Millersville University of Pennsylvania

A Case Study on the Anomalous Winter Weather Events of March 2018 in New Jersey

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Abstract

During March and early April of 2018, New Jersey experienced abnormally above average snowfall. In March, four nor'easters impacted the state on March 1st - 2nd, March 6th - 7th, March 13th, and March 20th – 21st. An additional snowstorm impacted New Jersey on April 2nd. This research includes a case study focused on the atmospheric conditions present during this period and explains the specific conditions that played a key role for the anomalous number of snowstorms in New Jersey in 2018. Specifically, the case study deals with a detailed explanation of related synoptic scale oscillations that were in favorable phases for the anomalous cold weather and snow events in the northeast. In addition, this case study investigates how the Sudden Stratospheric Warming (SSW) that began in early February of 2018 and lasted for several weeks, contributed to these specific conditions as result of the exact characteristics of the Stratospheric Polar Vortex (SPV) during the SSW.

Acknowledgements

Over the course of this process, I was extremely grateful to have the support and guidance of several intelligent and considerate people.

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Finally, I would like to send my appreciation to the Millersville University Honors College for giving me this tremendous opportunity to create, develop, complete, and defend my own research project. Doing this thesis has impacted my educational experience at Millersville in an exceptionally positive way. In addition, I extend similar gratitude to the Millersville Department of Meteorology. The faculty and staff from the entire department has helped in growing my knowledge and experience of meteorology.

With great thanks and appreciation,

Joshua T. Kinsky

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1. Introduction

Overall, the synoptic weather patterns for the winter of 2017-2018 were typical of the average climatology of a first year La Nina. Snowfall amounts were around average throughout most of New Jersey (nicknamed the Garden State) with a few storms that “threaded the needle” in typical La Nina fashion. Most New Jersey stations reported snowfall amounts around the climatological average from October through February. This overall trend of maintaining the climatological average through winter changed as February turned into March. The reason for this change had to do with the Sudden Stratospheric Warming (SSW) event that began in early February of 2018, and lasted for several weeks. Due to the nature of this SSW, a few important synoptic scale oscillations aligned in a favorable position for sufficient blocking that resulted in anomalous cold weather in the northeastern United States. As a result of these conditions, four nor’easters in March and one snowstorm in early April impacted the Garden State. Nearly every location in New Jersey received above average snowfall in March with some locations even recording record high snow totals for the month (Freehold and Marlboro recorded new March records of 19.5”). Therefore, this research paper is a case study focused on a possible explanation for the anomalous snowfall in New Jersey in 2018. The study will first include an overview of the climatology for this region and the related synoptic oscillations and teleconnections. Furthermore, it will investigate why the SSW in February of 2018 resulted in favorable blocking patterns. Each storm system will be reviewed through their synoptic setup, characteristics and impacts. The point of all of this research in to come up with an answer for why there was an anomalous amount of snowfall in New Jersey during March and early April of 2018.

2. Geography of New Jersey

According to New Jersey's Department of Environmental Protection, New Jersey can be roughly divided into four separate geographical regions. The four regions consist of (moving from south to north), the Coastal Plain, Piedmont, the Highlands, and Valley and Ridge. Each region has very distinct topographical characteristics that impact snowfall climatology.

The coastal plain is the largest geographic region covering the entirety of southern New Jersey. This region is flat with few notable hills and no mountains. Two notable features in this region include the Pine Barins in inner Atlantic, Burlington, and Ocean Counties and the New Jersey Shore which consists of very low-lying areas and several barrier islands. Figure 1 shows the physical extent of the region. Two notable large cities in this region are Trenton, the state capital, and Camden, which is directly across the Delaware River from Philadelphia.

The region directly north of the coastal plain is the Piedmont. This region extends from the border of the Delaware River in Hunterdon and Mercer Counties to the Hudson River and Bay extending into Bergen County (Figure 1). Compared to the coastal plain, this region has several larger hills and rocky formations, but not larger peaks, like the northern two regions. This region also is the most densely populated with several cities in the northeastern part (across the river from New York City) that include Newark, Paterson, and Elizabeth, New Jersey.

The region to the north of the Piedmont is the Highlands. This region extends from Northern Hunterdon and southern Waren Counties through upper Morris County to the border of upper Passaic and eastern Sussex Counties with New York state (Figure 1). There are several hills and mountains and some valleys with a few mountains having elevations of 1,200 plus feet. This region is remnants of a billion-year-old mountain range extending from Newfoundland to Mexico. This is also the first region with relatively no major cities, and it is much more sparsely populated than the previous two. However, there are still a few larger towns and small cities that include Hackettstown, Washington, and West Milford.

The northernmost region, the smallest of the four, is the Valley and Ridge. This region contains the Kittatinny Valley between the Mountains in the Highlands and The Kittatinny Ridge. This ridge is a part of the 400-million-year-old Appalachian Mountain range stretching from northern Georgia to the St. Lawarence Bay in Canada. The peaks in the Kittatinny Ridge reach over 1,500 to 1,800 feet. The region also borders the Delaware River to the west (Figure 1). This is the most sparsely populated geographic region, as there are mostly small towns and rural or forested areas.

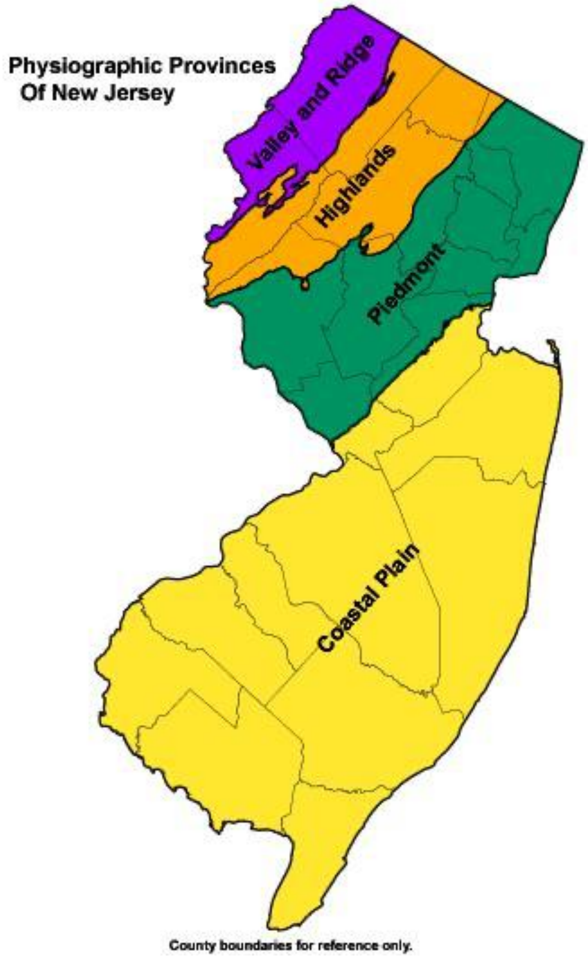


Figure 1: Map of the four geographic regions of New Jersey (State of New Jersey's Department of Environmental Protection, 2023)

3. Winter Snowfall Climatology in New Jersey with a Focus on March and April

This next section explores the winter snowfall climatology for New Jersey with a focus on the months of March and April. From the Office of New Jersey State Climatologist (ONJSC) at Rutgers University, there are seven stations that have adequate data records and are spread throughout portions of New Jersey. Those seven stations are: the regional airport KFWN in Sussex, KEWR or Newark Liberty International airport in Newark, Flemington, New Brunswick (Rutgers campus presumably), Freehold-Marlboro, Hammonton, and Cape May (Figure 3). The data was gathered and assembled from the ONJSC consisting of the average annual snowfall, average snowfall total (October-February) before March, and average snowfall total in March and April for each specific location. Overall, the average snowfall is the highest at KFWN in Sussex County (35.7 in) and decreases to the south and east (14.1 in at Cape May). Table 1 provides a complete dataset of all referenced values with respect to New Jersey snowfall climatology. The snowfall data differs by station as each station has a different number of years the data is available. The data available from ONJSC is not consistent for each year and each station. The following are the data periods that are available for each station in this study: Sussex (Jan 1893- Apr 2023), Flemington (Apr 1897 – Dec 2010, Nov 2014 – Apr 2023), Newark (Feb 1930 – Apr 2023), New Brunswick (Jan 1893 – Dec 1895, Jan 1912 – Apr 2023), Freehold-Marlboro (Nov 1931 – Jan 1982, Mar 1984, Feb 1987, Nov 1998- Apr 2010, Mar 2013, Nov 2014- Mar 2023), Hammonton (Nov 1930 – Feb 1990, Nov 2003 – Mar 2023), Cape May (Nov 1904 – Apr 1913, Nov 1926 – Apr 1932, Nov 1939 – Feb 1946, Nov 1966 – Apr 2023)

Location	Annual Average Snowfall (Inches)	Oct-Feb Average Snowfall (Inches)	March Average Snowfall (Inches)	April Average Snowfall (Inches)
Sussex	35.7	27.9	6.1	1.7
Flemington	31.1	24.1	5.8	1.2
Newark	27.9	22.5	4.7	0.6
New Brunswick	25.4	20.4	4.2	0.8
Freehold-Marlboro	23.5	19.2	4.0	0.3
Hammonton	17.0	13.9	2.6	0.5
Cape May	14.1	12.0	2.0	0.1

Table 1: Snowfall Climatology from Seven Stations in New Jersey Assembled from New Jersey's State Climatologists Office at Rutgers University.

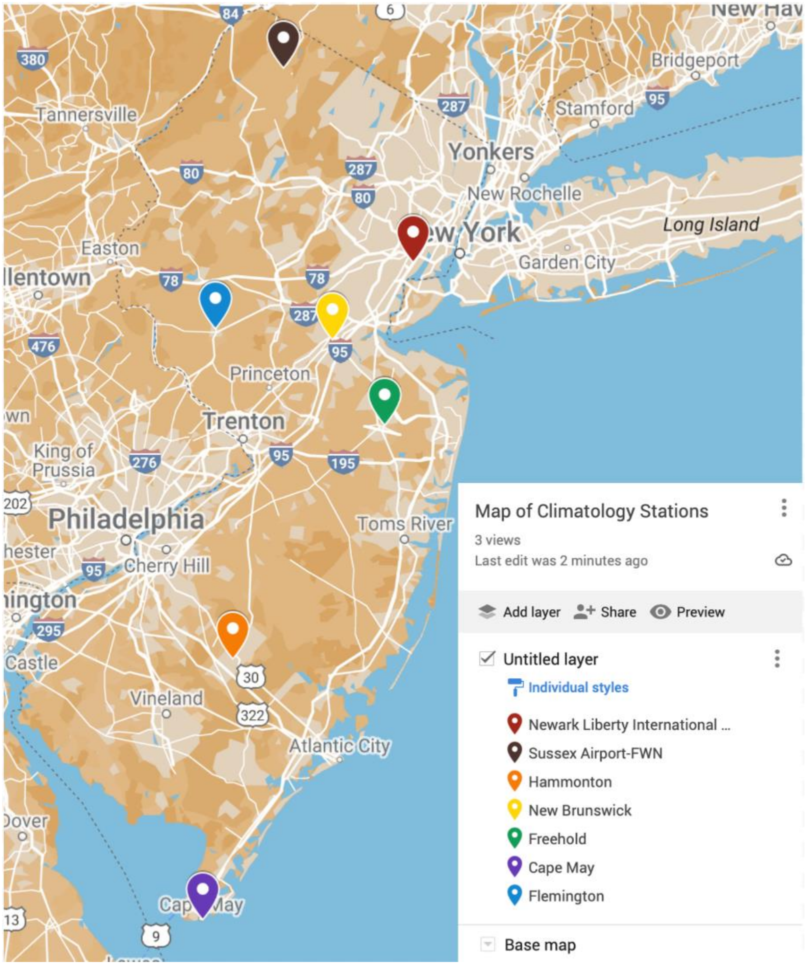


Figure 3: Map of the locations of each of the seven stations used for the climatological data utilized in this case study.

4. 2017-2018 Winter Snowfall in New Jersey with a Focus on March and April

Monthly data was compiled from the specific stations in section 3 from the ONJSC at Rutgers University for the 2017-2018 winter. The data is organized by snowfall totals for the winter, October (2017) through February (2018), March, and April (2018). The reason for this split in climatological data is due to the fact that this case study investigates the snowfall anomalies for the months of March and April.

Snow totals from October through February of the 2017-2018 winter were near average. Parts of the uppermost regions of the state were around average, the central portions were at or slightly below average, and the southernmost portions were above average. Overall, the first year La Nina allowed an average year in snowfall for New Jersey. For a complete analysis of each station, refer to figure 4 at the bottom of this section.

The snow totals for March and April were above average for large portions of the state. Snowfall anomalies for March were greatest in the interior portions of central New Jersey with Freehold-Marlboro breaking its monthly record for March at 19.5". One snowstorm at the beginning of April resulted in above average snowfall amounts for the entire month in many areas in the northern portion of New Jersey.

Location	Annual Snowfall (Inches)	Oct-Feb Snowfall (Inches)	March Snowfall (Inches)	April Snowfall (Inches)
Sussex	48.6	28.2	15.2	5.2
Flemington	45.7	20.1	21.6	5.2
Newark	39.4	21.2	13.2	5.0
New Brunswick	43.3	20.6	20.3	2.4
Freehold-Marlboro	40.5	19.0	19.5 (record)	2.5
Hammonton	22.3	16.2	6.1	0.0
Cape May	19.5	16.9	2.7	0.0

Table 2: 2017-2018 Winter Snowfall Totals from Seven Stations in New Jersey Assembled from New Jersey's State Climatologists Office at Rutgers University.

5. Relevant Oscillations and Teleconnections

The following oscillations and teleconnections described in this section are the important mechanisms that effect the winter synoptic weather pattern for the North American continent. The following Oscillations and teleconnections have an effect on the pattern throughout every season, however the effects during the winter are emphasized as this case study deals with that time period. These oscillations and teleconnections are important in the rationale for the anomalous cold weather in New Jersey during the time period of this case study.

a. The North Atlantic Oscillation (NAO)

The North Atlantic Oscillation (NAO) is an anomalous north-south dipole calculated by sea level pressure differences from two different locations. The northern location is centered around Greenland and the southern point is centered between latitudes of 35N to 40N near the Azores archipelago. The dipole is calculated by measuring the difference in normalized sea level pressure between those two areas. There are two distinct phases of the NAO: positive and negative.

When the NAO is in a positive phase, the synoptic set up consists of a deep surface low pressure over Iceland and a strong subtropical high pressure over the Azores archipelago (35N to 40N region). This phase results in more zonal flow throughout the mid-latitudes, as colder air is confined to northern regions of the Eastern North American Continent (northern Canada). As a result of this lack of cold air being blocked, the northeastern region of the United States typically experiences a milder and wetter air mass. In addition, very strong phases will result in above average temperatures for the eastern United States. Figures 5 and 7 illustrate the effects of the positive NAO on the 500mb height patterns and the impacts on surface temperatures.

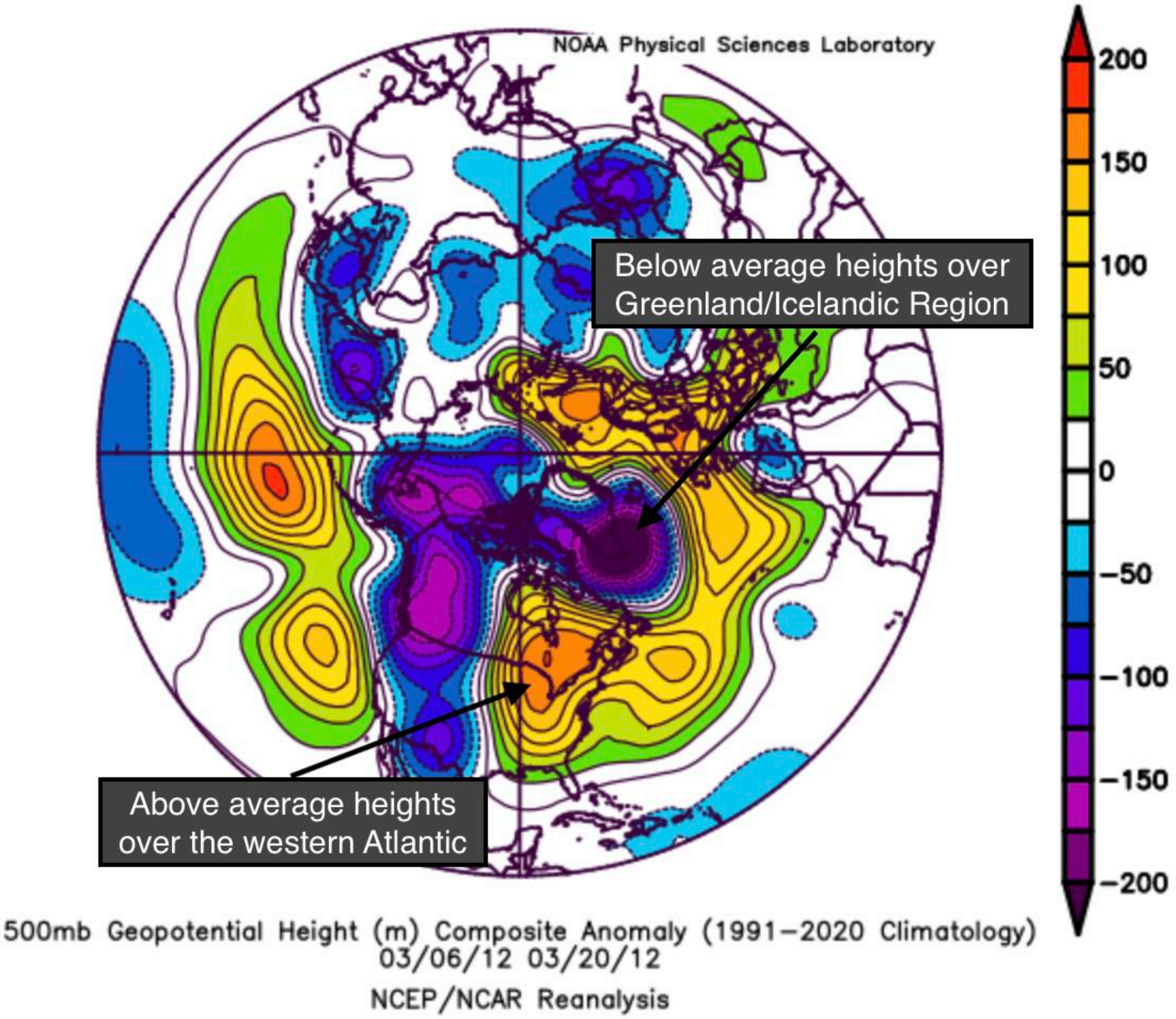


Figure 5: An example of a positive NAO between the dates of 03/06/12 to 03/20/12 shown by NCEP/NCAR's Archived Reanalysis data of the 500mb geopotential height anomalies (m) (NOAA's National Weather Service, 2020).

During a negative phase, a strong upper-level ridge of high pressure forms near or over Greenland. The ridge causes a reversal of the surface pressure dipole between Iceland and the Azores Archipelago. The high pressure over Greenland forces the Jet Stream to dip southward over eastern North America and effectively pushes Arctic air down into the midlatitudes. This often results in a colder and snowier regime for the northeastern United States. Figures 6 and 7 illustrate the effects of the negative NAO on the 500mb height pattern and the effects on surface temperatures.

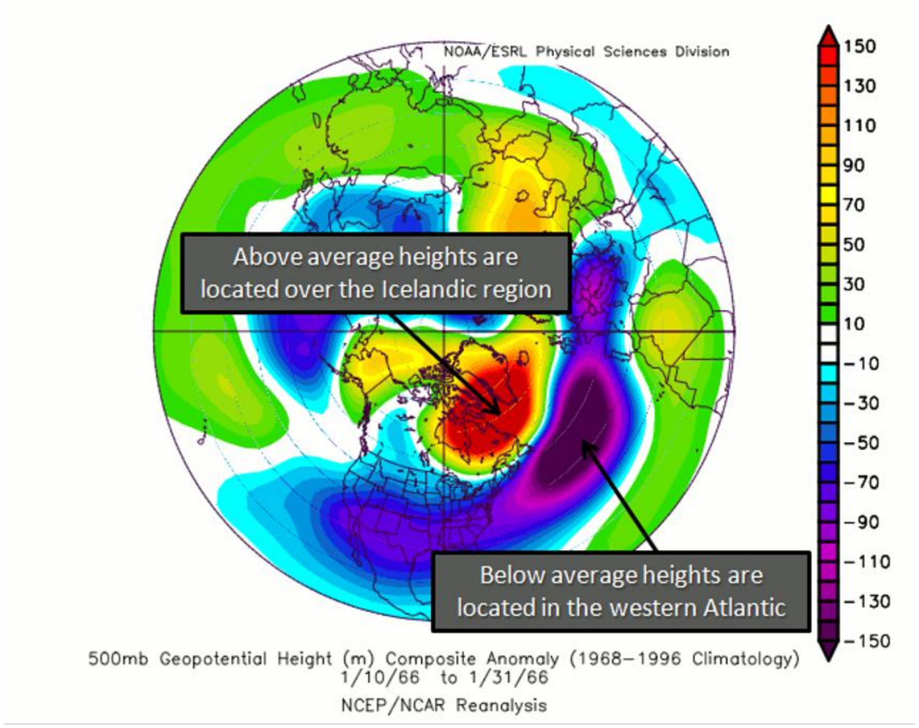


Figure 6: An example of a negative NAO between the dates of 1/10/66 to 1/31/66 shown by NCEP/NCAR's Archived Reanalysis data of the 500mb geopotential height anomalies (m) (NOAA's National Weather Service, 2020).

Overall, a positive NAO generally supports more zonal flow and warmer air masses for the northeastern United States, while a negative NAO results in more meridional flow and subsequent cold air outbreaks in the northeastern United States. Therefore, for a colder and snowier pattern across the Northeast, the NAO is often in its negative phase.

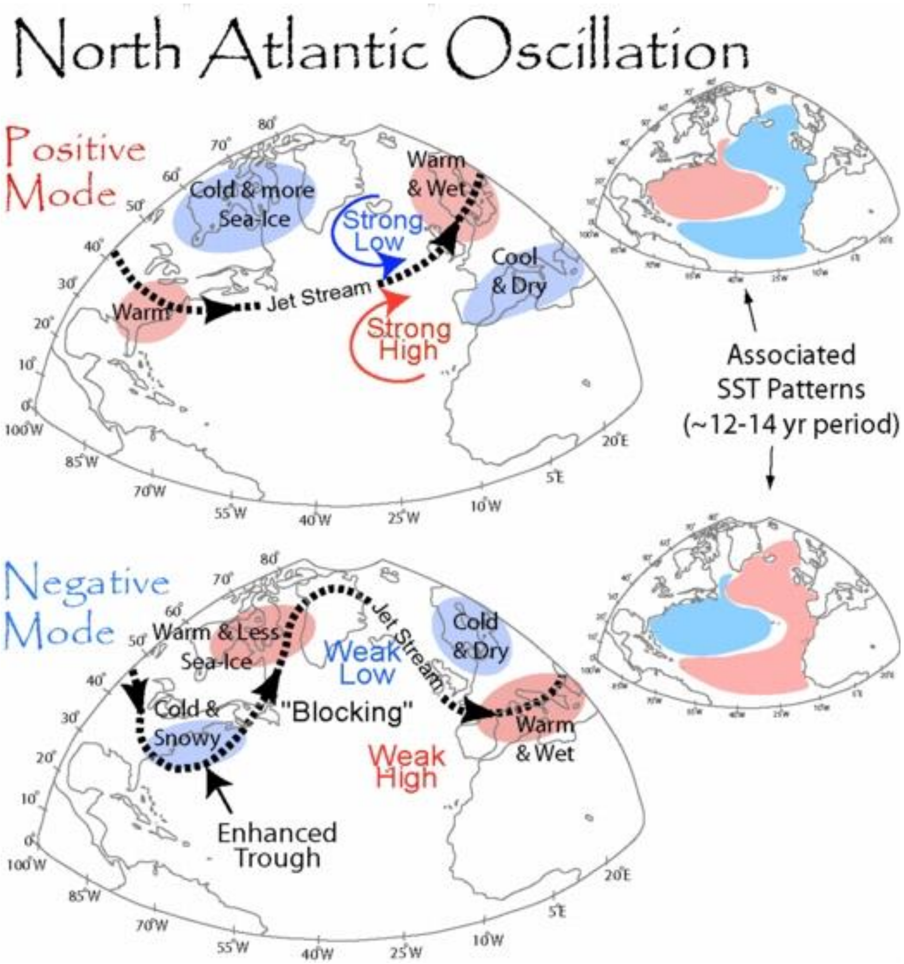
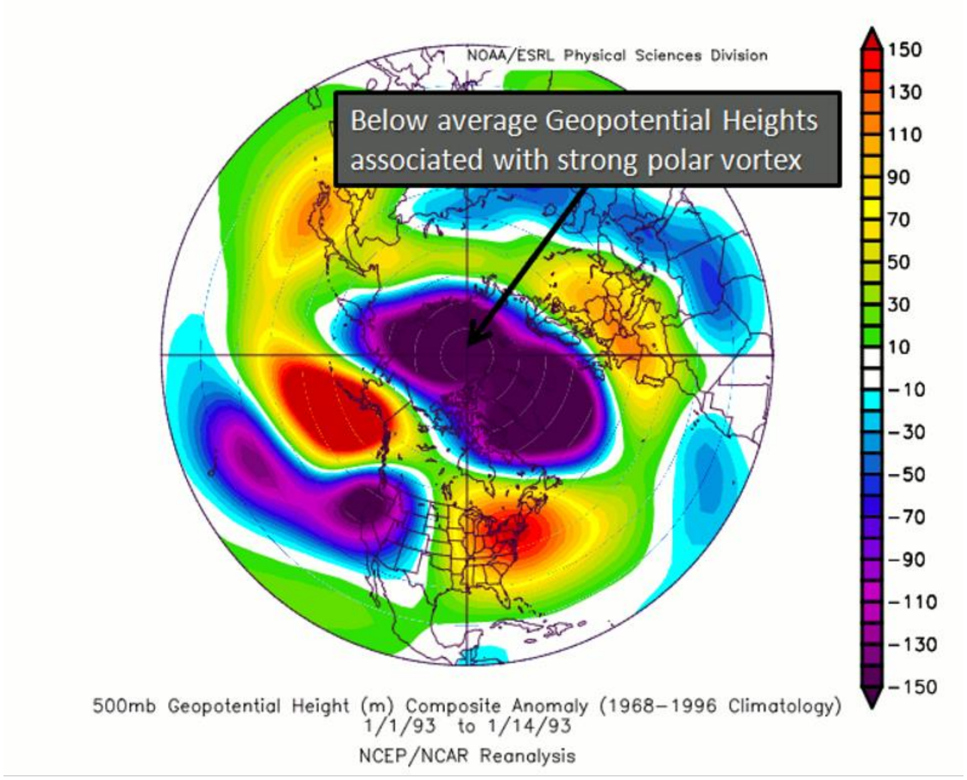


Figure 7: Surface effects from the different phases of the NAO (University of Michigan, 2023).

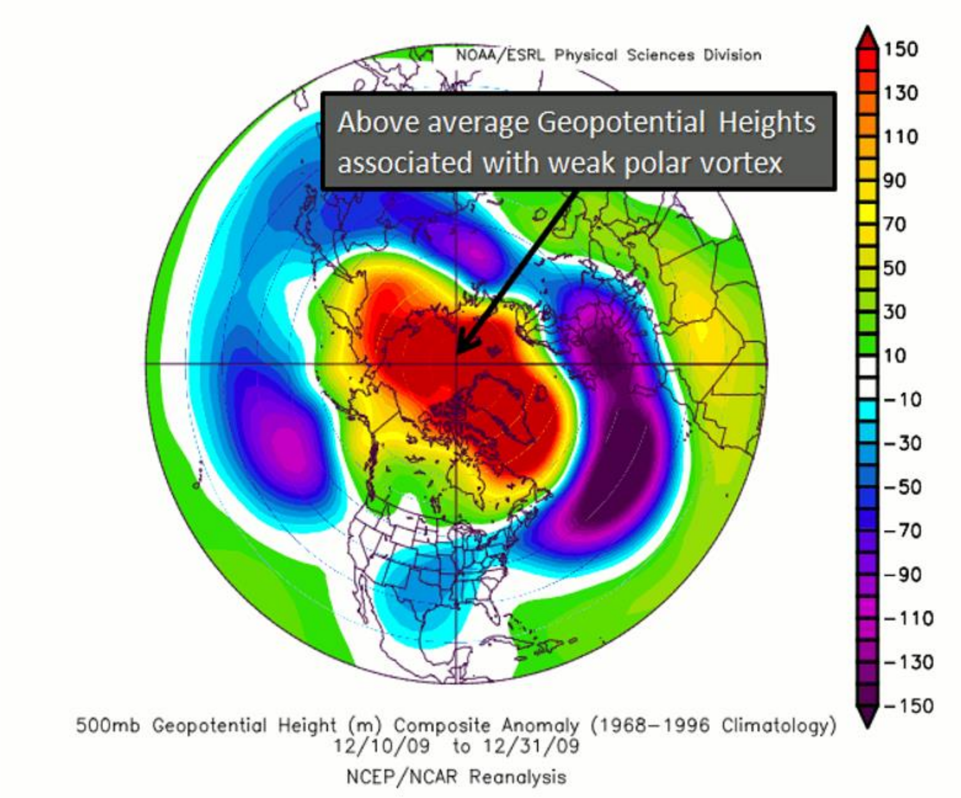
b. The Arctic Oscillation (AO)

The Arctic Oscillation (AO) deals with the strength of the polar vortex. The AO is similar to the NAO, but it is on a hemispheric scale where each phase may impact the synoptic pattern of the entire Northern Hemisphere. Like the NAO, the AO is defined in two phases: positive and negative. The positive phase of the AO consists of a much stronger polar vortex that results in a more zonal pattern. As a result, colder Arctic air remains in the polar regions of the Northern Hemisphere. In addition, areas in the midlatitudes are not inundated with colder Arctic air but instead tend to be mild. The negative phase of the AO consists of a much weaker polar vortex which results in a more meridional flow pattern. This flow pattern results in numerous "cold shots" for the midlatitudes as Arctic air masses invade the mid latitudes. In addition, the polar regions experience warmer-than-average air during this phase. The northeastern United States is more likely to receive higher snowfall anomalies during negative phases of the AO. For examples of the synoptic flow pattern during the positive and negative phase of the AO, refer to figures 8 and 9, respectively.



Below average Geopotential Heights associated with strong polar vortex

Figure 8: An example of a positive AO between the dates of 1/1/93 to 1/14/93 shown by NCEP/NCAR's Archived Reanalysis data of the 500mb geopotential height anomalies (m) (NOAA's National Weather Service, 2020).


NOAA/ESRL Physical Sciences Division

Above average Geopotential Heights associated with weak polar vortex

500mb Geopotential Height (m) Composite Anomaly (1968–1996 Climatology)
12/10/09 to 12/31/09
NCEP/NCAR Reanalysis

Figure 9: An example of a negative AO between the dates of 12/10/09 to 12/31/09 shown by NCEP/NCAR's Archived Reanalysis data of the 500mb geopotential height anomalies (m) (NOAA's National Weather Service, 2020).

c. The Eastern Pacific Oscillation (EPO)

The Eastern Pacific Oscillation (EPO) is a flow pattern that is centered in the eastern Pacific Ocean and Alaska. The EPO consists of two distinct phases: negative and positive. During a negative phase of the EPO, a strong ridge of high pressure develops over Alaska and the northeast Pacific which results in a trough over central Canada. As a result, Arctic air is forced down into the continental United States. This phase is more conducive for higher snowfall anomalies in the northeastern United States. When the EPO is in a positive phase, a persistent low pressure system forms over the Gulf of Alaska, preventing Arctic air from dropping into the

Continental United States. In addition, strong, westerly flow pushes mild Pacific air into the continental United States.

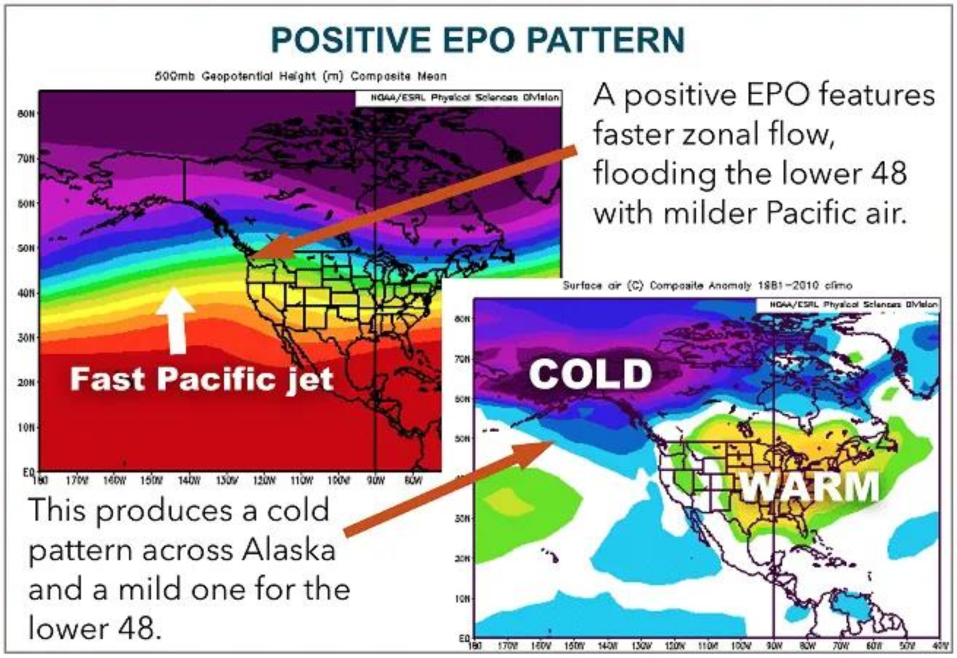
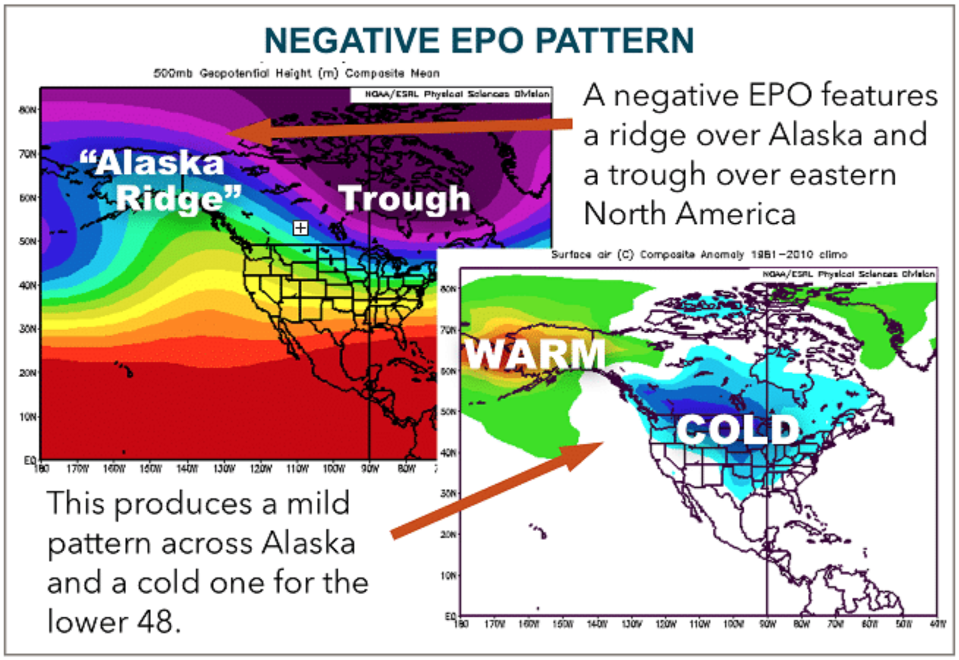


Figure 10: Effects of a positive EPO on the North American Continent (Strum, 2017)



NEGATIVE EPO PATTERN

A negative EPO features a ridge over Alaska and a trough over eastern North America

This produces a mild pattern across Alaska and a cold one for the lower 48.

Figure 11: Effects of a negative EPO on the North American Continent (Strum, 2017)

d. The Pacific North American Pattern (PNA)

The Pacific North American Pattern (PNA) is the flow pattern from the Pacific Ocean to the North American continent. Unlike the other synoptic scale patterns, the PNA is not an oscillation but rather a pattern of the synoptic flow (in this case of the North American continent). Like most other oscillations, this pattern consists of two distinct phases: positive and negative. The synoptic pattern of the PNA's negative phases includes a trough and below normal geopotential height anomalies over the western North American Continent with higher geopotential heights on the eastern side of the continent. This results in colder and wetter conditions for the western United States and a warmer and drier pattern for the eastern portion of the country. The pattern associated with the positive phase includes a trough and below normal geopotential height anomalies over the eastern North American continent with higher geopotential heights on the western side of the continent. This results in a colder and wetter pattern for the eastern United States and a warmer and drier one for the western portion of the country. A positive PNA is more favorable for an increase in snowfall anomalies in the northeastern U.S. Figures 12 and 13 show the patterns at 500mb for each phase of the PNA.

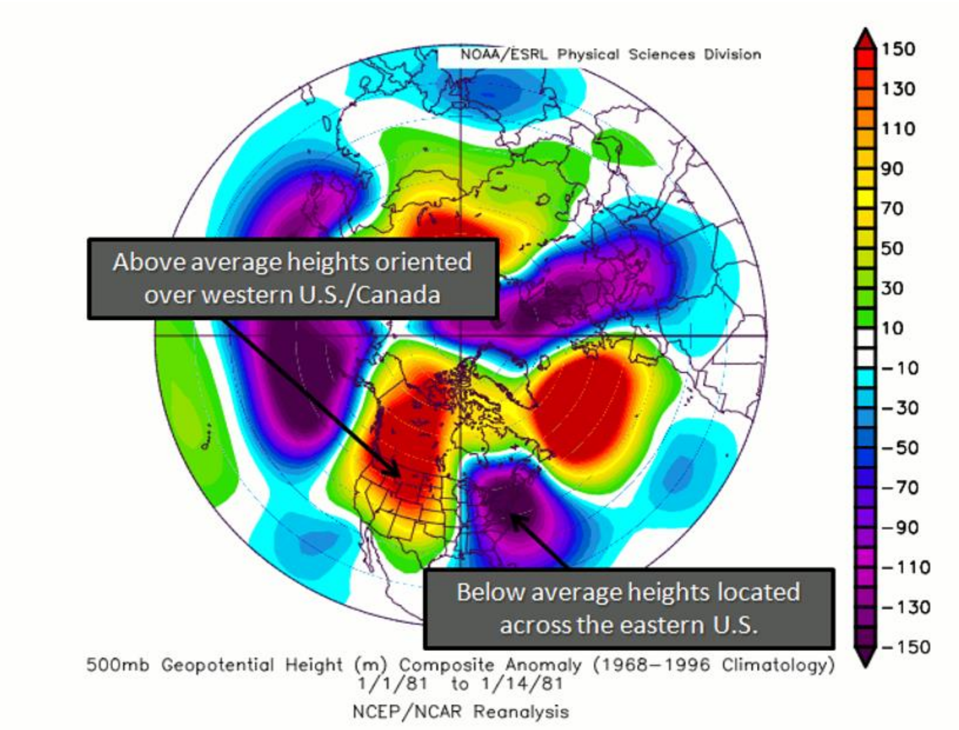


Figure 12: An example of a positive PNA between the dates of 1/1/81 to 1/14/81 shown by NCEP/NCAR's Archived Reanalysis data of the 500mb geopotential height anomalies (m) (NOAA's National Weather Service, 2020).

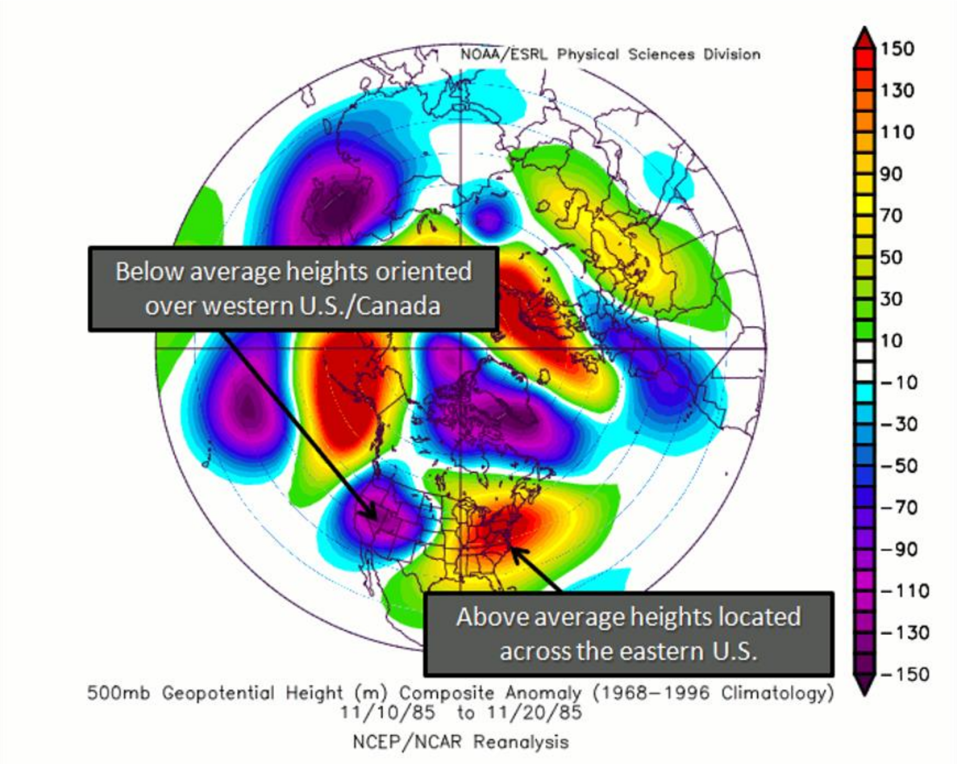


Figure 13: An example of a negative PNA between the dates of 11/10/85 to 11/20/85 shown by NCEP/NCAR's Archived Reanalysis data of the 500mb geopotential height anomalies (m) (NOAA's National Weather Service, 2020).

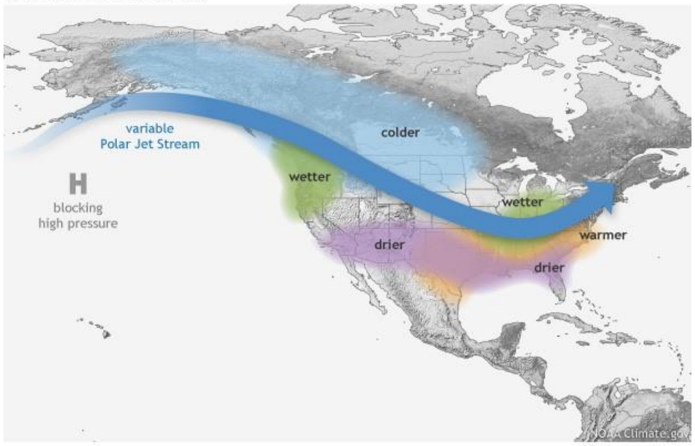
e. The El Nino Southern Oscillation (ENSO)

The El Nino Southern Oscillation (ENSO) is a pressure fluctuation in the equatorial regions and the sea surface temperature (SST) anomalies in the equatorial eastern Pacific. The centers of action of the pressure anomalies are the western and southeastern regions of the Pacific Ocean and the eastern Indian Ocean. These pressure and temperature anomalies are indicated by the Oceanic Nino Index (ONI). There are three phases of the ONI: El Nino, La Nina, and neutral. The ONI is positive (indicating the presence of El Nino) when the ocean temperatures at the equatorial Pacific Ocean are 0.5 degrees Celsius or more above average (anomalous warming). The ONI is negative (indicating the presence of La Nina) when the temperatures of the equatorial Pacific Ocean are 0.5 degrees Celsius or more below average (anomalous cooling). The ONI is in a neutral phase when the temperatures of the equatorial Pacific Ocean are between -0.5 to 0.5 degrees Celsius. The phase of ENSO influences global weather patterns and has large-scale impacts on the mid-latitude jet stream and overall synoptic pattern for the North American continent. The effects are felt largely during the winter months (Lindsey, R. (2017)).

The typical effects of the jet stream and overall synoptic pattern are illustrated in Figure 7. During El Nino, the Pacific Jet Stream is generally extended from the North Central Pacific across the southern United States and northern Mexico. This leads to an amplified storm track from that jet stream. This pattern results in wetter-than-average conditions throughout the southern states (California to the Carolinas) and into the coastal regions of the mid Atlantic, and drier-than-average conditions in the interior Midwest. Warmer-than-average conditions are often present in the north central to western states (Wisconsin through Oregon) with colder-than-average conditions throughout the southern United States (Texas through the lower mid Atlantic) (Lindsey, 2017).

For La Nina, the polar jet stream is the main driving force for the overall synoptic pattern for the winter. The Polar jet typically results in a trough in the western United States, resulting in cooler conditions from the Pacific Northwest to the north central states (Oregon to Minnesota). This trough also results in wetter than average conditions in the Pacific Northwest. The southern regions of the United States (California to the Carolinas) will largely remain much drier than average as storm systems typically track to the north of those regions. This storm track also results in wetter-than-average conditions across the central Midwest. For the southeast (Texas through the lower mid Atlantic), there are generally warmer than average conditions (Lindsey, R. 2017). Figure 14 shows the typical impacts of ENSO on the North American continent.

WINTER LA NIÑA PATTERN



WINTER EL NIÑO PATTERN

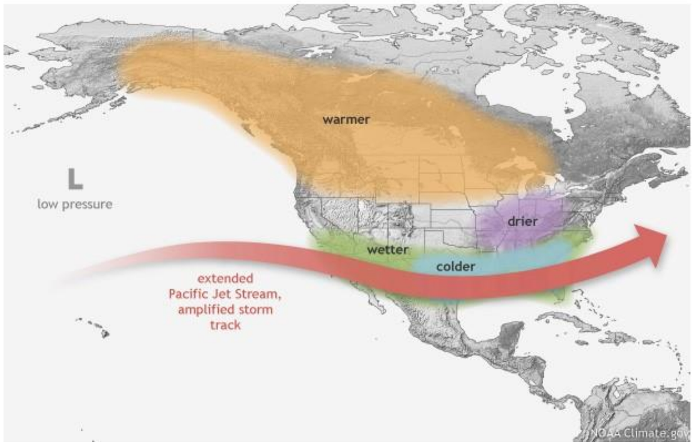


Figure 14: Map of typical synoptic weather patterns in the winter seasons during each phase of ENSO (El Nino and La Nina) (Lindsey, 2017).

f. The Pacific Decadal Oscillation (PDO)

The Pacific Decadal Oscillation (PDO) is defined as the SST anomalies in the northern Pacific Ocean. This oscillation has two phases: warm and cool. The warm phase is present when the SSTs are higher off the Gulf of Alaska and Pacific North American Coast (eastern Pacific Ocean) compared to the region in the western Pacific Ocean. Typically, this phase of the PDO results in a more positive PNA and a typical ridge formation over the western United States because of the higher SST anomalies. The cool phase is present when SSTs are lower off the Gulf of Alaska and the Pacific North American Coast (eastern Pacific Ocean) compared with the region in the western Pacific Ocean. Typically, this phase of the PDO results in a more negative PNA and subsequent trough formation over the western United States because of these lower SST anomalies. Although this oscillation generally follows a decadal cycle, it is often directly correlated with a strong positive (warm) or negative (cool) ENSO pattern.

g. The Madden Julian Oscillation (MJO)

The Madden-Julian Oscillation (MJO) is a global wavelike feature in the tropical and subtropical atmosphere, centered over the Indian and Pacific Oceans, discovered by Roland Madden and Paul Julian in 1971. As it is a global wavelike feature, the MJO influences the synoptic pattern of North America with the effects felt primarily during the fall, winter, and early spring months.

The MJO is defined as a cluster of thunderstorms that typically drift eastward along the equatorial Indian and Pacific Oceans. It moves in cyclic fashion and returns to its initial starting point in around 30-60 days, on average. The MJO consists of eight phases spread between the equatorial Indian and Pacific Oceans. Wherever the location of the strongest cluster of thunderstorms, or enhanced rainfall, is denotes the phase of the MJO. Phase one is located over the western Indian Ocean just off the equatorial coast of Africa, and this is where the wave typically originates. In phases two and three, the enhanced rainfall moves eastward over the Indian subcontinent and eastern Indian Ocean. In Phases four and five, the enhanced rainfall moves eastward over Indonesia. In Phases six, seven, and eight, the enhanced rainfall moves eastward into the Western and Central Pacific.

Each specific phase will have downstream synoptic effects on areas throughout the globe, including North America. Another important note is that the MJO may also be in a non-impacted phase (known as the "circle of death") when the cluster of thunderstorms weakens. As this occurs, the MJO has little or no impact on synoptic patterns throughout the globe as the patterns are influenced by other oscillations and teleconnections. As the MJO affects different regions throughout the globe, studies have shown that there is an effect on North America's synoptic pattern, primarily during the winter months. Thus, certain phases of the MJO promote high latitude blocking patterns. The phase of ENSO also affects how the MJO interacts with these blocking patterns.

6. Sudden Stratospheric Warming (SSW)

a. Definition

A Sudden Stratospheric Warning (SSW) is an event that occurs in polar regions at the level of the stratospheric vortex in either pole (although it is more common for them to occur in the Northern Hemisphere). Although "stratospheric warming" is a part of the name of an SSW, the actual definition does not include "stratospheric warming." The strict definition of an SSW is when the zonal mean zonal wind in the stratosphere (around 10 hPa) at 60 degrees North reverses from the typical westerly direction to easterly during the winter or early spring months (Junsu Kim et al, 2017). During the zonal-mean zonal wind reversal, temperatures typically increase in the upper stratosphere at the same latitude of the wind reversal. There is a direct link between the increase in these stratospheric temperatures anomalies' and the zonal mean zonal wind reversal. These temperatures in the stratosphere (60 degrees North) typically become warmer than stratospheric temperatures over the midlatitudes. This results in disruptions to the normal tropospheric synoptic pattern as more meridional flow ensues after an SSW (Junsu Kim et al, 2017).

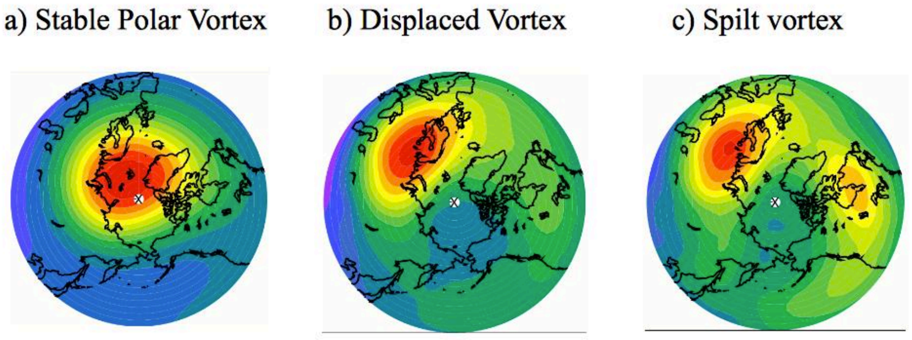
Balwin et al., 2020 discussed several different aspects of SSW events, including the behavior of the Stratospheric Polar Vortex (SPV) during an SSW. When an SSW couples with the troposphere, the lower (higher) heights in the stratosphere align with the lower (higher) heights in the troposphere. When an SSW does not couple with the troposphere, the lower or higher heights in the stratosphere do not align with each other. In this case, the effects of the SSW will be delayed by around two to four weeks. Baldwin, et al., 2020 have shown that around two out of three SSW events have the SPV couple with the troposphere, while the other third takes longer for the full effect of the SSW to reach the troposphere. Research from the same group of authors explained that the phase of the NAO impacts whether an SSW couples with the troposphere. When the NAO is in its negative phase at the time of an SSW, the SPV couples with the troposphere. When the NAO is in its positive phase at the time of an SSW, the SPV does not couple with the troposphere (Baldwin, et al., 2020). The final important aspect about whether an SSW may bring colder air into the Northeast or other areas in the mid latitudes is the location of where the SPV is displaced during the initial SSW.

b. Additional Background Information

In a presentation to the 2017 Annual Meeting of the American Meteorological Society in Seattle, Washington, Dr. Jonathan Forest Byrne Jr. presented on the impact SSWs have had on the Northeast urban corridor. In the years since 2000, the presenter had noticed a significant increase in Northeastern snowfall anomalies as Boston, Massachusetts, recorded seven of its last 10 snowiest winters since 2000. His general hypothesis on this matter was that it is a result of an increase of SSW events since 2000. He researched reasons for this increase in SSWs and concluded that it is a result of the increase in the Eurasian snow cover (Byrne Jr., 2017).

The research further explains how snow cover in Eurasia results in upward energy fluxes due to an increase of high pressures over Siberia. Due to an increase of high-pressure systems that settle over Siberia, upward energy fluxes occur which result in warming in the stratosphere. This warming allows for a weakening of the SPV and eventual reversal of the stratospheric winds, which meet the qualifications for an SSW. These SSW events result in downward propagation of high pressure into the troposphere over the polar regions. As a result, a negative AO is observed. It is also noted how an SSW has two general types of vortex impacts: displacement from its typical location above the poles, or a full vortex split into two lobes. A displacement from the poles is a weaker SSW while a full vortex split is stronger. Figure 15 illustrates the differences between these types of SPVs. The effects of this will impact how long anomalies may last in certain regions of the Northern Hemisphere's midlatitudes (Byrne Jr., 2017).

The BCC_CSM climate system model can be used to predict SSWs. Rao, et al. 2018 demonstrated the predictability of the model during the 2018 SSW. There were two periods of deceleration before the February 2018 SSW: one between January 12-19th and another between February 5th-15th. The first period was well modeled by the BCC_CSM, while the second period was poorly modeled. The deceleration of the zonal mean zonal winds during the second period (February 5th-15th) was more amplified than the model predicted. With that stated, the prediction of the SSW was modeled and predicted well within a week of the decelerating period. (Rao et al., 2018)



a) Stable Polar Vortex b) Displaced Vortex c) Spilt vortex

Figure 15: Different types of stratospheric polar vortexes (After O’Callaghan, 2013)

7. Discussion of the Synoptic Blocking Patterns for March 2018

As discussed earlier, an SSW event located in the Northern Hemisphere began in mid to late February 2018 and lasted for a few weeks. This was a strong SSW event as there was a complete split in the SPV. Due to this split, there were two main lobes of the SPV with one centered over the Caucuses in southwestern Russia and the other centered over central Canada. The one centered over Canada was stronger and larger than the one centered over the Caucuses (Lobe #1 in Figure 16). The lobe of the SPV over Canada (Lobe #2 in Figure 16) was in a favorable location for colder airmasses to invade the northeastern United States. The strength of this lobe was also a factor that allowed cold air to enter the eastern United States. In addition, as the NAO was not in a negative phase during the SSW (February 12th), the tropospheric effects were delayed until the beginning of March.

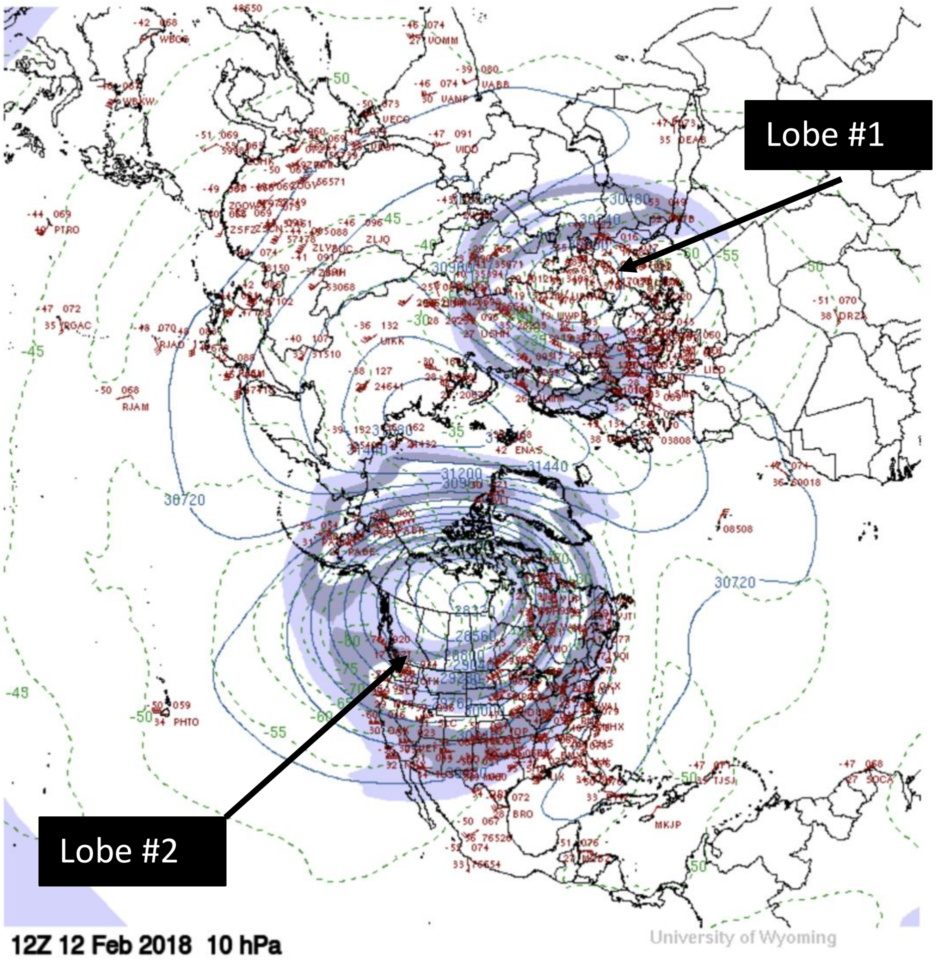


Figure 16: Geopotential Height Anomalies at 10mb (which represents the SPV) on February 12th, 2018. (University of Wyoming)

The movement of cold Arctic air into the Northeast can be attributed to some oscillations explained in Section 4 as they were the primary factors identified by this case study. The three blocking mechanisms that were the dominant forces and were the rationale for the Arctic air affecting the northeastern United States during March of 2018 were the AO, NAO, an EPO. Throughout March, each of these blocking mechanisms averaged out to be in the favorable phase for cold air in the Northeast. First, the AO (specific anomaly from normal: -0.941) was strongly negative which allowed for more cold air outbreaks throughout the midlatitudes in general.

Second, the NAO was negative (specific anomaly from normal: -0.91), resulting in a blocking high over Greenland that forced cold air into the Northeast. This allowed for cold air to be "blocked" into the northeastern United States. In addition to the NAO being in a strong negative phase, it was also centered in the Labrador Sea between southern Greenland and the province of Newfoundland and Labrador in Canada (which means that it was west based). This also increased the intensity and duration of the cold pattern. Third, the EPO was strongly negative during this period, which allowed for Arctic air to move into the entirety of the continental United States, including the northeast. As these three blocking mechanisms were all in a strong favorable phase for cold Arctic air for the Northeast, they overruled all other oscillations and teleconnections, as well as the climatology in March, to allow for this anomalous event to take place. Figure 17 provides an illustration of the average phases of those blocking patterns.

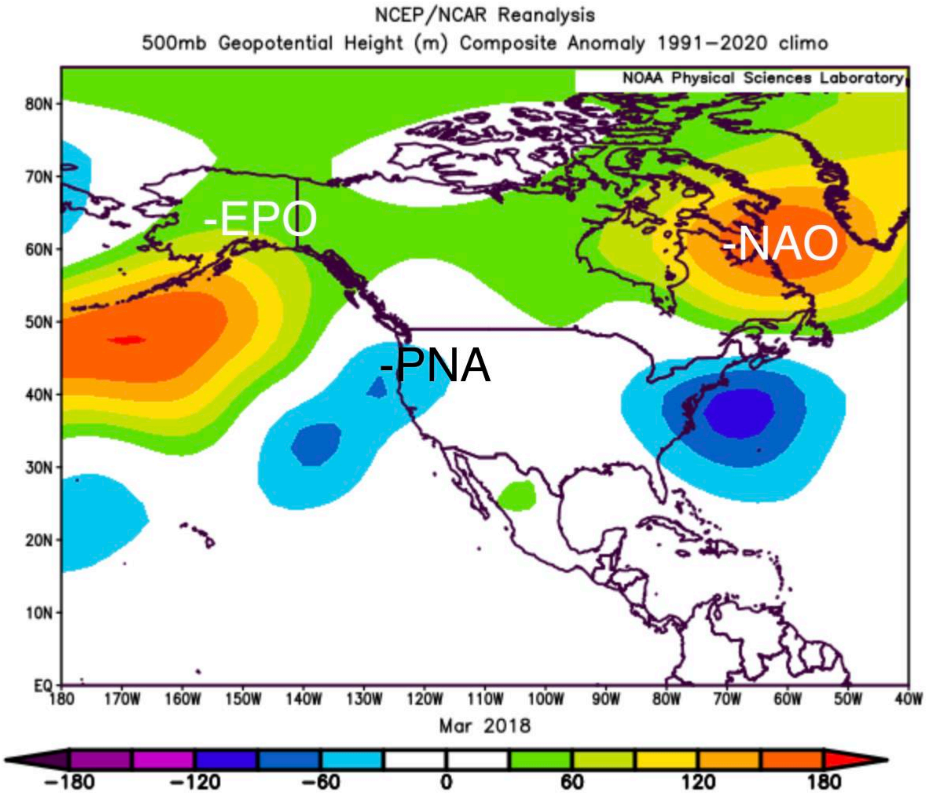


Figure 17: NCEP/CAR Reanalysis of Geopotential Height Anomalies at 500mb averaged out in March of 2018 (NCEP/NCAR)

Usually, a PNA of –0.91 will impact the strength of storm systems and their tracks and limit the amount of Arctic air in the northeast United States (-PNA is shown in figure 17). However, due to the other three factors described above, the effect of the PNA on the northeastern United States was negligible. March of 2018 was not like the typical negative PNA pattern where more troughs bring colder air into the western United States and more ridges bring warmer air into the eastern United States. In this case study, Arctic air was funneled into the entire continental United States, and that resulted in a pattern more favorable for troughs on both the East and West Coasts.

It is necessary to note other teleconnections that did not have an effect during March 2018 but are very impactful to the winter weather pattern in the continental United States. First, the MJO was in phases 1, 2, and 3 during the end of February into March. However, it was relatively weak and, therefore, did not have a significant impact on the synoptic patterns in the eastern United States. In addition, the La Nina was weakening into a neutral phase in March. The PDO was also in the unfavorable negative phase for cold events in the Northeast in March. As the anomalous winter weather effects during March were mainly a result of the SSW, the effects from La Nina and the negative PDO were marginal on the northeastern United States during this period. Therefore, for the purpose of this case study, further analysis of these three teleconnections/oscillations are not necessary as the four aforementioned teleconnections/oscillations were the dominant forcings during this event.

8. Comparison to Other SSW Years

An analysis of forty years of data (1983-2023) surrounding SSW events showed that there were 10 years (including the one in this case study) in which there was an SSW in February. Those years included: 1989, 1999, 2001, 2002, 2007, 2008, 2010, 2018, 2019, 2023. As this case study has dealt with the Northeast, the phase of the NAO was predominantly investigated during this aspect of the research. Since the NAO is one of the main factors in the blockage of colder air into the northeastern U.S., years that had negative NAO were also investigated to create a comparison. The point of a comparison to other years has been to investigate whether different late winter/early spring SSW events had similar effects to March and early April of 2018, with focus on snowfall anomalies for the early spring months in New Jersey. Only four of those years had a negative NAO during March: 2001, 2010, 2018, and 2023. The years (1989, 1999, 2002, 2007, 2008, 2019) that did not have a negative NAO during the month of March are likely the cases of when the SPV "coupled" with the troposphere.

The four other years (2001, 2010, 2018, 2023) likely had an effect a few weeks after the original SSW, meaning that the stratosphere did not immediately couple with the troposphere. However, the years 2001, 2010, and 2023 did not have the same anomalous winter weather effects as March 2018. The reason for this had to do with the location and strength of the SPV from the SSW. As the SPV was not in its most favorable location, the synoptic blocking and oscillations that resulted were not in the same favorable locations as they were in 2018.

In March of 2001, there was a negative west-based NAO and a positive PNA. These are both favorable phases for colder air to funnel into the Northeast. However, the EPO was not in a favorable phase for March since it had been in a positive phase. As a result, similar amounts (compared to the case study) of cold air were not funneled into New Jersey for higher snowfall anomalies. However, this year resulted in the greatest amount of March snowfall anomalies compared to the other two comparison years. But the synoptic set up was not as favorable as 2018, and therefore, the remarkable anomalous cold and snow for New Jersey had not been recorded in 2001. Figure 18 provides a visual depiction of the blocking patterns in March 2001.

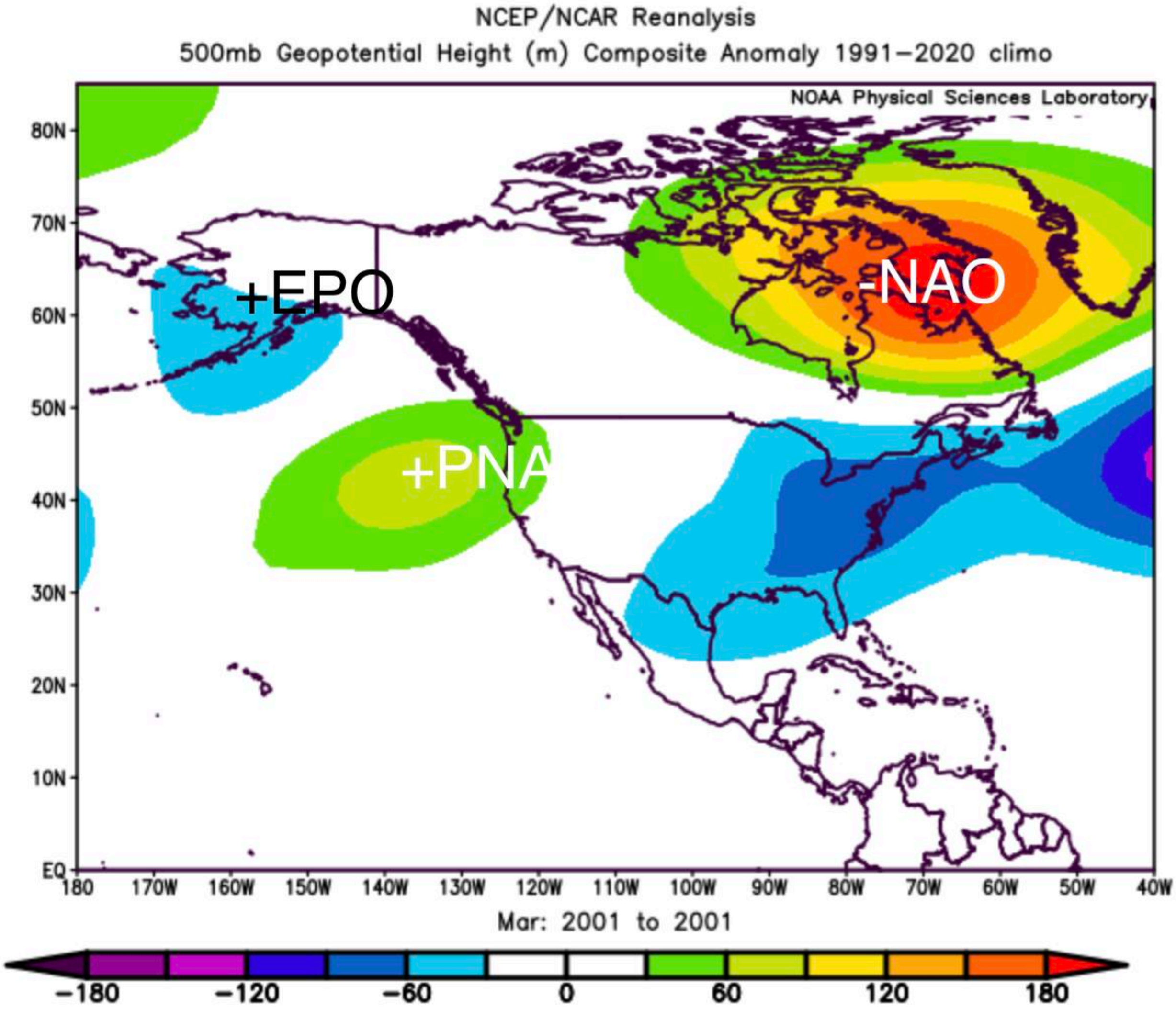


Figure 18: NCEP/CAR Reanalysis of Geopotential Height Anomalies at 500mb averaged out in March of 2001 (NCEP/NCAR).

In March 2010, although the NAO was negative, the Pacific oscillations (PNA and EPO) were both in unfavorable phases for anomalous snow and cold in New Jersey. The PNA was in a slightly positive phase while EPO was in an extremely positive phase. This resulted in an insufficient amount of cold air reaching the Northeast. Therefore, the snowfall anomalies were not higher than average. Figure 19 provides a visual depiction of the blocking patterns in March 2010.

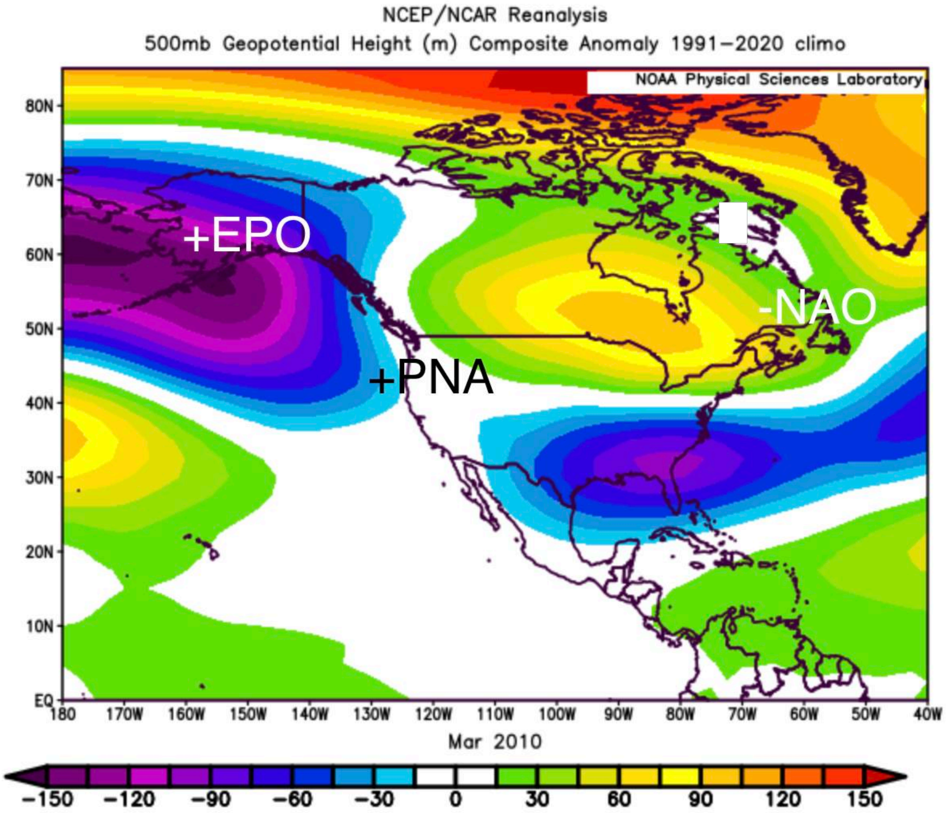


Figure 19: NCEP/CAR Reanalysis of Geopotential Height Anomalies at 500mb averaged out in March of 2010 (NCEP/NCAR)

In March 2023, there was a strongly negative NAO, but the Pacific oscillations were not in favorable phases for anomalous snow and cold in New Jersey. The PNA was strongly negative, and the EPO was slightly positive throughout the month. This strong negative PNA prevented cold air from reaching New Jersey. Instead, storms tracked farther north and west and brought snow to New England. Figure 12 provides a visual depiction of the blocking patterns in March 2023.

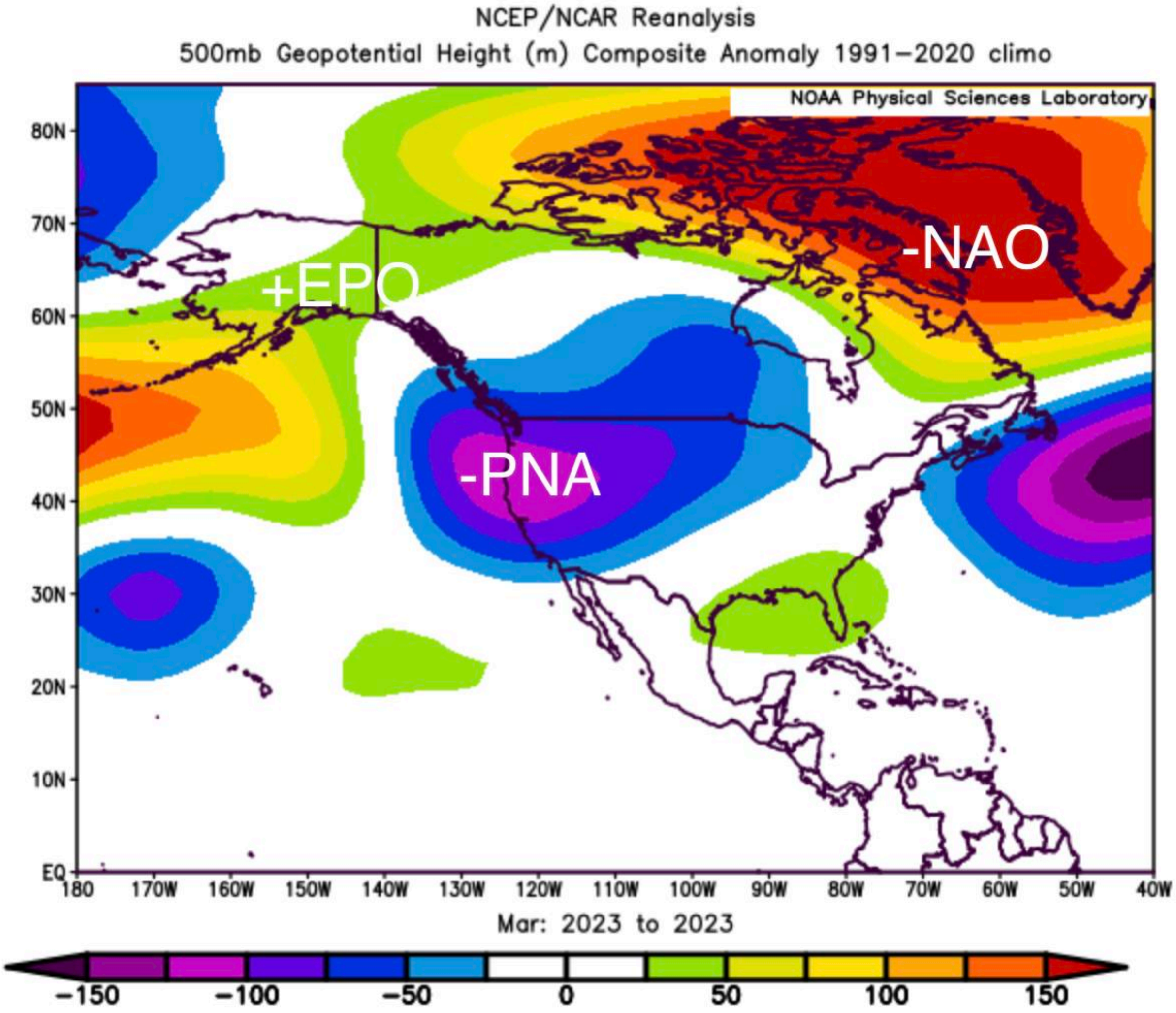


Figure 20: NCEP/CAR Reanalysis of Geopotential Height Anomalies at 500mb averaged out in March of 2023 (NCEP/NCAR).

Therefore, other synoptic blocking patterns such as the PNA, EPO, and MJO had more of an impact on the snowfall departures from normal for the other three years (2001, 2010, 2023). In addition, the reason why the other SSW events did not result in a dramatic increase in March's snowfall departure compared to the 2018 SSW had to do with the location and strength of the split of the SPV.

9. Overall Synoptic Pattern for March 2018 (Weekly)

Throughout the month of March 2018, the overarching synoptic pattern consisted of a moderate trough in the western United States, a weak ridge throughout the central states, and a stronger trough right off the northeastern coast. The temperature anomalies largely followed the jet stream pattern with below-normal temperatures on the West Coast, Northeast, and northern Great Plains and above average temperatures in the southern United States (National Center for Environmental Information, September 2023).

The first week of March (March 1-7) was dominated by zonal flow for the continental United States. There was an upper-level trough over the western portion of the United States, a weak ridge over the central U.S., and a trough off the East Coast. This resulted in above normal precipitation in the western portion of the United States. The storm tracks left most of the regions from the southwest to central plains and coastal northeast mostly dry. For the Northeast, there was a dip in the polar jet stream resulting in a low-pressure system moving eastward from the Midwest to the New England coastline. This was the main cause for the first two nor'easters in March (National Center for Environmental Information, September 2023).

The second week of March (March 8-15) was dominated by a smaller ridge that built in over the western states and a strong trough over the Central States. This strong trough funneled cold Canadian air into the Northern Plains and Southeast. The ridge in the West brought a warmer than average air mass into the Western States but was not strong enough to prevent Pacific weather systems from impacting the West Coast. Multiple low pressure systems would form over the Lower Mississippi Valley and move eastward into the mid-Atlantic region and off the coast of New Jersey. Systems typically intensified into nor'easters that would affect the northeastern coastline. The third nor'easter affected New Jersey during this period due to the increase in cold Arctic air and the favorable location of the formation of low pressure systems (National Center for Environmental Information, September 2023).

The third week of March (March 16-23) was dominated by upper-level troughs and closed lows migrating eastward due to the jet stream flow. The dominant pattern during that period were strong troughs along both coasts of the United States and a ridge in the Central States. Overall, it was mostly dry with higher-than-average temperatures in the Southwest and southern Plains. Many systems affected the West Coast from the Pacific Ocean. For the Northeast, the upper-level troughs resulted in cool and moist air masses. The final March nor'easter affected New Jersey during this time. This was also the system that brought the most snow to many areas throughout the Garden State.

The fourth and last week of March (March 24-31) was dominated by a ridge just off the West Coast of the United States, a strong trough in the north-central Plains and a weak ridge centered just to the west of the Mississippi River. The ridge on the West Coast resulted in drier and cooler air masses due to the northwesterly flow. Colder, Canadian air masses spread into the northern Plains and Midwest as they brought lower temperatures and above average precipitation to these regions. The fronts stalled as they reached the lower Mississippi to Ohio Valleys. As the storm track generally went from Texas to the Great Lakes region, the Southeast, central Plains, and Northeast generally remained drier than normal during this period (National Center for Environmental Information, September 2023).

10. Synoptic Setup and Description of Each System

a. March 1st - 2nd

i. Synoptic Setup

On March 1, at 12 UTC, there were two intense jet streaks at 300mb with one jet streak centered over Lake Ontario and the other centered over Missouri. A large shortwave trough amplified in the right entrance region of the jet streak centered over Lake Ontario and the left exit centered over Missouri. The trough axis extended from northern Missouri to Minnesota. Later on March 1st, the jet streak over Lake Ontario began to weaken, which resulted in the southern jet streak then over Tennessee becoming the sole factor from the upper-level jet in this system. The base of the trough was centered over Ohio and Kentucky, with strong areas of Positive Vorticity Advection (PVA) around 500mb just to the northeast of this location. A surface and lower-level low-pressure system formed out in front of the 500mb PVA. This surface low pressure was accompanied by strong, lower-level moisture advection at the 700mb and 850mb levels. Overnight, the upper-level trough began to strengthen which resulted in more PVA and a deeper low pressure. As the system shifted eastward, the center of the low-pressure system moved off the coast of New Jersey around 09 UTC on March 2nd. The 850 mb freezing line moved rapidly to the east overnight from the Pennsylvania-Ohio border around 00z March 2nd to around 50 miles off the coast of New Jersey by 12z on March 2nd as the cold air from Canada was funneled down by northerly winds in the mid-levels. As the Upper-level trough at 500mb deepened, the surface low pressure system strengthened. The trough deepened significantly until it was cut off from the rest of the jet stream and a cut-off low pressure system formed. This cut-off low-pressure system strengthened significantly as the geopotential height gradient increased on March 2nd. This resulted in a powerful nor'easter that affected the Northeast region and New Jersey.

ii. Description of the System

Precipitation in the form of rain began across the Garden State in the afternoon to evening hours of March 1st. Rain continued throughout the nighttime hours, with the rate being heavy (greater than 3 inches per hour) at times throughout the state as reports of heavy rain came from Newark Liberty International Airport, Atlantic City, Millville, and Trenton. As the center of the low pressure moved off the coast of New Jersey in the early morning hours of March 2nd, a Nor'easter formed. The formation of this Nor'easter shifted the winds from the north-northeast to north-northwest which resulted in cold, Canadian air rushing into the Northeast and Mid-Atlantic.

As this occurred, rain transitioned into a wintry mix throughout New Jersey. Areas in the higher elevations in the more northwestern portions of state were the first locations to transition over from rain to a wintry mix. Newark Liberty International Airport transitioned from rain to snow between 7-9am. Areas in the central part of the state, such as Trenton, Somerset, and Belmar, transitioned from rain to a wintry mix between 9-11am. Even some areas in the southernmost portions of the state transitioned from rain to a wintry mix. For instance, Millville, NJ, transitioned to a wintry mix between 12-2pm. Periods of moderate to heavy snow were reported up and down the state. Rates were more than an inch per hour for 2-3 hours in many locations in north and central New Jersey.

Winds strengthened significantly as the storm met the criteria outlined by Sanders and Gyakum's report in 1980 of bombogenesis, where a low pressure system drops 24mb in 24 hours. During the March 1st – 2nd event, the surface low pressure system dropped from 1002mb at 00 UTC March 2nd to 976mb at 00 UTC March 3rd with the system reaching an even lower pressure of 972mb at 18 UTC on March 2nd. These pressure falls occurred off the coast of the northeast as the tightening of the isobars resulted in stronger winds throughout the region. Sustained winds peaked at 25-35 mph across the state. Many locations across the Garden State recorded wind gusts of 45-60 mph, including Newark Liberty International Airport at 49 mph, Trenton Regional Airport at 52 mph, Millville at 53mph, Somerset Regional airport at 49 mph, and Atlantic City at 61mph.

As the storm began to move to the northeast, the rate of snow decreased as it tapered off after sunset on March 2nd with a few snow showers lingering throughout the Garden State until midnight. The stronger sustained winds of 25-35 mph began to wane as the storm moved farther to the east. Blustery and cold conditions continued on March 3rd as sustained winds reached 15-25mph and temperatures remained around 30-35 degrees Fahrenheit throughout the state. The winds decreased overnight on March 3rd as the system moved even farther out to sea.

The heaviest snowfall accumulations were concentrated in the higher elevations of the Valley and Ridge and Highlands geographical regions of New Jersey as some towns in the higher elevations of Sussex County received over a foot. Some of the lower elevations in those two regions received 2-6 inches of snow. In the piedmont regions, 2-5 inches of snow was recorded in the western portion, while some areas in the east experienced minimal accumulation. This included Newark which only recorded a trace of snow for the event. There were two relatively large pockets of 2-4 inches of snowfall accumulation in the central plain's geographical region. The coastal areas generally received a trace to an inch as the ocean's warming effect resulted in snow melting on contact. Figure 21 is a map of snowfall accumulations for this event.

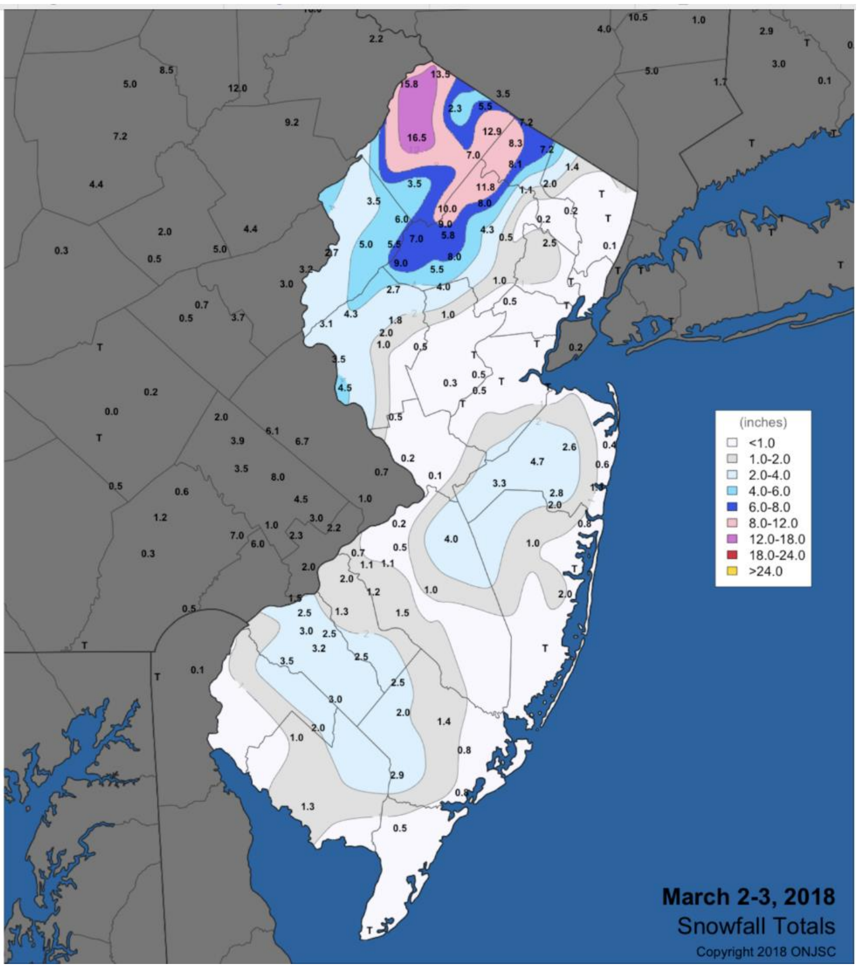


Figure 21: Snowfall reports and totals from the March 2nd – 3rd, 2018 snowstorm for New Jersey (Office of New Jersey State Climatologist (ONJSC) at Rutgers University, May 2023).

b. March 6th - 7th

i. Synoptic Setup

In the evening of March 6th an upper-level trough (500mb) that originated from Canada was centered over the central United States. This trough was already in a cut-off low pressure system formation as it was centered over the northern Plains. A weak ridge was centered over the eastern United States with its axis extending from Lake Erie to Georgia. The subtropical jet stream funneled moisture into the southeastern United States that formed a surface low pressure system. As the dip in the jet stream pushed eastward, this forced the trough at 500mb to move to the east. Additionally, the trough underwent rapid intensification and became negatively tilted. As a result, a strong area of PVA enhanced the system over the southeastern United States as it began to move to the north. This system began to impact the coastal regions of the Mid-Atlantic and Northeast, including New Jersey. Cold-air damning caused temperatures in the lower levels from the surface to 850mb to stay below or near freezing. As the upper-level trough at 500mb (which was now over Michigan) became more negatively tilted, it became in phase with the system that was located right off the coast of New Jersey. Another cut-off low formed off the coast of the Delmarva Peninsula early in the morning on March 7th. This cut-off low pressure strengthened as it moved northeast towards New England.

ii. Description of the System

After a few brief rain showers moved through the Garden State after sunset on March 6th, the main period of precipitation began to move from south to north. The precipitation started as snow and light rain in almost all areas after midnight on March 6th into the 7th. In areas generally northeast of Interstate 95 (I-95), the precipitation turned quickly over to snow due to dynamic cooling, as reported from the airports in Somerville and Trenton. The overnight rate of snow was light to moderate in those locations. The airports of Millville, Atlantic City, and

Belmar in south Jersey reported rain throughout most of the night. Areas just to west of the Hudson River, including Newark Liberty International Airport, also reported mixed rain and snow throughout the night.

As the low pressure deepened off the coast of the Mid-Atlantic, the system strengthened, and colder, Canadian air was advected into New Jersey. This resulted in the rain changing over to snow in most areas that were not already snowing. Newark Liberty International Airport and Belmar reported a change over to snow between 11:00am - 12:00pm on March 7th, and Millville and Belmar between 12:00-2:00pm on March 7th. As the rain changed to snow, many locations experienced heavy snowfall rates with visibilities of less than 0.25 miles.

Most of the state experienced snow throughout the remainder of the day. As the low pressure system continued to strengthen, heavier bands wrapped around it and affected New Jersey. As a result, heavy snow affected the Garden State throughout the day. Some locations, including Newark Liberty International Airport, the Airport in Trenton, and Atlantic City reported thundersnow during the heavy bands. After sunset, the snow began to taper off overnight as a few snow showers lingered. All snow ended in the state by 10pm on March 7th.

The snow totals throughout the Garden State ranged from a coating to over two feet. The concentration of the largest totals was in north central New Jersey in Morris and Passaic Counties. Locations in these counties recorded over a foot and a half of snow. Areas north and west of I-95 received over 8 inches of snow. The amounts dropped off significantly as areas to the south and east of I-95 experienced rain for a large part of the storm with coastal areas of southern New Jersey only receiving a coating to 3 inches. Figure 22 provides more information on the snowfall amounts.

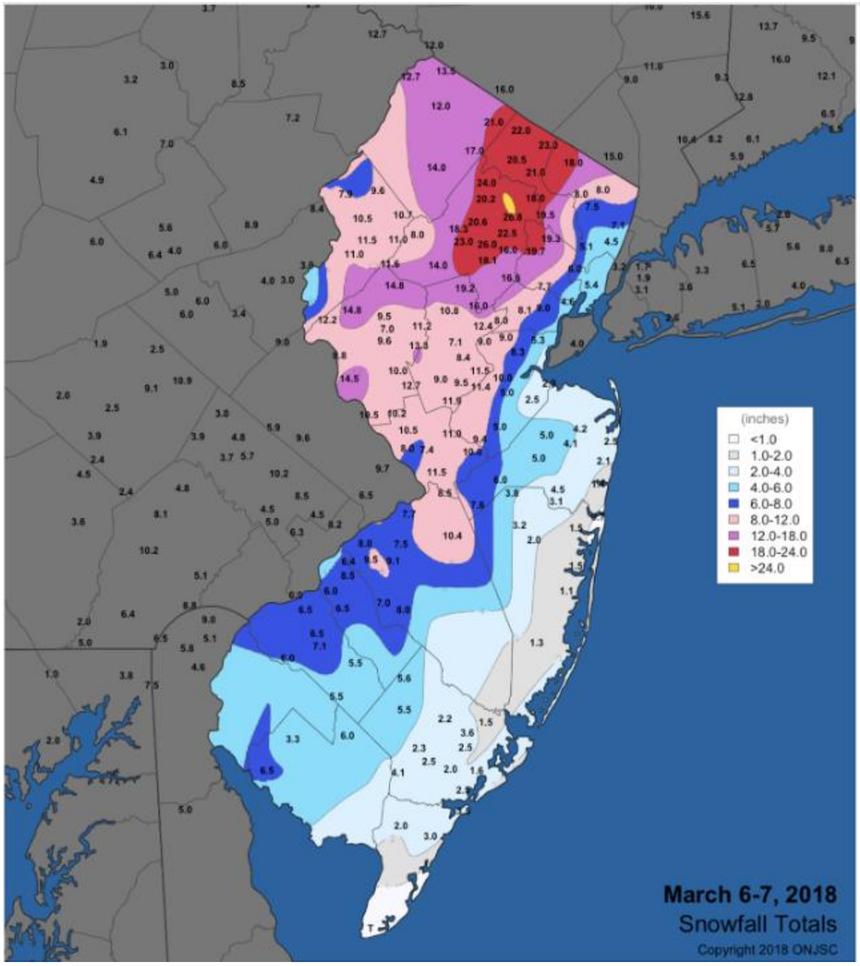


Figure 22: Snowfall reports and totals from the March 6th - 7th, 2018 snowstorm for New Jersey (Office of New Jersey State Climatologist (ONJSC) at Rutgers University, May 2023).

c. March 13th

i. Synoptic Setup

At 00 UTC March 12th a dip in the 250 mb polar jet stream was centered over the Midwest. This dip in the polar jet stream began to phase, or combine forces, with the subtropical branch of the jet stream. At the same time, a 500mb trough associated with the subtropical jet stream was centered over Arkansas. At the same time, another trough associated with the polar jet stream was centered over Lake Superior. This setup resulted in the formation of a low-pressure system around Kentucky and Tennessee as moisture from the Gulf of Mexico was forced into the southeastern United States. Throughout the day on March 12th, the 500mb trough centered over Arkansas strengthened and became negatively tilted as it moved eastward. The northern trough began to progress to the southeast throughout the day on March 12th. The low pressure system strengthened as it moved eastward until the trough moved northeast along the Eastern Seaboard. Although there was strong Warm Air Advection (WAA), the precipitation started out mostly as snow in the Garden state as there was some cold air damming in the lower levels with the 850mb freezing line south of New Jersey. The northern trough coupled with the southern trough in the Mid-Atlantic region overnight on March 12-13th. The low pressure system strengthened as it moved off the Mid-Atlantic coast and northeastward towards New England. Precipitation continued throughout the evening of March 12-13th until the system moved out of the Garden State in the morning hours of March 13th.

ii. Description of the System

Light rain showers associated with the system began to impact the Garden State between sunrise and noon on March 12th. As the storm strengthened, more significant precipitation began impacting the Garden State around noon on March 12th. The geographical regions of the valley and ridge, highlands, and piedmont all started as snow with a mix of rain and snow, or rain, in the coastal plain.

The airport in Trenton and Somerville first reported the main period of snow around 6pm on March 12th. Newark Liberty International Airport reported rain first around 4pm before snow began to mix in around half an hour later. Newark transitioned to all snow around 9pm. In the northern coastal plain, precipitation alternated between snow and rain. The airport in Belmar and

Millville reported snow for the first hour and a half before it changed to rain for a while. In areas along the coastline, the precipitation started out as rain before it changed over to snow. For instance, rain was reported in Atlantic City at 11am on March 12th, and it began to mix with snow around 4pm. The snow lasted from the night of March 12th into March 13th with all snow ending by the early morning hours of March 13th.

This event was predominately a light snow event with areas only in the mountains of northwestern New Jersey receiving between 4-8 inches of snow. Most locations in both the highlands and piedmont received 1-4 inches of snow. For the coastal plain, most areas in the northern areas recorded around 1-4 inches of snow with areas in the southern portions recording a general Trace to 1 inch. Overall, this system was relatively weak and generally a low impact event as New England experienced the brunt of this system. Figure 23 displays additional information on snowfall amounts across the state.

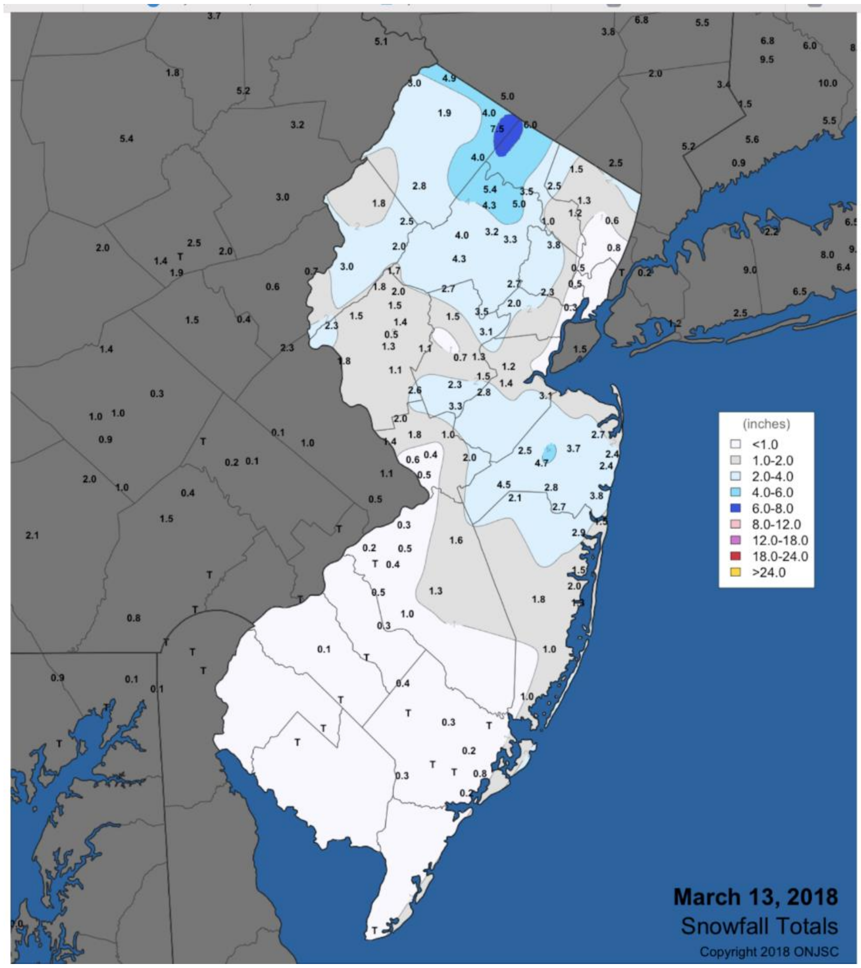


Figure 23: Snowfall reports and totals from the March 13th, 2018 snowstorm for New Jersey (Office of New Jersey State Climatologist (ONJSC) at Rutgers University, May 2023).

d. March 20th – 22nd

i. Synoptic Setup

On March 20th, a dip in the polar jet stream at 250mb combined with the subtropical jet stream over the central United States. A shortwave at 500mb formed early on March 20th. This shortwave quickly matured into a deeper trough over Illinois. As a result of this trough, a surface low pressure system formed over Kentucky. As the day progressed, the trough strengthened quickly over the central United States as a cut-off low pressure system formed. Additionally, the jet stream over the central United States at 250mb increased in intensity which resulted in the amplification of the lower layers of atmosphere and strengthening of the surface low. The jet stream at 250mb moved east with the cut-off low pressure system following suit. Due to the significant amount of cold air forced southward due to the dip in the polar jet stream, the center of the low pressure system stayed south of the Mason-Dixon line. In addition, the 850mb freezing line was well to the south and east of New Jersey. This resulted in primarily snow falling across most of the Garden State. The low pressure system moved off the coast around the Delmarva Peninsula as it continued to intensify and became a Nor'easter. The system moved quickly to the northeast towards Nova Scotia as it exited the mid-Atlantic region and New Jersey.

ii. Description of the System

On March 20th, precipitation began to affect the Garden State. The precipitation started as snow in the northern geographical regions of New Jersey (Mountains and Valleys, Highlands, Piedmont) while starting as rain in the southern region of the coastal plain. Some locations received a period of consistent precipitation at the start of the event, while other locations reported intermittent precipitation. For instance, Newark Liberty International Airport and the Airport at Somerset reported periods of mixed snow and rain during the late evening hours of March 20th. Trenton and Belmar experienced a mix of snow and rain for a few hours on March 20th ahead of the main portion of the storm that arrived on March 21st. For the southern region of the Garden State, stations in Millville and Atlantic City first reported precipitation in the afternoon of March 20th.

After the initial portion of the system brought snow showers to the northern portion of the state and a period of rain to the southern portion, the main system moved into the Garden State during the early morning hours of March 21st. The main system's precipitation was in the form of snow throughout the event in the northern geographical areas of the state, including the Mountains and Valleys, Highlands, and Piedmont. Areas in the Coastal plain region began as rain and transitioned over to snow from north-to-south as the storm progressed. Belmar started out as rain at 11pm on March 20th and transitioned over to snow between 4-5am on March 21st. Meanwhile, locations in southern regions of New Jersey (Millville and Atlantic City) mostly experienced rain overnight on March 20th with a full transition to snow between 8am-10am on March 21st.This system produced measurable snow across the entire state of New Jersey and dumped the most snow on central portions of the state. Most areas throughout the state received over 6 inches of snow. In extreme northern parts of the state, a coating to 3 inches was recorded due to the storm system's suppression. As the gradient of snow on the system's northern edge was tight, an area of 8-15 inches was recorded from the Pennsylvania border with Hunterdon County to the northern border of New York with Passaic County. Another area of 7-15 inches was recorded in the northern portion of the coastal plain regions. Due to the setup of the heavier snow bands during the storm, areas between these two locations (Somerset County and portions of northeastern NJ) recorded 4-8 inches of snow. Due to the longer changeover from rain to snow, the southern half of the Coastal Plain recorded around 4-8 inches of snow. Portions of Cape May County recorded only 2-4 inches of snow due to the delayed changeover. Figure 23 displays snowfall amounts across the state from this event.

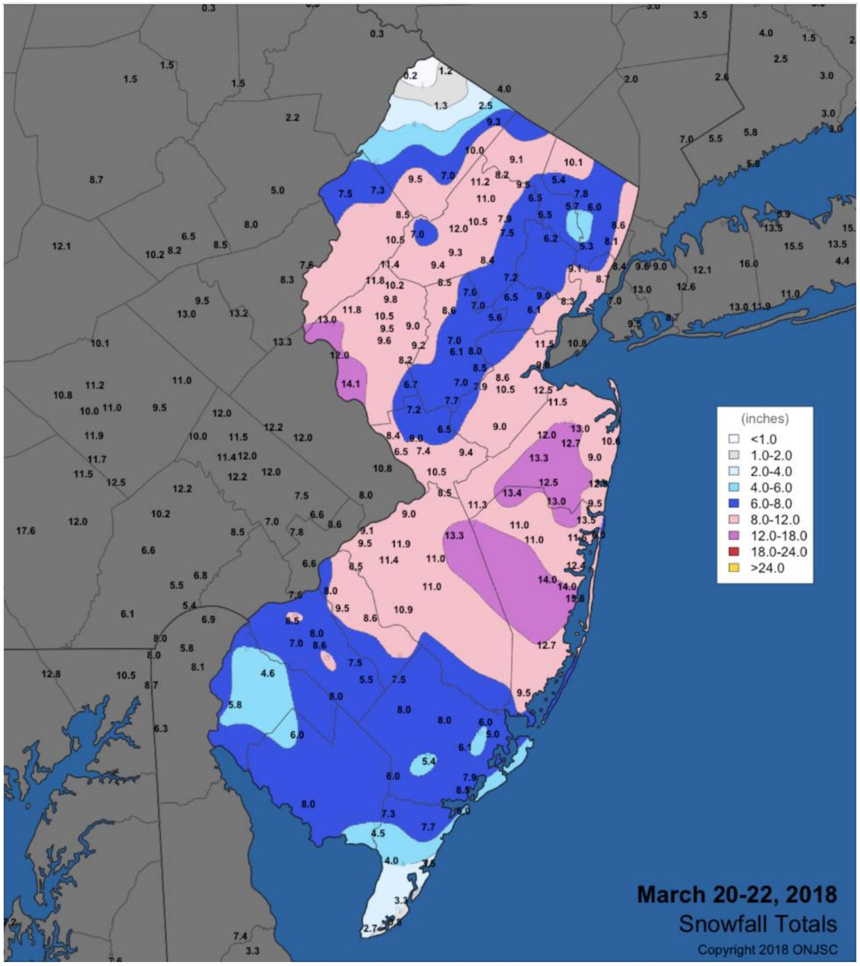


Figure 21: Snowfall reports and totals from the March 20th – 22nd, 2018 snowstorm for New Jersey (Office of New Jersey State Climatologist (ONJSC) at Rutgers University, May 2023).

e. April 1st – 2nd

i. Synoptic Setup

In comparison to the events in March, this one was not a quintessential Nor'easter but rather more of a mesoscale system. On April 1st, a strong branch of the polar jet stream at 250mb stretched from Washington State across the continent through Maine. There was a strong jet streak centered over southern Ontario with the vorticity maximum at 500mb in the right entrance region of this jet streak. Ahead of the vorticity maximum consisted an area of moisture with a surface low pressure system in central Illinois. As the day progressed, the jet streak moved eastward which resulted in an eastward flow of the vorticity maximum and system. The system moved eastward as it started to affect New Jersey overnight April 1st-2nd. Due to the nature of the system's setup, the air mass was much colder than the average for the month of April. Therefore, colder air in the lower levels resulted in the 850mb freezing line slicing through central New Jersey. The combination of the colder air mass and nighttime timing of the system allowed for snowfall in the northern half of the Garden State. This was a relatively short-lived system as it moved out to sea in the morning hours of April 2nd.

ii. Description of the System

Precipitation moved into the Garden State in the overnight hours from April 1st into April 2nd. For this storm, areas in most of the coastal plain region (south of I-95) received primarily rain, while areas in the southern piedmont and northern coastal plain received a mix of rain and snow. Areas in the northern piedmont, highlands, and mountains and valleys received all snow. This was another short-lived storm, only affecting the state for around 6-9 hours.

Newark Liberty International Airport and Somerset Airport first reported snow around 11pm April 1st until 12am April 2nd. Precipitation fell as snow throughout the event, and heavy snow was reported when a more intense band moved through northern New Jersey. Snow ended by 5-6am April 2nd. Precipitation started as light rain in Belmar and Trenton around 11pm April 1st to 12am April 2nd before changing over to snow. The heavier band stayed north of these areas which resulted in only light snow being reported. The snow transitioned over to light sleet in

Millville before ending by 5-6am on April 2nd. Atlantic City experienced light rain between 11pm April 1st to 4am April 2nd, with some light sleet lingering to sunrise on April 2nd.

The heaviest snow was concentrated in the northern portion of the state. A widespread 4-8 inches of snow was recorded in the mountains and valleys, highlands, and northern piedmont regions. 1-4 inches of snow fell in the southern piedmont and northern coastal plain. The rest of the coastal plain received a trace to 1 inch of snow. Figure 25 depicts snowfall amounts across the state for this event.

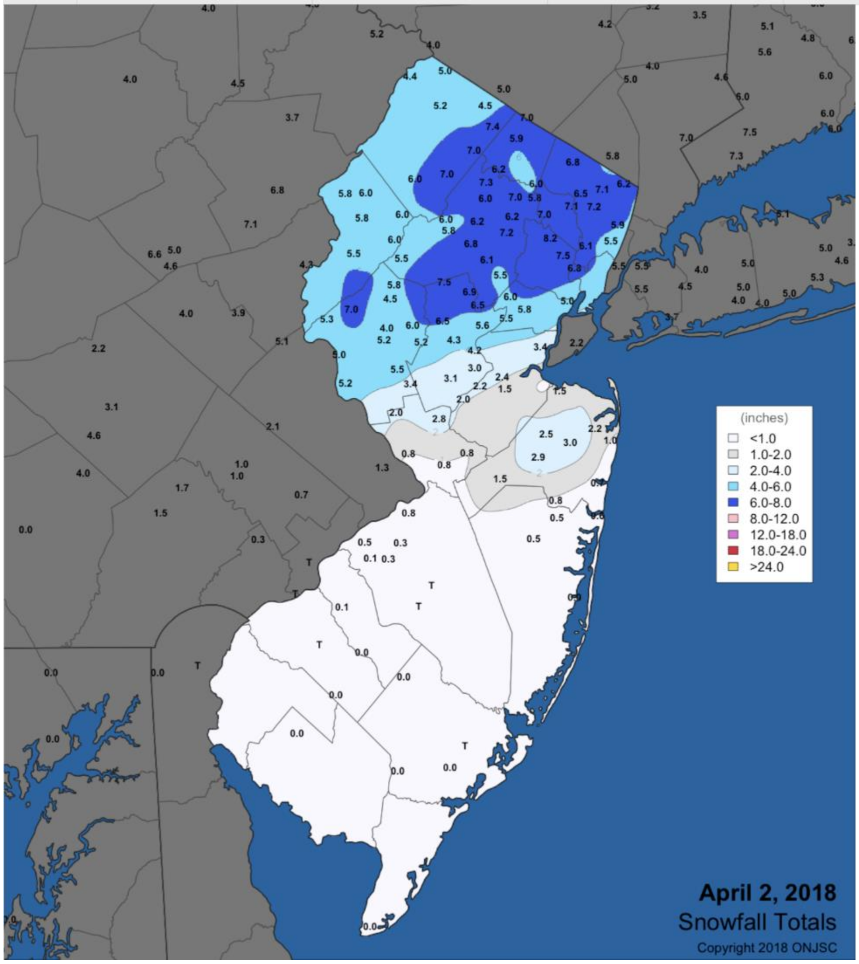


Figure 25: Snowfall reports and totals from the April 2nd, 2018 snowstorm for New Jersey (Office of New Jersey State Climatologist (ONJSC) at Rutgers University, May 2023).

11. Discussion and Summary

This case study investigated the reasons for the above average anomalous snowfall amounts in New Jersey in March of 2018. The SSW event on February 12th, 2018, resulted in a split of the SPV that resulted in the main lobe being displaced into central Canada. The position of this piece of the SPV, in addition to the NAO being in a positive phase (in February), resulted in the start of favorable blocking patterns that started to affect the Garden State. This favorable blocking pattern resulted in five snowstorms that impacted New Jersey from March to early April. The synoptic setup and impacts of each snowstorm were explored in detail. Additionally, this case study included background information dealing with New Jersey's geography and snowfall climatology, as well as various teleconnection patterns. Finally, some potential areas of future work and research are highlighted in the next section.

12. Future Work

There are a few areas related to this topic that could benefit from extended research in the future to garner better understandings of the impact from SSWs on wintertime climatology. During the study of systems in March 2018, it was difficult to find upper air graphical data (10mb) of the SPV from other SSWs before 2018. However, upper air data (10mb) has been more accessible in the past decade and will continue to be so in the future. Therefore, when SSWs occur in the future, it will be easier to get the necessary upper air data to observe, document, and analyze the specific strength, location, and makeup of the SPV during each event. Furthermore, which of these tropospheric effects will result in certain locations having anomalous winter weather would be important.

An additional area for future research is the causes of SSWs. From this research, there were a few hypotheses on what factors might trigger an SSW. For example, higher Eurasian snow cover in the fall could support SSWs in the winter months. There are many other ideas of the development of SSWs that were not included in this paper.

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