Platte River Power Authority

Extreme Weather Event and Dark Calm Analysis

June 12, 2023

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1. Executive Summary

Part 1 of this analysis provides an in-depth examination of historical weather data from 1973-2019, focusing on understanding the frequency, depth and breadth of extreme weather events along with the prevalence of extended periods of low or no wind solar generation known as Dark Calms. The study aims to shed light on the evolving patterns of these phenomena and their impact on the electricity market.

While the study could not find a statistically significant change in heatwaves over the past 5 decades, we were able to discover a statistically significant decrease at a 90 percent confidence interval ($p<=0.1$) in cold wave frequency for the locations included in this study. Furthermore, we were also able to discover at a 90 percent confidence interval ($p<=0.1$) a statistically significant decrease in heating degree days and unusually cold days. In contrast, we found out a statistically significant increase of cooling degree days and unusually hot days at a 90 percent confidence interval ($p<=0.1$) for majority of the locations included in the analysis. We were also able to determine a statistically significant decrease of weather conditions that lead to Dark Calms at a 90 percent confidence interval ($p<=0.1$).

Part 2 of this analysis provides a market perspective of extreme weather events and dark calms (DC) over the last five years of US energy market data. Providing a snapshot of how demand, market pricing, and supply react during extreme heat, cold, and DC events across the US. Our analysis focused on the recent extreme weather events including: Winter Storm Uri (February 2021), Winter Storm Elliott (December 2022), and the Pacific Northwest heat wave (June 2021). Quantifying demand and price volatility and uncertainty during times of extreme weather.

The study also shows descriptive statistics on magnitude and frequency of DC events occur across various regions. Highlighting the intermittence of renewable supply, which differs depending on local weather and the regions' solar and wind resource mix. The summary tables include DC events per year by percent of full renewable output as well as comparisons of DC renewable hourly generation to average and high renewable weeks of the year.

2. Extreme Weather Events

2.1. 50-Year Weather Analysis

ACES conducted an analysis of extreme weather events and Dark Calm Analysis for Platte River and to complete this project, ACES analyzed temperature data from the past 5 decades at 70 locations west of the Mississippi River. The results of each analysis and graphs to provide visualization of the findings are contained in this report. Each analysis was conducted for 70 locations west of the Mississippi River (the West Region), as well as for 27 locations in Colorado and its surrounding regions (the Colorado Region).

The analyses included the examination of heat waves, cold waves, unusually high and low temperatures, seasonal temperature anomalies, and Dark Calms (periods with no wind and solar generation). Figure 1 and 2 depict the locations where each analysis was conducted. Figure 1 represents the West Region, and Figure 2 represents the Colorado Region.

Figure 1.

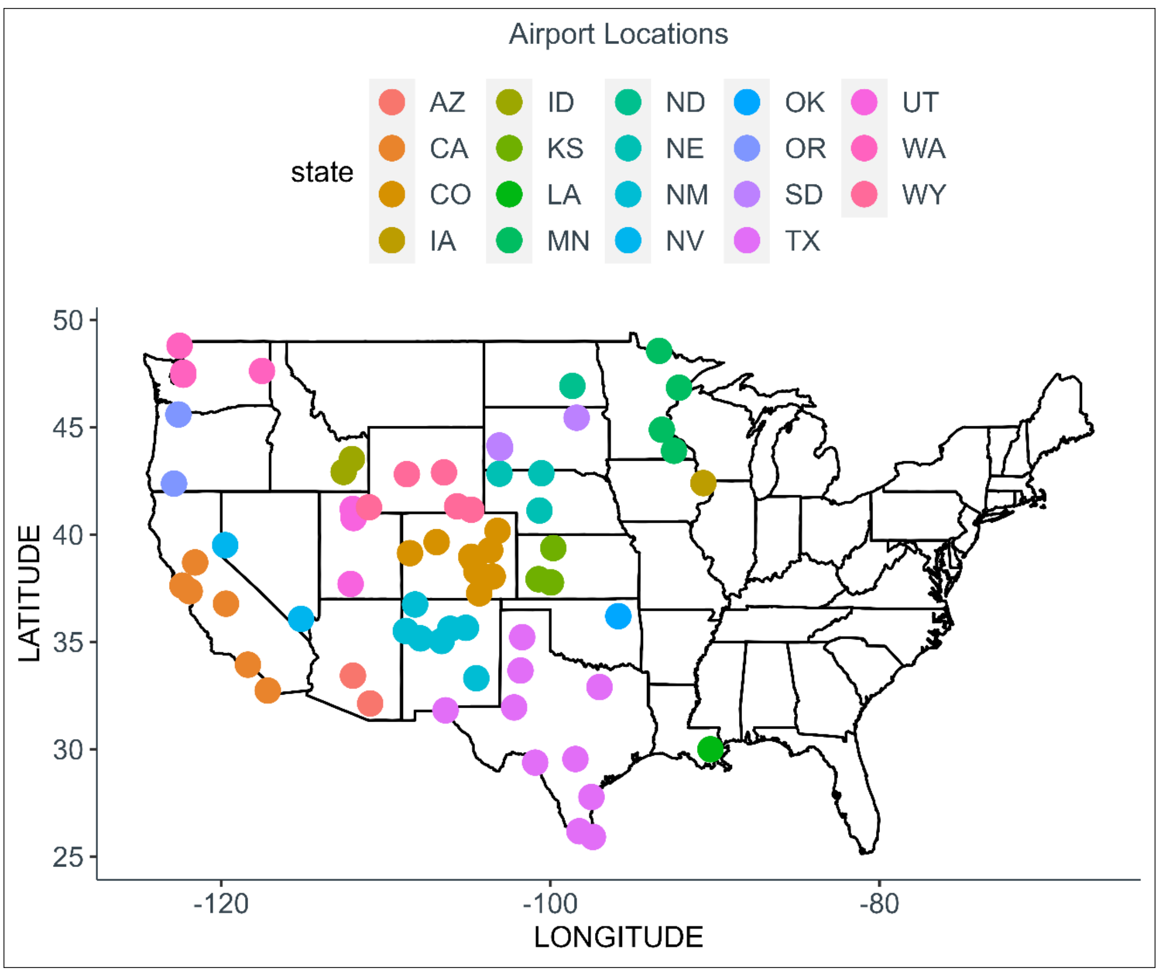
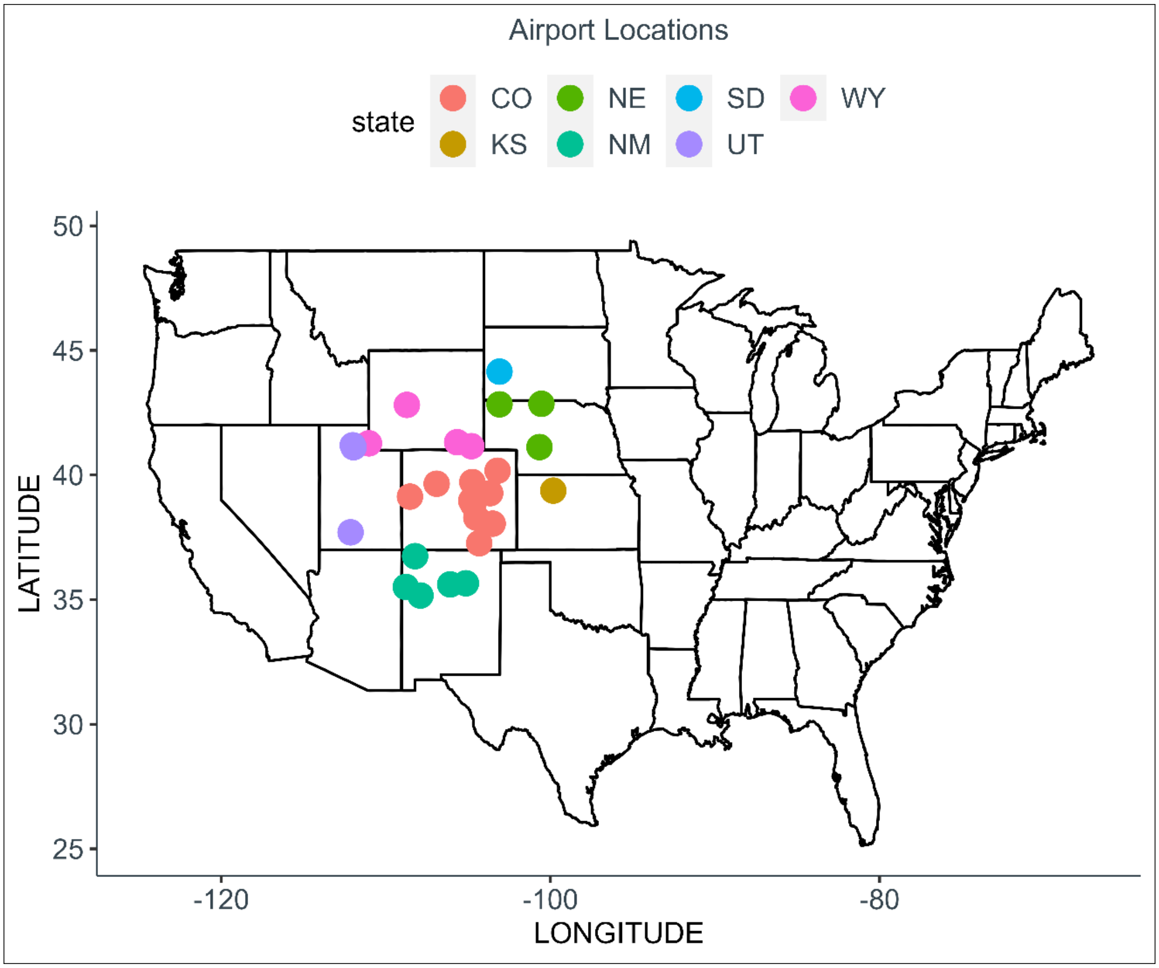


Figure 2.



2.2. Heat Waves

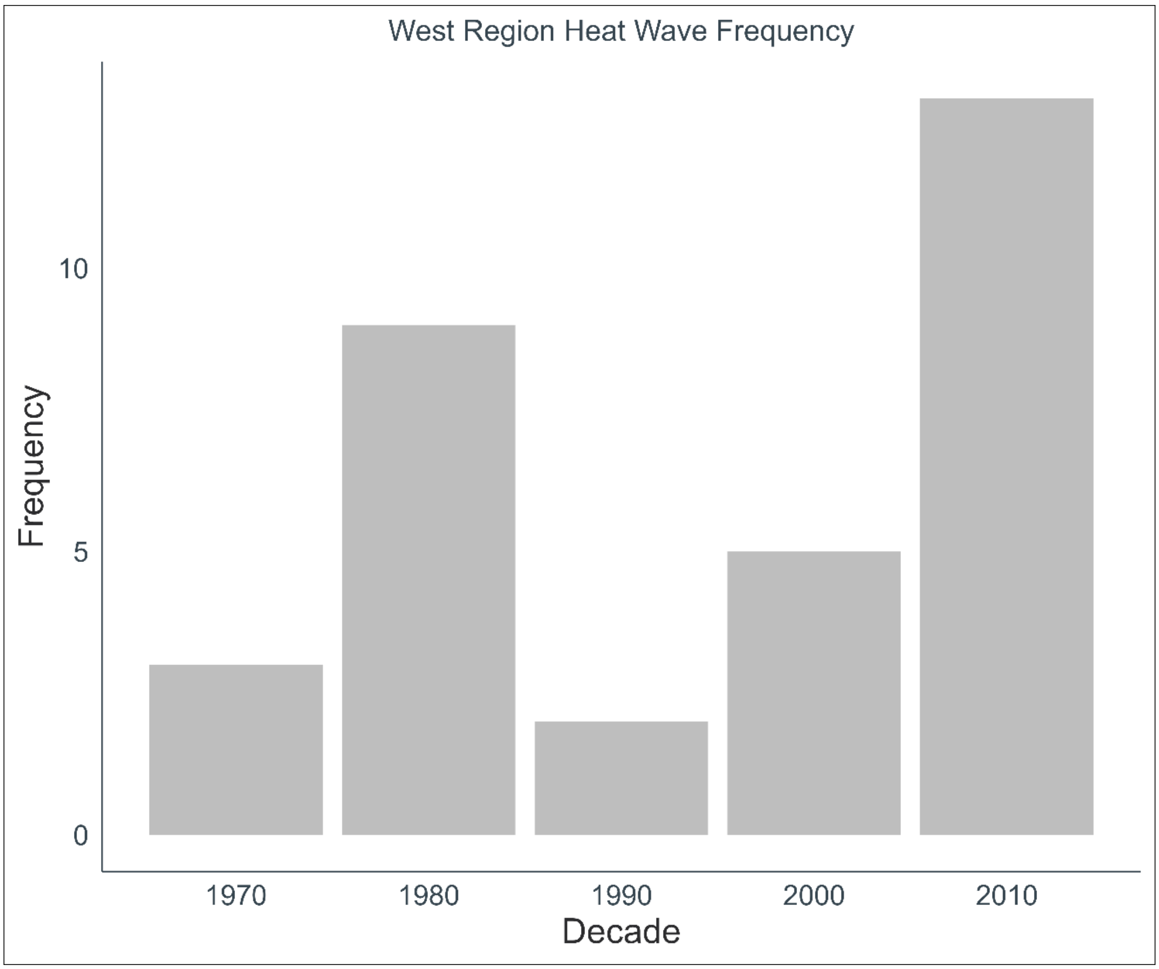
The Environmental Protection Agency's (EPA) climate change indicator metric defines heat waves as a period of two or more consecutive days during which the daily minimum apparent temperature (i.e., the actual temperature adjusted for humidity) at a particular weather station is higher than the 85th percentile of historical July and August temperatures (1981 to 2010) for that particular location. The July to August period from 1981 to 2010 was used to maintain consistency with other climatology metrics. The threshold determined by using the 85th percentile of July and August temperatures translates to the nine hottest days of July and August in an average year over the 30-year period. A top-nine hottest temperature would typically be classified as unusually hot. By adopting a location-specific threshold instead of a nationwide threshold, local variations in conditions are considered. To identify a heat wave, ACES compared the daily minimum apparent temperature of a particular location with its 85th percentile threshold. If the temperature exceeded the threshold for two or more consecutive days, it was considered a heat wave. ACES then examined the following three metrics for the heat waves:

- Frequency: the number of heat waves that occur each year
- Duration (breadth): the length of each individual heat wave in days
- Intensity (depth): the temperature during the heat wave

2.2.1. Heat Wave Frequency

Heat wave frequency is the number of observed heat waves per year. This metric was calculated for the West Region and the Colorado Region. In each case, individual heat waves were calculated based on localized threshold. Figure 3 below illustrates the heat wave frequency over the past 50 years for the West Region.

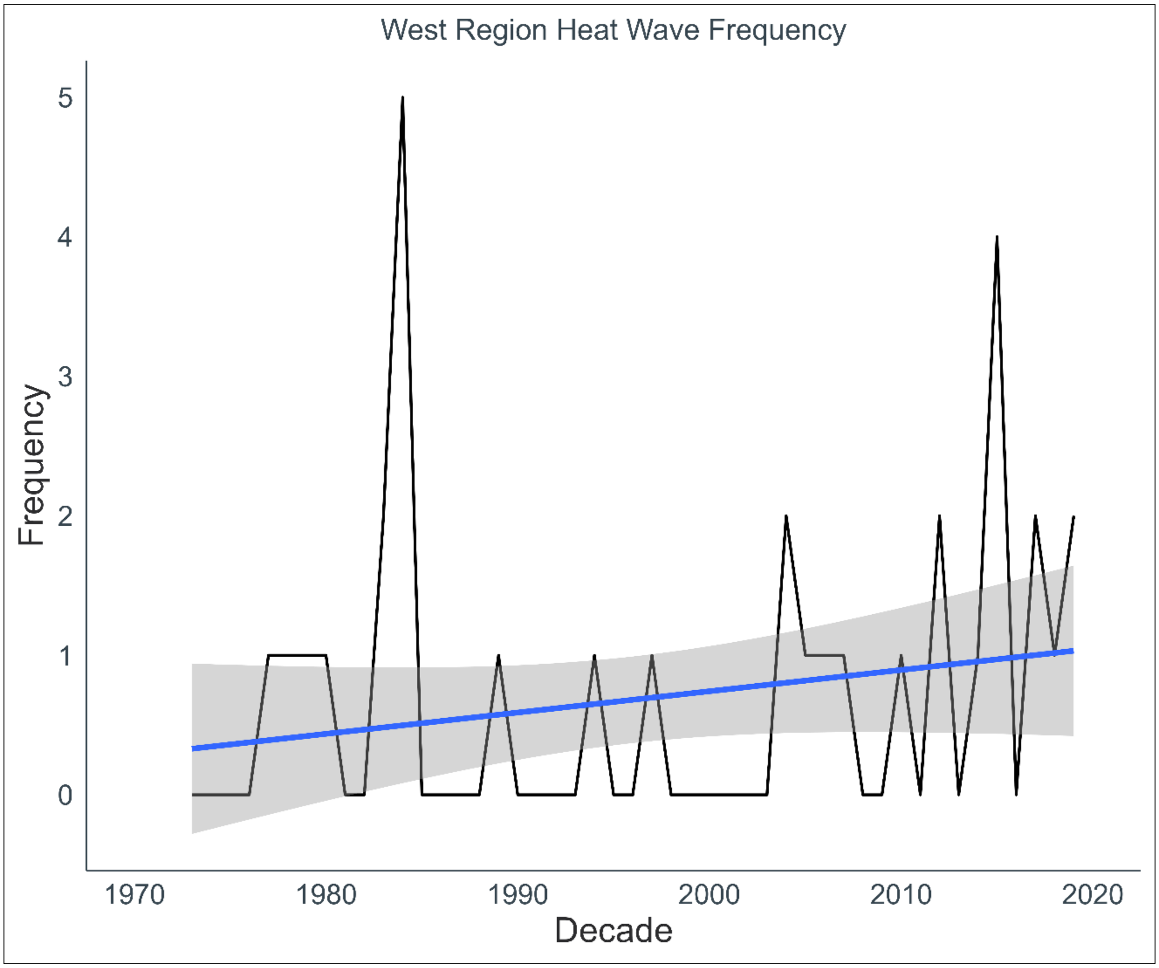
Figure 3.



Heat wave frequencies for the West Region appear to increase beginning in 1990. However, there were not any observations that could be classified as heat waves based on the EPA's heat wave definition for the locations ACES chose in the Colorado Region.

Additionally, Figure 3 illustrates that the highest heat wave frequency in the past 50 years was observed in the most recent decade in the West Region. Figure 4 on the next page shows the annual heat wave frequency as a line chart with a regression line to illustrate this trend.

Figure 4.

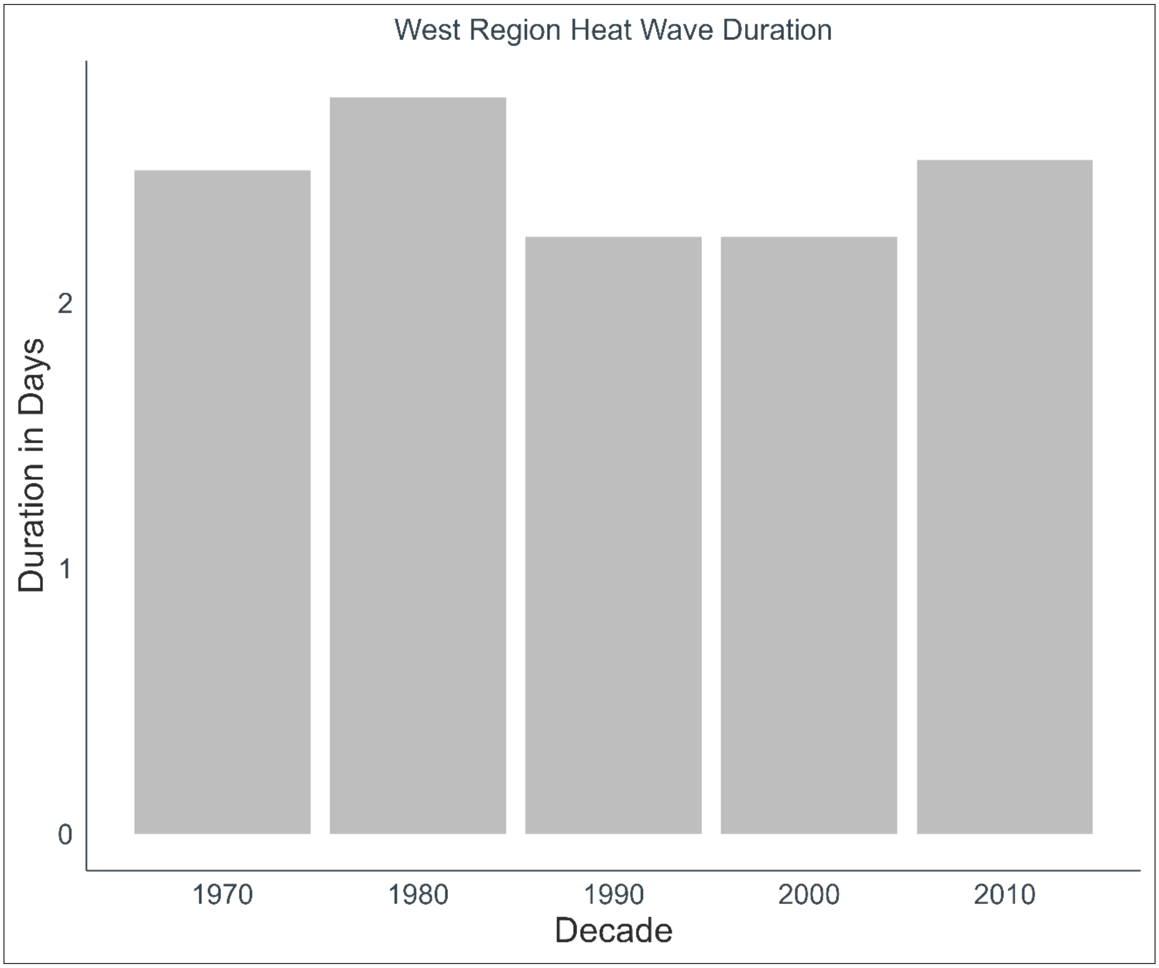


The least squares regression method was employed to determine if there was a statistically significant relationship or trend between heat wave frequencies and time (in years). Locations with significant trends at a 90% confidence level (p <= 0.1) were deemed to have a statistically significant result. However, the results were found to be statistically insignificant for both the West Region and the Colorado Region.

2.2.2. Heat Wave Duration (Breadth)

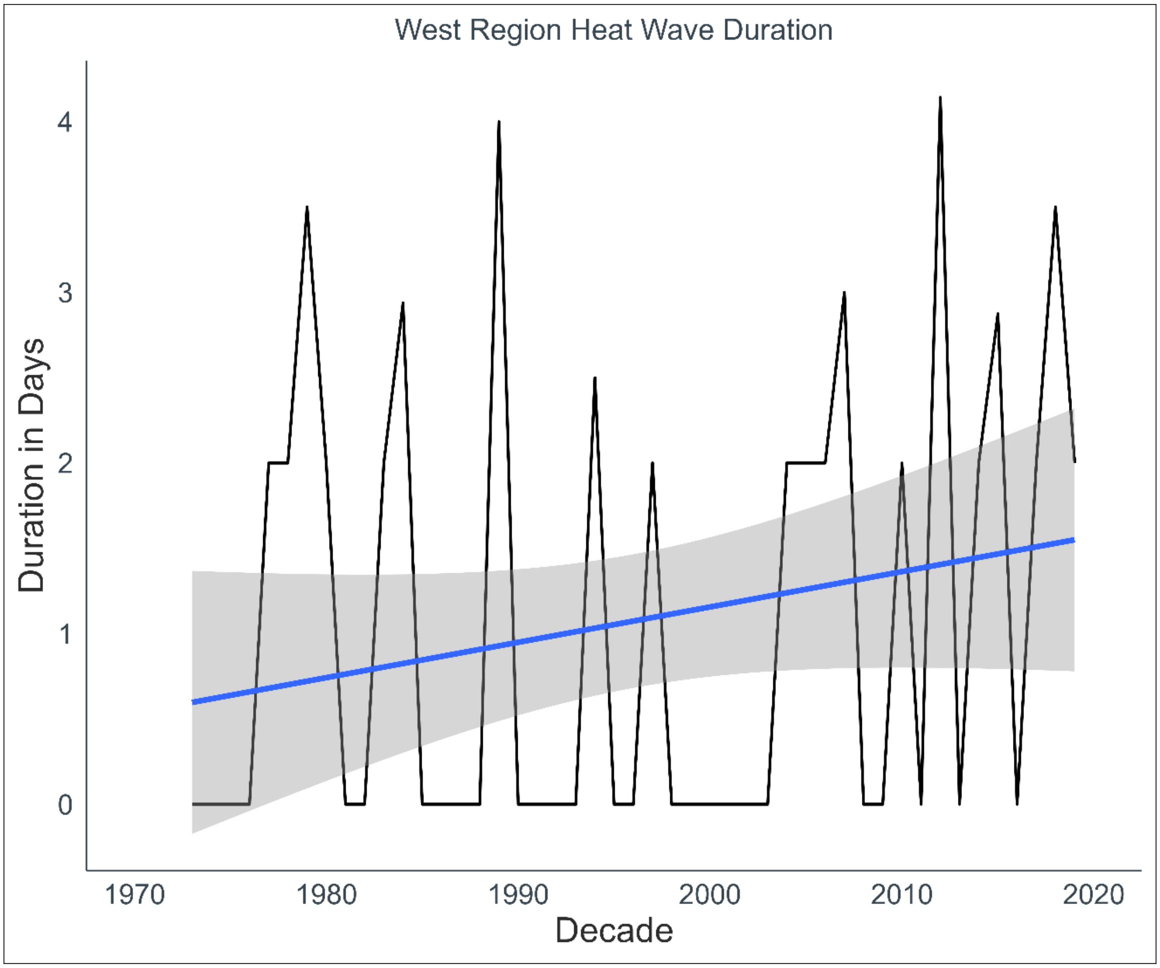
Duration refers to the length of each individual heat wave, measured in days. For an event to be classified as a heat wave, it must persist for at least two days. Therefore, the minimum duration of a heat wave in this analysis is two days. Figure 5 on the next page displays the average duration of each heat wave in the West Region over the past 50 years by decade.

Figure 5.



The duration of heat waves in the West Region was minimal during the 1990s and 2000s, but increased in the 2010s. Figure 6 on the next page displays the annual change in duration for the West Region, with the regression line depicting the overall trend.

Figure 6.



The least squares regression method was used to determine if there was a statistically significant relationship or trend between the duration of heat waves and time (in years). Locations with trends significant at a 90% confidence level ($p <= 0.1$) were deemed to have a statistically significant result. However, the results were found to be statistically insignificant for the West Region and the Colorado Region.

2.2.3. Heat Wave Intensity (Depth)

Intensity is a measure of the severity of a heat wave, which is obtained by calculating the difference between the observed apparent temperature of a location and the localized threshold for that location. The greater the difference, the more severe the heat wave. Figure 7 on the next page shows the average intensity of heat waves over the past 50 years in the West Region.

Figure 7.

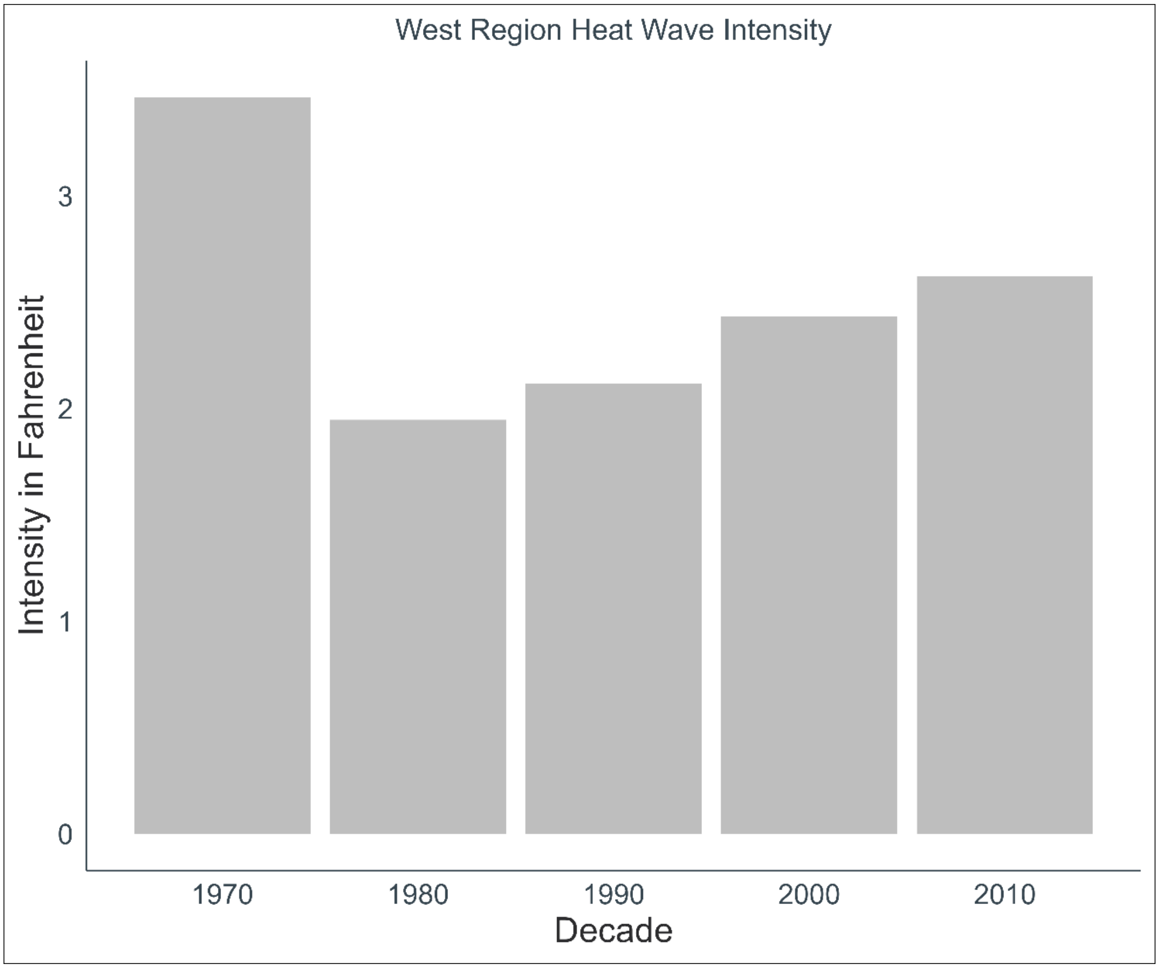
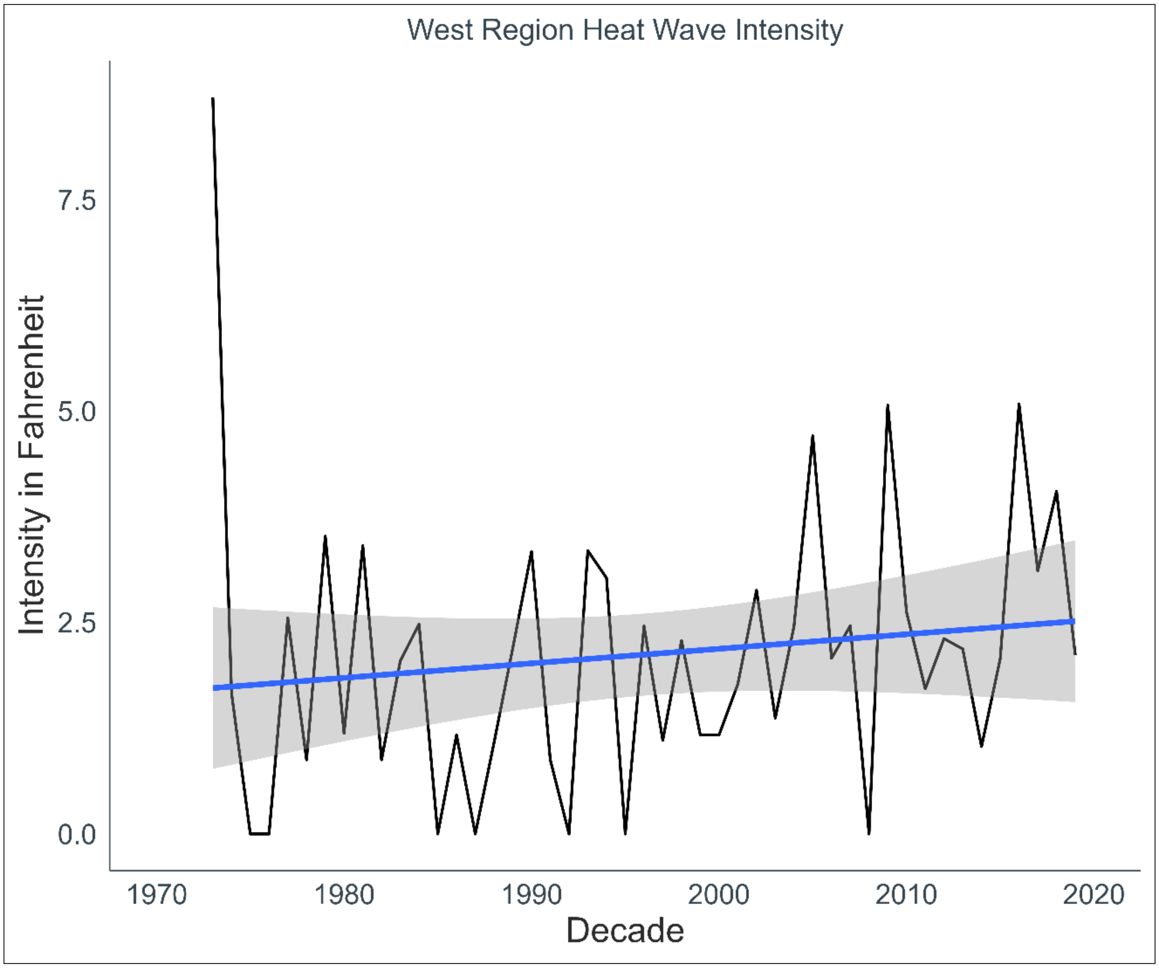


Figure 7 above illustrates that heat wave intensity peaked in the 1970s in the West Region. Since then, heat wave intensity has not reached that peak again, but has shown a gradual increase over the past 40 years.

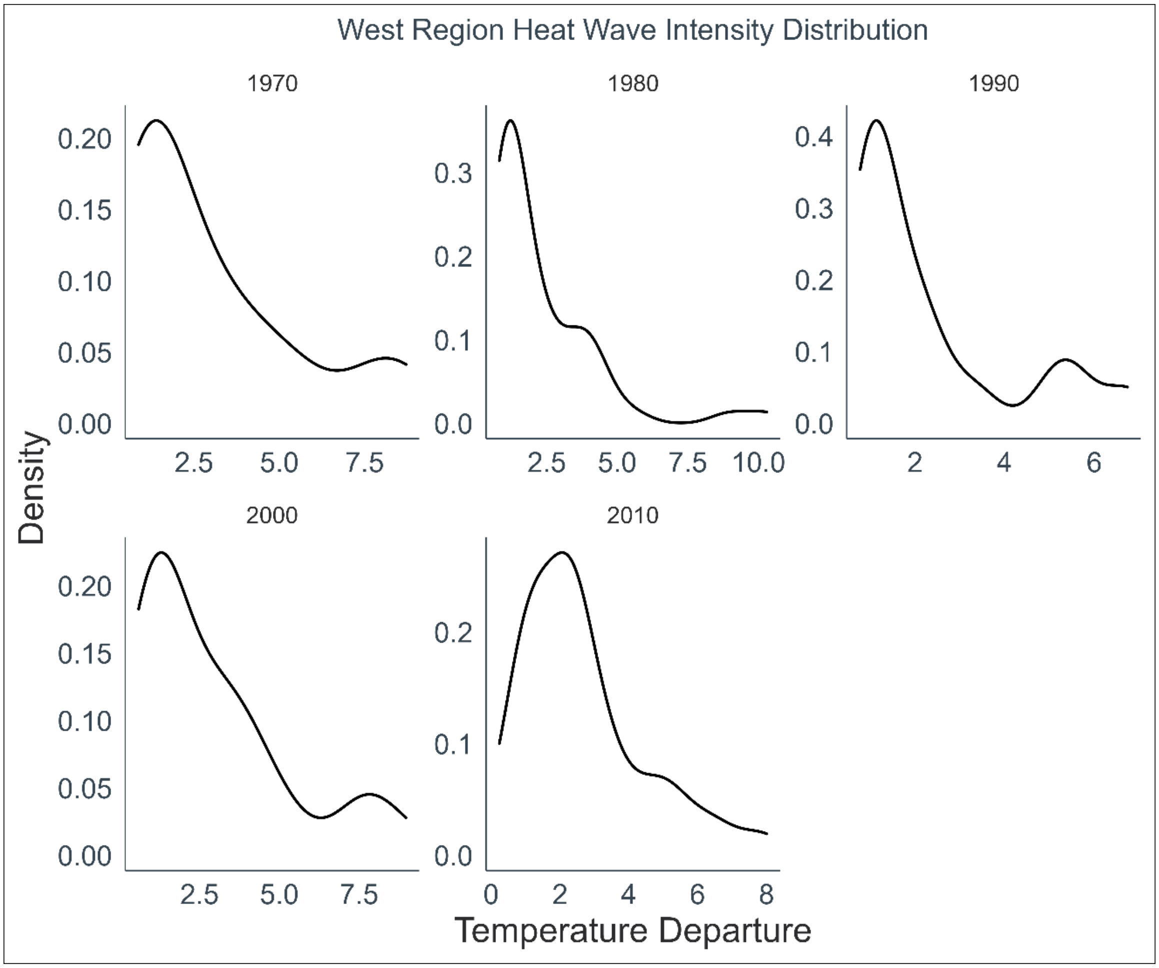
Figure 8 presents this information as a line chart with a regression line to show the overall trend.

Figure 8.



The distribution graph in Figure 9 on the next page shows the distribution of heat wave intensities over the past 50 years for the west region, without averaging. This graph provides details about the extremes of heat wave intensities.

Figure 9.



The distribution graph in Figure 9 shows that the 1980s had the highest temperature departure from the heat wave threshold, reaching up to 10°F for the West Region. ACES also used the least squares regression method to determine if there was a statistically significant relationship or trend between heat wave intensity and time (in years), with locations showing a trend significant to a 90% confidence level ($p <= 0.1$) considered to have a statistically significant result. However, the results showed no statistically significant trend for the West Region nor the Colorado Region. Figure 10 below summarizes the frequency of heat waves over the past 50 years by various duration groups for the West Region.

Figure 10.

Heat Wave Summary – West Region						
	48 Hours	72 Hours	96 hours	120 hours	144 hours	168 hours
Events per year	0.47	0.02	0.09	0.04	0.021	0.043

2.3. Cold Waves

The EPA's heat wave metric has been revised to define a cold wave as "a period of two or more consecutive days where the daily maximum apparent temperature at a particular weather station is lower than the 15th percentile of historical January and February temperatures (1981 to 2010) for that location." Using a location-specific threshold helps maintain variations that arise in different locations. Therefore, the selected threshold represents the local conditions and accurately classifies cold waves. If the daily maximum apparent temperature (adjusted for humidity) is less than the localized threshold for two or more consecutive days, it is considered a cold wave. The three metrics used to examine heat waves were also used to analyze cold waves in the West Region and the Colorado Region over the past 50 years. The three metrics are as follows:

- Frequency: the number of cold waves that occur every year
- Duration (breadth): the length of each individual cold wave in days
- Intensity (depth): how cold it was during the cold wave

2.3.1. Cold Wave Frequency

The sum of localized cold waves was used to draw conclusions about the frequency of cold waves in the West Region. Each individual region was also analyzed to understand the variation in the frequency of cold waves across regions. Figure 11 depicts the results of the analysis performed for the West Region and Figure 12 depicts the results of the analysis performed for the Colorado Region.

Figure 11.

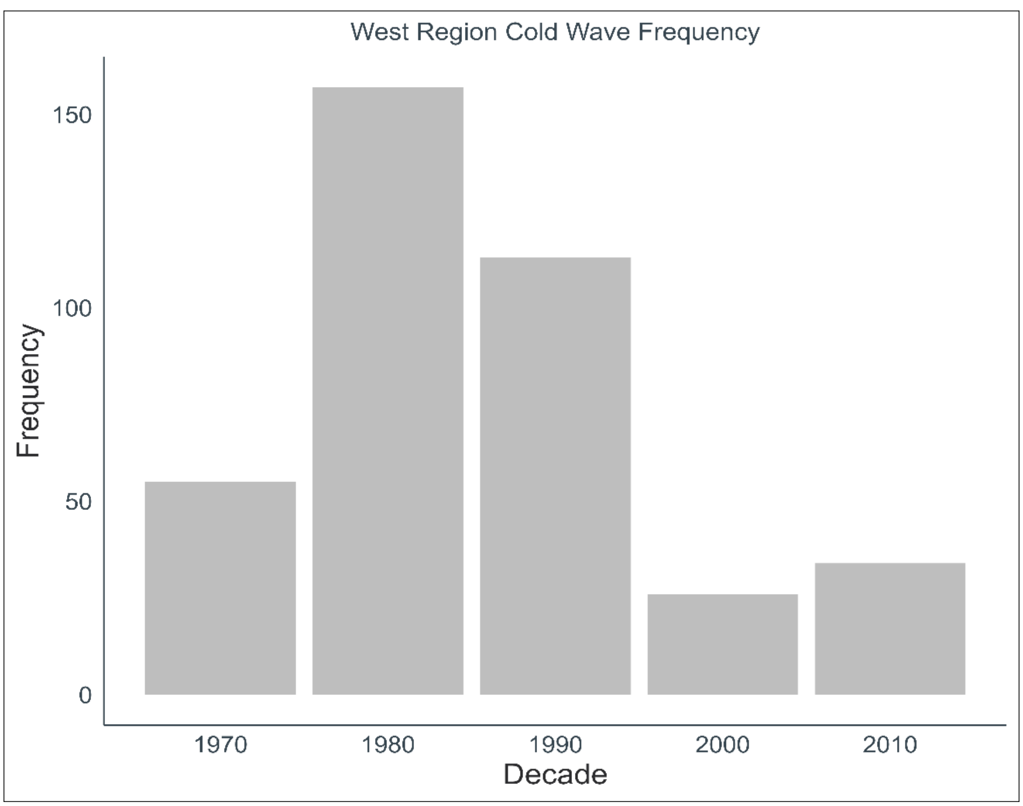
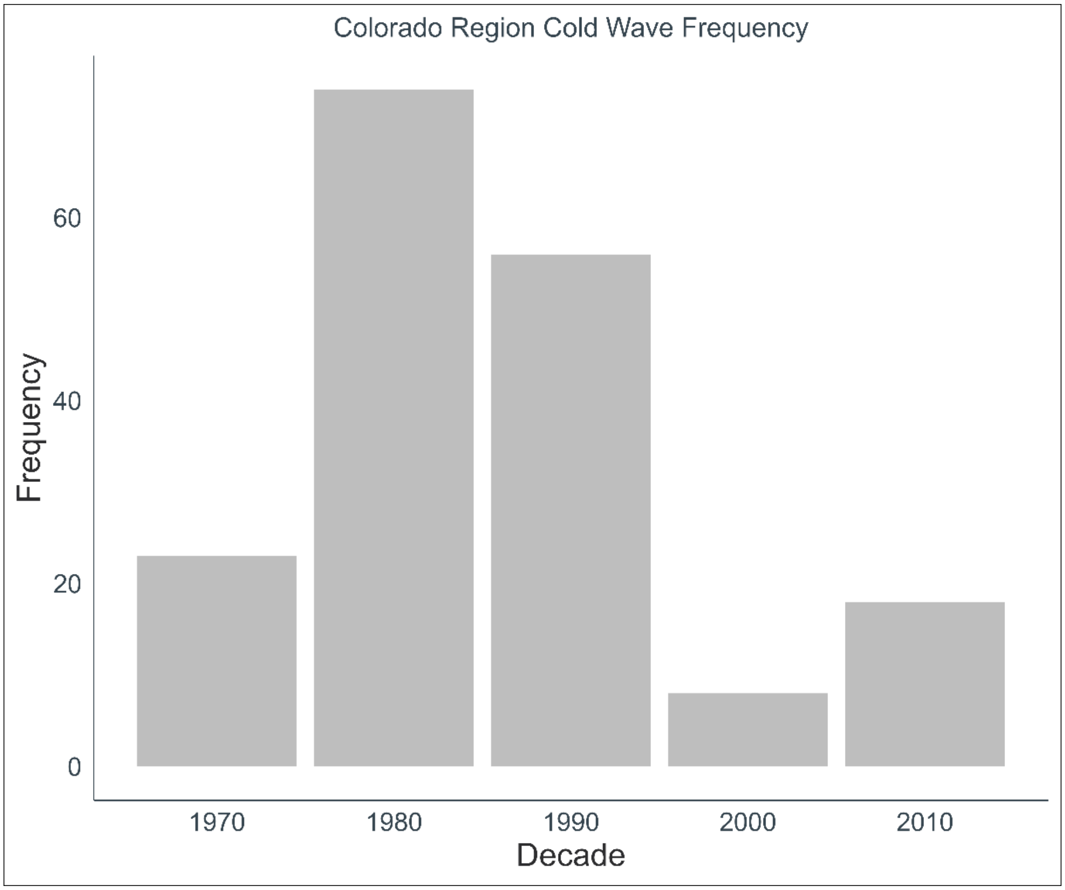


Figure 12.



Unlike heat waves, cold waves in the West Region followed the same pattern as those in the Colorado Region over the past 50 years. After peaking during the 1980s, the frequency of cold waves decreased for two consecutive decades before increasing again in the 2010s. The airports in the Colorado Region accounted for 39% of the total 70 airports analyzed. However, almost 45% of the cold waves occurred in the Colorado Region, indicating that this area overall experienced a higher frequency of cold waves compared to the West Region over the past 50 years. The frequency of cold waves decreasing over the decades is shown in Figure 13 and Figure 14 for the West Region and the Colorado Region, respectively.

Figure 13.

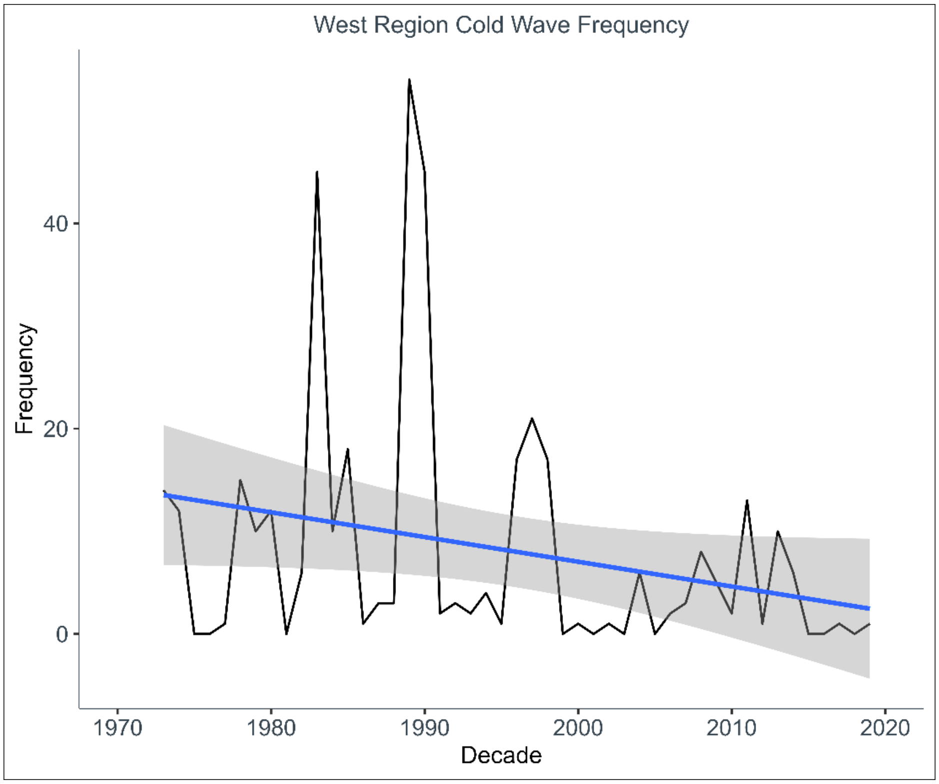
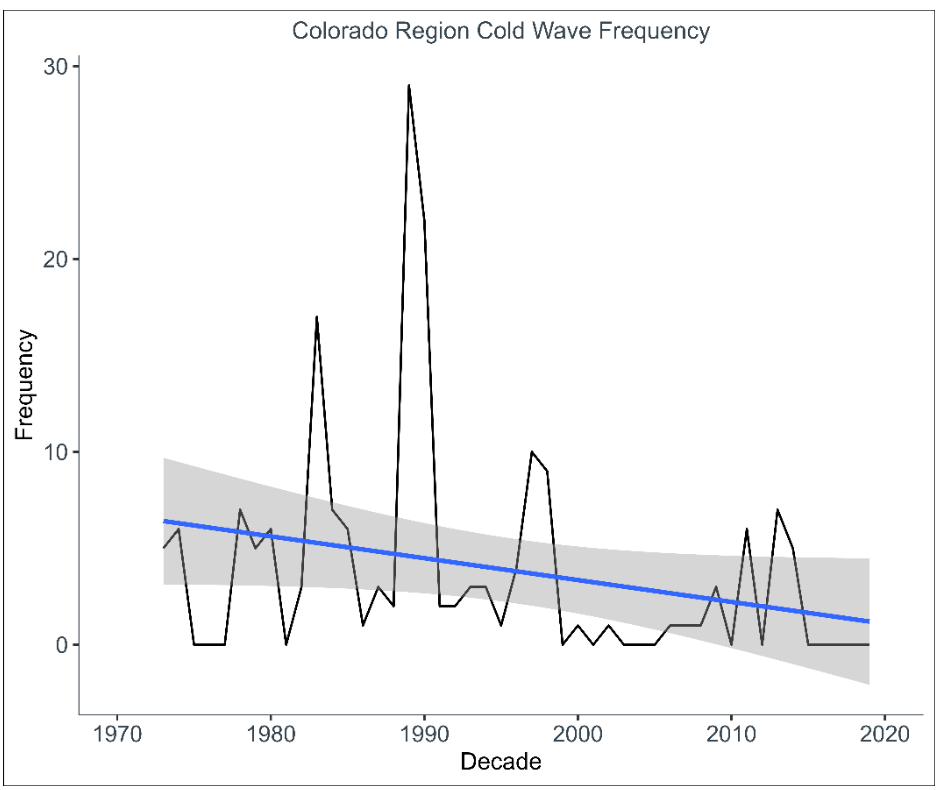


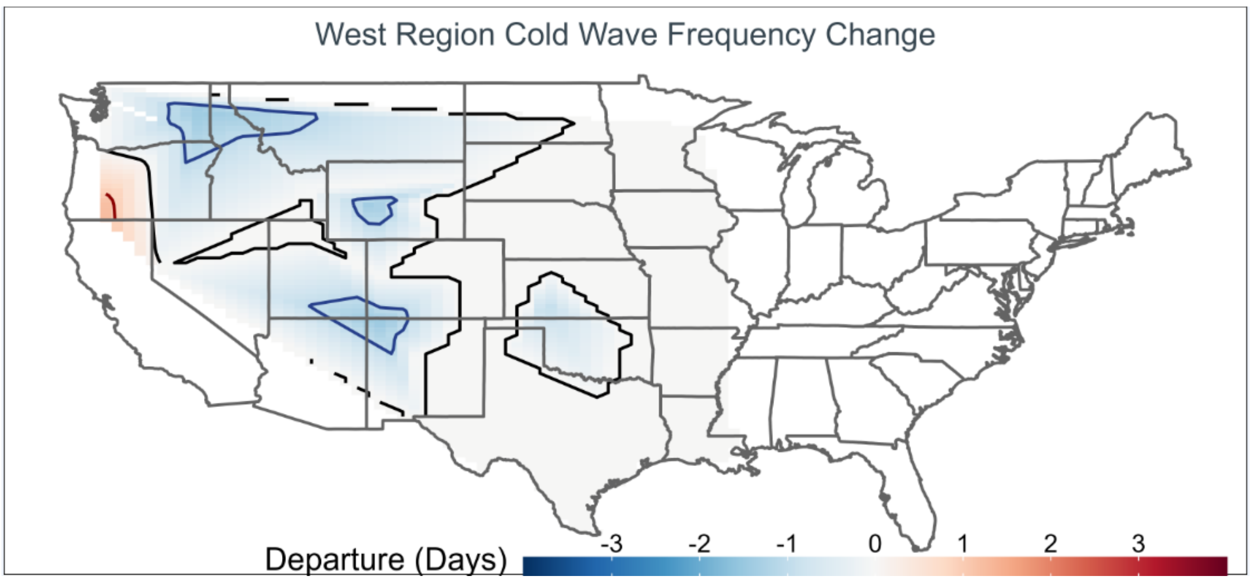
Figure 14.



The fitted regression line was used to indicate statistical significance at a 90% confidence level (p<=0.1). The results were statistically significant for the West Region and the Colorado Region, indicating a decrease in the frequency of cold waves over the past 50 years. The trend of the frequency of cold waves can be quantified and extrapolated using the fitted regression line. There were 11 fewer cold waves than 50 years ago in the West Region, which is a decrease of approximately 2.2 cold waves each decade. For the Colorado Region, the result indicates a decrease of 5 cold waves compared to 50 years ago, or a decrease of 1 cold waves every decade.

Examining the smaller regions within the West Region also provides insight into how the frequency of cold waves has evolved over the past 50 years in each location. Figure 15 on the next page shows the least square regression fitted on 50 years of data from each of these smaller regions, and the results were also extrapolated locally.

Figure 15.



The West Region mostly had a decrease in the frequency of cold waves over the past 50 years. However, some areas on the West Coast experienced an increase in the frequency of cold waves over the past 50 years. Overall, the results for the West Region suggest that there has been a decrease in the frequency of cold waves. Looking at the smaller regions within the larger area offers nuanced insight, such as the increase in the frequency of cold waves along the West Coast.

2.3.2. Cold Wave Duration (Breadth)

The duration, or breadth, of a cold wave is the measure of the length of the cold waves in days. The minimum duration required for an event to be flagged as a cold wave is two days. Figure 16 on the next page shows the duration of cold waves for the past five decades for the West Region, and Figure 17 shows the same information for the Colorado Region.

Figure 16.

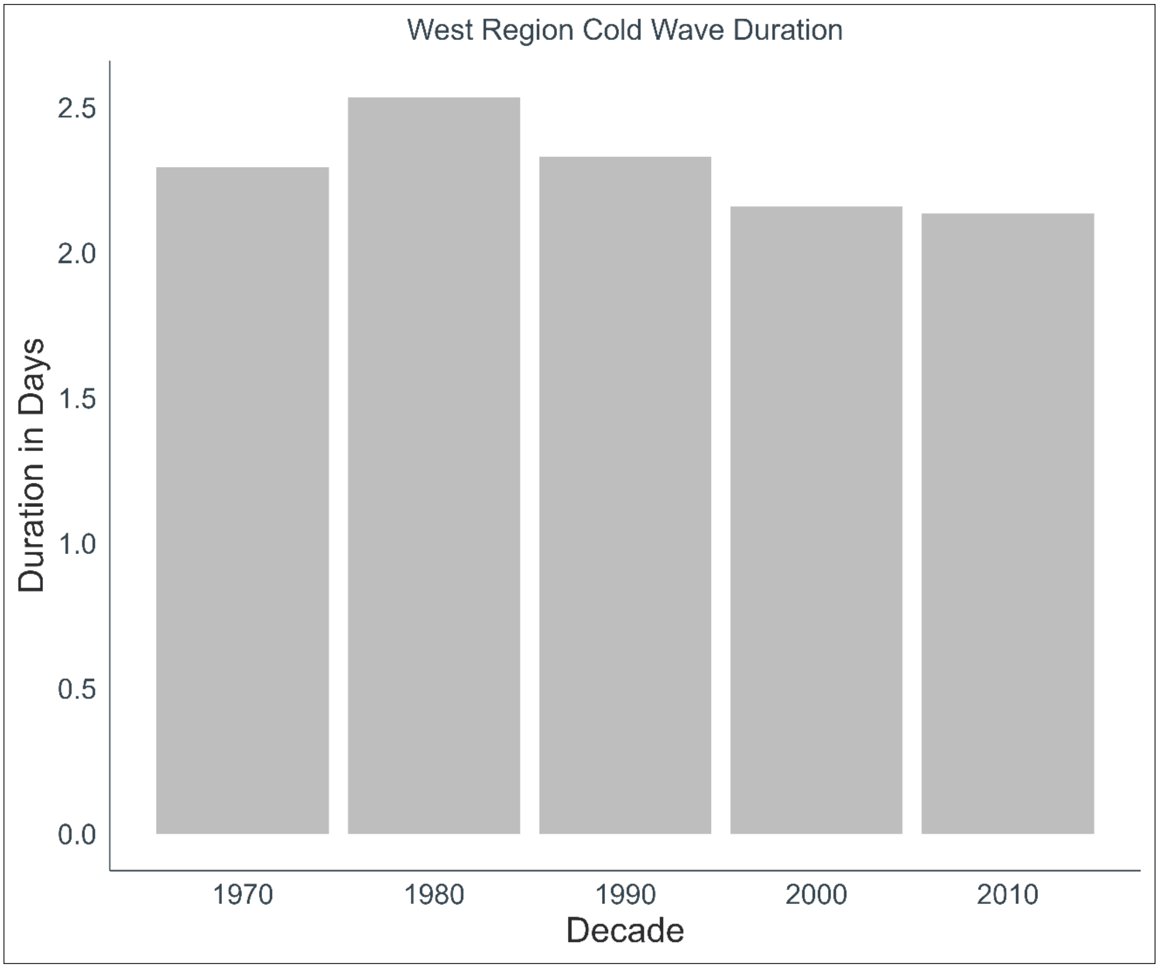
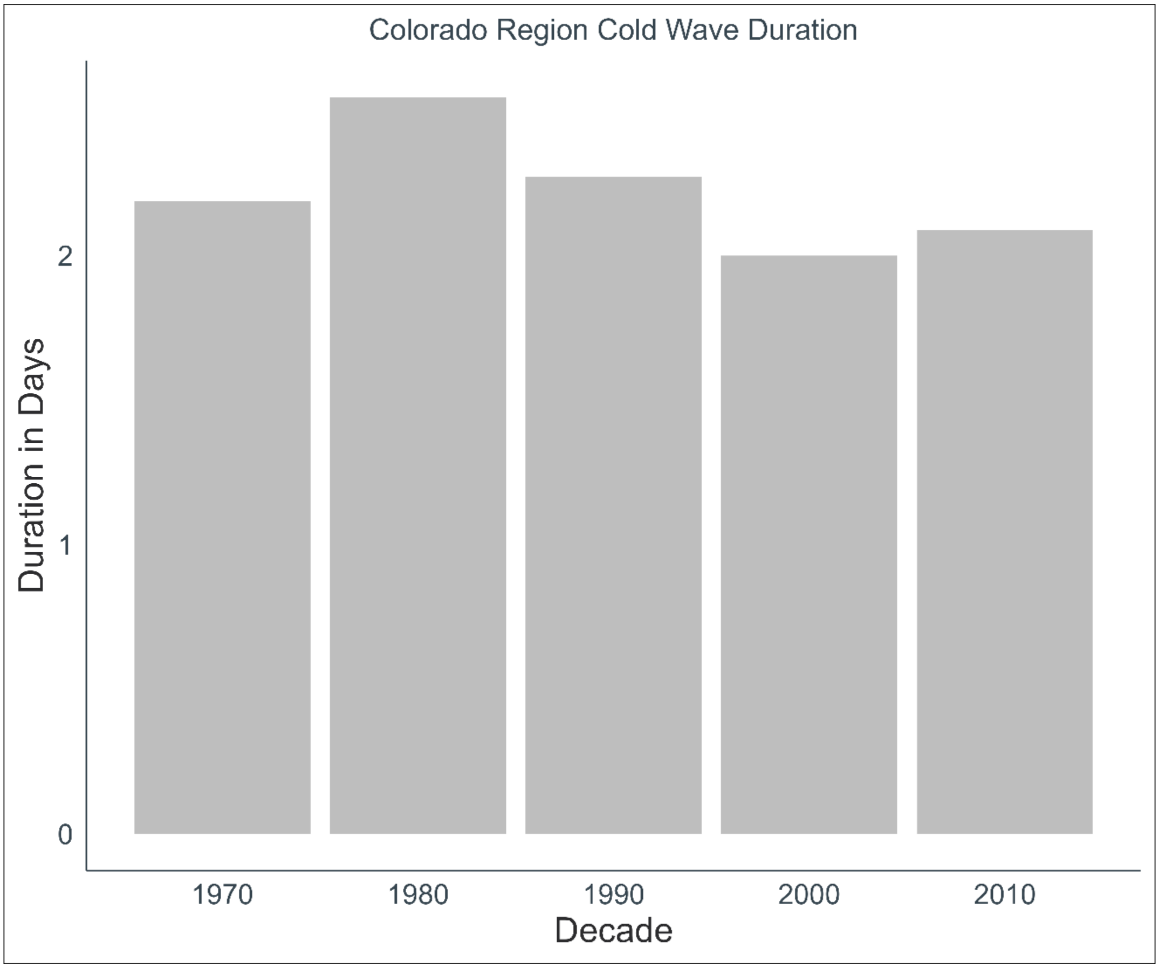


Figure 17.



The duration of cold waves for the West Region and the Colorado Region have similar trends. Both peaked during the 1980s and gradually decreased over the next few decades. Figure 18 on the next page shows the cold wave durations for the past 50 years for the West Region, and Figure 19 shows the same information for the Colorado Region.

Figure 18.

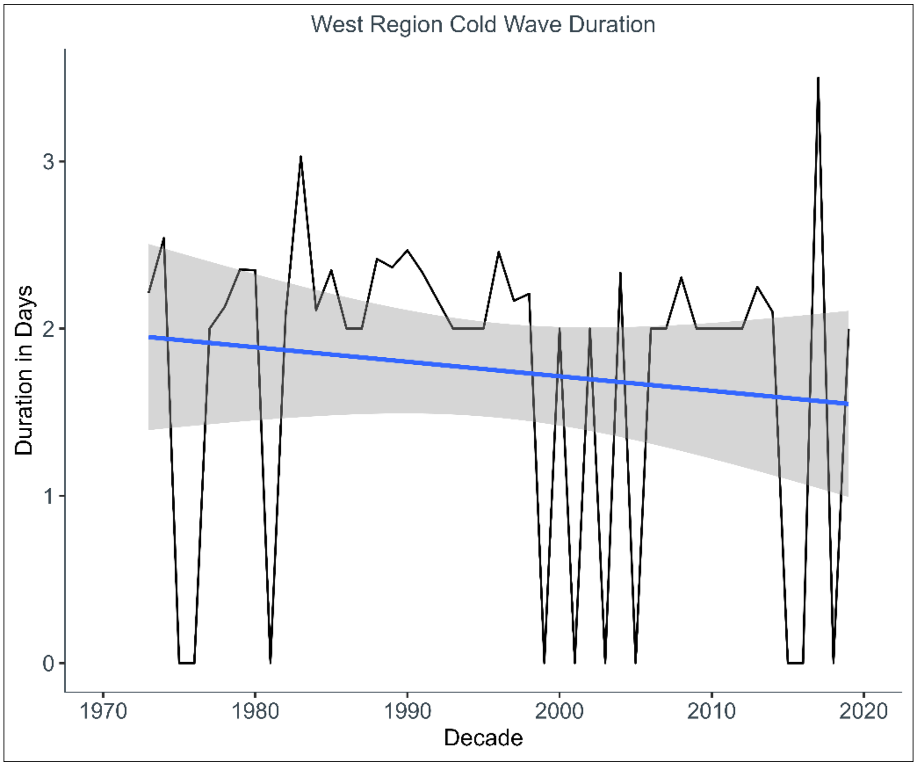
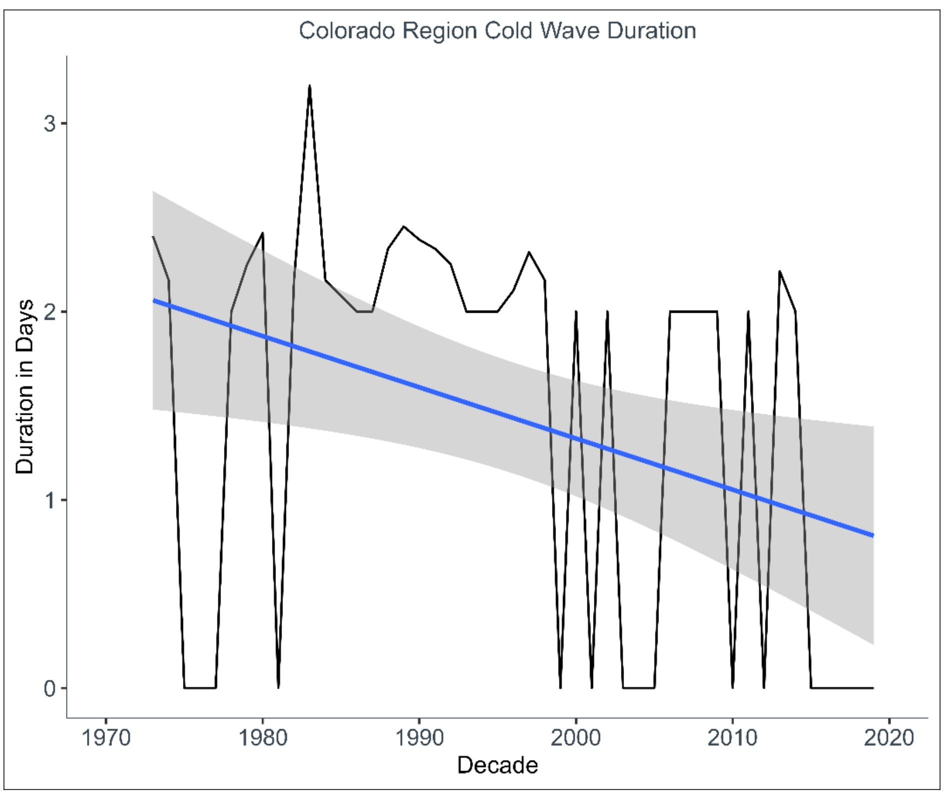


Figure 19.



At a 90% confidence level (p<=0.1), it cannot be included that if the duration of cold waves have increased or decreased over the past 50 years for both the West Region and Colorado Region. As can be seen in figure 20 there are areas that showed an increase in duration. There were also areas that had a decrease in duration of cold waves over the past 50 years.

Figure 20.

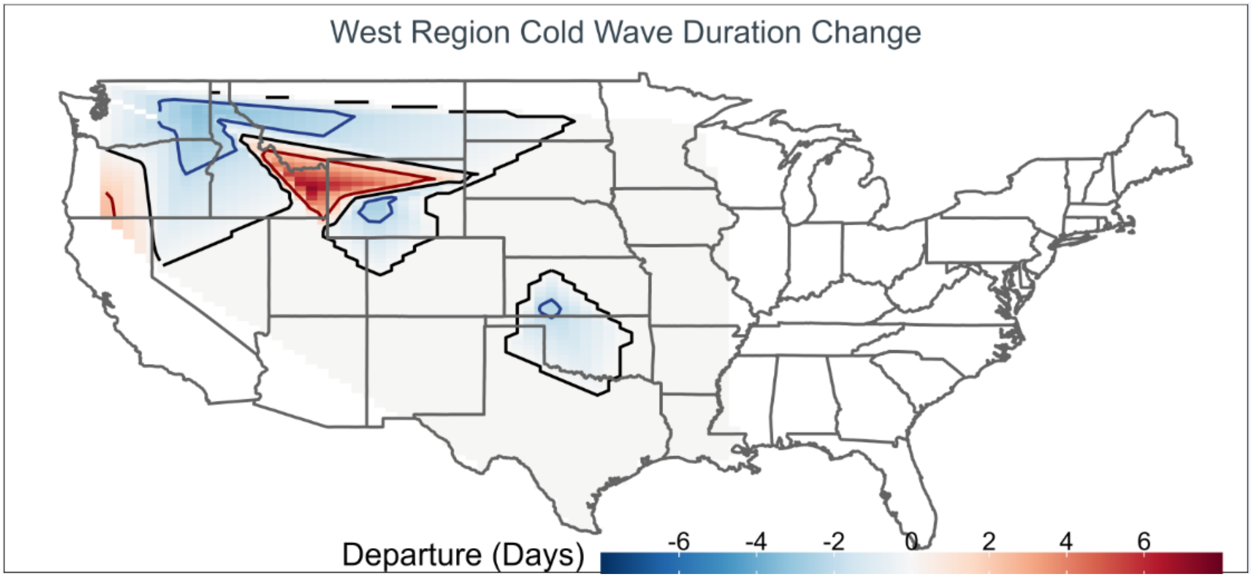


Figure 20 also indicates that there were areas that showed no change in cold wave duration over the past 50 years.

2.3.3. Cold Wave Intensity (Depth)

Intensity is a metric used to measure the temperature during cold waves. It is the difference between the localized threshold and the observed apparent temperature of a location. A wider gap indicates a severe cold wave. Figure 21 and Figure 22 on the next page show the average cold wave intensity for the past 50 years for the West Region and the Colorado Region, respectively.

Figure 21.

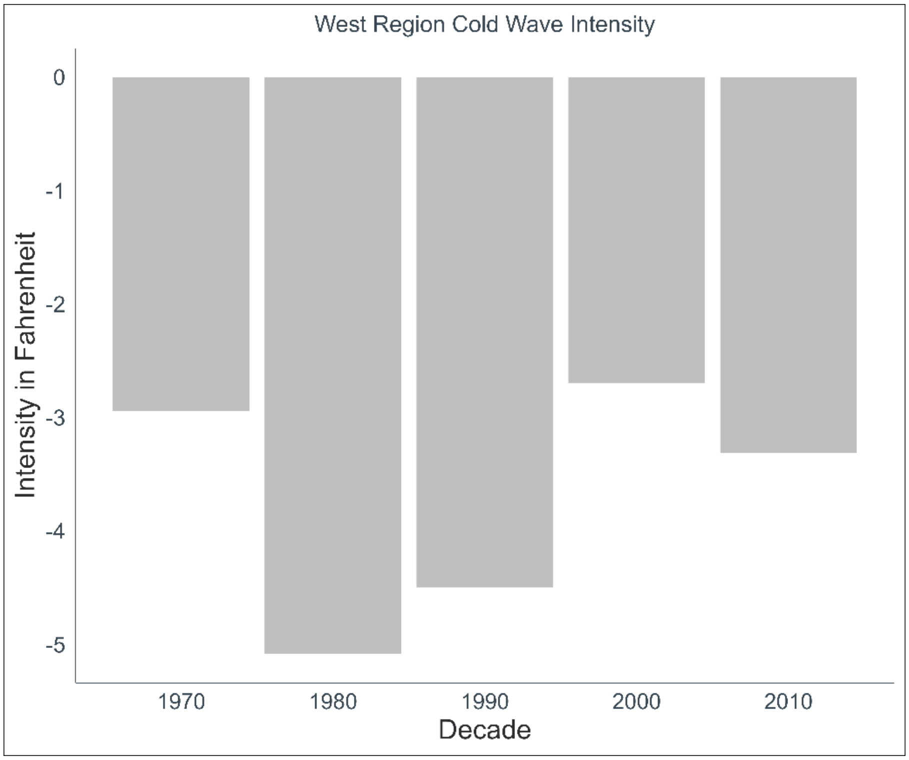
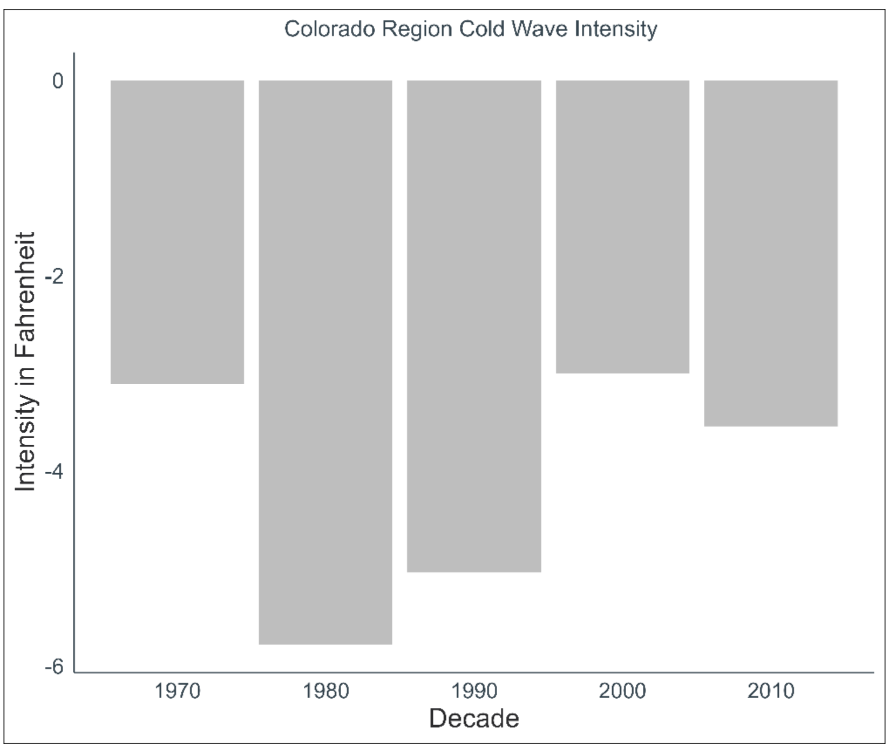


Figure 22.



The figures above indicate that the most intense cold waves in the past 50 years occurred in the 1980s and 1990s. The most intense cold waves in the West Region occurred in the 1980s, while the most intense cold waves for the Colorado Region occurred in the 1990s.

Figure 23 and Figure 24 show a steady decrease in the severity of cold waves over the past 50 years for the West Region and the Colorado Region, respectively. The regression lines show an upward trend, signifying that the difference between the localized threshold and the local temperature is getting narrower and closer to zero.

Figure 23.

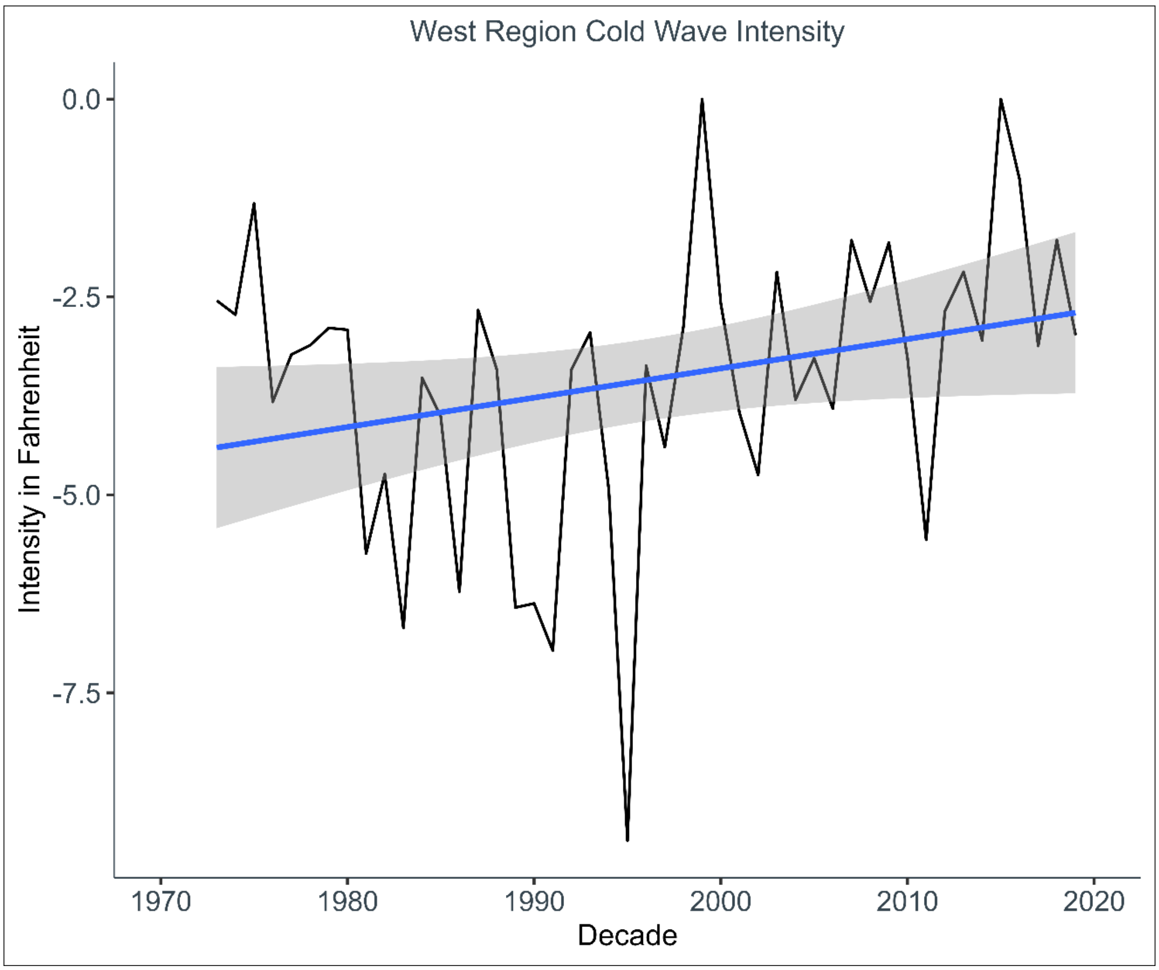
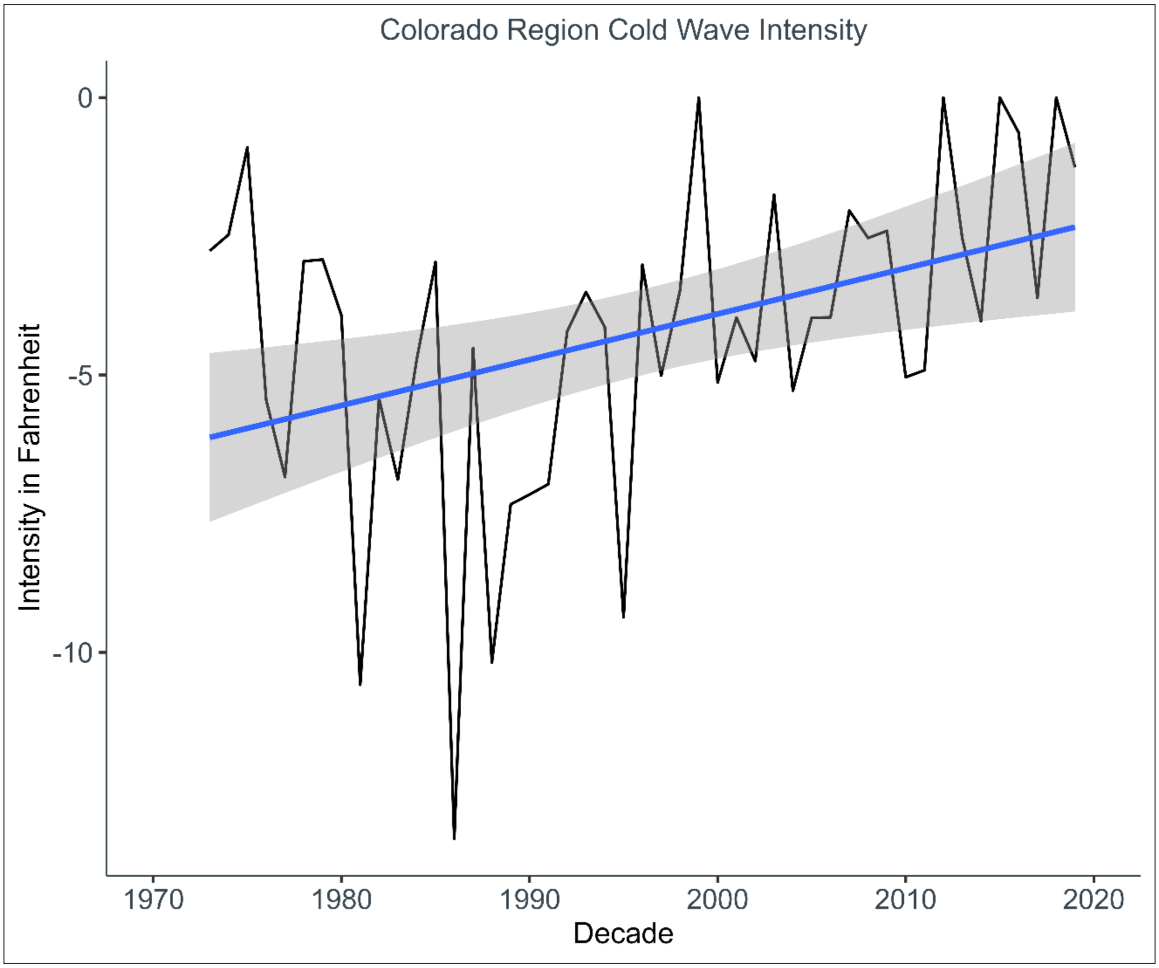


Figure 24.



ACES' analysis shows that it is not possible to conclude if there was an increase or decrease in cold wave intensity across the West Region and the Colorado Region at a 90% confidence level (p<=0.1). Figure 25 also shows mixed results whereby some places in the North West experienced an increase in cold wave intensity whereas other areas around the mid-west saw a decrease in cold wave intensity over the past 50 years. There were also areas included in the analysis that showed no change in cold wave intensity at a 90% confidence level (p<=0.1).

Figure 25.

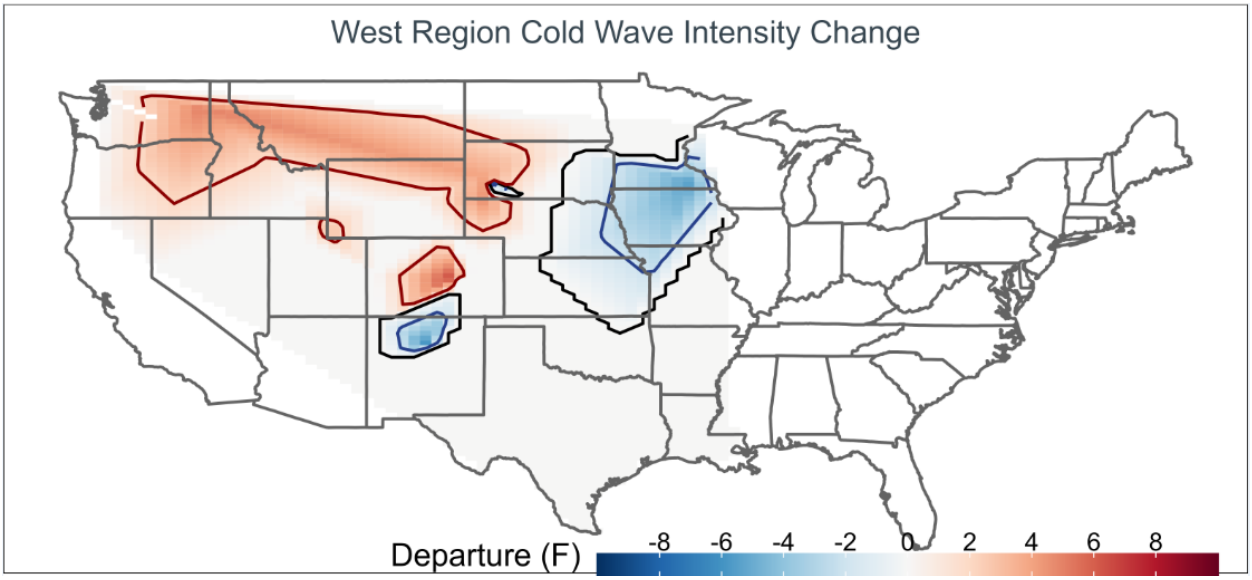


Figure 26 and Figure 27 below summarize the frequency of cold waves over the past 50 years by various durations.

Figure 26.

Cold Wave Summary – West Region													
Number of Hours	**48**	**72**	**96**	**120**	**144**	**168**	**192**	**216**	**240**	**264**	**288**	**312**	**336**
Events per year	4.9	1.7	0.9	0.4	0.17	0.08	0	0	0	0	0	0	0

Figure 27.

Cold Wave Summary – Colorado Region										
Number of Hours	**48**	**72**	**96**	**120**	**144**	**168**	**192**	**216**	**240**	**264**
Events per year	2.36	0.9	0.3	0.17	0.02	0.04	0	0	0	0

2.4. Unusual Temperatures

Heat wave and cold wave requires the event to last for at least two days in this analysis. ACES also considered the prevalence of unusually hot and cold temperatures without the requirement that they last for at least two days to better understand the pattern of heating degree days (HDD) and cooling degree days (CDD) over the past 50 years. According to the U.S. Energy Information Administration (EIA), degree days are measures of how cold or warm a location is. A degree day compares the mean (the average of the high and low) outdoor temperatures recorded for a location to a standard temperature, usually 65°F in the United States. The more extreme the outside temperature, the higher the number of degree days. A high number of degree days generally results in higher levels of energy use for space heating or cooling.

2.4.1. Heating Degree Days

The EIA defines HDDs as a measure of how cold the temperature was on a given day or during a period of days. Based on the EIA's calculation, a day with a mean temperature of 25°F has 40 HDDs. Figure 28 and Figure 29 show the annual trend of HDDs over the past 50 years for the West Region and the Colorado region.

Figure 28.

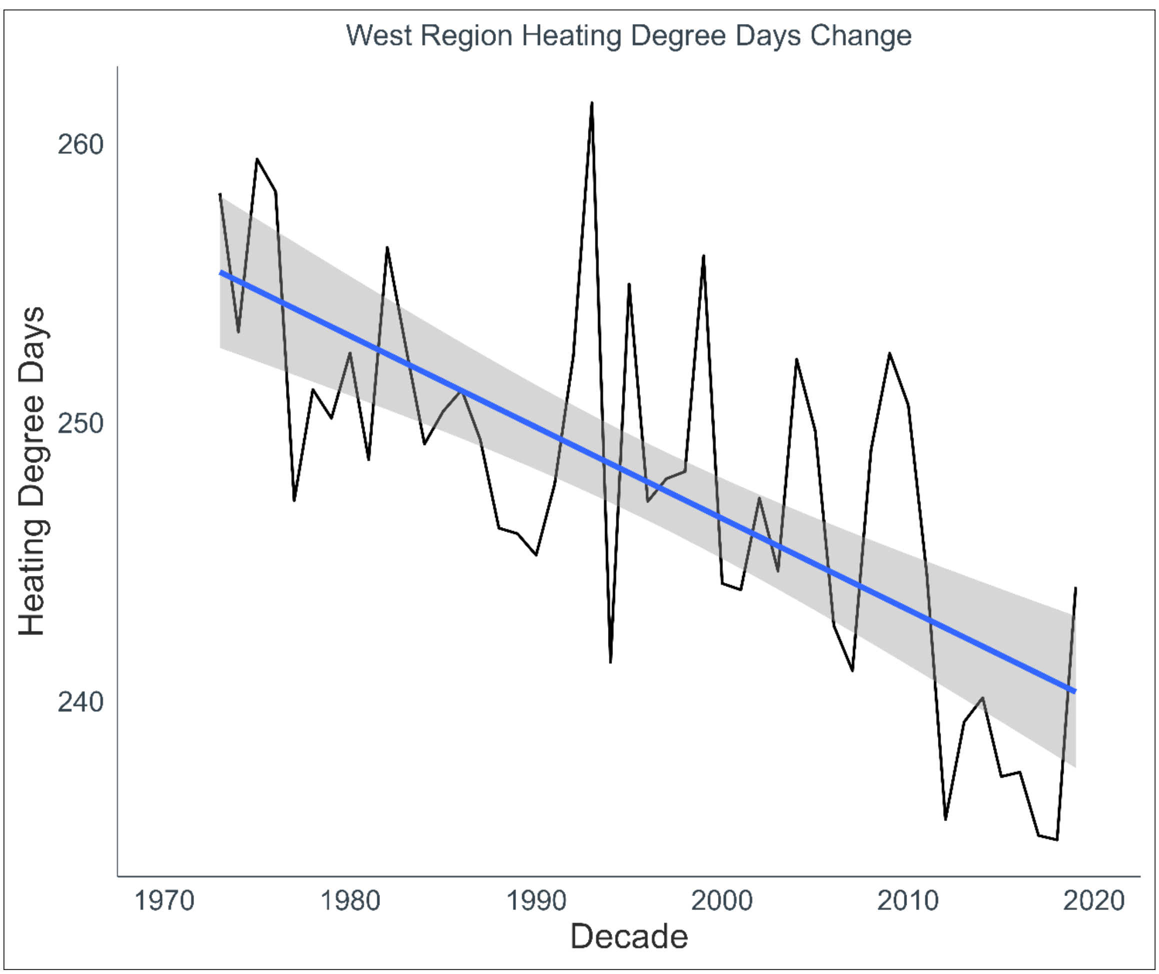
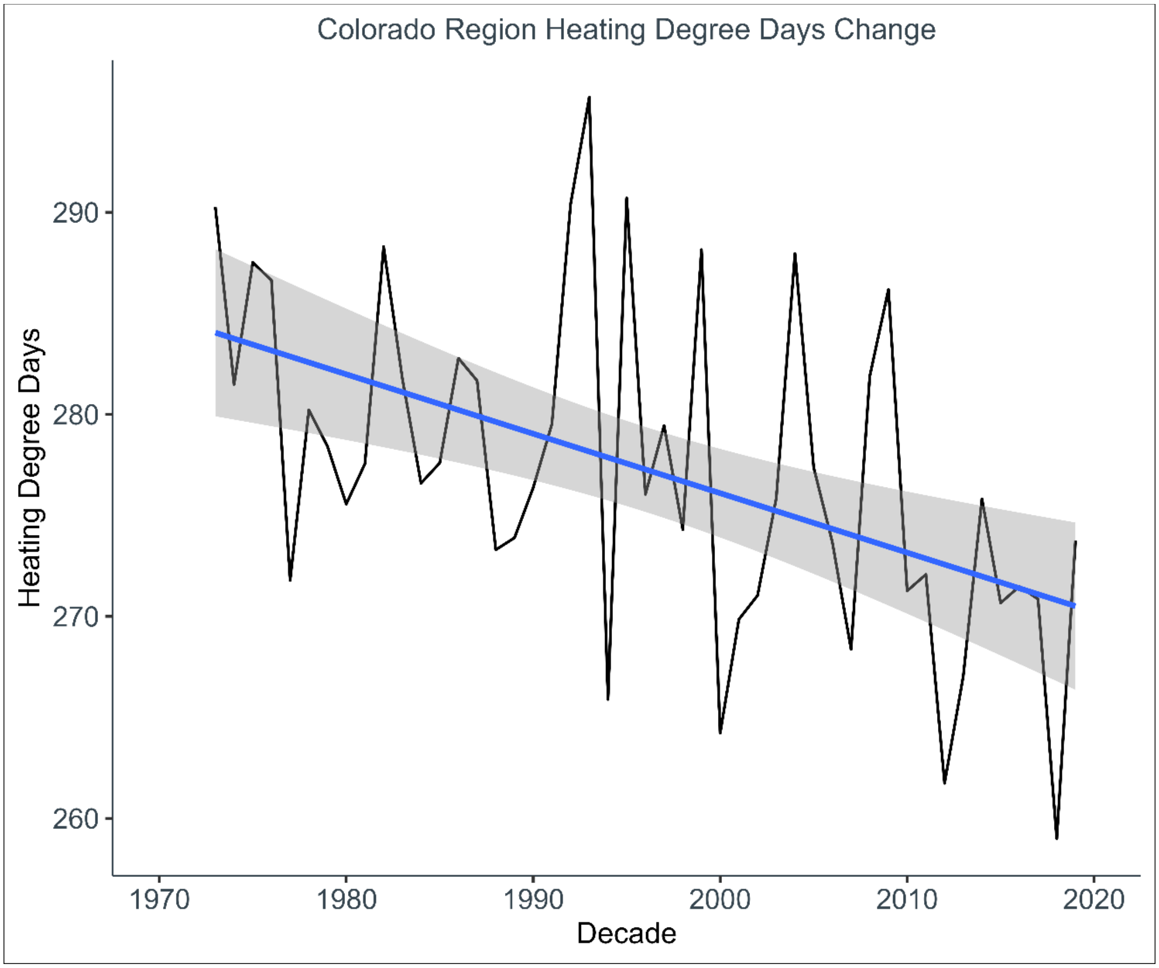
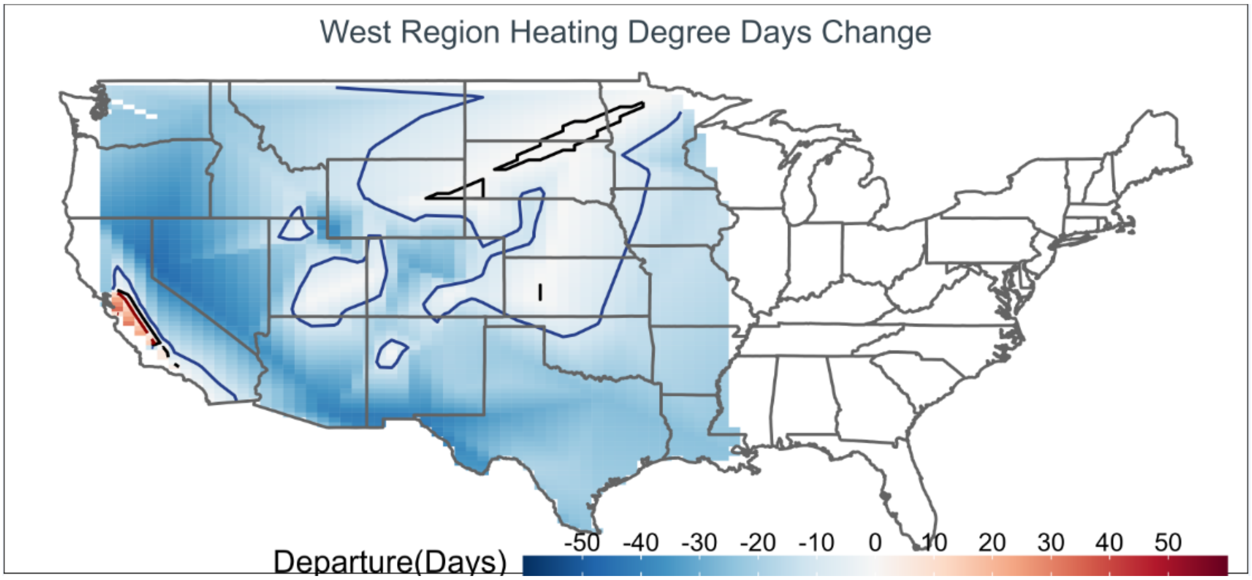


Figure 29.



The West Region had a statistically significant decrease at a 90% confidence level ($p<=0.1$) in heating degree days over the past 50 years. Using the regression line, the results can be interpreted as a decrease of 15 HDDs occurring in the past five decades across the West Region. The Colorado Region also showed a statistically significant decrease at a 90% confidence level ($p<=0.1$) in HDD over the past 50 years. By multiplying the regression coefficient by the number of years, ACES obtained a decrease of 13 HDDs for the Colorado Region over the past five decades. Figure 30 on the next page shows a map of HDD trends during the past 50 years.

Figure 30.



2.4.2. Unusually Cold Days

ACES examined the trends of unusually cold days over the past 50 years to enhance its analysis of HDDs. These two concepts, unusually cold days and HDDs, are closely related because colder days result in higher numbers of HDDs. In ACES' analysis, an unusually cold day is defined as a day with a daily minimum temperature lower than the 5^{th} percentile temperature of the historical 50-year period for a given location. Figure 31 and Figure 32 illustrate the overall trend of unusually cold days for the West Region and the Colorado Region, respectively.

Figure 31.

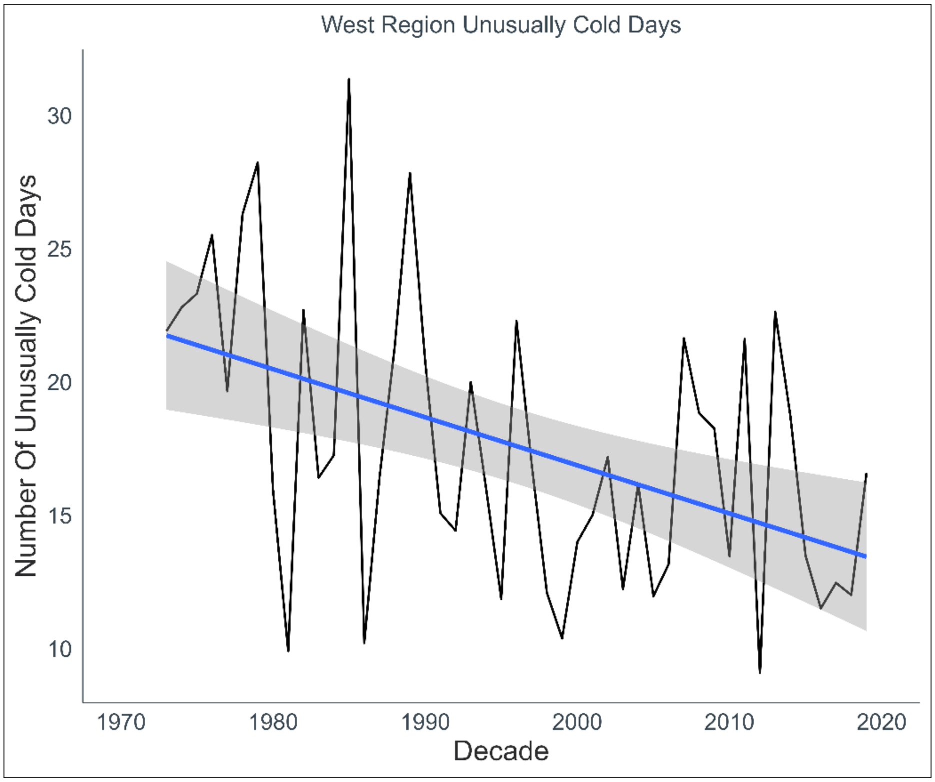
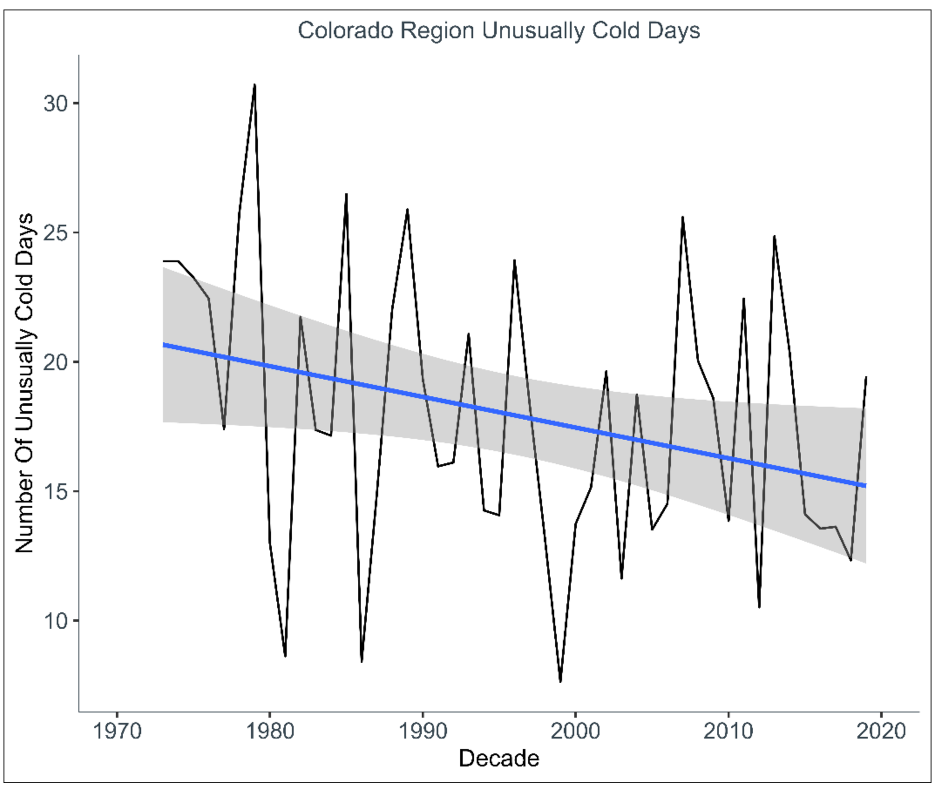
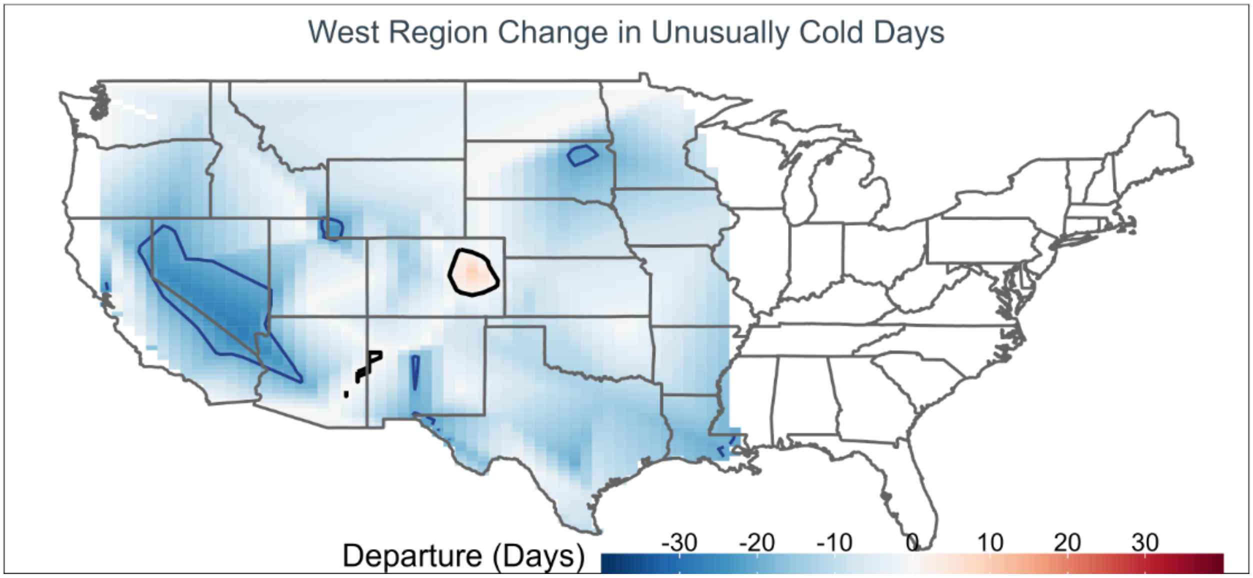


Figure 32.



The West Region and the Colorado Region experienced a statistically significant decrease of unusually cold days over the past 50 years at a 90% confidence interval (p<=0.1). Figure 33 below depicts the trend of unusually cold days for each location. Though the majority of the area experienced a statistically significant decrease in unusually cold days at a 90% confidence interval (p<=0.1), there were certain locations in Colorado that experienced an increase in unusually cold days.

Figure 33.



2.4.3. Cooling Degree Days

According to the EIA, CDDs are a measure of how hot the temperature was on a given day or during a period of days. A day with a mean temperature of 95°F has 30 CDDs. If the next day has a mean temperature of 100°F, it has 35 CDDs. The total for the two days is 65 CDDs. The annual trend of CDDs for the past five decades for the West Region and the Colorado Region are is illustrated in Figure 34 and Figure 35, respectively.

Figure 34.

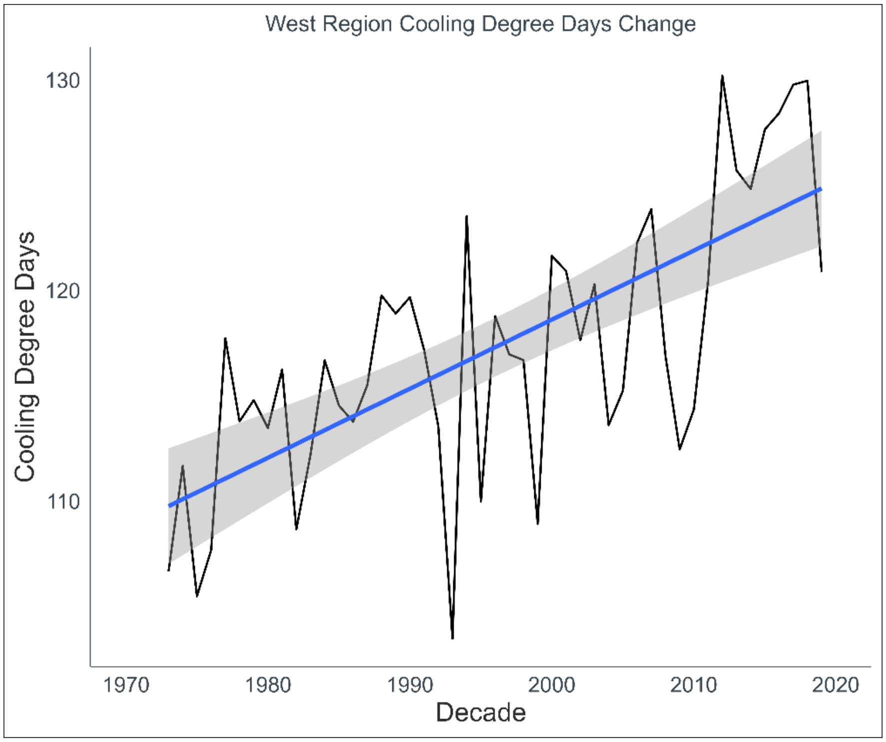
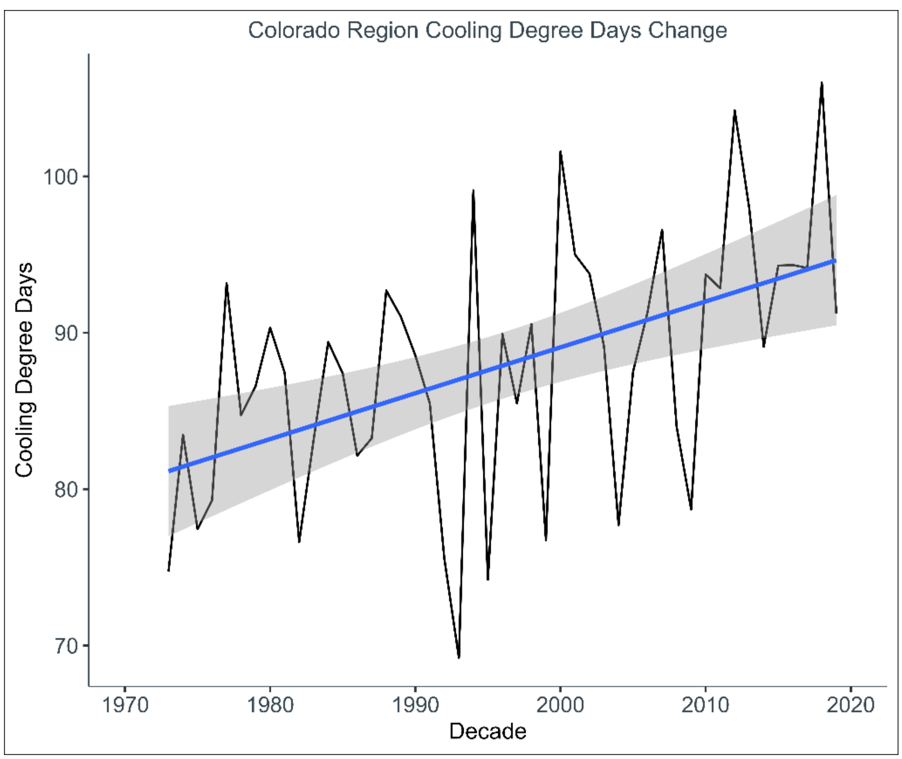


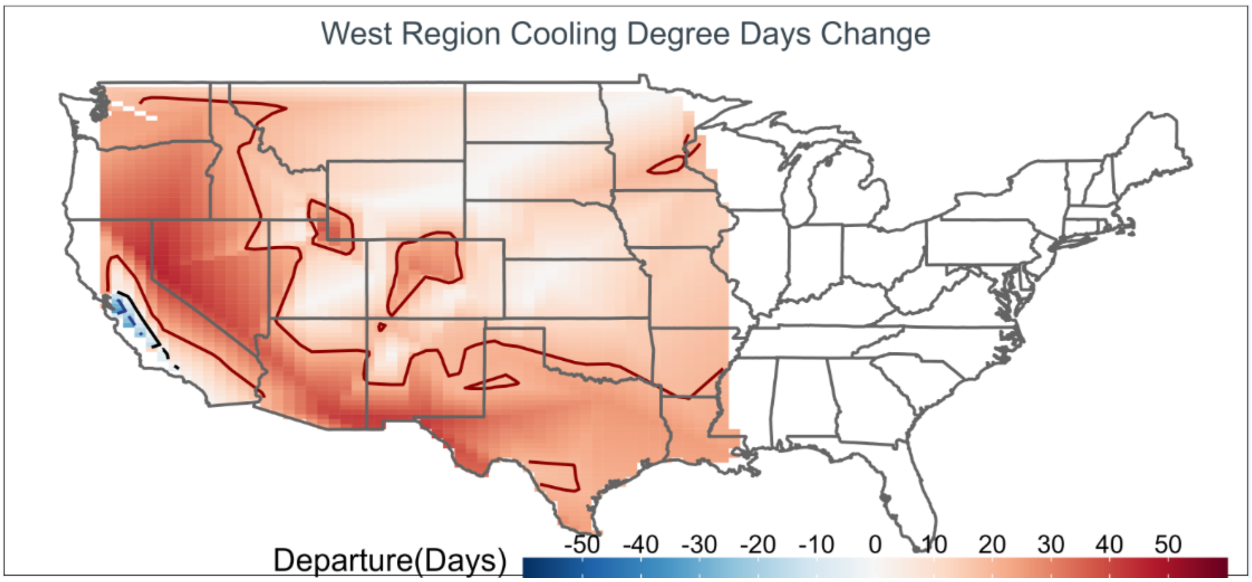
Figure 35.



The CDDs indicated in Figure 34 and Figure 35 have increased for the West Region and the Colorado Region. Both regions had a statistically significant increase in CDDs over the past 50 years at a 90% confidence interval (p<=0.1). Data extrapolated from the regression line suggests there has been an increase of 15 CDDs compared to 50 years ago for the West Region, and an increase of 14 CDDs for the Colorado Region.

Figure 36 below shows the CDD trends over the past 50 years for the West Region. Although the majority of the locations in ACES' analysis showed an increase in CDDs, there were some differences in the number of CDD increases. The locations further west showed a higher number of CDDs than the other locations.

Figure 36.



2.4.4. Unusually Hot Days

Considering the prevalence of unusually hot days over the past 50 years will also provide a unique insight to help understand CDDs. An unusually hot day is defined as a day with the daily maximum temperature greater than the 95th percentile of the 50-year historical temperatures at a specific location. Thus, this definition will yield temperatures in the top 5% of hottest temperatures recorded over the past 50 years for that location. Figure 37 and Figure 38 illustrate the trend of unusually hot days for the West Region and Colorado Region, respectively.

Figure 37.

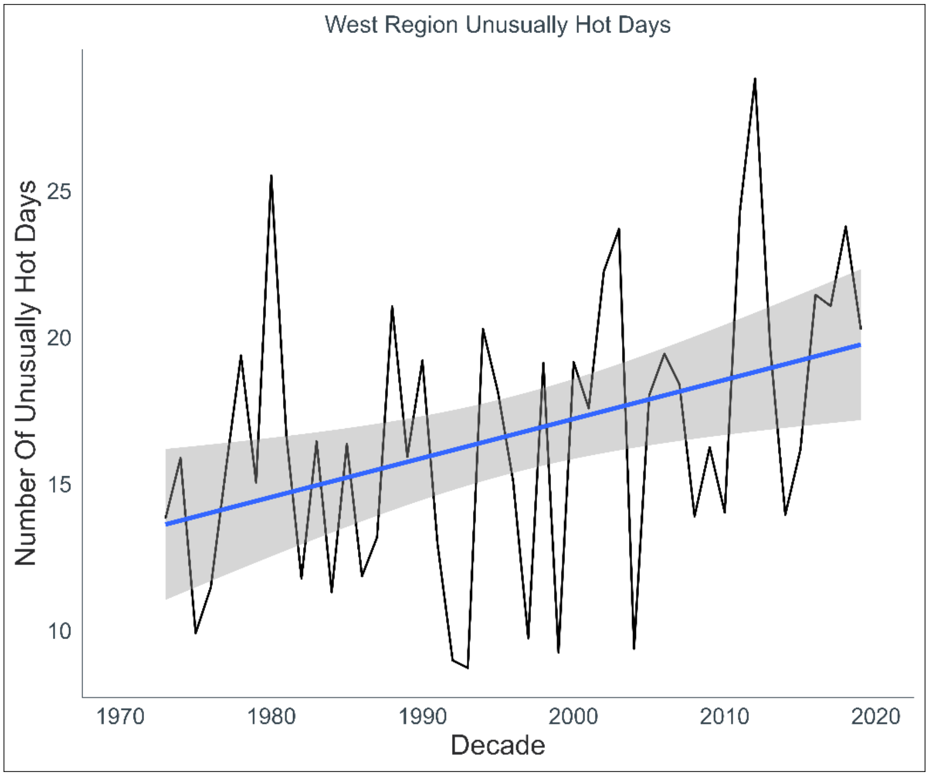


Figure 38.

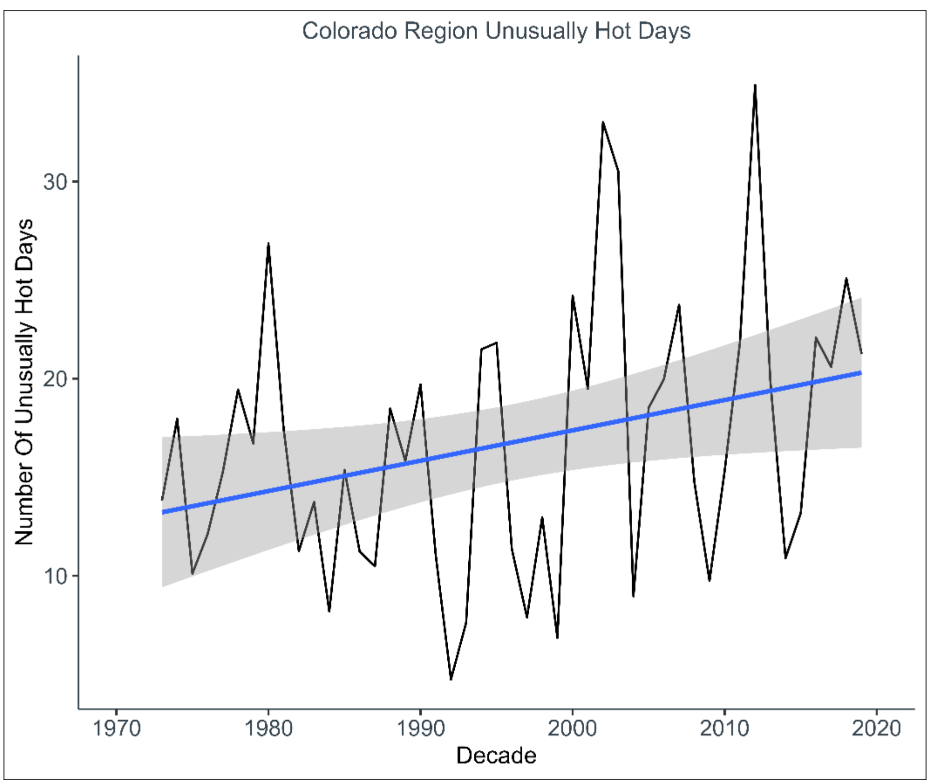
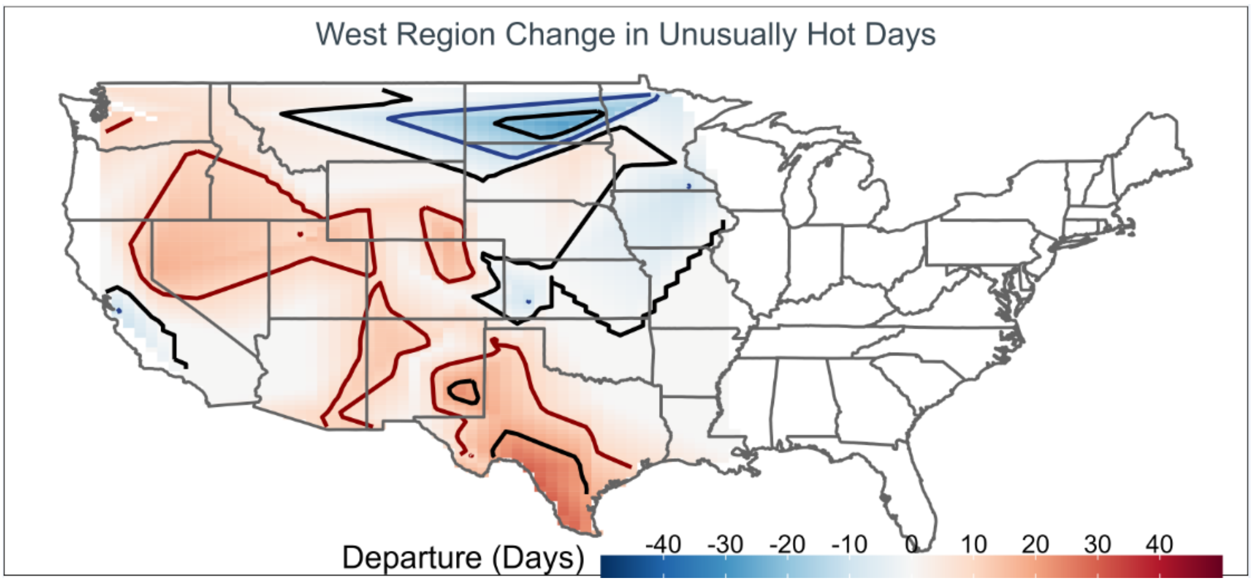


Figure 37 and 38 show that the occurrence of unusually hot days over the past 50 years have increased for both regions. Both regions showed a statistically significant increase at a 90% confidence level ($p<=0.1$). The West Region has experienced an increase of six unusually hot days over the past 50 years, while the Colorado Region experienced an increase of seven unusually hot days.

Figure 39 shows the results of all locations. Although unusually hot days have increased overall, considering each location individually provides greater insight into the distribution of unusually hot days across the region. Areas in the north experienced a decrease in unusually hot days, while locations in the south had an increase in unusually hot days.

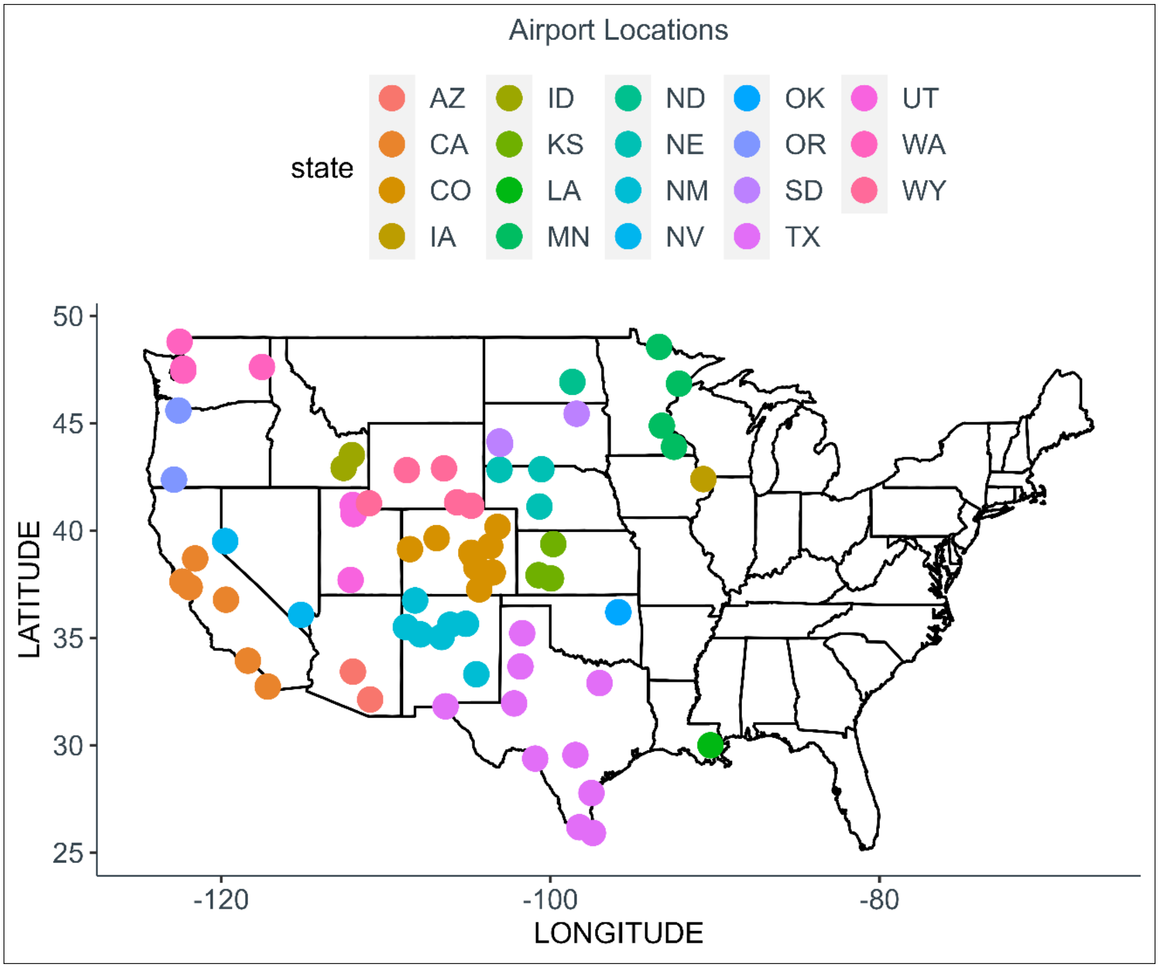
Figure 39.



2.5. Dark Calm

A dark calm is defined as a phenomenon with extended periods of low or no wind or solar generation. A dark calm poses a significant risk for the electric grid, which is experiencing a surge of renewable energy sources that are dependent on wind and solar. This section refers to a dark calm as it relates to weather data rather than energy production data. ACES utilized the National Aeronautics and Space Administration (NASA) Power Data Access Viewer's application programing interface (API) to query the necessary solar irradiance (in W/m^2) and wind speed data (in m/s at 100m) for the past 20 years to perform the dark calm analysis. The complete data set for these variables was easily accessed through the API, and ACES determined it was the closest indicator of solar and wind generation. Solar and wind farms are built primarily in areas that meet a certain minimum requirement of solar irradiance and wind speed. Since ACES did not consider solar and wind generation when selecting locations to analyze, a bias may exist. The locations used for this analysis are shown in Figure 40 below.

Figure 40.



ACES set manual thresholds in this analysis to identify a dark calm. The manual threshold is applicable to this study because using localized percentiles as a threshold would not be indicative of actual dark calms since solar and wind generation require a fixed minimum threshold, and regional percentile thresholds would introduce a different localized threshold for each region. Some regional thresholds would vary significantly from the actual minimum value required for solar and wind generation, creating a strayed definition of a dark calm, which would not be a useful indicator of an actual dark calm resulting from low wind and solar generation.

ACES set a practical minimum threshold for solar irradiance and wind speed in which observations below these thresholds would be considered insufficient for solar and wind generation. The thresholds were 100 W/m^2 for solar irradiance and 5 m/s for wind speed, respectively. Figure 41 on the next page shows the wind power curve for commonly used 1,500 kW turbines from different manufacturers.

Figure 41.

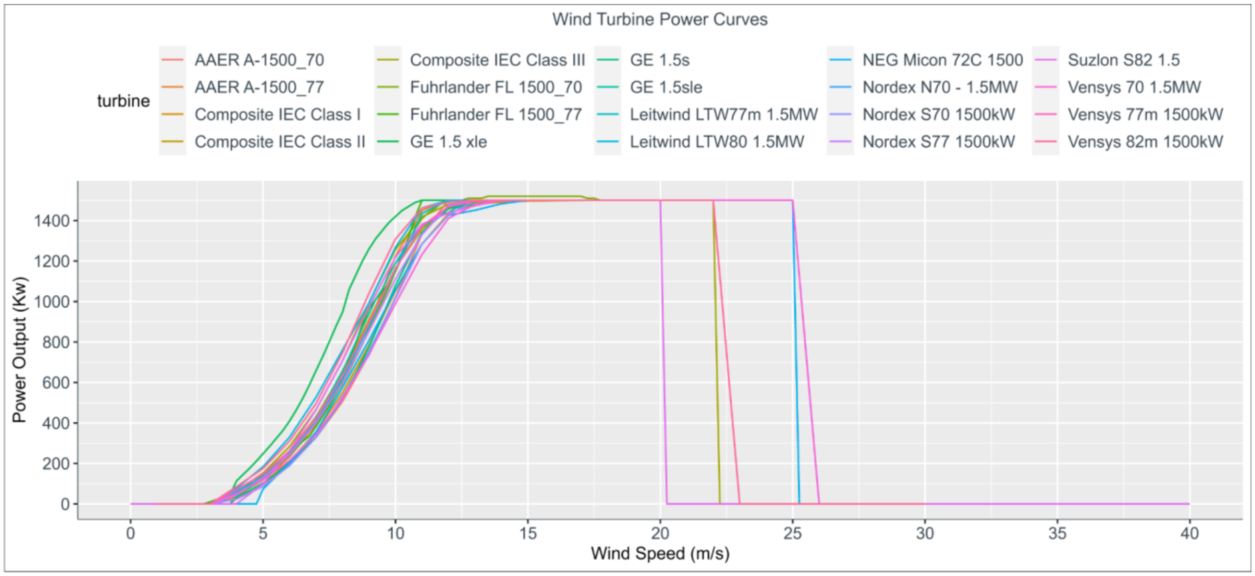
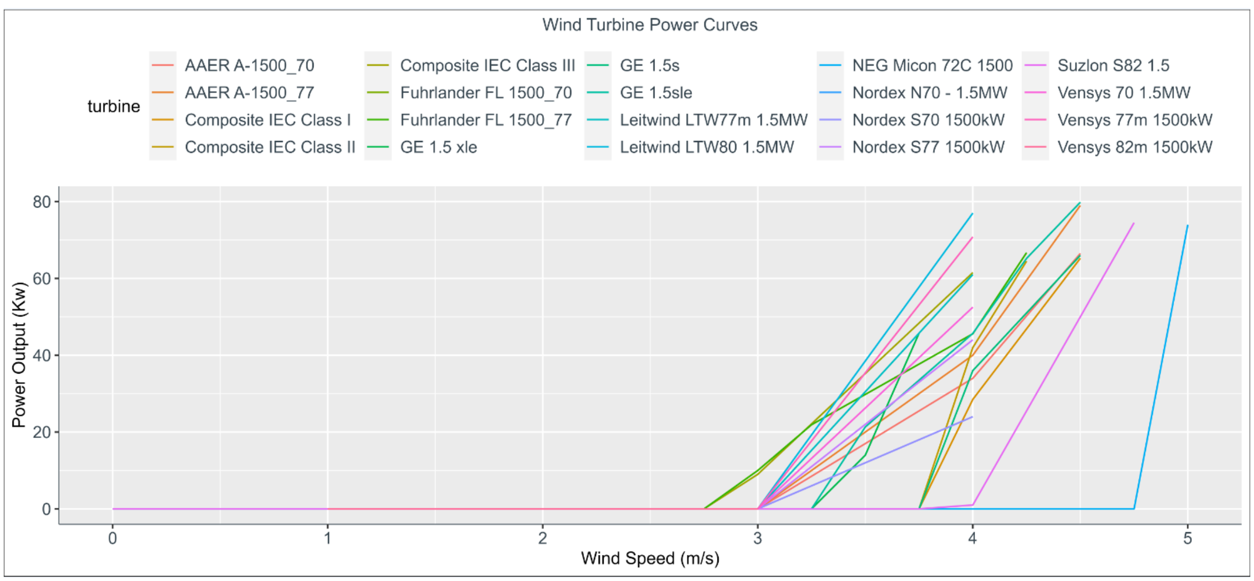


Figure 42 on the next page focuses on the important data in Figure 41, and provides a clear view of the output of the turbines at wind speeds below 5 m/s. All 1,500 kW turbines in ACES' data set had wind power output lower than 80 kW or below 5% of their capacity for wind speeds less than 5 m/s.

Figure 42.



Next, ACES aggregated the hourly data by day and filtered out the dark calm days, which had a daily average solar irradiance lower than 100 W/m^2 and wind speed at 100m less than 5 m/s. Once those days were isolated, ACES performed a least squares regression analysis to identify the dark calm trend observed in the data over the past 20 years. Figure 43 on the next page depicts the result of this analysis, and shows a decrease in dark calm days in different regions with one exception in Colorado.

Figure 43.

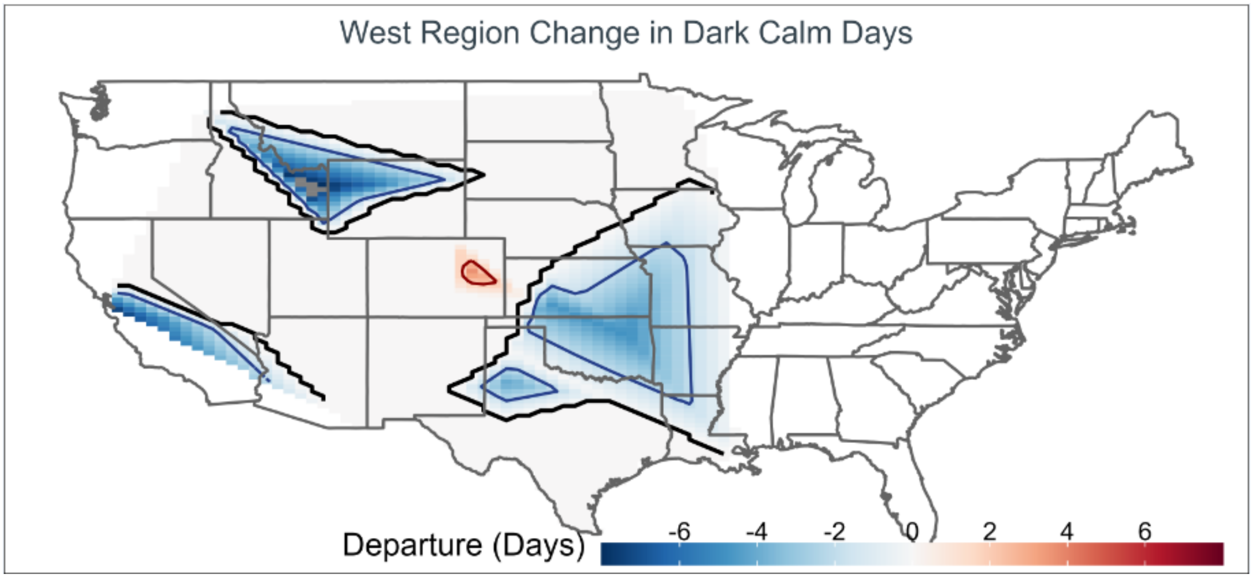


Figure 44 below summarizes the frequency and duration of dark calm events over the past 20 years.

Figure 44.

Dark Calm Summary – Number and Duration of Events Per Year										
Output Threshold	Duration (Hours)									
	24	48	72	96	120	144	168	192	216	240
<5%	744.35	25.15	9.25	3.4	1.95	1.2	0.8	0.2	0.25	0.3
Output Threshold	264	288	312	336	360	384	408	456		
<5%	0.1	0.1	0.05	0.05	0	0	0	0.05		

3. Five-Year Dark Calm and Extreme Weather Event Abstract

This section of the report analyzes dark calms and extreme weather events across various U.S. energy markets during the most recent five years of information, which includes more renewable generation. As previously noted, dark calm events are periods when little to no wind and solar energy can be generated due to weather patterns. The five-year market impact analysis focuses on the most extreme weather events over the past few years, highlighting price and load movements. Additionally, the market analysis measures dark calms by various ISO/RTO footprints, highlighting when dark calms occur and comparing dark calm events to near-normal conditions from a market standpoint.

3.1. Dark Calms

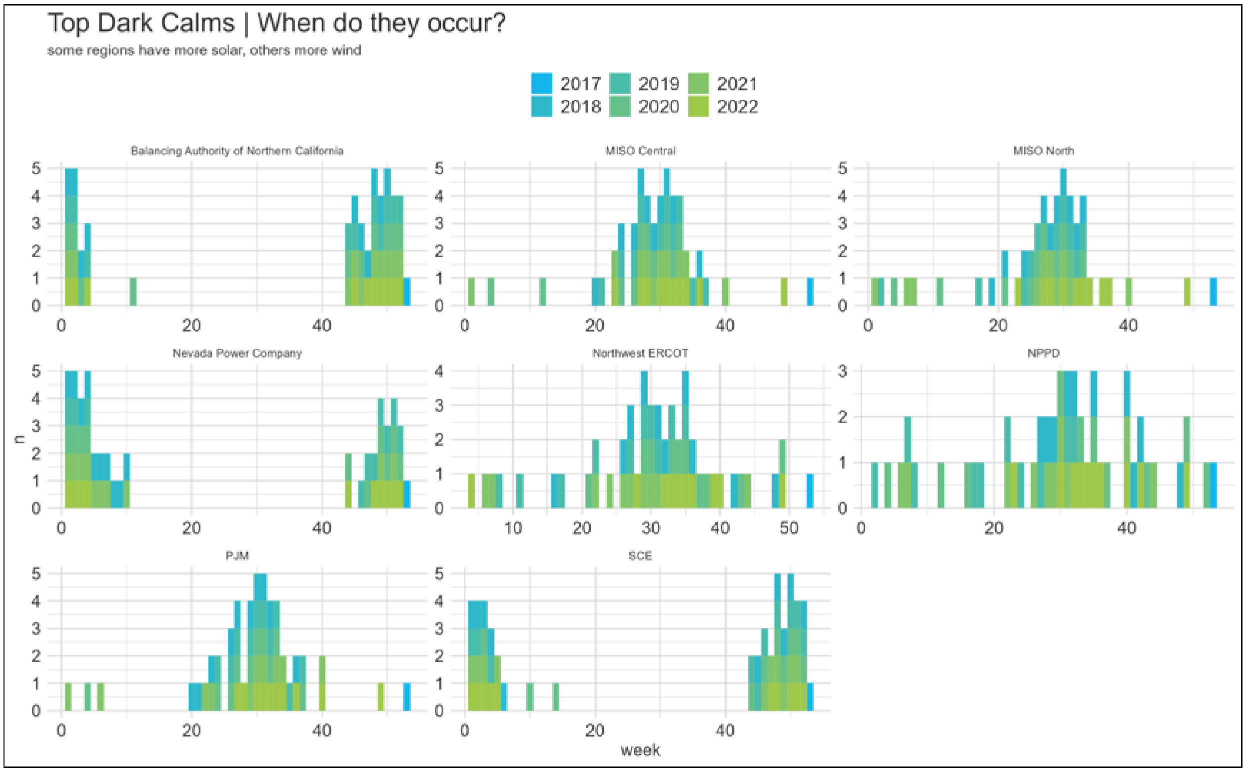
3.1.1. Five-Year Market Impact Analysis

Complementing the weather analysis, ACES isolated dark calm events across various markets and geographic locations in the U.S. Depending on the renewable mix in the footprint, (solar and wind capacity combined), market-based dark calms differ depending on the amount of solar and wind penetration in the area. In locations with heavy wind generation, dark calms occur during the summer when wind lulls, whereas, in locations with heavy solar generation, dark calms occur during the winter when there are fewer hours of daylight. The following sections highlight these events, when they occur, and how these dark calms differ from near-normal conditions for each location analyzed.

3.1.2. Dark Calms: Time of Year

Figure 45 below shows when dark calms typically occur within the course of a year, focusing on occurrences heavily influenced by the region and their total capacity by technology type. ACES screened the top 10 dark calm weeks by year using market history from the past five years to show during which weeks they occur. Overall, regions with high wind penetration experience dark calm events during the summer, and regions with high solar penetration experience dark calm events during the winter.

Figure 45.



3.1.3. Dark Calms: Hourly Generation

Figure 46 on the next page shows a summary of renewable generation in Northwest ERCOT during the last five years when the average installed capacity of wind was approximately 20% of the market's installed capacity, and average installed capacity of solar was closer to 10%. Using these weeks to make dark calm comparisons, ACES compared dark calm weeks to weeks with near-normal output and weeks with heavy renewable output. ACES plotted all five years of hourly data with the mean hourly shape for each type of week (dark calm, near normal, and heavy renewable output). The results show the significant difference in renewable output depending on the local weather, and demonstrate the intermittent nature of renewable resources. The chart shows the average hourly shapes during various conditions. Dark calms in Northwest ERCOT typically occur in the summer when cooling demand is typically higher than normal.

Figure 46.

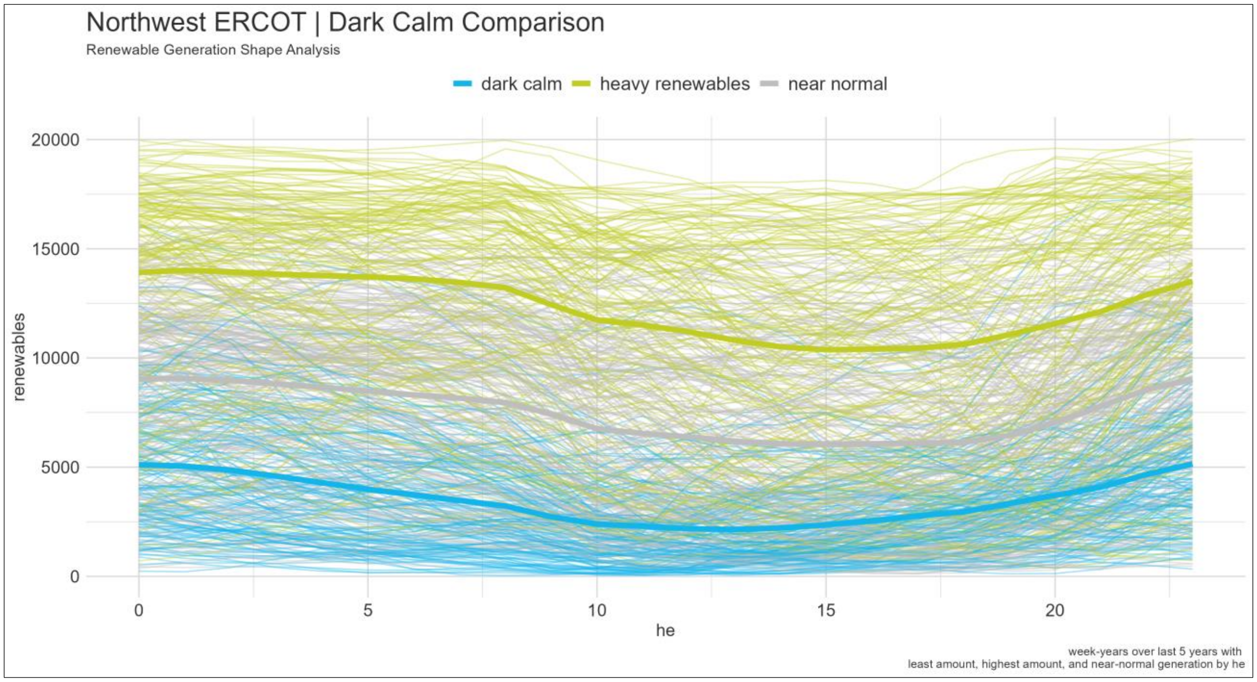
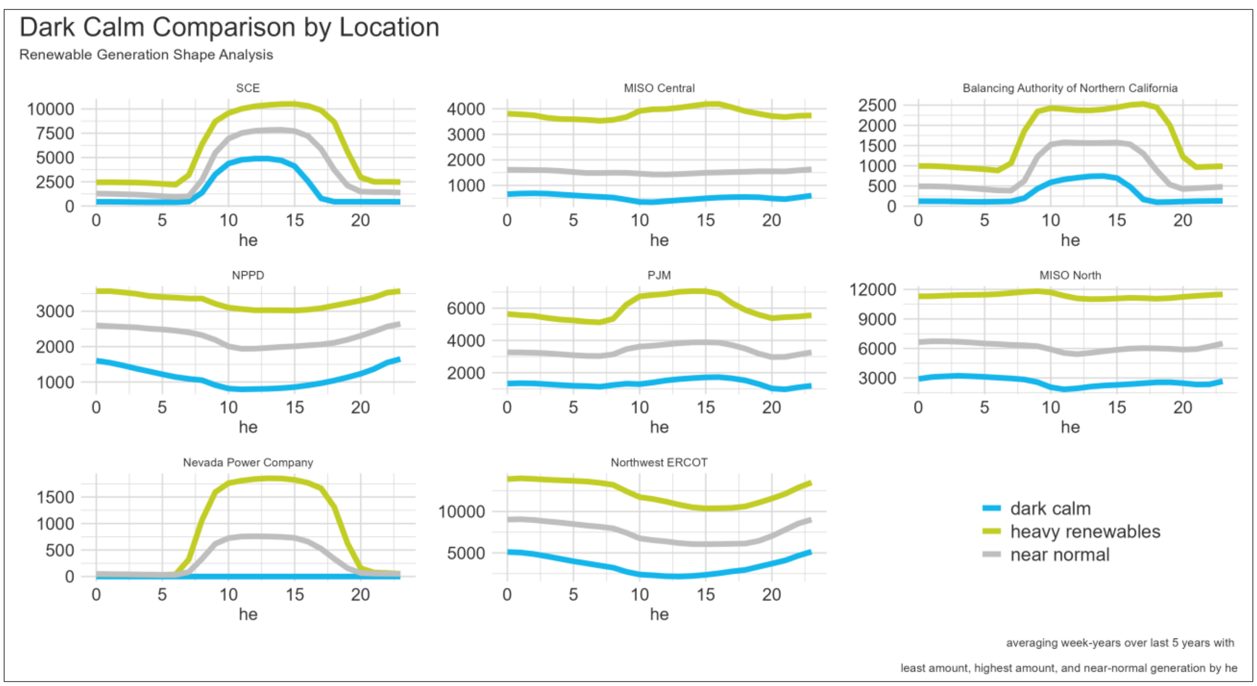


Figure 47 below contains the mean hourly shape for the regions ACES analyzed.

Figure 47.



These charts detail the wide range of generation shapes that can occur in each footprint, depending on local weather. Installed capacity differs across each region. MISO and ERCOT have more wind, whereas

Nevada, BANC, and SCE have more solar. Installed renewable capacity by ISO/RTO is also included in the appendix.

3.1.4. Dark Calms: Duration and Magnitude

The duration of dark calms and total renewable output can be broken down for model parameterization. Figure 48 below shows total dark calm events by location using percentage thresholds and rolling timeframes, which are the average number of events per year based on each footprint. MISO Central has an average of 11 48-hour dark calm events when renewable generation is at 10% of the annual maximum output. Dark calms occur across the U.S., but each footprint has its own unique duration and magnitude.

Figure 48.

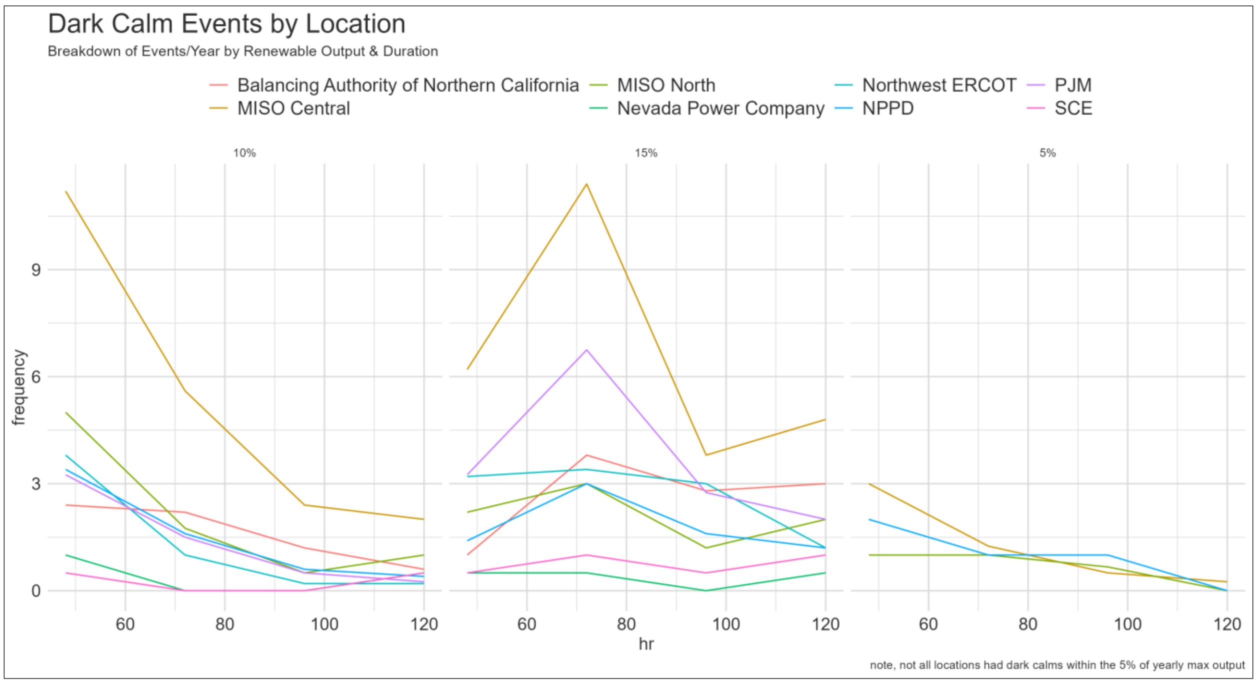


Figure 49 below references the chart values in Figure 48.

Figure 49.

Dark Calm Events by Location				
% of Full Output	48 Hours	72 Hours	96 Hours	120 Hours
MISO Central				
5%	3.0	1.25	0.5	0.25
10%	11.2	5.6	2.4	2.0
15%	6.2	11.4	3.8	4.8
MISO North				
5%	1.0	1.0	0.67	0.0
10%	5.0	1.75	0.5	1.0
15%	2.2	3.0	1.2	2.0
Northwest ERCOT				
10%	3.8	1.0	0.2	0.2
15%	3.2	3.4	3.0	1.2

The average number of events per year in Figure 49 are useful, but averaging the data can conceal some of the specifics related to each event. Figures 50 through 52 show the diversity of the dark calms shown in Figure 48 and Figure 49, including a 120-hour dark calm for MISO Central and a 72-hour and 96-hour dark calm in northwest ERCOT at different renewable output levels.

Figure 50.

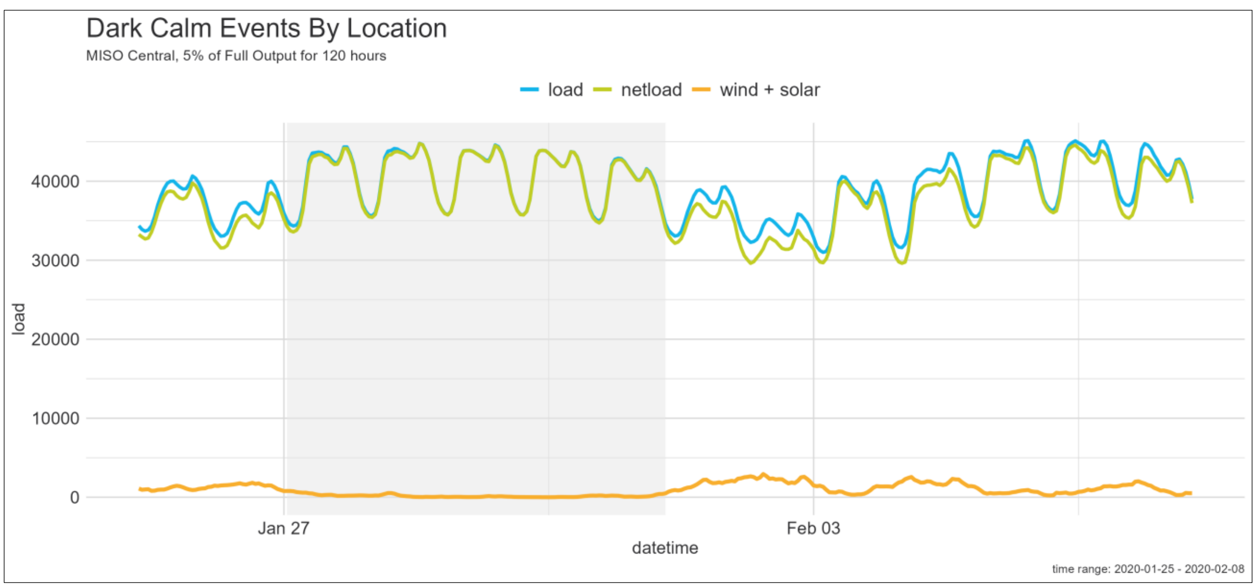


Figure 51.

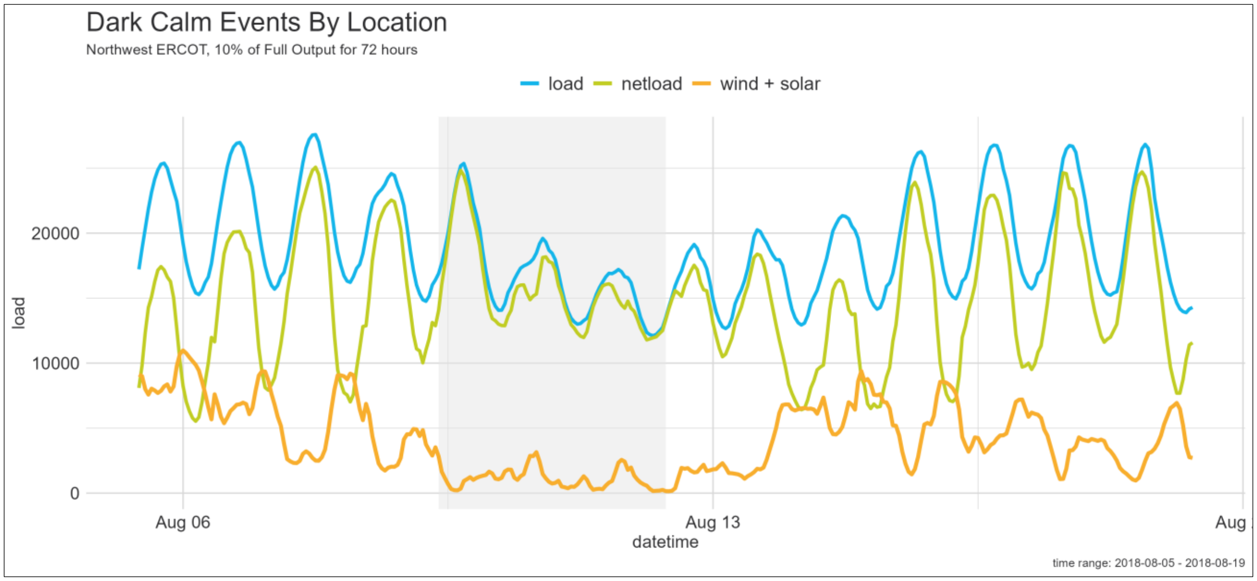
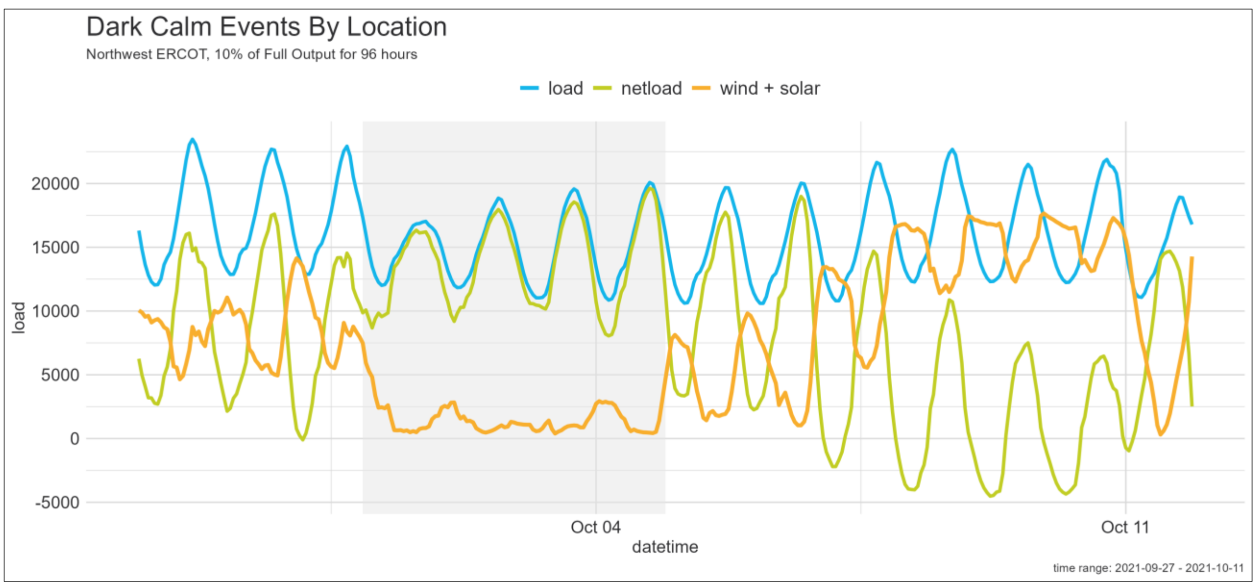


Figure 52 shows the volatility of renewable energy, and highlights a 96-hour dark calm followed by extremely high winds that offset load and resulted in negative net load values following the wind lull.

Figure 52.



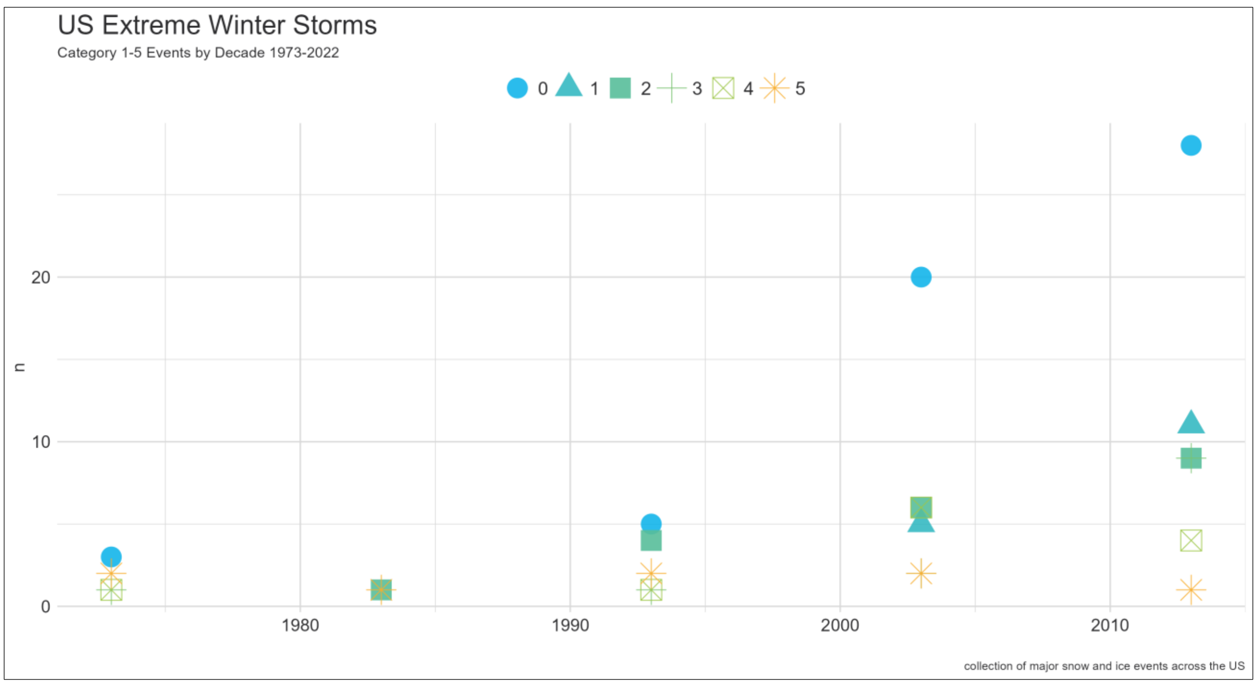
4. Extreme Weather Events

4.1. 50-Year Weather Analysis

4.1.1. Event Trends by Year and Category

ACES aggregated the top snow/ice events across the U.S. and conducted a frequency and impact analysis by year. Figure 53 shows the trend of weather events by category. The categories refer to the regional snowfall index in the U.S., which ranges from zero to five, with five being most extreme and zero being a nuisance. The total number of category four and five storms have remained the same each decade, whereas the number of category zero through three have increased in frequency over time. Although extreme and major storms have not necessarily changed over time, the total number of major, significant, notable, and nuisance storms have increased over time, as highlighted in Figure 53.

Figure 53.



4.2. Five-Year Market Impact Analysis

ACES isolated the most recent extreme weather events for an in-depth market perspective. The following sections outline the overall impact of extreme weather events on renewable generation, load, and pricing.

4.2.1. Winter Storm Uri: February 13 through February 17, 2021

During Winter Storm Uri, low temperatures were the primary driver of increased load, and the extreme weather led to extreme power demand. Natural gas supply bottle-necked due to the extreme power demand, leading to extremely high fuel and power prices across CAISO, MISO, SPP, and ERCOT. Figure 54 on the next page highlights the events across ISOs/RTOs, as conditions were the most extreme in ERCOT.

Conditions deteriorated during the week of February 10 through February 16, 2021, with temperatures decreasing from the 30°F range to lower than 10°F by the end of the week, and snowfall began on February 14. With the severe weather, generators in ERCOT experienced operational issues throughout the week. Prices reached extreme levels by February 13. Day-ahead (DA) prices at LZ_North averaged $2,765/MWh and real-time (RT) prices averaged $3,400/MWh. Prices increased to around $9,000/MWh on February 15 and 16.

Emergency conditions were in place through the morning of February 19. DA locational marginal prices (LMP) averaged around $7,500/MWh for the first half of the week, while RT prices hovered around $9,000/MWh. Once the emergency in ERCOT was lifted, DA prices returned to the high $20/MWh range by the end of the week, and RT prices decreased to an average of $4.76/MWh due to periods of negative pricing. Loads declined over the week as temperatures increased and conditions improved.

Power prices also increased significantly across CAISO, MISO, and SPP during the Winter Storm Uri, but ERCOT experienced the highest prices due to power supply shortages and to the fact that it is an energy-only market with high price caps. Additionally, ERCOT also reached and sustained scarcity pricing around the clock each day. In previous scarcity pricing events in ERCOT, prices did not sustain $9,000/MWh for a full hour.

Figure 54.

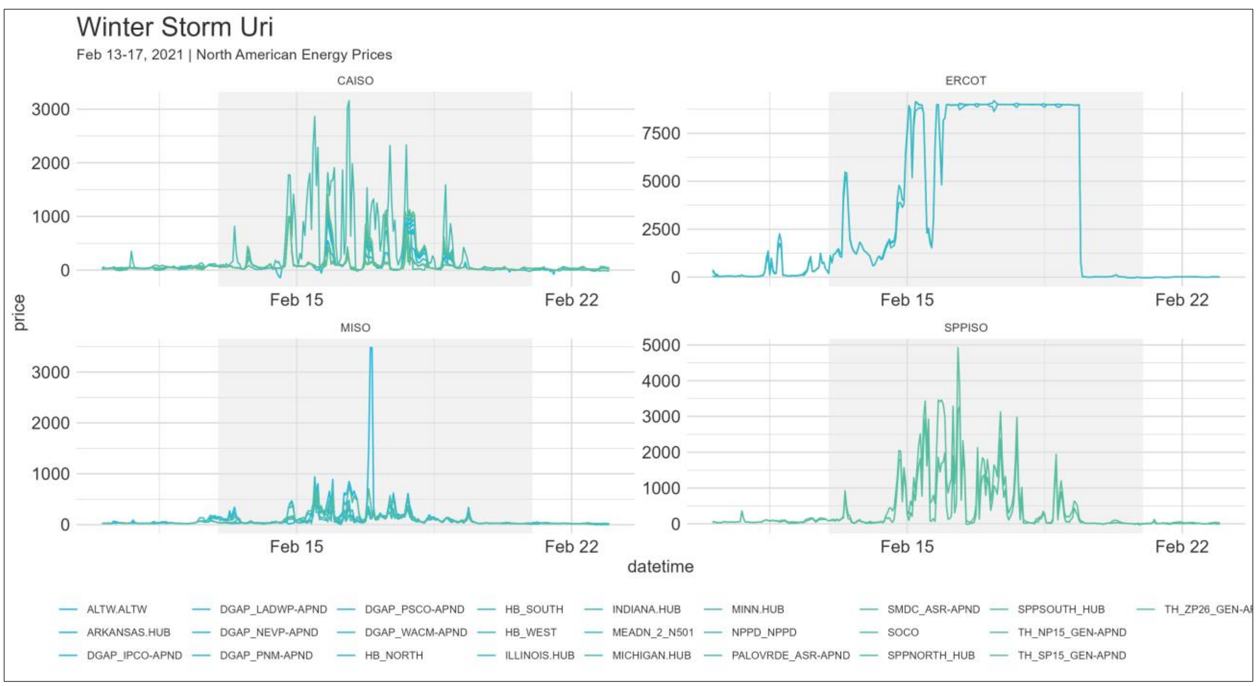


Figure 55 below shows prices during Winter Storm Uri in CAISO, ERCOT, MISO, and SPP.

Figure 55.

Winter Storm Uri

Feb 13-17, 2021 | Daily Mean Pricing

market	price_name	02/12/2021	02/13/2021	02/14/2021	02/15/2021	02/16/2021	02/17/2021	02/18/2021
CAISO	DGAP_IPCO-APND	$61.14	$75.10	$157.10	$146.12	$114.16	$192.36	$110.88
CAISO	DGAP_LADWP-APND	$64.42	$90.71	$169.97	$253.38	$169.73	$370.06	$198.44
CAISO	DGAP_NEVP-APND	$57.92	$86.55	$143.41	$223.02	$174.90	$380.19	$203.83
CAISO	DGAP_PNM-APND	$62.16	$87.82	$169.95	$246.60	$179.95	$410.76	$209.68
CAISO	DGAP_PSCO-APND	$62.72	$82.10	$164.38	$203.79	$151.06	$316.56	$166.21
CAISO	DGAP_WACM-APND	$63.09	$82.34	$164.11	$206.32	$153.02	$323.08	$171.20
CAISO	MEADN_2_N501	$62.00	$91.79	$171.55	$263.15	$195.79	$447.75	$227.12
CAISO	NPPD_NPPD	$70.40	$116.29	$393.95	$1,118.76	$820.48	$793.44	$244.74
CAISO	PALOVRDE_ASR-APND	$59.61	$90.16	$169.88	$260.42	$187.78	$439.40	$223.04
CAISO	SMDC_ASR-APND	$78.46	$73.35	$163.91	$114.32	$88.90	$106.60	$70.81
CAISO	TH_NP15_GEN-APND	$72.90	$70.95	$163.43	$110.55	$87.47	$104.17	$70.86
CAISO	TH_SP15_GEN-APND	$61.40	$93.01	$173.69	$277.72	$217.46	$485.84	$243.50
CAISO	TH_ZP26_GEN-APND	$63.84	$73.49	$168.69	$119.97	$94.96	$123.19	$75.64
ERCOT	HB_NORTH	$383.81	$1,931.47	$2,435.54	$6,807.33	$8,993.52	$9,025.97	$9,000.77
ERCOT	HB_SOUTH	$353.79	$1,856.82	$2,246.52	$6,747.84	$8,952.64	$8,951.75	$8,964.11
ERCOT	HB_WEST	$388.43	$1,937.84	$2,413.92	$6,810.59	$8,998.90	$9,024.51	$9,003.23
MISO	ALTW.ALTW	$68.38	$104.44	$105.83	$289.02	$177.04	$229.70	$99.11
MISO	ARKANSAS.HUB	$44.10	$38.44	$39.50	$277.82	$686.11	$265.89	$93.68
MISO	ILLINOIS.HUB	$81.28	$78.31	$95.43	$216.49	$144.94	$167.23	$82.07
MISO	INDIANA.HUB	$44.77	$30.36	$50.43	$136.34	$109.35	$156.29	$82.38
MISO	MICHIGAN.HUB	$43.32	$30.88	$54.36	$145.51	$100.52	$159.02	$78.72
MISO	MINN.HUB	$59.79	$81.54	$104.51	$309.14	$170.15	$218.93	$89.53
MISO	SOCO	$44.74	$48.81	$68.84	$280.41	$338.98	$222.99	$79.20
SPPISO	SPPNORTH_HUB	$72.97	$118.40	$400.28	$1,143.59	$848.54	$817.66	$254.27
SPPISO	SPPSOUTH_HUB	$100.53	$151.05	$538.78	$1,890.76	$1,371.22	$1,204.84	$347.56

Figure 56 shows the change in mean daily peak price before, during, and after the weather event highlighting the change in peak pricing.

Figure 56.

Winter Storm Uri | Peak Price Trends

mean of daily peak price before, during, & after the event

Mean Daily Peak	MISO Central	MISO North	NPPD	Nevada Power Company	Northwest ERCOT	PJM	SCE
before	$65.73	$106.73	$328.37	$75.17	$338.38	$74.23	$92.72
during	$269.67	$485.81	$2,317.23	$892.60	$2,345.15	$178.15	$1,083.01
subsequent	$63.73	$74.54	$83.25	$67.41	$89.67	$50.48	$69.52

In addition to high power prices during Winter Sturm Uri, natural gas prices also increased significantly in ERCOT due to supply shortfall and transmission bottlenecks. The natural gas supply shortage occurred due to shut-ins across the western half of the U.S. and extended to markets served by central and western U.S. supplies, including Chicago and Southern California, but not areas served by Western Canadian Sedimentary Basin, Haynesville, or Appalachian supplies on the margin, such as Transco Zone 6 or Henry Hub. In Texas particularly, production decreased while demand increased due to the extreme cold weather.

Figure 57.

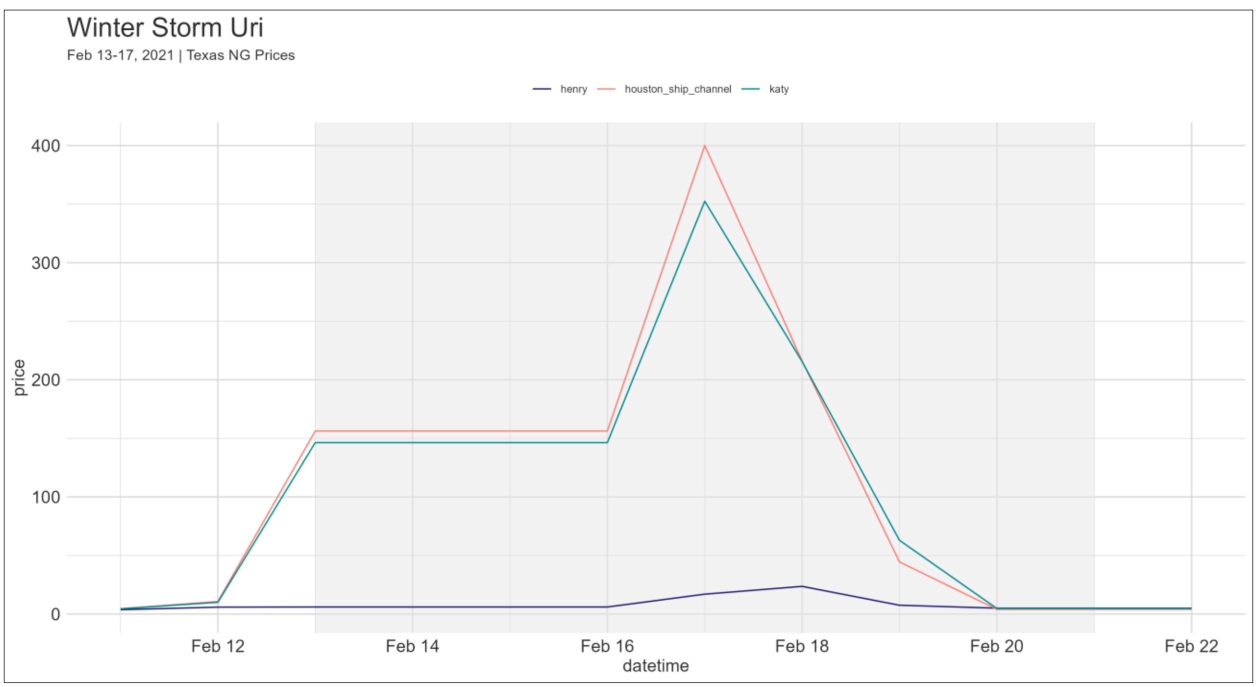


Figure 58 shows the change in mean daily gas price before, during, and after the weather event highlighting the change in natural gas prices.

Figure 58.

Winter Storm Uri | Natural Gas Trends

mean of daily gas prices before, during, & after the event

Mean Daily Price	Henry Hub	Houston Ship Channel	Katy
before	$3.79	$19.33	$18.26
during	$11.71	$216.97	$201.43
subsequent	$4.19	$8.34	$10.93

As temperatures decreased, loads increased significantly is due to the increase in residential heating demand. Figure 59 below shows the changes in load in the various markets during Winter Storm Uri.

Figure 59.

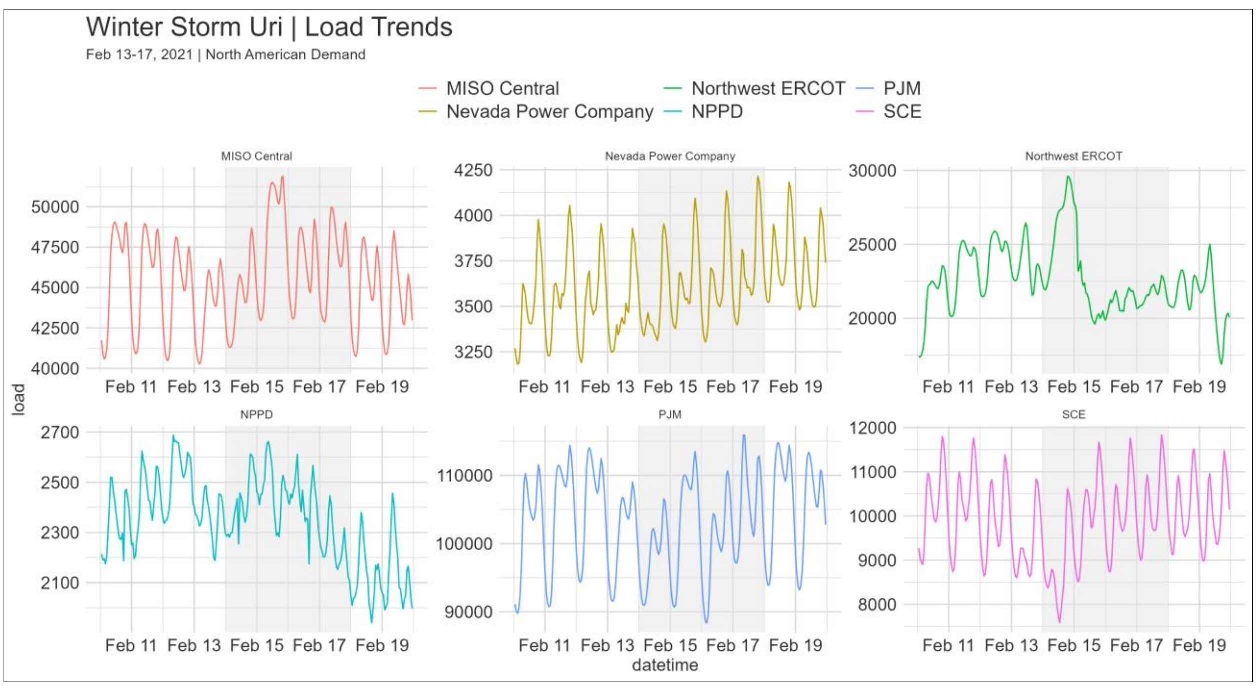


Figure 60 shows the change in mean daily peak before, during, and after the weather event highlighting the change in peak loads. For instance, in NW ERCOT mean daily peak load was 1.26 times larger during the event compared to the week before.

Figure 60.

Winter Storm Uri | Peak Load Trends

mean of daily peak load before, during, & after the event

Mean Daily Peak	MISO Central	MISO North	Nevada Power Company	Northwest ERCOT	NPPD	PJM	SCE
before	46,918.07	20,927.75	3,982.55	19,873.39	2,449.28	110,046.28	11,456.09
during	49,582.55	21,094.83	4,115.20	25,123.84	2,542.58	112,285.76	11,478.80
subsequent	43,106.99	18,723.93	4,041.25	17,623.28	2,132.51	104,415.17	11,384.12

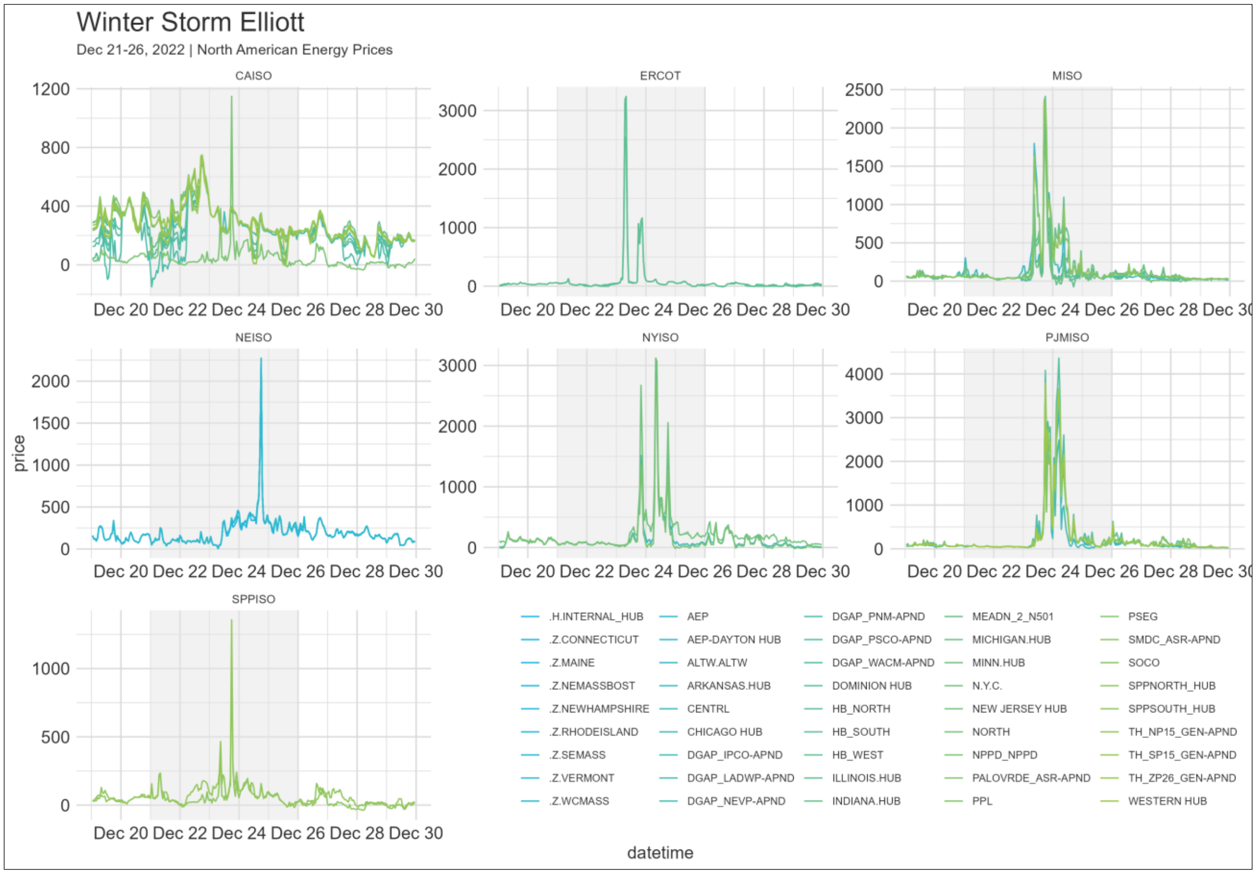
4.2.2. Winter Storm Elliott: December 21 through December 26, 2022

Winter Storm Elliott occurred in December 2022. During the event, load forecasts were miscalculated as temperatures across the U.S. were much lower than the National Weather Service forecasts indicated, which exacerbated the need for supply and caused unexpected price volatility.

Although Winter Storm Elliott was not as extreme as Winter Storm Uri, the ISOs/RTOs were not prepared. Weather forecasts had up to 20°F of error across the U.S., which set in motion a series of cascading events during which extreme prices were experienced across all ISOs/RTOs, including PJM.

Figure 61 below shows prices during Winter Storm Elliott in the various markets.

Figure 61.



As temperatures decreased to below expectations, RT loads were much higher than the respective DA forecasts. Heating demand increased loads across the U.S., and unprecedented demand and pricing ensued, leading to load shedding in various parts of the country, including Tennessee and the Carolinas. Peak loads across northwest ERCOT were approximately 20,000 MW before the storm and increased to more than 30,000 MW.

Figure 62 shows the change in mean daily peak price before, during, and after the weather event highlighting the change in peak pricing.

Figure 62.

Winter Storm Elliott | Peak Price Trends

mean of daily peak price before, during, & after the event

Mean Daily Peak	Balancing Authority of Northern California	MISO Central	MISO North	NPPD	Nevada Power Company	Northwest ERCOT	PJM	SCE
before	$429.72	$116.99	$74.10	$92.11	$428.39	$93.60	$114.26	$454.97
during	$425.18	$701.42	$425.98	$302.00	$398.29	$313.01	$1,321.62	$405.35
subsequent	$191.00	$74.31	$34.20	$42.20	$190.23	$36.98	$60.79	$192.39

Figure 63 below shows the changes in load in the various markets during Winter Storm Elliott.

Figure 63.

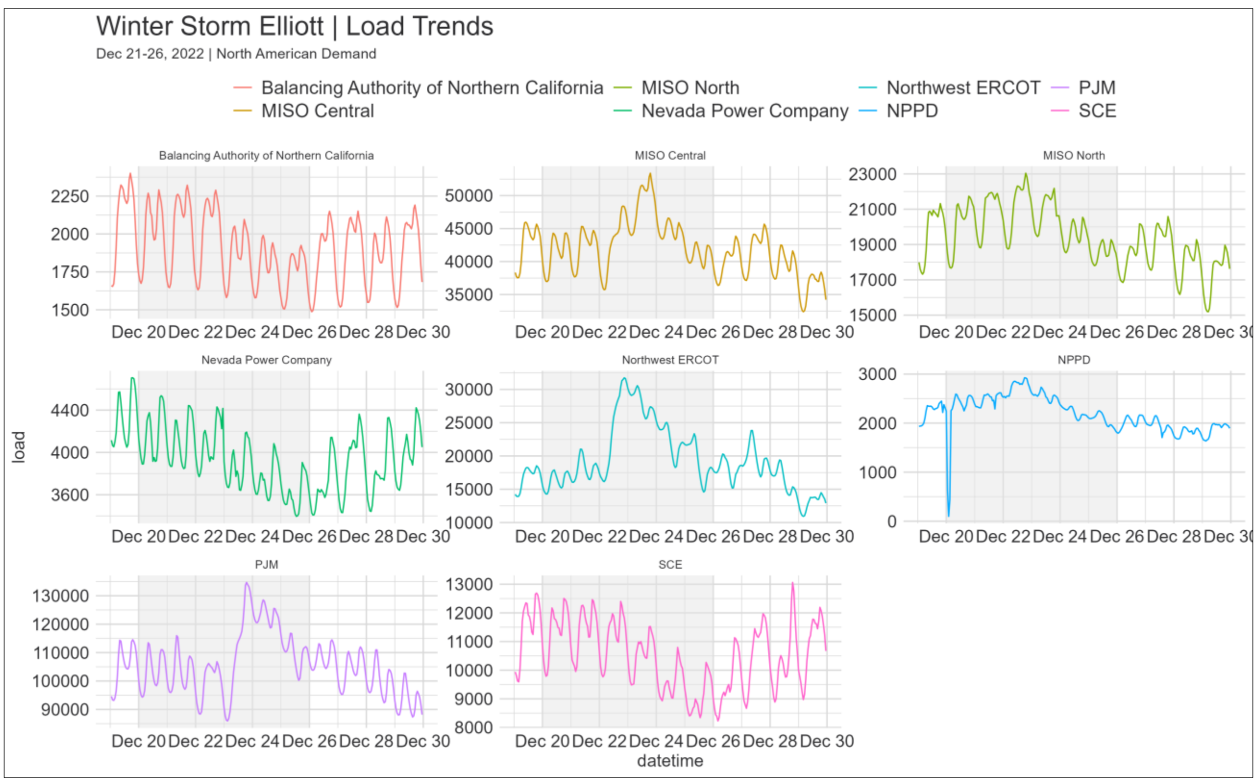


Figure 64.

Winter Storm Elliott | Peak Load Trends

mean of daily peak load before, during, & after the event

Mean Daily Peak	Balancing Authority of Northern California	MISO Central	MISO North	Nevada Power Company	Northwest ERCOT	NPPD	PJM	SCE
before	2,290.22	43,793.73	20,320.89	4,597.67	17,908.92	2,241.21	107,938.41	12,560.22
during	2,128.83	46,848.10	21,194.20	4,199.33	25,373.66	2,511.96	119,551.96	11,431.17
subsequent	2,040.50	38,792.40	18,627.64	4,224.50	16,426.59	1,970.47	96,691.19	11,617.17

Figure 64 shows the change in mean daily peak before, during, and after the weather event highlighting the change in peak loads. For instance, in NW ERCOT mean daily peak load was 1.42 times larger during the event compared to the week before.

4.2.3. Extreme Heat Wave: June 25 through July 7, 2021

In late June 2021, a heat wave of unprecedented magnitude impacted the Pacific Northwest (PNW) region of Canada and the U.S. This heat event yielded the hottest June on record in North America.

The extreme heat wave was primarily in the PNW, but hot temperatures moved east, creating higher than normal load and pricing across the ISOs/RTOs in early July. This event also had residual effects on MISO and other markets. However, price increases were lower relative to the price increases during Winter Storms Uri and Elliott. Figure 64 on the next page shows prices in the various markets during the extreme heat wave in the PNW.

Figure 65.

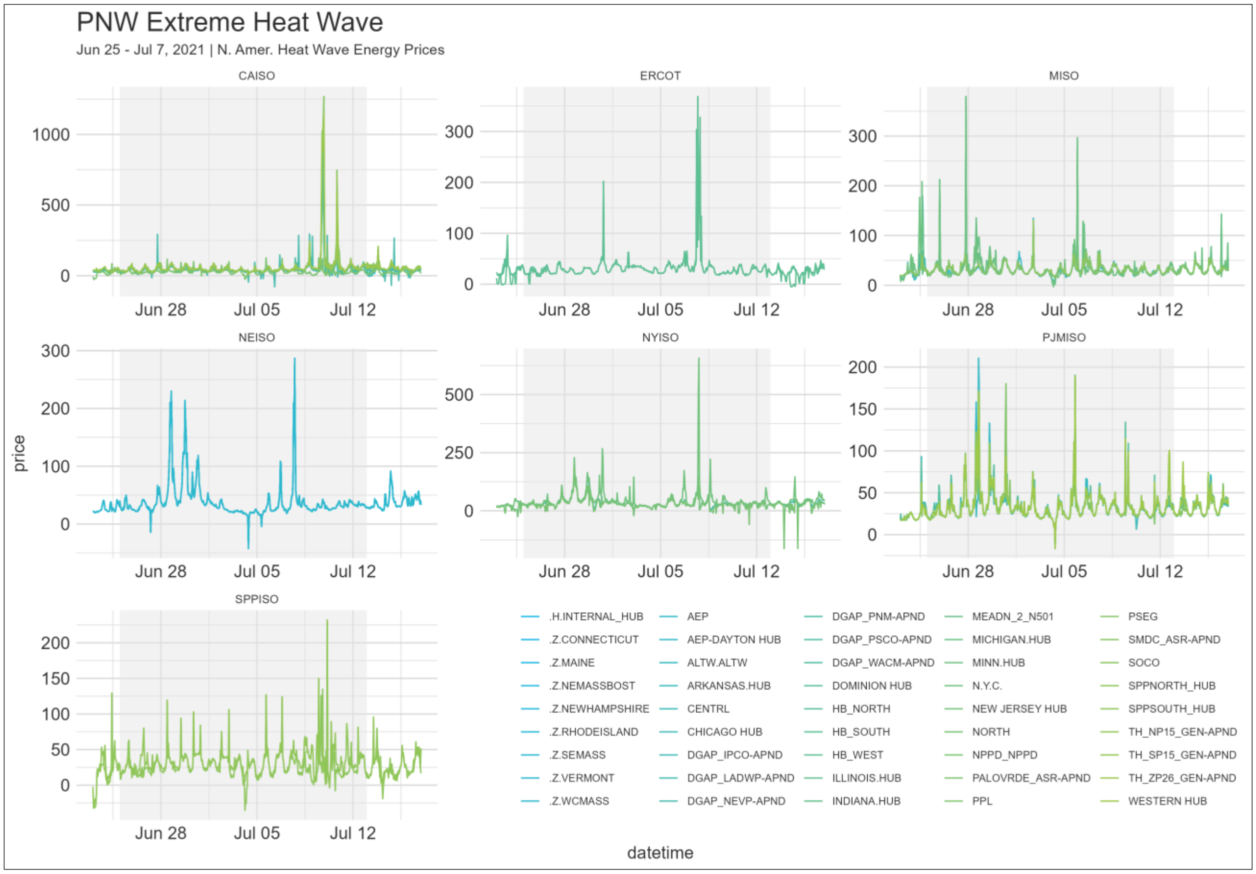


Figure 66 shows the change in mean daily peak price before, during, and after the weather event highlighting the change in peak pricing.

Figure 66.

PNW Heat Wave | Peak Price Trends

mean of daily peak price before, during, & after the event

Mean Daily Peak	Balancing Authority of Northern California	MISO Central	MISO North	NPPD	Nevada Power Company	Northwest ERCOT	PJM	SCE
before	$88.81	$41.71	$76.00	$53.74	$82.53	$59.54	$77.37	$93.65
during	$74.58	$124.01	$115.85	$72.07	$96.32	$72.90	$86.66	$81.84
subsequent	$201.29	$68.11	$65.27	$75.49	$203.36	$76.88	$77.45	$209.05

As temperatures increased, loads also increased as residents turned on their air conditioning to combat the heat. Figure 67 shows the demand across various markets, and indicates that hot weather events have less of an impact on loads compared to extreme cold weather events.

Figure 67.

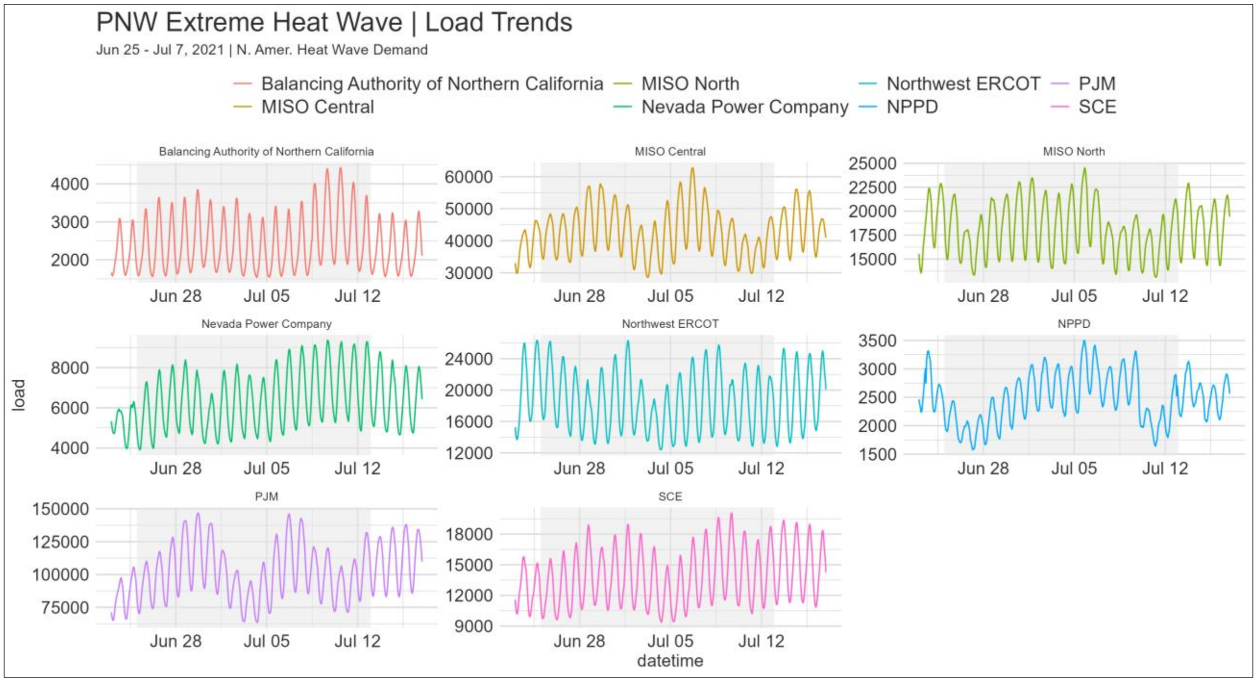


Figure 68.

PNW Heat Wave | Peak Load Trends

mean of daily peak load before, during, & after the event

Mean Daily Peak	Balancing Authority of Northern California	MISO Central	MISO North	Nevada Power Company	Northwest ERCOT	NPPD	PJM	SCE
before	3,572.67	48,113.61	20,991.03	7,961.67	25,044.03	3,025.26	110,008.27	16,754.44
during	3,477.77	53,002.50	21,725.93	7,992.00	23,150.13	2,854.11	125,279.70	17,187.69
subsequent	3,734.56	50,414.13	21,652.67	8,883.50	23,871.29	2,922.39	124,325.09	19,133.38

Figure 68 shows the change in mean daily peak before, during, and after the weather event highlighting the change in peak loads. Note that the heat wave event did not affect load to the same extent as extreme winter storms.

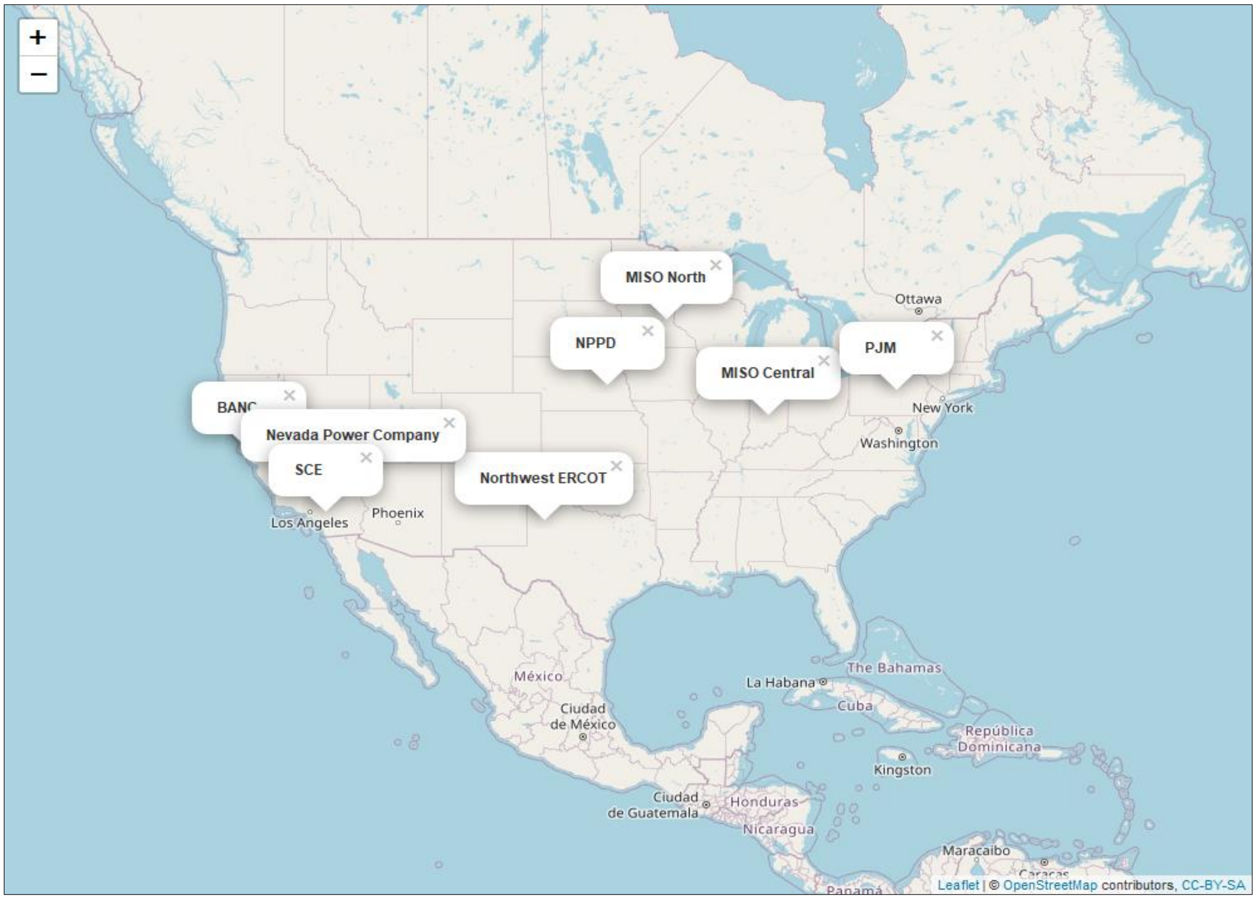
5. Market Impact Summary

Over the past five years, various weather-driven events have caused highly volatile power pricing and demand. The most extreme cases occurred during the winter, such as Winter Storms Uri and Elliott. These events can cause pricing and demand uncertainty across U.S. energy markets due to extreme cold and hot weather. The increase in weather-driven demand and intermittent renewable resources creates more volatility in power prices. Additionally, dark calms have shown to occur during the winter for various footprints with significant amounts of solar generation, requiring additional capacity to cover demand. These weather events must be modeled to fully capture portfolio risks and uncertainties.

6. Appendix

6.1.1. Map of Locations

Figure 69.



6.1.2. ISO/RTO Renewable Capacity: History and Projection

Figure 70. (NOT PUBLIC INFORMATION)

NOTE: FIGURE 70 SHALL NOT BE SHARED PUBLICLY. THE PROJECTED CAPACITY BY YEAR IS NOT PUBLIC INFORMATION AND IS PROPIETARY S&P Global DATA

7. References

Weather data was collected via the National Oceanic and Atmospheric Administration (NOAA) and NASAPOWER API market data was collected via the EIA's API, Yes Energy Data Signals API, and additional information via ACES proprietary databases. Capacity data was collected via S&P Global Market Intelligence.

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