CHAPTER 6

Subseasonal to Seasonal Weather Patterns

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CHAPTER 6

Subseasonal to Seasonal Weather Patterns

Oklahoma faces significant changes in its natural environment and human systems due to weather patterns over short periods—ranging from 10 to 90 days. Weather on this timescale, known as subseasonal to seasonal (S2S) weather, include rainfall and temperature patterns and sometimes more extreme events (e.g., heavy rainfall, heatwaves) that can be particularly costly and disruptive.

Diagnosing trends in S2S weather patterns are especially difficult to address because they are happening alongside debates about the role of human activity in driving climate change. These debates can make it harder for people to recognize and respond to the impacts of S2S weather. On the science side, the S2S timescale lies in a "predictability desert." That is, the timeframe starts at the end of the more traditional "weather models" used for forecasting (out to 10 days) but ends short of seasonal (3–9 months) timescales, where signals from the ocean and land offer good prediction skill at those times. Indeed, S2S forecasting represents the "new frontier" in forecasting. To tackle these challenges, S3OK researchers focused on advancing research that facilitated:

- Better understanding of the basic processes driving S2S patterns
- Improving models and predictions of basic S2S phenomenon
- Developing S2S data for managing water, carbon/water cycles, and infrastructure in Oklahoma
- Better understanding of the social dynamic considerations of S2S

By improving S2S forecasting and integrating insights from public perceptions, researchers aimed to help community leaders and residents find practical and socially sustainable solutions to the growing risks from extreme weather events. This chapter provides a broad overview of S2S dynamics and critical context for work S3OK researchers advanced through the project. This includes:

1. What is Subseasonal to Seasonal (S2S) Weather
2. What Drives S2S Weather Patterns
3. Improving S2S Forecasting
4. Social Dynamic Considerations of S2S
5. How S2S Drives Wicked Problems and the S3OK Challenge Areas

What is Subseasonal to Seasonal (S2S) Weather?

Oklahoma is part of the Great Plains, a region stretching from southern Texas to North Dakota and eastern Montana. This area experiences some of the most dynamic and extreme weather in the country, including:

- **Severe thunderstorms** with high winds, large hail, and tornadoes
- **Winter storms** that bring heavy snow, ice, and exceptionally cold temperatures
- **Extended heatwaves** during summer

Adding to this complex and dynamic weather landscape, Oklahoma sits in a transition zone between the dry west and the wetter east. This unique position causes precipitation amounts to

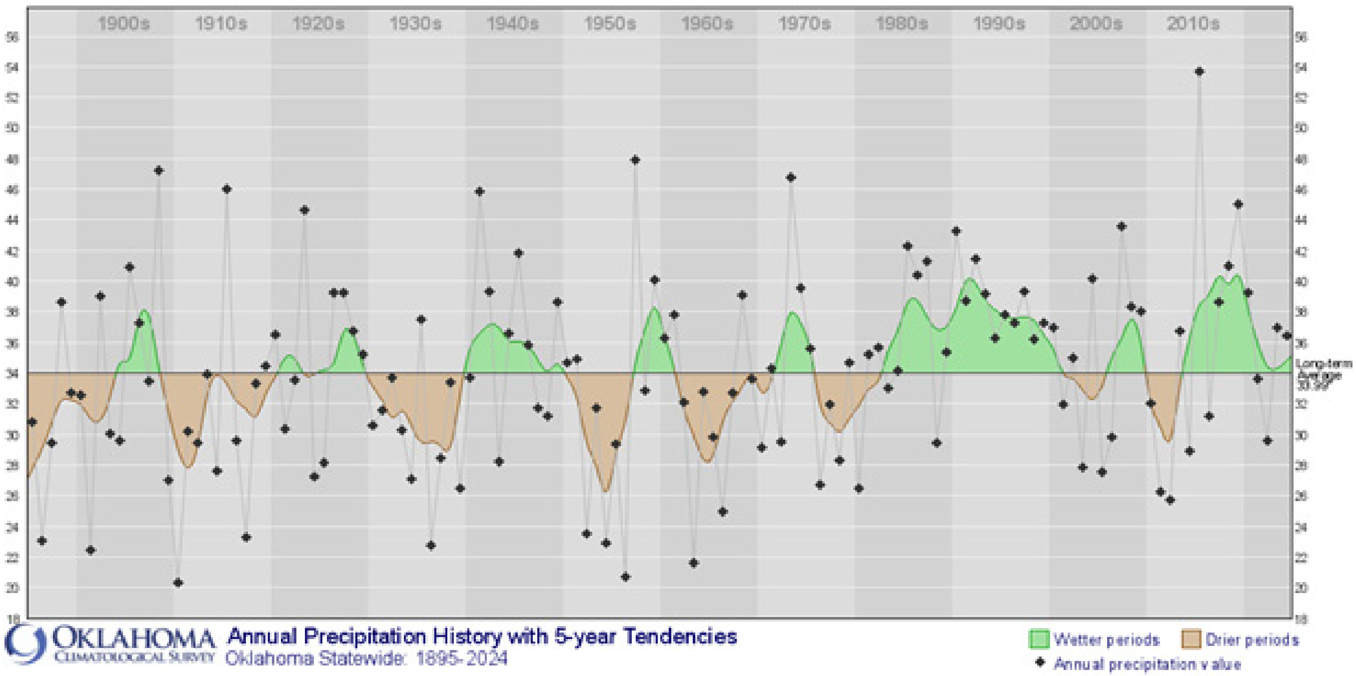


Figure 6.1. Statewide-average annual precipitation totals (inches) in Oklahoma from the late 1890s to 2024 (black line with diamonds) and the 5-year running mean value (thin brown/green line). Periods of time colored brown indicate drought periods, and periods of time in green indicate pluvial periods. *Courtesy of the Oklahoma Climatological Survey.*

vary greatly from year to year **(Figure 6.1)**. As a result, the region sees large swings in weather and temperature over S2S timeframes, making it especially challenging to predict and manage weather impacts.

Advancements in meteorological observational networks, computational power, and physics-based numerical weather prediction models have steadily improved forecast accuracy for short- to medium-range forecasts, up to about 5–10 days[1] (Bauer et al., 2015). Today, the frontier for weather prediction is in the S2S time range. Beyond this window, forecasting enters what scientists call a "predictability desert"[2], characterized by major opportunities to improve forecasting accuracy.

Despite these challenges, improving S2S predictions is a top priority in meteorology because of their immense value across multiple sectors[3]. Affected sectors include:

- Public health[4]
- Renewable energy[5]
- Agriculture[6]
- Water resource management[7]

Many of these applications focus on anticipating extreme weather events that have significant social and economic impacts at S2S timescales, such as:

- Prolonged heatwaves
- Cold spells
- Droughts
- Heavy precipitation
- High wind conditions

Unlike short-term weather forecasts, which provide *deterministic* predictions – i.e., specific temperature, precipitation, and wind values for a given location, S2S forecasts are largely *probabilistic*. This means they explicitly offer a range of particular weather patterns that could occur rather than the specific values shown by deterministic forecasts. The challenge of predicting extreme weather at S2S timescales is especially pronounced since extreme events are rare and driven by complex interactions across different components of the climate system.

What Drives S2S Weather Patterns?

Scientists use recurring, quasi-stationary flow patterns called modes of climate variability to describe the large-scale atmospheric circulation. This is a core principle of S2S forecasting. These recurrent flow patterns of upper-level ridges and troughs shape temperature and precipitation trends across mid- and high-latitude regions, including Oklahoma.

Modes of climate variability evolve amidst differing background states of the climate system structured by other larger-scale, slower-evolving climate phenomena, such as:

- **The Madden-Julian Oscillation (MJO):** An eastward-moving pattern of tropical thunderstorms that moves around the equator and influences weather locally and elsewhere across the globe **(Figure 6.2)**.
- **El Niño-Southern Oscillation (ENSO):** A **recurring** warming (El Niño) or cooling (La Niña) of the tropical Pacific Ocean, which has widespread impacts on atmospheric circulation and seasonal weather trends **(Figures 6.3a and b)**.
- **The Stratospheric Polar Vortex:** A high-altitude (10-50 km above the surface) counterclockwise circulation in the Arctic that appears during the winter months. When the vortex is strong (i.e., strong winds and circular in shape), the jet stream (i.e., storm track) remains further north and cold air remains at high latitudes in the Arctic. When the vortex is disturbed/weakened, the jet stream below shifts southward, allowing cold air to invade the middle latitudes and sometimes extreme winter storms **(Figure 6.4)**.

Understanding and predicting the evolution of these cross-scale interactions is critical for improving S2S predictions. However, this task is made even more complex by climate change, which is altering the frequency, intensity, and behavior of extreme weather events[8, 9]. As warming continues, historical weather patterns may shift, requiring ongoing refinements to S2S forecasting models to keep pace with these changes. By improving our ability to predict weather conditions weeks to months in advance, S2S forecasting has the potential to enhance disaster preparedness, optimize energy and agricultural planning, and support more resilient decision-making in the face of a changing climate.

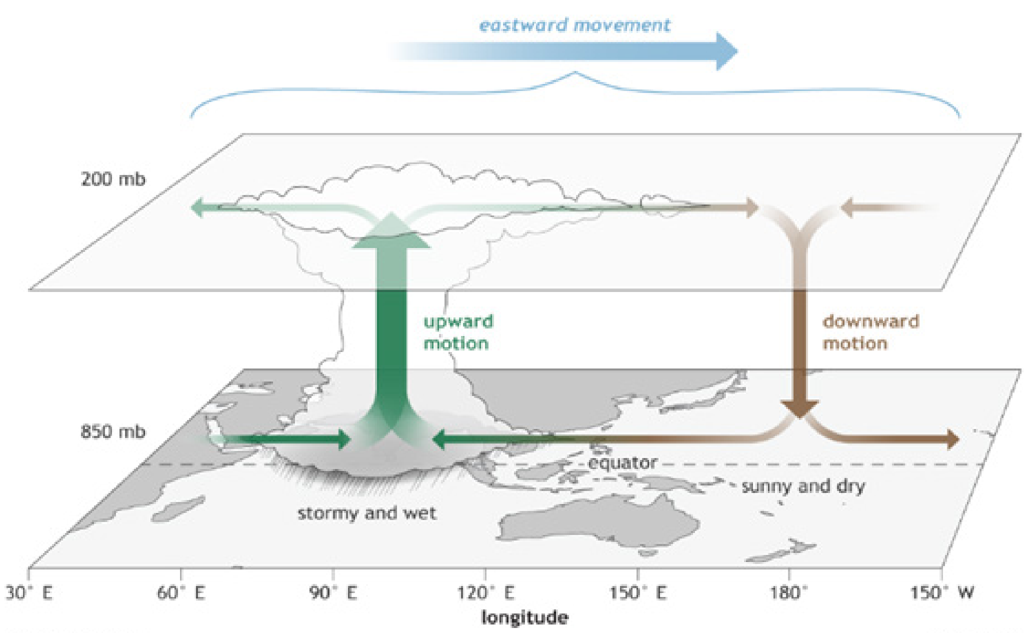
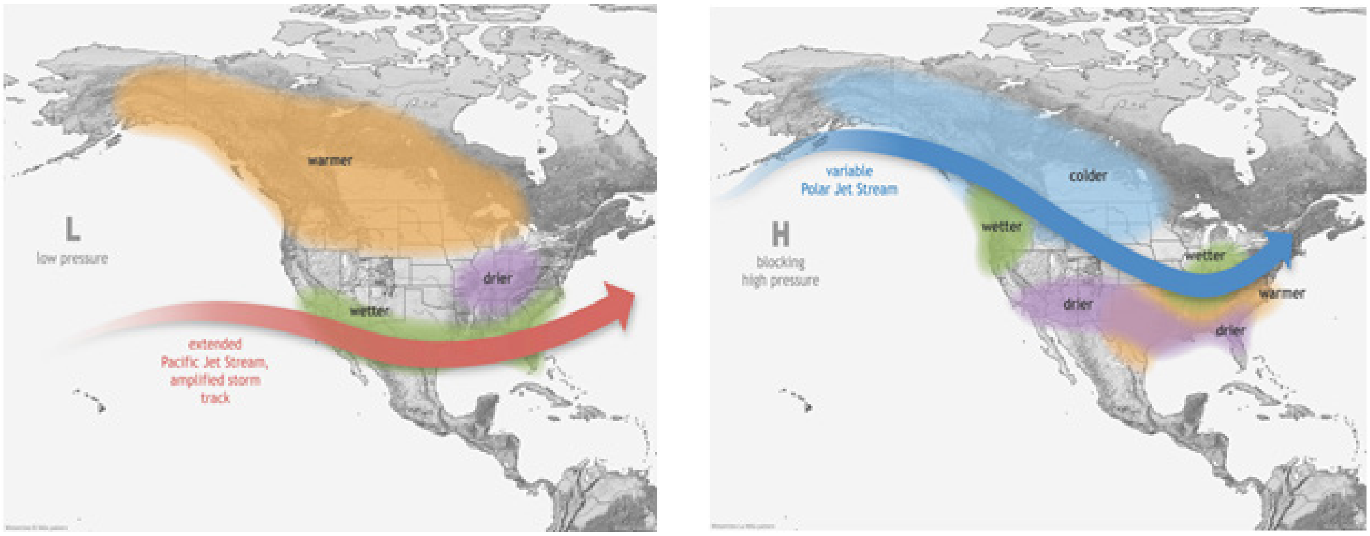


Figure 6.2. Illustration of the Madden-Julian Oscillation, a couplet of stormy and wet conditions and relatively dry conditions both upstream and downstream of the rainy area. *Courtesy of NOAA.*



Figures 6.3a and b. ENSO creates widespread seasonal weather trends based on El Niño or La Niña patterns. *Courtesy of the National Weather Service.*

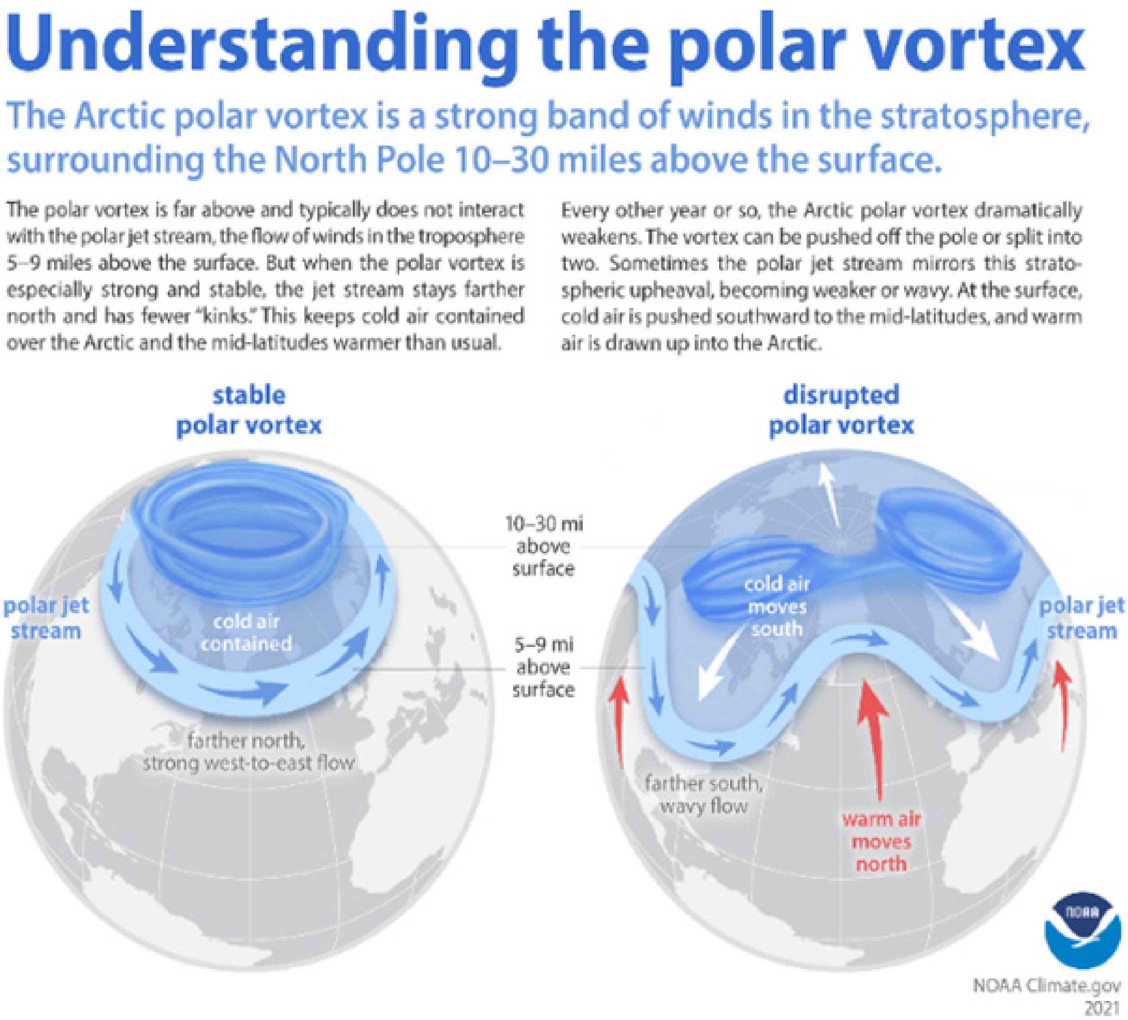


Figure 6.4 The *Stratospheric* Polar Vortex, though it resides tens of kilometers above the surface in the Arctic, can influence the jet stream below and affect temperature and precipitation patterns across the Northern Hemisphere. *Courtesy of NOAA.*

Improving S2S Forecasting

To improve the accuracy and usability of S2S weather forecasts, researchers within the S3OK project focused on improving our understanding of the fundamental processes that drive S2S weather patterns. Their work spans three key areas:

1. Identifying the mechanisms behind shifts in S2S variability.
2. Improving models' predictive skill for critical S2S phenomena.
3. Developing innovative S2S datasets to support resource management and infrastructure resilience in Oklahoma.

Oklahoma provides an ideal natural laboratory for advancing S2S forecasting due to the year-round nature of its highly dynamic, variable, and extreme weather conditions. The region experiences frequent and abrupt temperature swings, severe storms, droughts, and other extreme weather events that challenge existing forecasting capabilities. By improving S2S predictability in Oklahoma, researchers aim to develop insights that can be applied more broadly to other regions facing similar climatic variability. Three primary research areas underpin S3OK's contributions to advancing S2S insights:

- **Temperature Extremes** – Investigating patterns and drivers of prolonged heatwaves and cold spells to improve early warning systems.
- **Flash Droughts** – Understanding the rapid onset of drought conditions, their precursors, and their potential predictability.
- **Weather Precipitation Whiplashes** – Examining the causes and consequences of sudden shifts between extreme wet and dry conditions.

S3OK is shaping the future of forecasting and its applications for resilience planning. The following sections will summarize key findings from selected projects, focusing on:

- Temperature extremes
- Heatwaves
- Cold air outbreaks and temperature whiplash
- Flash droughts
- Precipitation whiplashes

Improving S2S Forecasting of Extreme Temperatures in Oklahoma

Oklahoma's geographic location makes it particularly susceptible to large temperature variability throughout the year. During the warm season, intense and prolonged heatwaves, influenced by heat transport from both the Gulf of Mexico, recently renamed the Gulf of America, and the Desert Southwest. During the cold season, extremely cold Arctic air masses can emerge southward from Canada and rapidly move south and eastward (the Rockies act as a natural barrier for the cold, dense air), introducing extremely cold temperatures.

With the relatively warmer, more moist air mass to the south, storm systems that pass nearby during these cold air intrusions can tap into this moisture, creating snow and ice storms that introduce multiple risks to Oklahoma's agriculture, roadways, and energy and water infrastructure. To build better resilience and preparedness for these extreme temperature impacts in Oklahoma, the S3OK team sought to improve forecast skill for both extreme heat *and* cold on S2S timescales.

Heatwaves

Oklahoma is no stranger to extremely hot temperatures during the summer. Additionally, the region's summertime circulation patterns, which frequently feature persistent high-pressure systems, foster extreme temperatures by enhancing solar radiation and drying out the land surface. Temperatures of 90°F or higher occur, on average, about 60–65 days per year in the western panhandle to about 115 days in southwest Oklahoma[10] (OCS, 2025). Western Oklahoma experiences about 40 days at or above 100°F, decreasing to about 15 days per year as you head eastward[10] (OCS, 2025). Moreover, with climate change driving temperature increases and amplifying its variability, the risk of more frequent, longer-lasting, and more severe heatwaves is ever-present[9].

To address these concerns, the S3OK S2S research team focused on two key areas:

1. **Reexamining how heatwaves are defined and determined**, particularly in the context of human health and environmental impact.
2. **Examining the rise of winter heatwaves** ("warm spells") and their socioeconomic consequences in Oklahoma.

Reexamining Heatwaves using Wet Bulb Globe Temperature

Traditional definitions of heatwaves often focus on air temperature alone, but this approach overlooks other critical factors affecting heat stress, such as humidity, solar radiation, and wind speed[11]. Davis et al. (2024)[11] tackled this issue by analyzing heatwaves using **Wet Bulb Globe Temperature (WBGT)**, a more comprehensive metric that incorporates multiple atmospheric variables to assess the true risk to human health **(Figure 6.6)**. According to WBGT standards, values exceeding 88°F pose a high to extreme risk to human health during outdoor exposure.

Key findings from the study include:

- The frequency of high- and extreme-risk WBGT days in the Southern Great Plains has tripled over the past ~60 years.
- The greatest absolute increases in WBGT are occurring during winter months, signaling a potential lengthening of the warm season.

Examining the Emergence of Winter Heatwaves

Grace et al (2024)[12] analyzed the increase in winter heatwaves or warm spells throughout the Southern Plains region. The study highlighted a notable rise in the frequency and intensity of winter heatwaves, with an exceptional case occurring in December 2021. These events, while less studied than summer heatwaves, can have profound agricultural, ecological, and socioeconomic impacts, disrupting winter crop cycles, increasing wildfire risk, and straining energy resources due to sudden fluctuations in heating and cooling demands.

Understanding and Improving S2S Forecasting of Heatwaves in Oklahoma

One of the primary obstacles in subseasonal forecasting is the limitations of current operational S2S models in predicting heatwaves beyond two weeks[11,12]. This limitation is largely due to model difficulties in capturing North American weather regimes—persistent, recurrent atmospheric patterns that influence regional temperatures.

However, S3OK research identified key opportunities for improving S2S heatwave predictions:

1. Identifying "forecasts of opportunity"—or specific times when forecast skill improves relative to the mean skill. One such "forecast of opportunity" is above average MJO activity in the Indian Ocean and Maritime Continent, which has strong links to heatwaves in the Southern Great Plains[11].
2. Identifying and predicting the evolution of specific North American weather regimes in the S2S models[11,12].

The findings from these studies underscore the urgent need for improved S2S forecasting of heat extremes, particularly as climate change alters the frequency, duration, and intensity of both summer and winter heatwaves. By refining heatwave definitions, leveraging new predictive indicators, and identifying windows of enhanced forecast skill, researchers are paving the way for more actionable, extended-range forecasts.

Cold Air Outbreaks and Temperature Whiplash

Despite winters overall getting warmer on the average, extreme cold temperatures still occur and can have tremendous impacts. The most recent example was in February 2021, when for about two weeks, extremely low temperatures and several inches of snow caused tremendous strains on water, transit, and electricity infrastructure[13]. Because of events like February 2021 and others in the recent past, the S3OK research team made significant strides in improving long-range forecasting of **cold air outbreaks (CAOs)** and **temperature whiplash events**, two phenomena that pose substantial challenges for forecasting and preparedness.

Identifying New Sources of Predictability of CAOs

To improve long-range predictions of extreme cold air outbreaks, Millin et al. (2022)[14] developed the first-of-its-kind CAO database for the Central U.S., extending back to 1950. Their research identified two primary weather regimes associated with CAO formation:

1. **The Arctic High Regime:** Characterized by higher-than-normal pressure throughout the Arctic and over to Greenland, leading to deep cold air intrusions into the Central and Eastern U.S.
2. **The Alaskan Ridge Regime:** Defined by a blocking high-pressure system over the Gulf of Alaska, which redirects Arctic air southward into the Plains. This regime is associated with some of the most intense CAOs across the Central US over the last 75 years.

Recognizing these weather regimes, the study also linked their formation to key subseasonal predictors, providing advance warning up to 14 days before a CAO event:

1. Arctic **High CAOs** are often preceded by a weakened stratospheric polar vortex, which shifts the jet stream southward and makes it "wavier." The result is higher-than-normal pressure over the Arctic and the expulsion of frigid air out of the Arctic and into the middle latitudes, including the Central US. Because of the strong high across the Arctic, these CAOs tend to be longer-lasting.
2. Alaskan **Ridge CAOs** are influenced by changes in tropical convection and another phenomenon known as stratospheric wave reflection, whereby wave energy moves upward over Siberia but is then redirected eastward and downward over Canada. Both of those processes promote a stronger high pressure system over Alaska, resulting in southward flow of Arctic air down the US Plains. Wave reflection is particularly unique and interesting because the mechanism requires a stronger than normal stratospheric polar vortex, which differs from the prevailing paradigm and what we see for Arctic High CAOs.

The team also took their knowledge of CAO formation mechanisms to connect North American weather regimes and peak energy demand in the Southwest Power Pool (SPP) region[14]. Since operational models have skill in forecasting these weather regimes up to 14–20 days in advance[15], subseasonal weather regime forecasts could enhance energy load predictions and improve preparedness for wintertime energy demand surges.

Predicting Wintertime Temperature Whiplash Events

Sudden swings from anomalously warm to anomalously cold temperatures (or vice versa) over just a few days, known as "temperature whiplashes," can have severe socioeconomic consequences, including infrastructure damage, agricultural losses, and increased energy demand volatility. Research by Giannakopoulos and Furtado (2025)[16] defined and characterized temperature whiplash events across the US Southern Plains during the winter. Their findings indicate a notable increase in "hot-to-cold" whiplash events since the 1990s, underscoring the growing climate variability in the region.

Key subseasonal predictors of these "hot-to-cold" whiplash events for the Southern Plains mirrored some of the same found for CAOs (1) The Alaskan Ridge regime prior to the event, which disrupts normal weather patterns and allows cold air to move southward.; and (2) wave reflection, which reinforces high pressure near Alaska and Canada.

These characteristics present forecasts of opportunity, meaning that S2S models may have enhanced skill in predicting whiplash events under certain atmospheric conditions.

Implications for S2S Forecasting and Climate Resilience

The findings from the above-mentioned studies highlight promising avenues for improving subseasonal forecasting of extreme temperature events, particularly through weather regime-based forecasting strategies. By leveraging these new insights, the S3OK research team is bridging the gap between weather and climate predictions, advancing more reliable tools for managing weather extremes in a changing climate. With continued advancements in S2S modeling, researchers aim to:

- Enhance early forecasting for CAOs, heatwaves, and temperature whiplash events.
- Improve energy demand forecasting, particularly in vulnerable grid regions like the Southwest Power Pool (SPP).
- Provide decision-makers with more actionable insights to mitigate the socioeconomic impacts of extreme temperature swings.

Flash Droughts: Understanding Their Increasing Frequency and Predictability Challenges

Unlike traditional droughts, which develop gradually over months or years, flash droughts emerge suddenly and intensify rapidly, driven by a combination of critical precipitation deficits and elevated evaporative demand. These events are often amplified by atmospheric conditions like blocking highs, periods of time when areas of high pressure over the region remain quasi-stationary for several days to weeks, keeping the weather very warm, sunny, and dry. Oklahoma's diverse landscape and complex seasonal weather patterns make it especially vulnerable to these rapid-onset droughts.

Key findings from Christian et al. (2023a)[17] indicate that flash drought occurrences are increasing globally due to climate change, with large increases projected in North America and Europe under high-emission scenarios. This trend raises concerns for agriculture, water supply, and ecosystem stability in Oklahoma and other drought-prone regions. Fellman et al. (2025)[18] investigated these flash drought events over the Southern Great Plains and their potential impact of flash drought events on winter wheat productivity in the region. Results indicate that flash drought events from July to October, just before and during the planting of winter wheat, have the most significant negative impacts on winter wheat productivity the following spring in Oklahoma. These events deplete the soil moisture contained in the ground, and cause below-average soil moisture conditions to persist throughout much of the growing season due to limited precipitation experienced during the winter months.

Forecasting flash droughts on the S2S timescale using existing dynamical models remains a challenge. Christian et al. (2024)[19] highlighted difficulties in implementing specialized flash drought indices into operational forecasts, as flash droughts exhibit distinct seasonal patterns (peaking in spring and early summer for Oklahoma). As such, flash droughts remain challenging to predict on subseasonal timescales. In an analysis of the 2022 flash drought events, Christian et al. (2024)[20] found that current subseasonal prediction models underestimated both the speed of onset of these events. A major limitation was the inability of models to accurately simulate land-atmosphere interactions, a critical component in the rapid intensification of drought conditions.

Precipitation Whiplashes: Advancing S2S Forecasting of Precipitation Extremes in Oklahoma

Oklahoma's highly variable climate makes it particularly susceptible to rapidly developing droughts and extreme precipitation swings. Understanding these phenomena at the S2S scale is essential for improving disaster preparedness, water resource management, and agricultural planning. The S3OK research team has made significant progress in advancing the prediction and characterization of two critical hydrometeorological hazards: flash droughts and precipitation whiplash events.

Predicting Rapid Shifts Between Extremes: The Challenge of Precipitation Whiplash Events

Oklahoma sits at the convergence of arid western and humid eastern North America, resulting in a sharp zonal precipitation gradient (**Figure 6.5;** PRISM Climate Group, 2004). As a result of its unique geography, Oklahoma experiences annual precipitation values that vary as much as 50 to 60 in. in the southeast of the state to 16 to 20 in. in the northwest. This divide, however, can change on subseasonal to interannual scales[21, 22, 23, 24, 25], making Oklahoma prone to rapid transitions in precipitation extremes.

As a result, Oklahoma is also prone to precipitation whiplash events—sudden transitions between extreme wet and dry conditions[26]. These events can lead to severe cascading impacts, including:

- Wildfire outbreaks following anomalously wet periods[27, 28, 29, 30]
- Flash drought development due to rapid drying[27, 28, 29, 30]
- Decreased water quality from hydrological shifts[27, 28, 29, 30]
- Flash flooding from sudden heavy rainfall events[27, 28, 29, 30]

Given the profound impact each of these precipitation whiplash events has on the economy, agriculture, and social well-being, the challenge and need for predicting these rapid shifts between extremes is urgent.

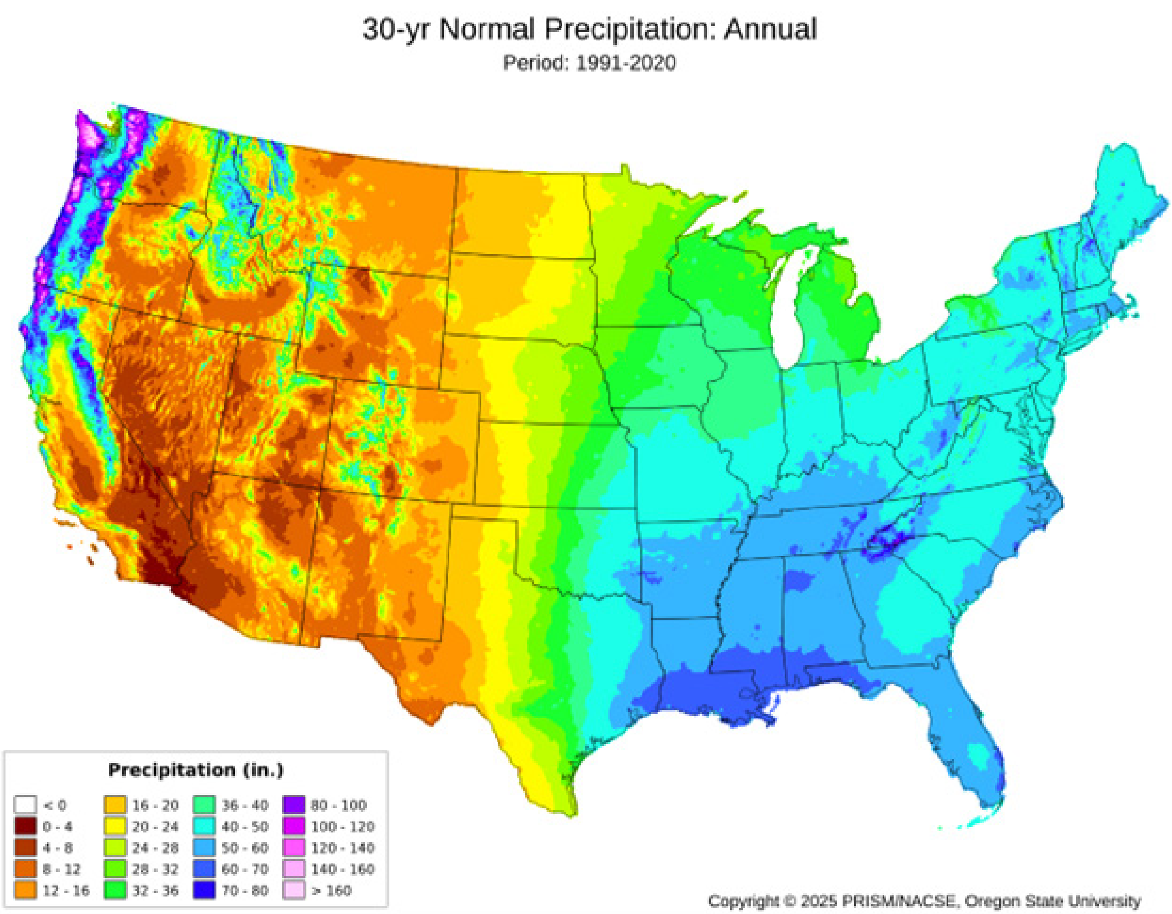


Figure 6.5. 30-year (1991–2020) climatological mean annual precipitation (in) across the Contiguous 48. Data from PRISM. Note that across Oklahoma, there is a very sharp east-to-west change in the average annual precipitation.

Linking Precipitation Abnormalities to Wildfire Risk

In a study of wildfire risk across Oklahoma, Puxley et al. (2024)[31] investigated the role of preceding precipitation anomalies in fueling extreme fire seasons. Their analysis revealed a strong lag correlation between high precipitation 8 months prior and increased wildfire frequency and acreage burned in the following spring.

The study identified a distinct wet-to-dry transition pattern in seasonal precipitation anomalies, in which:

- Above-average spring vegetation growth, driven by excessive rainfall, creates abundant fuel for future fires.
- An anomalously wet summer followed by a dry winter reduces vegetation moisture, making conditions highly flammable by the next spring.

These findings provide valuable insights for wildfire forecasting and could provide a valuable tool for decision-makers seeking to develop longer-term fire management strategies based on subseasonal precipitation trends across Oklahoma.

Defining and Predicting Precipitation Whiplash Events at the S2S Timescale

S3OK researchers Puxley and Martin (2025)[32] are working to define precipitation whiplash events using the standardized precipitation index (SPI) with 30-day rolling precipitation accumulation totals. Once identified, their research aims to examine:

- Climatology of precipitation whiplash events in Oklahoma.
- The synoptic drivers responsible for these rapid transitions.
- The relationship between precipitation whiplash events and wildfire and flood risks.
- How these dynamics might change in the future.

Improving S2S Forecasting and Climate Adaptation

The S3OK research on flash droughts and precipitation whiplash events highlights the urgent need for more reliable S2S forecasting tools that can anticipate rapid hydrometeorological shifts. By improving our understanding of land-atmosphere interactions, atmospheric blocking patterns, and precipitation variability, researchers can help inform more effective early warning systems for droughts, floods, and wildfires.

Future work will focus on refining predictive models, integrating subseasonal atmospheric indicators, and enhancing decision-making frameworks to mitigate the socioeconomic and environmental impacts of these extreme events. As Oklahoma continues to experience increasing climate variability, these efforts are critical for building climate resilience across the region.

Social Dynamic Considerations of S2S

Understanding the social dynamics of S2S weather phenomena is essential for improving resilience to extreme climate events. S2S extremes can have profound socioeconomic consequences, disrupting agriculture, energy demand, public health, and infrastructure systems.

However, the impacts of these events are not solely physical; they are deeply intertwined with public perception, awareness, and preparedness. The ability of communities, industries, and policymakers to respond effectively to S2S weather extremes depends on how well these risks are communicated and understood. Misinformation, lack of predictive confidence, or low public trust in forecasts can hinder proactive decision-making, increasing vulnerability.

As climate variability intensifies, maintaining current insight into the social dimensions of S2S phenomenon is crucial in ensuring that scientific advancements translate into actionable strategies for reducing societal risks. This section details collaborative work advanced that provides insight into public perceptions of S2S extreme events:

- Assessing public understanding of S2S forecasting for extreme events
- Evaluating public perceptions and socioeconomic impacts of S2S extreme events
- Bridging the gap between perception and reality
- Understanding awareness of drought through digital behavior
- Assessing implications for policy and risk communication

Assessing Public Understanding of S2S Forecasting for Extreme Events

As noted above, S2S forecasts are becoming increasingly accurate, yet their societal benefits remain poorly understood. Key questions—who might use them, for what purposes, and under what circumstances—have yet to be fully addressed. To begin exploring these questions, an S3OK study[33] surveyed Oklahomans, yielding the following key findings:

- **Awareness of S2S forecasts is limited**: Just over half of Oklahomans (57.3%) were aware that S2S forecasts for temperature and precipitation are currently available.
- **Usage among those aware is low**: Among Oklahomans familiar with S2S forecasts, just 19% reported using them "regularly" or "frequently." Most relied on local TV or non-government websites for access. Common applications included planning for travel, outdoor activities, and agriculture or gardening.
- **Perceptions of accuracy and relevance were key barriers**: Thirteen percent of respondents viewed current S2S forecasts as too inaccurate or unreliable, while 10% were unsure how these forecasts aligned with their daily needs.
- **Support for further investment was strong**: Despite low awareness and concerns, 70% of Oklahomans said they would vote in favor of improving S2S forecasts if there were no cost to them. Of those who said they would vote in favor of improving S2S forecasting if there were no cost to them, over 50% expressed willingness to support such a proposal even if it incurred a cost of up to $20 annually for the next decade. Additionally, more than 60% indicated they would use S2S forecasts if improvements were made.

Evaluating Public Perceptions and Socioeconomic Impacts of S2S Extreme Events

Beyond assessing public understanding of S2S forecasting, insight into how people perceive and respond to subseasonal-to-seasonal extreme events plays a critical role in shaping societal resilience and adaptation strategies. While meteorological records and key science advanced by S3OK research on S2S provide objective measurements of extreme events, public awareness and concern often do not align with actual climate trends. This misalignment has important implications for disaster preparedness, policy responses, and risk communication.

Bridging the Gap Between Perception and Reality

S3OK researchers leveraged survey data and meteorological records to analyze the discrepancies between public perception and observed climate extremes using statistical analysis and spatial visualization techniques. They found that:

- The public is more concerned about sudden, high-impact events like tornadoes but is less aware of slow-developing climate phenomena, such as droughts.
- Despite their devastating long-term consequences, droughts receive less public attention, likely due to their gradual onset and cumulative impacts.
- Public education and outreach efforts need to be expanded to increase awareness of slow-onset but intensifying climate extremes.

Understanding Awareness of Drought Through Digital Behavior

Another study examined public awareness of droughts by analyzing Google Trends search data alongside the U.S. Drought Monitor (USDM) records. The study found:

- People generally do not respond to moderate drought conditions, likely because they do not perceive immediate impacts on daily life.
- There is an average two-week delay in public attention to severe drought conditions, indicating that awareness only increases once tangible impacts—such as water restrictions or crop damage—become evident.
- This delayed response suggests that individuals are reacting reactively rather than proactively to droughts, highlighting the need for improved communication strategies and early warning systems to enhance preparedness.

Assessing Implications for Policy and Risk Communication

These findings emphasize the complex social dimensions of S2S climate extremes, demonstrating that public perceptions do not always align with meteorological reality. As climate variability increases, it is essential to:

- Develop targeted public outreach campaigns that emphasize the long-term consequences of slow-onset climate events.
- Improve early warning systems and communication strategies to engage communities before extreme events reach crisis levels.
- Enhance cross-sector collaboration between scientists, policymakers, and local communities to translate S2S forecasts into actionable strategies for risk reduction.

By integrating social science insights with meteorological advancements, S3OK research is helping to close the gap between perception and reality, fostering more informed decision-making and resilient communities in the face of S2S climate extremes.

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