño (ENSO cold phase) tornado activity is suppressed. This is borne out by work from the late 1990s and early 2000s[14] which has shown the general tendency for decreased tornado activity to be correlated with El Niño and increased tornado activity to be correlated with La Niña. The general supposition is that during La Niña the southern US is generally warmer than normal, and the north-south temperature gradient across the US is increased; this increased gradient strengthens the jet stream across the US, which provides some of the energy used to create severe storms.

It is worth reiterating the words of caution above – all academic work so far produced that links ENSO and severe storm activity is based on limited data and therefore has limited statistical validity. It is doubtful, given the locally weather-driven nature of severe storms, that ENSO could explain more than 10% - 20% of the variance in activity.

Pacific Decadal Oscillation (PDO)

The Pacific Decadal Oscillation (PDO) is a naturally occurring climate variability in the Pacific Ocean. The PDO is often described as being ENSO-like, however, it differs in two important respects:

1. The primary signal of the PDO (warming and cooling of Pacific SSTs) is observed above 20N in the Pacific (the primary ENSO signal is a warming/cooling along the Equator).
2. The PDO has a time scale of 50-70 years (each warm or cool phase lasting 20-30 years), which contrasts with the ENSO timescale of 3-5 years.

The cause of the PDO is presently under investigation and no theory has gained primacy. The pattern of the PDO is shown below in Figure 4.

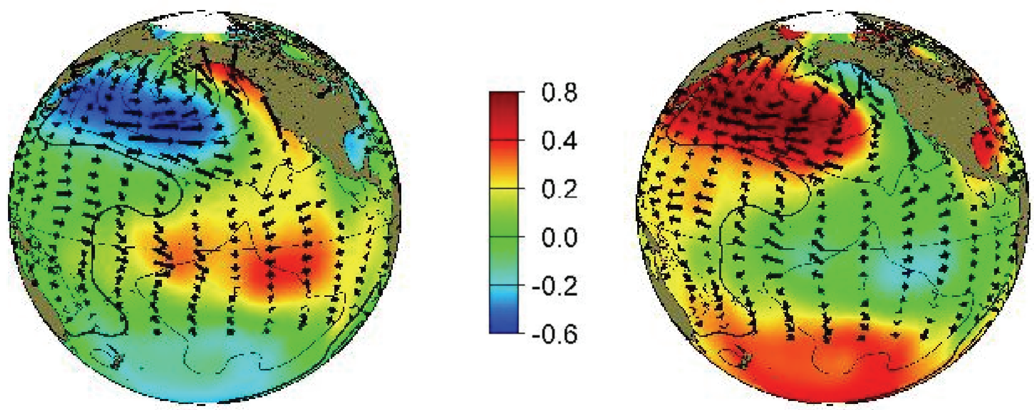

FIGURE 4:
Pacific Sea Surface temperature Anomaly Patterns Associated With Warm (Left) and Cool (Right) Pacific Decadal Oscillation Phases
(SOURCE: JISAO, University of Washington)

Some recent studies have found that there is an elevated risk of severe storm activity during a PDO negative (cold) phase during the late spring and early summer in the United States and a reduced risk during PDO positive (warm) phase. We caution that some of the studies showing this correlation are preliminary, but the indications are that the PDO has a measureable correlation to severe storm activity.

Other Climate Impacts

Beyond the somewhat tenuous ENSO connection, there is little evidence that severe storms are significantly influenced by other climate variabilities. This is not unexpected since severe weather is just that – weather systems of the type that typically cross the United States every 3-5 days, just more intense than average. It is possible, indeed likely, that various climate patterns will ultimately impact severe storm activity by influencing the overall weather system, but given the local and highly variable nature of severe weather, pulling any pattern from the noise will require much longer datasets than are presently at our disposal.

Summary

ENSO	LIKELIHOOD
Cool Phase (La Niña)	Increased Activity
Warm Phase (El Niño)	Decreased Activity

PDO	LIKELIHOOD
Negative (Cold)	Increased Activity
Positive (Warm)	Decreased Activity

WILD FIRE

Formation

Wild fire refers to any uncontrolled fire occurring in a rural setting. Taking combustible vegetation as fuel, wild fires can occur almost anywhere except Antarctica. Wild fires can be initiated by a variety of natural (lightning, volcanic eruption) and man-made (arson, power cable arcing, accident) sources.

The type of fuel for wild fires will impact the spread and methods of subsequent control:

- **Surface Fuels (and Surface Fires).** These fires consume grass, shrubs, litter, and woody material lying on the ground.
- **Ladder Fuels (and Ladder Fires).** These consume live and dead small trees and shrubs, live and dead lower branches from larger trees, and any other biomass (lichens, moss, vines, etc.) located between the surface fuels and the tree crowns.
- **Crown Fuels (and Crown Fires).** These consume biomass suspended above ground in tree tops (or other vegetation).

Fire behavior is heavily dependent on the type of fuel being consumed. For example, an abundance of ladder and crown fuel will enable fires to climb into the crowns and will sustain crown fires once they are started. Crown fires are considered the most severe threat to the local ecology and infrastructure, given that they can rapidly kill large numbers of trees and move great distances.

MAN MADE WILD FIRE AS A WEAPON

Fire has often been used, historically, as a thermal weapon. The Scots frequently used the setting of fire as a weapon against the English in the Wars of Independence. England then used the same tactic against France during the Hundred Years War as a form of economic warfare. The Mongol armies routinely set grass fires as a distraction. Finally, the adoption of literal "scorched earth" tactics have been used widely through history up through Kitchener's use in the Boer War and the Soviet retreat from the Nazi onslaught during Operation Barbarossa during the Second World War.

Both weather and climate are major drivers of wild fire activity. An abundance of dead and/or dry fuels forms one aspect of wild fire activity – prolonged periods of drought and hot weather can create these fuels. Secondly, for a rapidly spreading fire, strong prevailing winds are requirement.

Climate Impacts

El Niño Southern Oscillation (ENSO) & Pacific Decadal Oscillation (PDO)

As is now becoming a common theme, ENSO, due its ability to impact weather across the United States, is a major climate factor influencing wild fire in the western US. In general:

- El Niño events bring drier weather to the northwestern US and wetter weather to the southwestern US.
- La Niña events bring wetter weather to the northwestern US and drier weather to the southwestern US.

The pattern of wet/dry across the western US generally crosses over (from wet to dry) around 45N (the latitude of northern California). What is generally seen in the data[15] is that the amount of area burned is higher in Washington, Oregon, and northern California during El Niño years; the area burned is higher in southern California, Arizona, Nevada, Utah, and Colorado during La Niña years. The pattern, however, is not as simple as first appears since a persistent climate state over a number of years is necessary for droughts, and thus major wild fires, to occur. Typically, one year of La Niña (for example) is not enough to see wild fire outbreaks in southern California – it is the work of several years.

The PDO (described previously) has an influence on the likelihood of western US wild fire but it does not work alone — it acts to reinforce the impact of ENSO. During El Niño, northwestern US wild fire is enhanced with a warm (or positive) PDO; during La Niña, southwestern US wild fire is enhanced with a cool (or negative) PDO.

Other Climate / Weather Variables

In the southern California area, a particular meteorological construct, the Santa Ana winds, has a distinct impact on wild fire outbreaks. The Santa Anas are winds that sweep down off the Great Basin and Mohave Desert into southern California in the late fall and early winter, often bringing very warm, dry air at great speed (wind speeds in excess of 40 mph are common). The Santa Anas with their speed, heat, and dryness can quickly create an abundance of fuel for wild fires and can fan existing wild fires. The Santa Anas are not easily predictable on seasonal time scales since they rely on a particular atmospheric set up – a high pressure over the Great Basin with a low pressure off the California coast.

Summary

	WARM PDO	COOL PDO
El Niño	Much Increased Wild Fire in the Northwestern US / Decreased Risk in the Southwestern US	Increased Wild Fire in the Northwestern US / Decreased Risk in the Southwestern US
La Niña	Increased Wild Fire in the Southwestern US / Decreased Risk in the Northwestern US	Much Increased Wild Fire in the Southwestern US / Decreased Risk in the Northwestern US

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1 We note that wild fire per se is not a true weather peril, but the causes of wild fire are primarily weather driven so it is included here.

2 Schlesinger, M. E. and Ramankutty, N., (1994). "An oscillation in the global climate system of period 65-70 years". Nature 367 (6465): 723–726

3 The Atlantic began warming in the 1960s, the postulate goes, but the warming was masked in the 1970s and 1980s by pollution, which cools the atmosphere. After the passing and implementation of the Clean Air Act in 1970, with amendments in 1990, less pollution from the US East Coast passed over the Atlantic. This allowed the warming produced by global climate change to emerge from the pollution "shadow" and we observed increasing Atlantic SSTs.

4 A measure of the deviation of the SSTs in the tropical North Atlantic from a mean taken between 1951 and 2000. A positive value shows SSTs warmer than average.

5 Anomaly of named storms relative to the average taken between 1951 and 2000.

6 La Niña is sometimes referred to as to El Viejo ("the old man")

7 These are not waves, per se, but packets of warm water traveling beneath the ocean surface. Kelvin waves travel eastwards across the Pacific. When they reach South America the waves split north/south along the coast, producing westward traveling Rossby waves. Upon reaching the western side of the Pacific, the Rossby waves produce new Kelvin waves. The non-linear interaction between the Kelvin and Rossby waves creates ENSO.

8 Technically, the warming only appears in the Nino 3.4 area of the Pacific for a Modoki El Niño as compared to the Nino 1, Nino 2 and Nino 3.4 areas seen with traditional El Niño.

9 Also known as the Northern Annular Mode or Northern Hemisphere Annular Mode (NAM).

10 Variations take the southerly point as Lisbon, Portugal, or Gibraltar. One benefit that using data from Gibraltar has is the length and quality of data collected there.

11 The Azores High is synonymous with the Bermuda High in this situation.

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Dr. Steve Smith of TigerRisk Partners has been researching weather phenomena for 20 years, including the last 12 years in the reinsurance / insurance market and has prepared this white paper on catastrophic weather perils in the United States. Dr. Smith is a Fellow of the Royal Meteorological Society, a member of the Institute of Physics, a Chartered Physicist, and holds a doctorate in atmospheric physics and a first class honors degree in physics, both from Oxford University.

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