Predicting Wildfire & Winter Storms

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Executive Summary

The Oklahoma Army National Guard identified wildfire and winter storms as among the most significant weather-related challenges to which they must respond. This study was undertaken to assess the state of knowledge of prediction of wildfires and winter storms and sources of predictability that may help the National Guard to anticipate potential deployment and training requirements.

Fire is a natural part of the environment, with a recurrence interval of about 4-6 years in Oklahoma. Fire needs fuel, heat, and oxygen. Heat is provided by high temperatures, oxygen by winds, and fuel from grasses, shrubs, and trees. Wildfire has become more frequent and more intense in recent years, particularly due to a buildup of fuels. Wildfires may become larger and more intense during drought, when there is an abundance of dry fuels. The greatest risk for large fires to occur is when there is a pocket of warm air across central Oklahoma and an approaching upper-level storm system to the west.

Winter storms are most likely to occur on the east side of upper-level low-pressure systems. Warm air moves northward, potentially creating a thin layer that may melt falling ice crystals, causing them to re-freeze on contact with the surface (ice storm) or re-freeze before reaching the surface (sleet). The depth and location of elevated warm layers is extraordinarily difficult to predict; hence the type and amount of winter precipitation is a very difficult forecast challenge. Ice storms are favored in locations north of a stationary or warm front.

Day-to-day weather conditions cannot be skillfully forecast more than about seven days in advance. Small-scale atmospheric features that are too small to resolve with observing systems and models, such as warm air rising over a parking lot, amplify or attenuate over time. These unresolved features may become dominant weather systems as time goes forward. Consequently, prediction of things like afternoon surface temperatures, humidity, and winds, or an elevated warm layer during a winter storm, can only be resolved on a matter of days.

However, larger-scale atmospheric features that set up conditions favorable for fires or winter storms may be predictable on a subseasonal to seasonal scale (about 2 weeks to 3 months). The atmosphere, ocean, land, and ice are inter-connected. As air moves around the globe, it brings characteristics of its source region. Intense tropical thunderstorms in the western Pacific Ocean can add energy to the atmosphere that can affect weather patterns in North America. These *teleconnections* mean that if we can accurately resolve conditions in the tropics and Arctic, it may give indication of future weather patterns in Oklahoma.

Ocean patterns are a critical element of the weather and climate system. Oceans are able to store – and release – vast amounts of heat, which becomes energy for the atmosphere through the process of thunderstorms. The oceans go through periods of relative warming and cooling, which affects atmospheric patterns above those regions as well as regions downstream.

The most prominent ocean pattern is the El Niño Southern Oscillation (ENSO). During an El Niño event, the tropical Pacific Ocean warms more than usual. Increased thunderstorm activity

over the warmer water transmits energy to the atmosphere, which is carried downstream and often results in stormier patterns across the Southern U.S. in winter. Its cousin, La Niña, is a cooling of tropical Pacific Ocean waters, which causes air to flow northward into Canada before plunging southward, bringing cold, dry air with it. La Niña events have been related to severe droughts in the Southern Plains during the following spring and summer.

On longer time scales, the northern Pacific and Atlantic oceans go through warm or cool phases, on the scale of decades. These persistent patterns can affect the strength and location of semi-permanent weather patterns, particularly near Alaska and in the Atlantic Ocean near Bermuda. These can affect the track of weather systems, causing cooler and drier winters in Oklahoma, or the movement of hurricanes across the Atlantic Ocean.

The atmosphere can mirror these warm and cool phases as well, although these usually change on much shorter time scales. The North Atlantic Oscillation (NAO) is an atmospheric pattern that affects the strength of a semi-permanent low-pressure system near Iceland and the Azores (Bermuda) High. When both are strong, cold air in the Arctic is kept "bottled up" to the north, but when it weakens, cold air can surge southward. Anticipating changes in the NAO can provide an indication of an impending cold air outbreak, which enhances the probabilities of winter storms.

A tropical connection, called the Madden-Julian Oscillation (MJO), is a couplet of an area of active thunderstorm development, with upward motion, with a downstream area of subsidence, causing decreased thunderstorm activity. MJO waves usually begin over the Indian Ocean and move eastward. These waves make a complete circle around the globe over 30-60 days. As the waves migrate slowly eastward, it can affect flooding, drought, cold air outbreaks, and extreme heat events over the United States.

So, while daily weather conditions are not possible to predict with any appreciable skill beyond about seven days, other Earth system models that include factors like MJO, ENSO, NAO, and other large-scale atmospheric circulations may be able to resolve features that may make atmospheric patterns supportive of significant weather events. For example, the MJO couplet could produce rising motion (low pressure) to the west and descending motion (subsidence) to the east, which causes warming at the surface. This could set up a pattern of an area of warm air with an approaching low-pressure system that would be favorable to wildfire outbreaks. Likewise, the interaction of the MJO and NAO can indicate future cold air outbreaks that could be supportive of winter storms. While such predictions cannot pinpoint locations for wildfires or winter storms, they may be useful in anticipating the need for response and provide an opportunity to begin preparations well before an event occurs.

Project Overview

The Oklahoma Army National Guard is deployed, often on short notice, for managing a number of weather-related events. In order to assist them with anticipating potential deployments, a team of researchers at the University of Oklahoma investigated predictability of weather conditions that may result in a need for deployment. In particular, through conversations with the National Guard, wildfires and winter storms were identified as the weather events that most surprise them. To address these concerns, a review of predictability was undertaken and is summarized here.

In addition to potential deployments, seasonal predictions of active wildfire or winter storm patterns may be useful for training purposes. National Guard members complete training throughout the year, but each round of training has specific features. Improving training for response to weather events has to be worked in with other training requirements. Consequently, if it appears that there is a heightened risk of wildfires in the coming months, there may not be sufficient opportunity for scheduling specialized training. Extending the outlook on potential risks allows the National Guard to schedule training to the types of events to which they are most likely to be called to respond.

The sections that follow provide an overview of atmospheric patterns that set the stage for major wildfire and winter storm events. This is followed by a discussion of weather conditions that are likely to result in significant fires or winter storms. The third section discusses global weather and climate patterns that operate on seasonal and longer time scales, but can influence daily weather patterns and make certain events more or less likely. The last section concludes with a discussion of predictability. Although individual events are difficult to forecast for more than a few days to a week, improvements in understanding the connectivity of the climate system to weather conditions provides expectations that seasonal forecasts of significant events will improve over time.

Sources of Predictability

Weather patterns evolve quickly and, as shown above, are not predictable more than a few days in advance. However, larger-scale atmospheric patterns that favor the development of surface features that can aid in active weather patterns are, to some degree, predictable on longer time scales. Ocean heat content associated with features such as the El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and Atlantic Multidecadal Oscillation (AMO), vary on the scale of years to decades, setting up jet stream patterns that affect that distribution of heat and energy around the globe. Other atmospheric features such as the North Atlantic Oscillation (NAO), Arctic Polar Vortex, and Madden-Julian Oscillation (MJO) can affect weather patterns across the globe weeks in advance.

While these large-scale features provide some indication of potential severe weather events, they are not able to pinpoint the location or time of such events. They can give an indication that storms are favorable across western Oklahoma several days in advance, but they cannot tell that a storm will affect Elk City, Oklahoma, on a particular afternoon. Related to wildfire and winter storms, it is therefore impossible to tell if major population centers are likely to be affected by an event, but it can indicate heightened risk that may warrant preparatory actions.

Global Circulation

Air movement is connected around the globe. What happens far away affects weather elsewhere. Because of this, we cannot predict weather more than a week or so in advance, but we can more successfully predict large-scale features that produce weather patterns favorable to certain local conditions, such as wildfires, winter storms, or severe thunderstorms.

Weather prediction is limited by chaos theory. Any atmospheric process re-distributes energy in a way that can amplify its effects over time. Warm air rising over a parking lot transfers energy from the Earth's surface into the atmosphere, where it may combine with (or cancel out) other energy sources, causing a change in intensity of weather features as the air moves away from the source. This was the famous "butterfly effect", where a butterfly flapping its wings in China can affect development of a thunderstorm in America. It is impossible to measure and model conditions of the atmosphere on such a fine-scale basis, so over time these unresolved variabilities become larger, eventually overwhelming the data that can be measured and modeled.

The way energy is transferred is through global circulations. Air moving from the equator toward the poles gets turned to the right in the Northern Hemisphere, creating a jet stream – a river of fast-flowing air that circulates around the entire Earth (Figure 1). Localized sources of energy, such as thunderstorms, warm oceans, or even rising thermals, affect the amplitude (or "waviness") of the jet stream, transferring that energy as parcels of air move downstream with the winds.

The waves in the jet stream produce troughs and ridges. Troughs are areas where cold air is spilling toward the equator, and ridges are associated with warm air moving from the equator toward the poles. In the northern hemisphere, this means cold air moving southward (troughs) and warm air moving northward (ridges). The jet stream flows around the base of troughs and the top of ridges, creating a wavy pattern around the globe (Figure 2). The stronger the difference in temperature, the stronger (more energetic) the jet stream will be.

As troughs move across regions with active weather or anomalous heat, such as the equatorial Pacific Ocean, energy from those heat sources is added to the jet stream. This energy is transported with the trough as it moves away from the source, affecting the orientation of troughs and ridges downstream and contributing to developing weather patterns in distant places. Thunderstorms are particularly efficient at transferring heat from the surface to the middle atmosphere, so troughs moving across regions of active thunderstorms will have a lot of energy added to the mid-levels of the atmosphere.

As troughs move eastward, they combine with other localized sources of energy, creating surface low- and high-pressure systems and fronts, which can be the formation for thunderstorms, enhanced winds, drought, and other weather features. So, while it is not possible to track the actual energy from a localized source that can lead to weather patterns far distant in space and time, it is possible to track these longer-wave atmospheric features and anticipate potentially active weather patterns even weeks in advance.

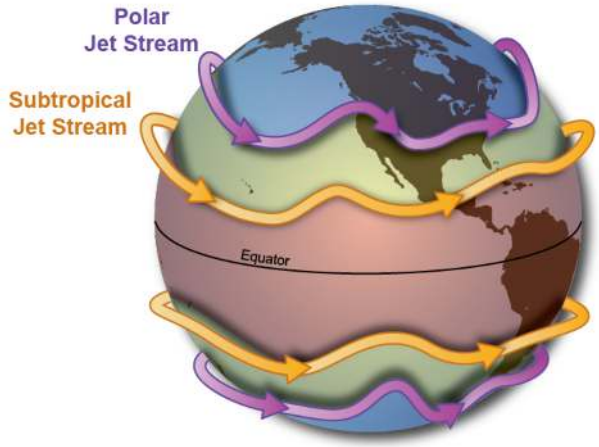

Figure 1. As air moves poleward, it gets turned because of the Earth's rotation, resulting in bands of high-speed winds that traverse the globe, known as jet streams. Source: National Weather Service JetStream.

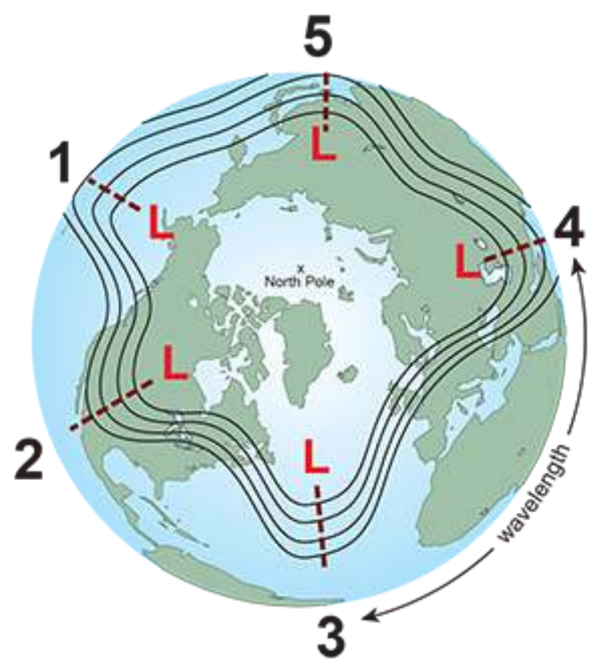

Figure 2. Troughs (dashed lines) and ridges around the globe. The jet stream flows around the base of the troughs, below the low-pressure systems (L) from west to east. Source: National Weather Service JetStream.

What Makes a Skillful Forecast?

Scientists use the concept of skill to measure the accuracy of a forecast. For weather forecasts, this is often based on how it performs to some other forecast, such as climatology. For example, if the normal (average) high temperature for a day is 90 degrees, then the climatology forecast for the day would be 90 degrees. If the weather forecast predicts 95 degrees, then the skill is measured by whether the actual temperature is closer to 95 degrees or climatology (90 degrees). If the actual high is 93 degrees, then the forecast is considered more skillful; if is 92 degrees than the climatology forecast would be more skillful. Day-by-day weather can vary greatly, so forecast errors are measured over time to determine whether they are better than the baseline forecast.

But as we mentioned, it is impossible to create a skillful forecast weeks in advance, at least on a consistent basis. Climatology will always out-perform such a long-range weather forecast. So, instead, organizations such as NOAA's Climate Prediction Center predict whether temperatures and precipitation averaged over an extended period are more likely to be above, near, or below normal. The extended period can be several days, such as their 6-10 day or 8-14 day forecasts, or longer, such as their monthly and seasonal (3-month) outlooks. These 3-category forecasts are then validated as successful if temperatures or precipitation falls within the predicted tercile (splitting climatology into 3 categories - below, near, or above).

Evaluation shows that the monthly and seasonal outlooks more often than not have a positive skill (Figure 3). This suggests an ability to anticipate large-scale atmospheric patterns months in advance, although many forecasts still fall below zero, indicating that a random forecast – or throwing darts – yielded a more accurate forecast that month. Two other caveats with these forecasts: (1) forecasts are made for broad regions, such as "Oklahoma" rather than particular places such as "Oklahoma City"; and (2) these are only predicting average conditions compared to normal over the course of the forecast period and not predicting individual storm events. Thus, it is possible to have an ice storm during a month when the monthly forecast accurately predicted warm and dry, or a wildfire during a forecast cool, wet month. It should also be noted that skill may vary seasonally (i.e., it is easier to predict conditions in some months of the year compared to others).

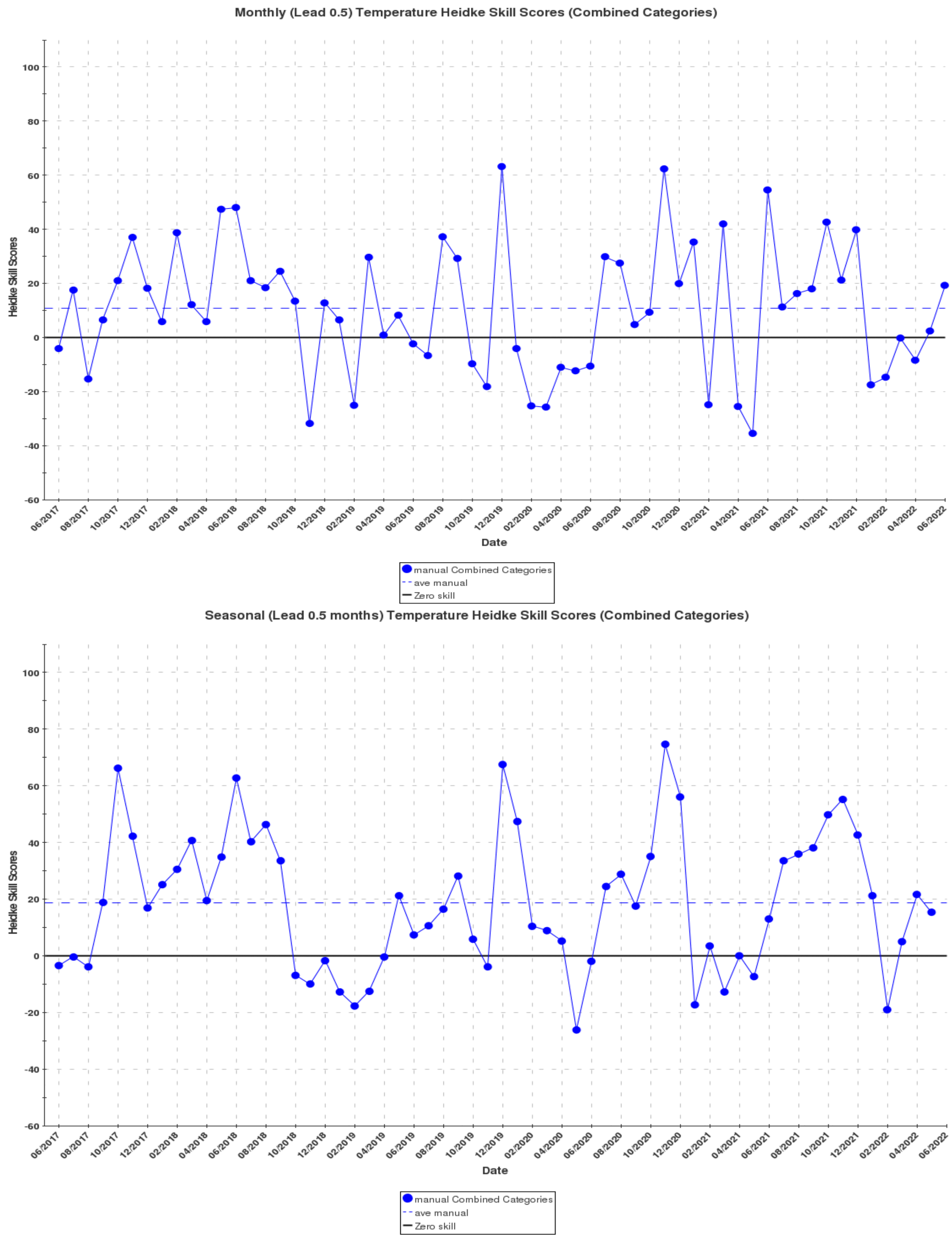

Figure 3. Climate Prediction Center skill scores for monthly (top) and seasonal (bottom) forecasts. Each dot is the forecast for a particular month during the past five years. Values greater than zero indicate an improvement compared to a random forecast. Source: NOAA Climate Prediction Center.

Weather Conditions Associated with Wildfire and Winter Storms

Predicting the outbreak of wildfires or the occurrence of winter storms more than a few days in advance is extraordinarily difficult. However, there are some atmospheric (weather) patterns that favor such events. Wildfires are more likely to occur on hot, dry, and windy days, and winter storms need a combination of shallow cold air and sufficient moisture. There are other variables that are the difference between big events and small events, or even no event at all. The status of vegetation and soil moisture play a critical role in controlling fire behavior, along with the topography, and one degree of difference in the near-surface atmosphere can be the difference between an ice storm and a cold rain.

Weather Patterns Related to Wildfire

Fire is a widespread, natural feature of the environment. It actually provides many benefits to ecosystems, but also has many negative impacts to human society. In recent years, wildfires have become larger, more intense, and more destructive. Partially, this is due to buildup of fuels. In many forested areas, decades of wildfire suppression led to accumulation of fuels – branches and tree limbs, leaf litter, dead and dying trees – that would normally have been burned in more frequent but less intense fires. In Oklahoma, encroachment of juniper and cedar trees have replaced some grasslands with volatile trees that burn intensely.

Fires are naturally common across much of the United States, with an annual or semi-annual occurrence. A variety of environmental and social factors influence wildfire growth and whether a fire overcomes initial attack efforts and becomes a large wildfire (Abatzoglou et al., 2018). In cooler and wetter areas, fires are less frequent, but still possible, particularly during drought when fuels have a chance to dry. In the grasslands of the Plains states, fires historically burned through at least once a decade, with a frequency of 4-6 years in Oklahoma and even more frequently in central Texas (Figure 4).

Fires need three things: fuel, heat, and oxygen. Fuel is in the form of grasses, sticks, logs, and trees. High temperatures provide the heat, bringing those fuels closer to their ignition point and also lowering the relative humidity (increasing vapor pressure deficit) which dries out fuels, especially fine fuels like grasses. Once a fire has been ignited, rising warm air draws air in from surrounding areas, which provides a continuous source of oxygen. High temperatures from combustion also radiate outward, drying nearby vegetation and making it easier to ignite.

The fire environment consists of fuel, topography, and weather. Fuel ranges from fine fuels such as grasses that can be easily ignited to larger sticks and logs. Organic material in the soil can also ignite, causing lower-intensity but longer-lasting fires. The shape of the landscape can affect fire dynamics. South-facing slopes and windy locations may be favorable due to drier vegetation and flow of oxygen. Fires burning upslope can heat higher elevation vegetation in advance of the fire front, as hot air rises from below. Fortunately, topography does not change and fuels change fairly slowly, so fire potential may be anticipated weeks or even months in advance. The wildcard is weather conditions.

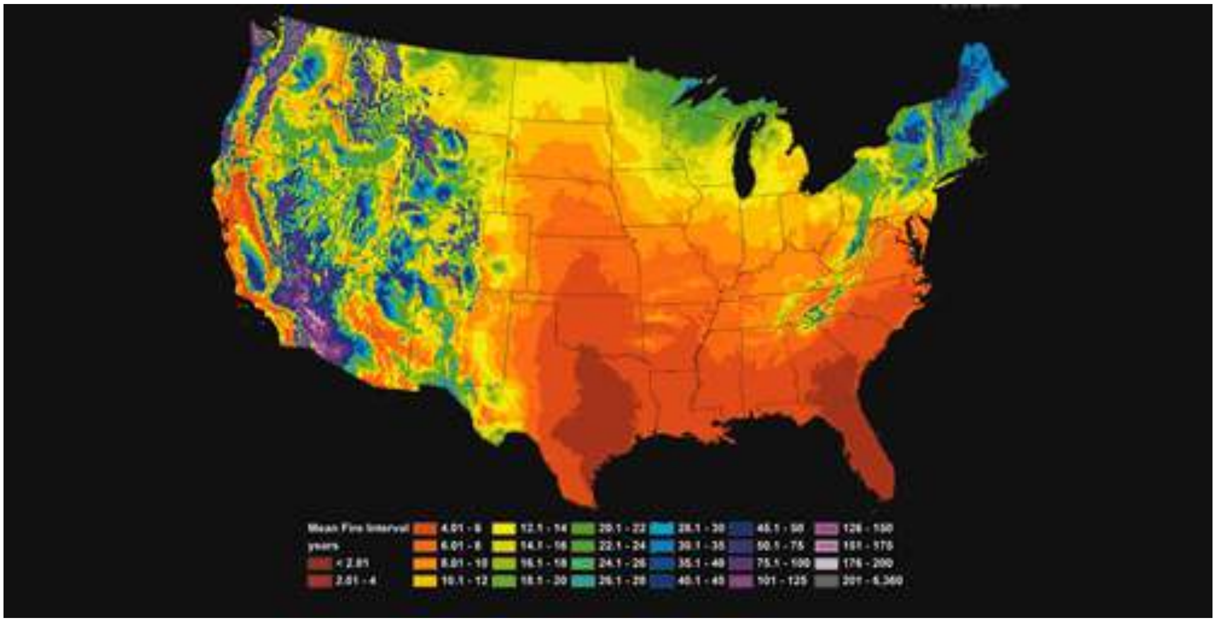

Figure 4. Estimated fire frequency from 1650-1850. Source: U.S. Forest Service

Weather conditions provide day-to-day factors that influence the likelihood and spread of fires. High temperatures and strong winds are critical to starting and sustaining a fire. Likewise, low humidity and long periods without precipitation allow fuels to dry and ignite more easily. Thunderstorms in dry environments may produce lightning but little rain, providing sparks without the water that would normally put out the fire. Of course, human-related ignition sources are a critical factor, and unlike other variables are nearly impossible to anticipate.

Fires may spread along the ground, along the surface, and through tree tops. Ground fires are slow-burning and slow moving, based upon organic materials in the soil which do not move. Surface fires are more intense, and more typical of grassland ecosystems. Surface fires involve grasses, leaf litter, and sticks and logs laying on the surface. If weather conditions and topography support rapid spread, these fires may become very intense and destructive. Crown fires are those that move among tree-tops and are the most intense and destructive. If fires can climb ladder fuels – low branches from the ground to the treetops – it can spread from one treetop to the next. These types of fires are nearly impossible to extinguish and may have to wait for changing weather conditions that bring rainfall or snowfall.

A study by Reid et al. (2010) found that there was no statistically significant relationship between air temperature and wildfire size. Their study showed that maximum temperatures above 70 degrees Fahrenheit seemed sufficient to support fires of all sizes. Higher minimum temperatures, remaining above about 50 degrees Fahrenheit, showed some correlation with larger fire size, although that relationship was not statistically significant.

Humidity and wind speed were strongly correlated with fire size and both statistically significant. Nearly all fires required a minimum relative humidity below 40% and daily average humidity below 60%; the largest fires feature minimum relative humidity below 20% and average humidity below 50%. Average and maximum wind speed both had strong positive relationships with wildfire sizes. The largest fires had sustained wind speeds in excess of 15 miles per hour and averaged nearly 40 miles per hour for peak wind gusts during the day.

The National Wildfire Coordinating Group (NWCC, n.d.) defines “critical fire weather” as requiring low relative humidity, strong surface winds, unstable air, and drought. Drought is important for drying vegetation, making it easier to reach its ignition point when heated, however it is not necessary. Fine surface fuels, such as grasses, can dry quickly, especially when dormant, making fire easy to spread on any hot, dry, and windy day.

East of the Rocky Mountains, including in Oklahoma, critical fire weather patterns are associated with the periphery of high-pressure areas intersecting with cold fronts. Cold fronts are associated with instability, allowing air to rise, which draws in surface air to replace it. This can accelerate wind speeds in the vicinity of updrafts. Cold fronts are also associated with shifting winds, which can turn a narrow wind-driven fire into a long fire front. Terrain can also accelerate winds from descending air from the high-pressure area funneled through narrow valleys and mountain passes. The effect is not as pronounced in Oklahoma as compared to much of the Western U.S., but terrain-driven winds can contribute to micro-climates that make fires harder to control.

A typical progression is for high pressure to provide warm, dry conditions for several days. This contributes to drying vegetation, particularly grasses which lose moisture quickly. As the high-pressure weakens or moves away, wind speeds increase while remaining warm and dry. This is the primary concern for ignition of fires. As the air gradually becomes more unstable as a cold front approaches, air rises that can help ventilate any ongoing fires. Lastly, the arrival of the cold front changes the wind direction, extending the fire line. A strong cold front may also lower temperatures and raise relative humidity, reducing fire intensity and providing an opportunity to suppress the fire (especially at night), although the passage of maritime cold fronts from the Pacific (as opposed to polar cold fronts from Canada) may not lower the temperature that much, while sustaining strong winds and a relatively dry air mass.

In addition to local weather variables such as air temperature, humidity, and wind speed, recent work suggests that there are some larger-scale atmospheric patterns that are associated with significant wildfire outbreaks in the Southern Plains (Lindley et al. 2017). These larger-scale patterns may be more predictable on seasonal to subseasonal (S2S) timescales than the local weather variables. Two features stand out: a low-level thermal ridge (an area of relatively warmer temperatures), typically oriented south-to-north (Lindley et al. 2014), and an approaching trough (low-pressure area) in the middle of the lower atmosphere. The favored area for wildfires is to the west of the low-level thermal ridge and to the east of the wind maximum aloft. According to Lindley et al. (2017), “these features have proven useful in forecasting the evolution, intensity, and areal scope of regional wildfire outbreaks.”

In an examination of 11 widespread and destructive fire episodes occurring between 2006 and 2014, Lindley et al. (2017) found that the low-level thermal ridge has a width of 150-300 km (about 100-200 miles). Within this zone, surface temperatures ranged from 77 to 104 degrees Fahrenheit with an anomaly (compared to either side of the thermal ridge) of 7 to 29 degrees F. These are often, but not always, associated with drylines, with the thermal ridge actually located ahead of the dryline along the low-level moisture gradient, not aligned with the lowest relative

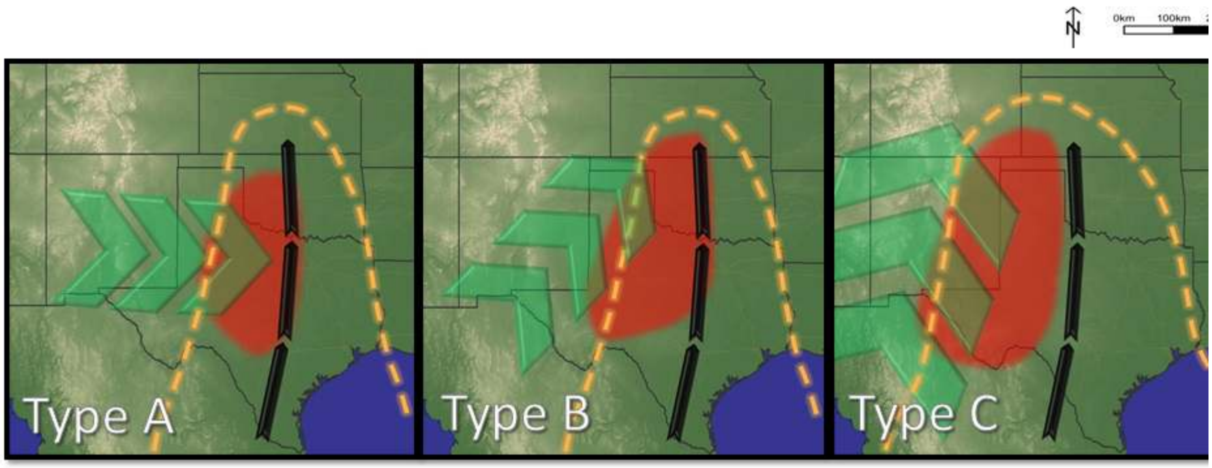

Figure 5. Conceptual models for three configurations of interacting wind fields aloft and low-level thermal ridges that are fire-effective on the southern Great Plains. Shown are 500-millibar wind maximum (green arrows), low-level thermal ridge (broken black line), and periphery of positive 850-millibar temperature anomalies (orange dashed line). From Lindley et al. (2017).

humidity that can be found behind the dryline. When upper-level winds flow nearly perpendicular to the low-level thermal ridge, the zone of fire-favorable environments will be narrower, compared to a broader area when upper-level winds are more parallel to the ridge (Figure 5).

Of course, fire intensity and frequency are dependent upon available fuel and ignition sources. For many decades, the focus of fire management has been on fuel modification with success on certain landscapes but limited improvement on others. Because humans are a dominant ignition source over the majority of North America there is reason to believe improvements in fire prevention may be a key to reducing fire impacts. Indeed, the United States Forest Service (USFS) has been reporting fire causes since it began collecting systematic data on fires in 1905, with the explicit purpose of helping land managers design fire prevention programs (Keeley & Syphard, 2018).

An important characterization of anthropogenic ignitions is that the most abundant ignition sources are not always associated with the greatest area burned. Thus, a topic in need of further study is how to sort out those ignition sources that are most damaging, how those have changed over time, and in light of future needs, how climate change is likely to affect different ignition sources and losses. For example, it has been demonstrated for the state of Victoria, Australia, that some ignition sources, such as electrical distribution lines, may be limited in number but result in much more severe fire consequences. If some ignition sources play a larger role in area burned, these might be targets for closer scrutiny and fire-management planning. This potential has been demonstrated for parts of southern California over recent decades, where powerlines have been shown to cause a substantial amount of area burned. Other important factors were arson and equipment (Keeley & Syphard, 2018).

Weather Patterns Related to Winter Storms

Winter storm hazards include heavy snowfall, blowing and drifting snow, high winds, extreme cold, ice storms, and resultant traffic accidents. Ice storms, in particular, can be more devastating to infrastructure than heavy snowfall. Winter storms are created by extratropical cyclones, those familiar low-pressure systems in the atmosphere above us that track around the Earth. These areas of low pressure are created by the polar and subtropical jet streams and move around the globe from west to east. The east side of low pressure troughs are areas where low-level formation of fronts is favored. When the polar and subtropical jet streams are close together, it favors rapid cyclogenesis – rapidly developing storms that become very intense very quickly. Strong contrasts between warm and cold air at the surface combined with high wind speeds aloft are associated with such rapidly-developing storms.

Winter storms follow several different tracks (Figure 6). The ones that affect Oklahoma most significantly are the "Colorado Lows" formed from deep troughs across the Western United States, with the low pressure then moving eastward out of Colorado or New Mexico. Storms that move further south from Oklahoma can bring in strong cold air, but usually do not produce as much precipitation in the state, although they can later move along the Atlantic Coast bringing Nor'easter conditions to New England.

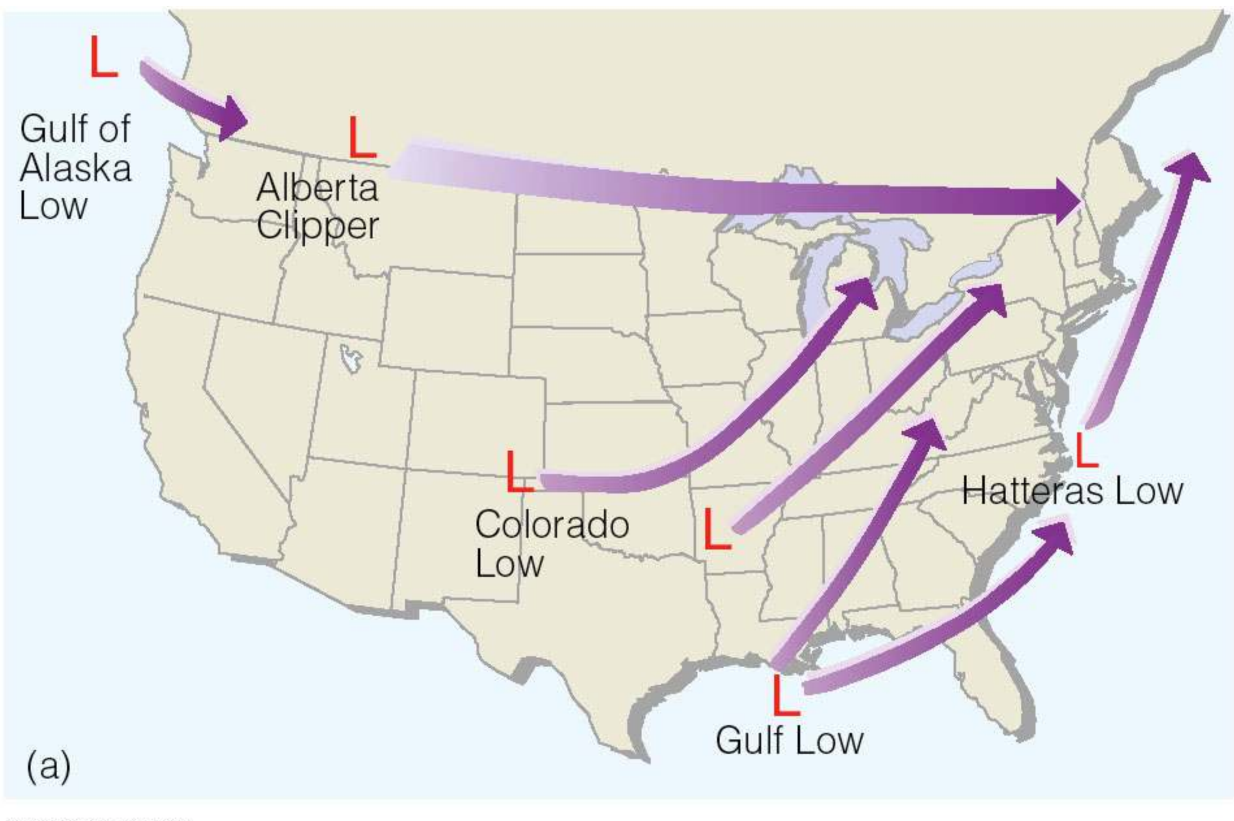

Figure 6. Winter Storm tracks across the United States. Source: University of Illinois Urbana-Champaign

Aside from storm tracks, a critical element is the temperature profile of the lower atmosphere, between the surface and the clouds. This profile will determine whether the storm produces snow, rain, sleet, or freezing rain (Figure 7). If it is cold all the way through the lower atmosphere, then ice crystals falling from the cloud will remain frozen, producing snow at the surface. If there is a warm layer below the clouds all the way to the ground, then ice crystals will melt, giving rain. The challenge comes when there is a layer of warm air in between the cloud and the surface. The depth of that warm layer determines whether melting ice crystals have time to re-freeze before interacting with the surface or not. If it is a thin layer of warm air and elevated above the ground, there should be sufficient time for the melted ice crystals to re-freeze into small ice pellets, which produces sleet. Sleet will accumulate on the ground, but the frozen pellets do not stick to trees or powerlines. If the layer of warm air is thicker, the melted ice crystals will not have time to re-freeze. Instead, they will freeze on contact with any surface that is below freezing, including trees, powerlines, and other structures which are in the shallow layer of below-freezing temperatures at the surface. This coats everything with a layer of ice and it will accumulate. The ice thickness will grow as more rain falls. Consequently, freezing rain is much more devastating in terms of damage to trees and power structures.

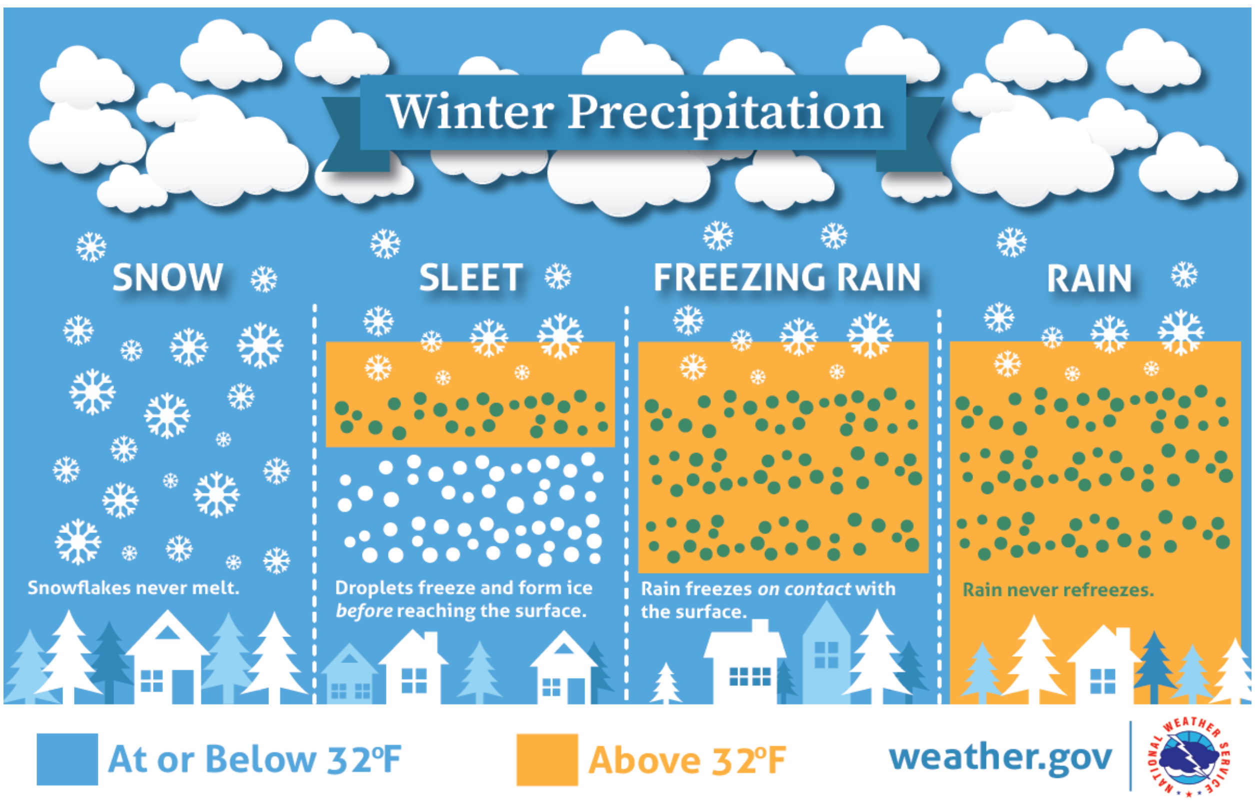

Figure 7: Temperature profile of the lower atmosphere associated with different winter weather types. Source: National Weather Service

Blizzards are defined as events with wind speeds greater than 35 miles per hour, visibility of less than one-quarter of a mile, and duration of at least 3 hours. It does not require new snowfall; simply existing snow on the ground being blown around by the high winds can produce blizzard conditions, even if there is no new snowfall accumulation. Hazards associated with blizzards

include disorienting whiteout conditions, hypothermia caused from extreme wind chill values, and impassable roadways.
Ice storms are usually more damaging and more costly than blizzards. Blizzards may occur over a wide area and can be very disruptive, but ice storms are harmful to infrastructure, particularly power lines. As those power lines are brought down, it may take weeks, or even months, to restore all the power connections. This creates a need for opening shelters to those who have lost the ability to heat their dwellings. It also poses a risk for those running portable generators; if the generators are not properly ventilated, carbon monoxide may accumulate, causing suffocation.

Ice storms typically form on the north side of a stationary or warm front. The warm, moist air mass to the south of the front lifts up over the shallow layer of cold air, which causes the precipitation above to melt in the warm air and then re-freeze on contact with the surface.

Predicting winter weather type is very difficult, even on the scale of a few hours. Although there are a lot of observations at the surface, data from above the surface is much more sparse. Consequently, forecasters often do now know the profile of the lower atmosphere, which is critical in determining precipitation type. Uncertainty in computations by computer models means small changes may go unnoticed; it only takes a change of one degree to transition from rain to snow. Models that project days or weeks in advance are unable to resolve these small but important differences.

Consequently, in trying to predict the possibility of winter weather events weeks in advance, it is necessary to rely on large-scale features that may be associated with winter weather. For Oklahoma, that would mean looking for instances of an upper-air trough to the west of Oklahoma, which can create a surface low-pressure system in eastern Colorado or New Mexico which then moves northeastward. A warm front or warm, moist air being drawn northward from the Gulf of Mexico would be another large-scale feature that may interact with the front and produce conditions favorable for winter storms. However, no model is capable of resolving whether it would be cold enough through the entire lower atmosphere for snow or whether there may be a small intervening layer of warm air that could produce ice.

Global Weather and Climate Patterns

El Niño and La Niña

Seasonal forecasting aims to offer helpful information about the climate that may be anticipated over the months. El Niño Southern Oscillation, often known as ENSO, is a worldwide phenomenon that significantly affects the climate. ENSO is characterized by an anomaly in sea surface temperature (SST) that is centered over the equatorial Pacific Ocean. El Niño is associated with warmer-than-normal SST, either in the central Pacific Ocean or eastern Pacific Ocean off the coast of Peru. It's cousin, La Niña, is associated with cooler-than-normal SST in those same regions. The anomalies are most prominent during the Northern Hemisphere winter months and affect the jet stream and subsequent weather patterns across much of the Earth. In fact, even though connections between El Niño and weather patterns are weaker during the summer, research shows that it is reduces hurricane activity in the Atlantic Ocean (Patricola et al. 2016).

The way ENSO is able to influence weather patterns is through migration of the jet stream across the SST anomalies. In the case of El Niño, excess energy from thunderstorms over the warmer waters is transmitted into the atmosphere and carried downstream, causing stormier patterns across the southern U.S. during winter (Figure 8). However, it is not a perfect relationship. Sometimes El Niño does not result in enhanced precipitation, but its presence does "stack the deck" toward an expectation of wetter winter. Conversely, cooler SST during La Niña favors development of a high-pressure system (ridge) across the Pacific, which pushes the jet stream northward into Alaska and Canada. The jet stream then dips southward across the western U.S., bringing cooler and drier air across much of the central United States during La Niña winters. Strong La Niña events have been associated with drought the following spring and summer in the Southern Plains.

Decadal Oscillations

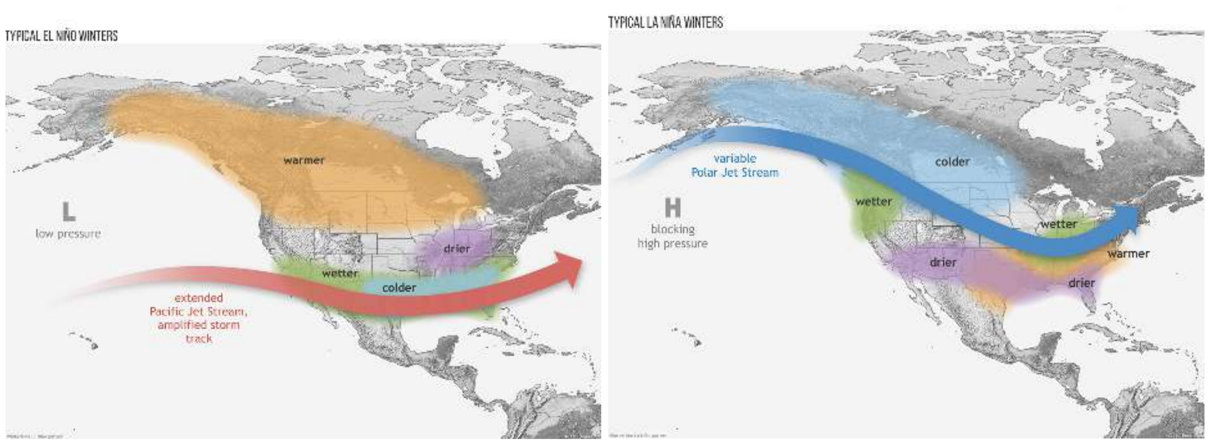

Figure 8: Conceptual model of ENSO effects on the jet stream and resulting patterns of temperature and precipitation during El Niño events (left) and La Niña events (right). Source: NOAA Climate.gov.

Like ENSO, the northern Pacific Ocean goes through warm and cool cycles, but these last much longer than El Niño and La Niña events. In fact, the Pacific Decadal Oscillation (PDO) may take as long as 30 years to complete a cycle (Figure 9). During a warm (positive) phase the eastern part of the Pacific Ocean warms while the western part cools; this is reversed during a cool (negative) phase.

During the warm phase, the "Aleutian Low", located near Alaska in the northern Pacific, is stronger and shifted southward, causing more warm, tropical air to flow northward along the North American west coast. This results in higher than normal temperatures along the coast, but then flow from Canada on the other side of the ridge results in cooler and drier air across the eastern United States.

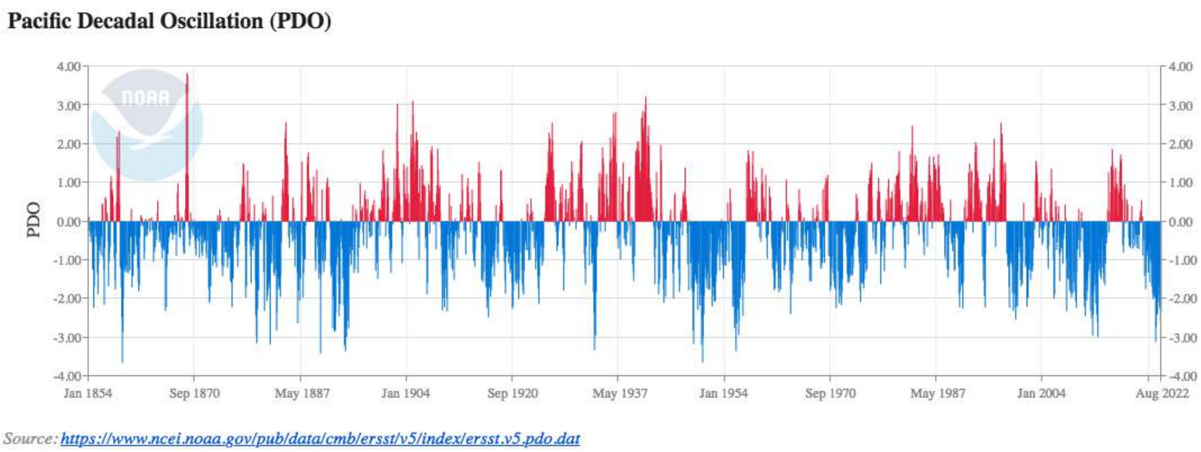

Figure 9. The Pacific Decadal Oscillation (PDO). Red indicates above-average sea-surface temperatures in the northern Pacific Ocean; blue indicates below-average. Source: National Centers for Environmental Information.

Similarly, there is a long-cycle variation in the Atlantic Ocean, termed the Atlantic Multidecadal Oscillation (AMO) (Figure 10). The AMO is less pronounced than the PDO, but still has a significant pattern on the movement of weather systems. Changes in atmospheric circulation may be related to location and strength of the Azores (Bermuda) High, which can affect the track of hurricanes across the Atlantic Ocean. The positive (warm) phase has been related to severe droughts in the U.S. Midwest and Southwest (NOAA POD n.d.). Tropical storms also appear more likely to mature into hurricanes during the positive phase of the AMO as well (NOAA CPO n.d.), although there is some controversy as to whether the frequency of stronger tropical storms and hurricanes is due to climate change rather than AMO (Mann and Emanuel 2006).

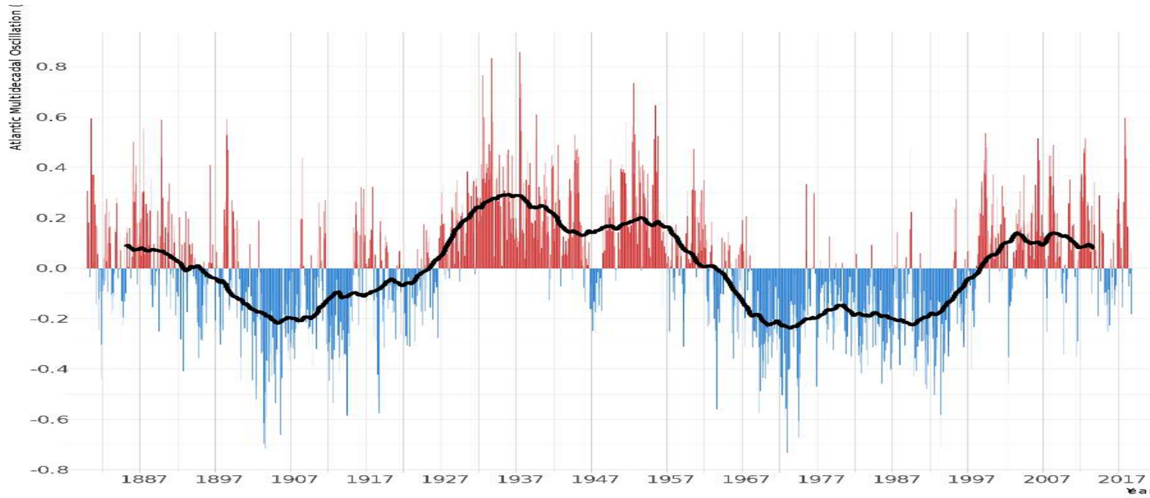

Figure 10. The Atlantic Multidecadal Oscillation (AMO). Red indicates above-average sea-surface temperatures in the northern Atlantic Ocean; blue indicates below-average. Source: National Physical Sciences Laboratory.

North Atlantic Oscillation

The North Atlantic Oscillation (NAO) is a change in atmospheric patterns over the North Atlantic Ocean. The NAO affects the strength of the Icelandic Low pressure and the Azores High to its south (Figure 11). The jet stream flows between the Icelandic Low and Azores High, from west to east. During winter, the Icelandic Low is at its strongest due to the greater temperature difference between the cold polar areas and the subtropical Atlantic. When the low pressure is stronger than average, the jet stream is strengthened, which keeps cold air "bottled up" to the north. During summer, the Icelandic Low is weaker, so the influence of the NAO is diminished.

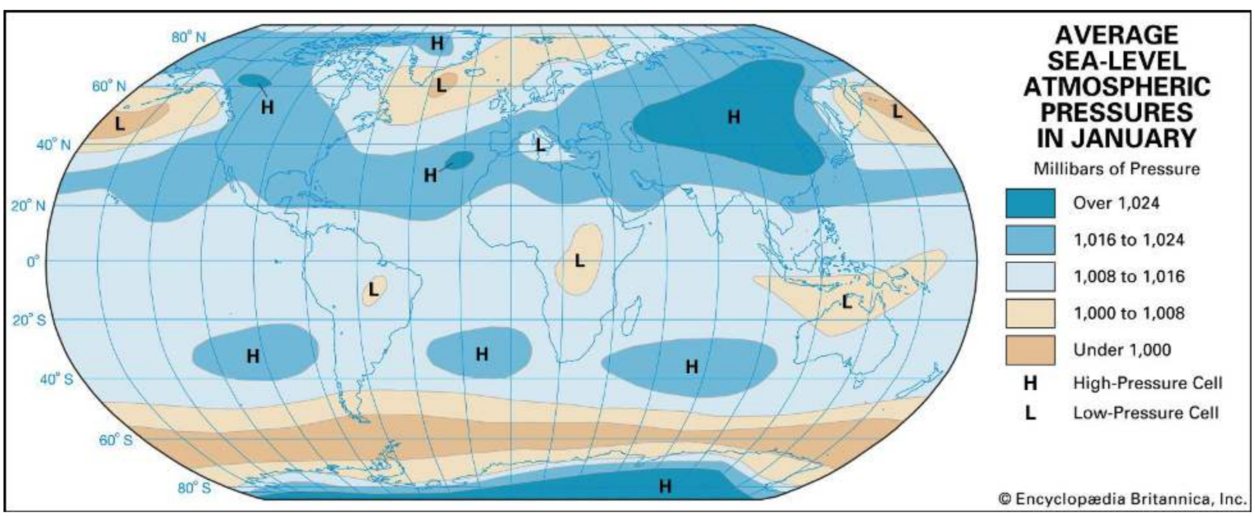

Figure 11. Average atmospheric pressure in January. Note the dominant, nearly stationary, low-pressure system near Greenland and Iceland. Source: Encyclopedia Britannica.

During a positive phase of NAO, both the Icelandic Low and Azores High are strengthened. The increased pressure difference results in a stronger jet stream and a northward shift in the storm track (NOAA CPO n.d.). This causes colder than average temperatures across Greenland, warmer than average temperatures across the eastern United States and southern Europe, and an increased storminess in northern Europe.

During a negative phase of the NAO, both the Icelandic Low and Azores High are weaker than average. Because of the decreased pressure difference, the jet stream is weaker, which allows it to become wavier. This allows cold air to spill southward across the eastern United States and northern Europe, resulting in stronger and more frequent cold air outbreaks (Figure 12).

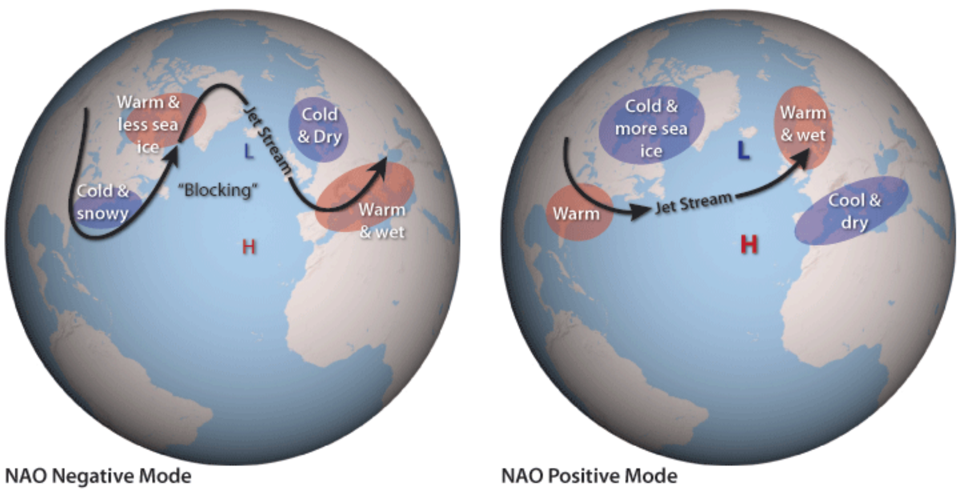

Figure 12. During the negative phase of the NAO (left), the jet stream is wavier, allowing more frequent and intense cold air outbreaks, as compared to the positive phase (right) which generally results in warmer and drier conditions across the eastern United States. Source: NOAA Climate.gov.

The NAO can change phases rapidly (over several weeks) or persist for several months. The NAO appears to be affected by multidecadal variability as well; during the period of the 1950s-1970s, it was dominated by the negative phase, resulting in colder winters across the eastern U.S., compared to the 1980s through mid 1990s where it was dominated by the positive phase, resulting in fewer cold air outbreaks (NOAA CPC n.d.)

Arctic Polar Vortex

While weather occurs in the troposphere, the layer of the atmosphere closest to the Earth's surface, the layer above it – the stratosphere – also has an effect on global weather patterns. Unlike the troposphere, which cools with higher elevation, the stratosphere is reversed, warming with increased height. This inhibits vertical motion, so that the stratosphere is dominated by horizontal winds. For a long time, the stratosphere was thought of as a lid on the troposphere, where vertical motion capable of producing tremendous storms, ended. But over the past several decades, scientists have come to understand connections between the troposphere and stratosphere that are able to affect global weather patterns.

The Arctic polar vortex is a band of strong westerly winds that forms during winter. Due to the lack of sunlight in the Arctic during winter months, the air cools, developing a large pool of extremely cold air (a similar feature happens over Antarctica in the Southern Hemisphere's winter). The strong winds flowing around this pool of cold air keeps it from escaping southward toward the equator.

The polar jet stream, which operates in the troposphere, tends to some degree to mirror the polar vortex. When the polar vortex is strong and winds keep the cold air in place, the polar jet stream tends to flow predominantly west-to-east and tends to stay farther north (what meteorologists call "zonal flow"). This brings milder weather across the United States. It is also associated with the positive phase of the NAO.

From time to time, energy from the troposphere can create atmospheric waves that move upward into the stratosphere, knocking the circulation out of balance. These "sudden stratospheric warming" events displace the cold air away from the pole, perhaps creating lobes that can drive southward, bringing the intense cold air with it (Lee et al. 2019). These warming events are followed in subsequent weeks by changes to the polar jet stream, which becomes wavier and allows the cold air in the troposphere to also move southward (Figure 13). These patterns may become 'stuck' with a series of deep troughs and steep ridges that may remain nearly stationary for days or even weeks, such as in February 2021. Meanwhile, the warm air surging northward in the ridges causes warming in the Arctic, which weakens the Icelandic Low and leads to a reversal of phase of the NAO.

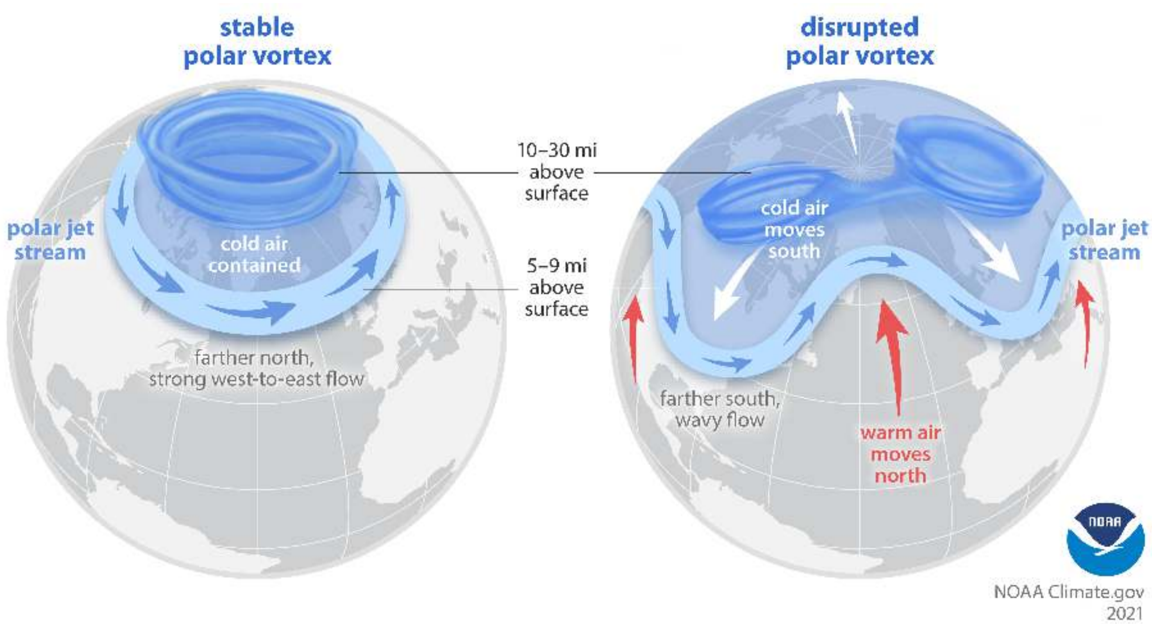

Figure 13. Conceptual model of the Arctic Polar Vortex, showing a stable condition (left) and an unstable condition (right), where the pool of cold air has been disrupted by sudden stratospheric warming. Source: NOAA Climate.gov.

This does not mean that every cold air outbreak is associated with changes of the polar vortex. Because the polar jet stream in the troposphere is not directly connected to the polar vortex in the stratosphere, it will from time to time meander, allowing cold air to move southward and warm air to move northward. Likewise, sometimes the polar vortex can become disrupted with no effects at the surface. Yet in stronger stratospheric warming events, it becomes more likely that the polar jet stream will also become displaced and lead to a significant cold air outbreak, although it is difficult to predict the location that will most likely be affected.

Madden-Julian Oscillation

The Madden-Julian Oscillation (MJO) is a couplet of an area of enhanced precipitation with an area of suppressed precipitation which forms in the tropical western Pacific Ocean (Figure 14). This couplet migrates eastward across the tropics and makes a complete circle around the globe over a period of 30-60 days. As these waves migrate slowly eastward, it causes changes in jet stream patterns that can affect flooding, drought, cold air outbreaks, and extreme heat events over the United States, along with monsoons and tropical cyclone development (Higgins et al. 2000; Riddle et al. 2013; Zhou et al. 2012).

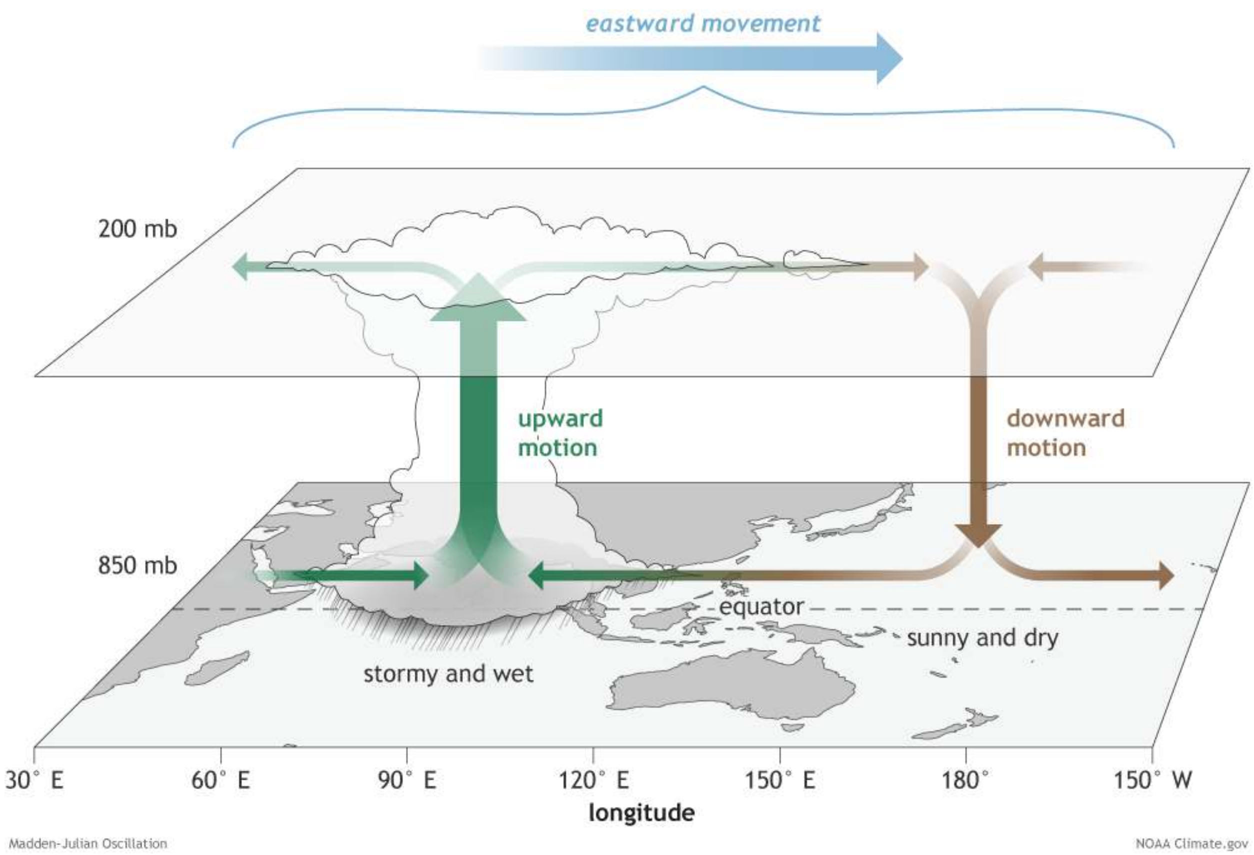

Figure 14. The surface and upper-atmosphere structure of the MJO showing an enhanced phase (convective thunderstorms) over the Indian Ocean and a suppressed phase (descending, dry air) over the west-central Pacific Ocean. The entire system shifts eastward over time, eventually circling the globe and returning to its point of origin. Source: NOAA Climate Prediction Center.

The intensity of the MJO couplet varies over time. An active phase is considered when a strong couplet develops and shifts eastward with time. The impacts are similar to ENSO, with enhanced precipitation associated with more active convection, but operate on a scale of weeks rather than entire seasons. The status of ENSO can affect the strength of an MJO wave; during El Niño events, MJO waves traversing abnormally warm waters are strengthened, enhancing both the convection and downstream subsidence (descending, dry air). The combined effects may lead to extreme weather events (Zhang 2013).

Prediction

All of these different "modes" of motion of the atmosphere and ocean make this a complex system. Each mode is difficult to predict; much more so trying to predict the interactions of each of these components. But as understanding of each of these processes grows and improvements occur in observations and computer modelling capacity, there are small, incremental improvements in predictions.

For the subseasonal scale of forecasting for a few weeks to months, many of these slowly-varying modes, such as PDO and AMO, can be considered essentially stationary (Figure 15). This simplifies the predictions a bit, so some of the faster-varying modes such as MJO can be better resolved and used to anticipate potential storm patterns or cold air outbreaks. Proper initialization of land surface conditions, particularly soil moisture, can be an important source of predictability, especially in areas with strong land-atmosphere feedback such as the Southern Plains during spring and summer (Meehl et al. 2021). Coupling between the atmosphere, ocean, land, and sea ice is important for scales beyond 2 weeks.

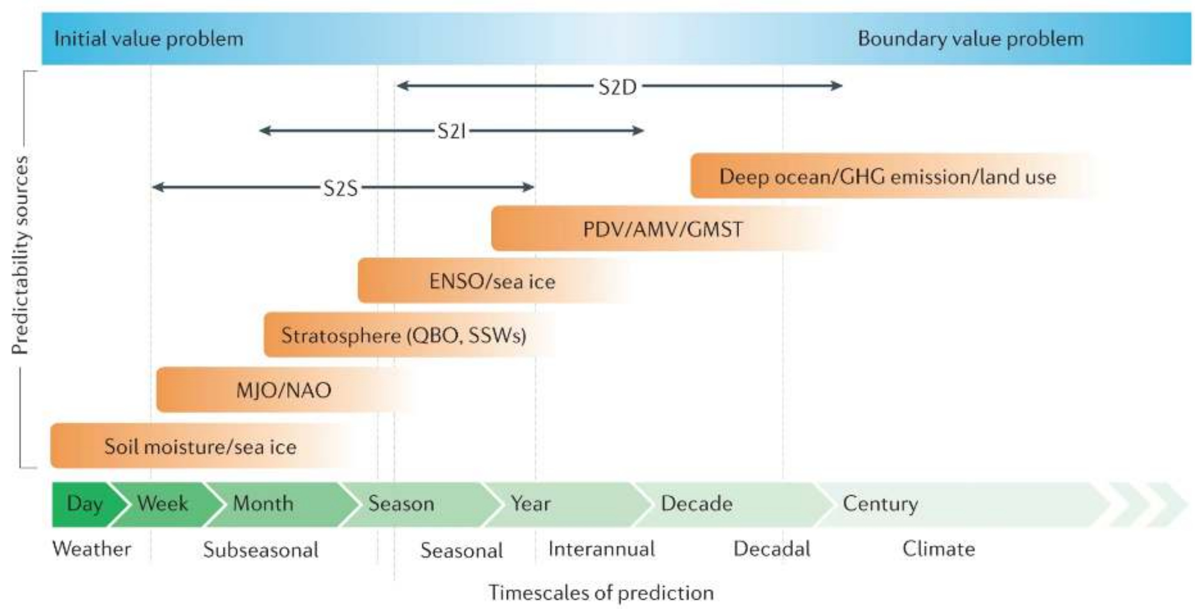

Figure 15. Timescales and sources of predictability for subseasonal to seasonal (S2S), seasonal to interannual (S2I), and seasonal to decadal (S2D). For the S2S scale, MJO, NAO, stratospheric warming, and ENSO are the most important sources of predictability. Source: Meehl et al. (2021).

In order to make predictions, computer models first must create accurate representations of the current state of the Earth system, including the atmosphere, oceans, land, and ice. The more accuracy and detail that can be achieved in model initialization, the better their likelihood in detecting features that have an impact on global weather patterns over time. Higher-resolution numerical models, similar to those used for daily weather forecasts, can be adapted to seasonal to subseasonal scales (Meehl et al. 2021). This provides higher resolution for initialization, as compared to longer-term climate models that predict conditions over decades. However, many of these models do not include detailed ocean-atmosphere coupling, which is crucial to predicting more slowly-evolving features such as ENSO.

No single model run will produce an accurate result. Therefore, initial conditions are changed slightly and the model is re-run, with the process repeated multiple times. This creates an ensemble forecast, which has been shown to be more accurate than relying upon a single run of a model. However, such ensembles require vast computational power. In order to obtain operational forecasts that can be used in a timely fashion, some equations must be simplified, which will over time introduce more errors into the forecast. As the ability of super-computers grows, the ability to resolve finer-scale features improves, with expectations that skill of forecasts on the S2S scale will similarly improve.

Recent work has shown that the NAO may be predictable as much as a year in advance (Dunstone et al. 2016). The NAO appears to be linked to climate variability in the tropical Pacific and the strength of the stratospheric polar vortex. Improving skill in these components, may thus increase skill in the NAO, resulting in improved forecasts of winter temperatures and storminess across the eastern United States.

Other research has shown that the MJO is related to NAO events (Jiang et al. 2017). Enhanced convection over the tropical western and central Pacific Ocean during an active MJO event is related to subsequent strengthening of NAO, leading to persistence of NAO patterns for approximately 30 days. During inactive MJO periods there is little effect on NAO persistence, with patterns lasting only about 10 days.

Meehl et al. (2021) find some skill in predicting the MJO and NAO, and on longer time scales in predicting ENSO and ocean and atmospheric variability in the North Atlantic region. Some models are able to accurately predict MJO up to 4 weeks, although most models struggle with eastward movement of the anomalies. Successful MJO prediction enables improved prediction for extreme events, such as storm tracks, atmospheric rivers, and tornadoes (Zheng et al. 2019; DeFlorio et al. 2019; Baggett et al. 2018).

Lin et al. (2021) show a pronounced connection between the NAO and MJO, with the phase of the NAO preceding changes in the MJO. Their study shows that a strongly positive NAO is followed about 20 days later by reduced convection in the Indian Ocean and enhanced convection over the Western Pacific. Likewise, a strongly negative NAO event flips the pattern, with enhanced convection in the Indian ocean and suppressed convection over the Western Pacific.

The stratosphere is another important component of S2S predictability. Sudden Stratospheric Warming (SSW) events can persist for up to 60 days and relate to the negative phase of the NAO. Thus, being able to accurately predict SSW events can improve prediction of NAO phase, which in turn may improve prediction of MJO events which can affect extreme weather events weeks later.

So what does this have to do with prediction of wildfire and winter storms? As mentioned previously, individual events are difficult to predict more than a few days in advance. But features such as the MJO, NAO, Sudden Stratospheric Warming, ENSO, and other oceanic circulations, do have some predictability for weeks or seasons in advance. Zhang (2013) examined the relationship between MJO phase and fire. While there were relationships in some areas, such as in Canada or Mexico, the relationship with much of America was not conclusive. However, both Zhang (2013) and L'Heureux and Higgins (2008) noted a stronger relationship between MJO and cold air outbreaks in the eastern United States.

As computing capability and scientific understanding of these processes continues to advance, expectations are that predictive skill will increase on subseasonal and seasonal time scales. The relationship between S2S sources of predictability, such as NAO and Sudden Stratospheric Warming, seems stronger, such that improvements in advance warning of arctic outbreaks, and associated winter weather conditions, is more likely to occur than advance warning of fire weather conditions, where the connections to sources of predictability are more tenuous. Even so, it will remain impossible to predict local factors that affect the type and amount of winter precipitation beyond a few days. But the extended predictive capabilities could help to prepare contingencies; for example, if an outbreak appears likely, advance preparations could be made for supplies that could be needed and to prepare personnel for deployment should the event become more certain.

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FIGURES

Figure 1. Global jet stream patterns. Source: National Weather Service, https://www.weather.gov/jetstream/jet

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Figure 6. Winter storm tracks. Source: University of Illinois, https://www.atmos.illinois.edu/~snodgrss/Midlatitude_cyclone.html

Figure 7. Winter atmospheric profiles. Source: National Weather Service, https://www.weather.gov/fsd/winter_preparedness

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Figure 9. Pacific Decadal Oscillation. Source: National Centers for Environmental Information, https://www.ncei.noaa.gov/access/monitoring/pdo/

Figure 10. Atlantic Multidecadal Oscillation. Source: NOAA Physical Sciences Laboratory, https://psl.noaa.gov/data/timeseries/AMO/

Figure 11. Average atmospheric pressure in January. Source: Encyclopedia Britannica, https://www.britannica.com/science/climate-meteorology/Atmospheric-pressure-and-wind

Figure 12. North Atlantic Oscillation. Source: NOAA Climate.gov, https://www.climate.gov/news-features/understanding-climate/climate-variability-north-atlantic-oscillation

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Figure 15. Timescales of predictability. Source: Meehl et al. (2021), https://www.nature.com/articles/s43017-021-00155-x