

Major Winter Weather Events during the 2012-2013 Cold Season

Michael S. Ryan¹, Amanda Fanning, Mary Beth Gerhardt, David Hamrick, Paul
J. Kocin, Kwan-Yin Kong, Jason Krekeler, Richard Otto, Frank J. Pereira,
Brendon Rubin-Oster

NOAA/NWS/Weather Prediction Center, College Park, MD

¹ *Corresponding author address:* Michael S. Ryan, NOAA/NWS/Weather Prediction Center, 5830
University Research Court, College Park, MD 20740; email: michael.s.ryan@noaa.gov

1. Introduction

Winter storms cause millions of dollars in damage and disrupt countless lives across the United States every year. They directly cause an average of 24 deaths in the U.S. each year (2003-2012 average), with an additional 27 deaths each year caused by cold temperatures (NWS 2013). Winter storms produce a variety of precipitation including snow, sleet, and freezing rain, often with high winds, extreme cold, and coastal flooding in addition to the precipitation. Some parts of the U.S. are more prepared than others, and thus the impact of winter storms varies widely by region. Winter storm activity varies widely from year to year, in connection with large-scale atmospheric phenomena such as the North Atlantic Oscillation (NAO), Arctic Oscillation (AO), and El Nino-Southern Oscillation (ENSO).

Because winter storms cover spatial scales much larger than that of an individual NWS office, WPC is well-positioned to provide guidance on these storms. One role of the WPC is to provide winter storm specific forecasts for the U.S. These include quantitative precipitation forecasts (QPF), low-tracks, and probabilistic heavy precipitation (rain, snow, freezing rain) forecasts.

The WPC issues Storm Summary products for high-impact winter weather events that affect multiple NWS county warning areas, affect commerce and transportation, and are likely to attract media attention. Storm Summaries contain information on the current location and intensity of a storm system, a summary of rain and snowfall accumulations, and a short term forecast for the storm system. The purpose of this article is to provide an overview of the 2012-2013 cold season and the most notable winter weather events for which the WPC issued Storm Summaries. For the purposes of this article, the cold season is defined as September 15 - May 15.

These dates align with the dates that the Winter Weather Desk at the NOAA/NWS Weather Prediction Center (WPC) is active.

Section two of the article describes the data used for the images in the article. Section three of the article provides an overview of the large scale patterns that affected North America during the cold season. Section four of the article discusses the individual details of the most significant winter storms of the cold season. Finally, conclusions are given in section five.

2. Datasets

NCEP/NCAR Reanalysis data (Kalnay et al. 1996) were used to create the seasonal and monthly anomaly graphics referenced in section three. Snowfall analyses shown are interpolated snow analyses from the National Operational Hydrologic Remote Sensing Center (NOHRSC). The NOHRSC analyses are created using observed snowfall data received in SHEF (Standard Hydrometeorological Exchange Format) over AWIPS (Advanced Weather Interactive Processing System) (NOHRSC 2005). The data are then interpolated temporally using preprocessed RADAR (Radio Detection and Ranging) data (Stage II) as well as spatially using a weighting function (NOHRSC 2005). Snowfall data are not interpolated above 1640 feet in elevation in the eastern U.S. and above 5741 feet in the western U.S. In northern Idaho, Washington, and Oregon snowfall data are not interpolated above 2625 feet. For further details on the data assimilation and interpolation schemes used in the NOHRSC snowfall analyses the reader is referred to NOHRSC 2005. An additional source of snowfall analyses used in this article is the Ridge II snowfall analysis from NWS Southern Region, which incorporates CoCoRaHS (Community Collaborative Rain, Hail and Snow Network) and NWS Cooperative Observer (COOP) observations (<http://www.srh.noaa.gov/ridge2/snow>). Monetary damage and casualty reports

included in this article are taken from official NWS Storm Data publication, Storm Data and Unusual Weather Phenomena (www.ncdc.noaa.gov/oa/climate/sd).

3. Seasonal Overview

The 2012-2013 cold season was a very active one for some portions of the contiguous U.S. (CONUS), while relatively non-eventful for others. The season got an early start in late October across the southern and central Appalachians as Hurricane/Post-Tropical Storm Sandy interacted with an intense upper-level trough to bring a major winter storm to areas from North Carolina to Pennsylvania. Barely a week after Hurricane Sandy, an early-season Nor'easter brought a winter storm to areas that had just been devastated by coastal flooding and surge from Sandy. From mid-November through much of December the winter storm activity shifted to the western U.S. and the northern plains/Upper Midwest. In late December the stormy pattern shifted eastward again, with several winter storms affecting areas from the South and the northern plains/Great Lakes to the Northeast through the rest of the cold season.

The seasonal mean 250 hPa winds showed a split flow pattern across the CONUS with two distinct anomalous wind maxima evident. One 250 hPa wind maximum extended from the Pacific Ocean into the northwestern states and northern U.S. Rockies, with a second Subtropical jet maximum evident from near Hawaii to Baja California and into the south central CONUS (*Fig. 1*). The 500 hPa pattern for the cold season (October-April) shows a ridge at 500 hPa over Greenland and northeastern Canada, a mean trough from central Canada into the U.S. Midwest, and another ridge over the north Pacific/Bering Sea and Alaska (*Fig. 2*). The North Atlantic Oscillation (NAO, Barnston and Livezey, 1987) was negative very early in the season (October) but then became largely neutral for the remainder of the cold season (*Fig. 3*). The Arctic Oscillation (AO, Thompson and Wallace, 1998) was relatively neutral for much of the season

before turning more sharply negative in March (*Fig. 3*). The Pacific-North American (PNA, Barnston and Livezey, 1987) index was also negative (albeit weakly) during most of the cold season (*Fig. 3*).

4. Individual Event Summaries

a. Post-Tropical Storm Sandy (28-31 October)

1) Meteorological Overview

At the end of October, 2012, one of the most memorable storms in recent U.S. history made landfall along the New Jersey coast. A negative NAO, or strong blocking pattern in the north Atlantic, set the stage for this historic event. Sandy originated as a tropical depression in the southwestern Caribbean Sea on Monday, 22 October. The storm quickly increased in size and intensity while tracking north through the Caribbean, and by 15 UTC on 24 October, Sandy had strengthened to a category one hurricane near Jamaica. Hurricane Sandy continued its northward track into the Atlantic, and then on 27 October, the storm turned briefly northeastward away from the United States. However, the strong ridge over the north Atlantic prevented Sandy from going out to sea, and instead, the storm eventually began to interact with a mid-latitude trough digging into the Ohio/Tennessee valleys and re-curved northwestward toward the U.S. East Coast. This unique interaction between a tropical and mid-latitude low-pressure system accelerated and strengthened Sandy as it approached the U.S. coast on Monday, 29 October.

The large wind field, combined with a long easterly fetch over the Atlantic, enhanced storm surge along the Eastern Seaboard from the Chesapeake Bay to Cape Cod as the storm approached the U.S. coast, and the full phase of the moon on 29 October aided in creating extreme high tides and storm surges. Similar to most tropical events, winds increased with the approaching storm, and anomalous moisture streaming inland allowed for heavy rains from

Virginia to New Jersey. The most significant rains fell over the Delmarva Peninsula, with a maximum of 12.83 inches of rain reported in Bellevue, MD. According to the final report issued by the National Hurricane Center (Blake et al., 2013), Sandy officially became the largest hurricane to develop in the Atlantic since 1988, spanning nearly 1000 miles in diameter. On the afternoon of 29 October, the storm was still offshore, but the minimum central pressure lowered to 940 hPa. Also according to the Sandy report issued by the National Hurricane Center, at 2224 UTC, a 945.5 hPa pressure was recorded at Atlantic City, NJ, which set a record for the minimum sea-level pressure ever recorded north of North Carolina in the United States. Sandy made landfall just south of Atlantic City, New Jersey at around 00 UTC Tuesday, 30 October, shortly after the National Hurricane Center declared it had transitioned from a hurricane to a post-tropical storm (*Fig. 4a*).

The storm gradually weakened after making landfall, but the combination of strong dynamic cooling from the deep-layered cyclone moving westward into the Mid-Atlantic States and cold air advection from the west-northwest lowered temperatures enough to change rain over to snow along the higher elevations of the central and southern Appalachians. An expansive area of strong low-level winds surrounded the storm, and the northwesterly flow over the Appalachians enhanced snowfall rates on the northwestern slopes of the terrain. Measurable snow was reported from the Smoky Mountains in Tennessee and North Carolina into southwestern Pennsylvania (*Fig. 4b*).

After tracking through southern New Jersey and westward across southern Pennsylvania, Sandy took a turn to the north Tuesday evening, 30 October. The storm caused gusty winds, lakeshore flooding, and some snow showers across portions of the Great Lakes as it moved north

through western Pennsylvania, and finally, Sandy crossed Lake Erie and exited the U.S. by Wednesday morning, 31 October.

2) Impacts

Sandy impacted 24 U.S. states and caused over 50 billion dollars in damage. The hardest-hit areas were along the New Jersey coastline and into Long Island, where rising ocean waters washed out protective beaches and damaged hundreds of thousands of homes and businesses. In New York City, storm surge and tropical storm strength winds closed subway stations and the New York Stock Exchange. Also, the impacts from Sandy shut down multiple airports and train stations across the Northeast, and residents of New York and northern New Jersey were faced with a major gas shortage after the storm. Heavy rains and flash flooding were the main hazard in the Chesapeake Bay area, where the storm closed several schools, business, and major highways across the northern Mid-Atlantic States. Farther inland, record-breaking early-season snow fell in the Appalachians from the Smoky Mountains to Western Maryland. The most significant totals were over the higher elevations of West Virginia as well as North Carolina, where three feet of snow were observed (*Fig. 4b*). The rain, snow, and winds from Sandy left over 8 million people without power from the Atlantic coast to the Great Lakes, and some homes in New York and New Jersey were without power for weeks after the storm. Damage from the winter storm component alone from Sandy amounted to over \$31 million. One death directly resulted from the winter storm component of Sandy, when a tree fell on a person in West Virginia due to the heavy snow and high winds.

Sandy also created a stir in the meteorological community. The unique hybrid storm left room for debate on what exactly to call the storm, which was given labels such as “Frankenstorm” and “Superstorm Sandy”. The National Weather Service referred to the storm as

“Post-Tropical Storm Sandy”. Even within the NWS, the uncertainty on the exact time Sandy would transition from tropical to post-tropical led to some confusion as to which office should be issuing statements on the storm and what types of watches and warnings should be posted across the Mid-Atlantic and New England States. Despite the debates and uncertainty, Sandy was a very well-forecast storm. NWS forecasters highlighted the event six days in advance, which provided government responders and the public time to prepare for the event.

b. Early Season Nor'easter (6-7 November)

1) Meteorological Overview

A strong early November winter storm impacted areas of the coastal Northeast U.S., which only a week earlier dealt with the destructive impacts from Hurricane Sandy and its extratropical transition. The pattern aloft during this period featured an anomalous ridge across the central Great Basin/Desert Southwest which favored negative heights over the eastern states. A split flow regime was in place with an active southern branch of the jet carrying shortwave energy from the lower Mississippi valley to the Southeastern U.S. coast on 6 November. This impulse turned northward in response to downstream ridging where the system gained a negative tilt across the coastal Carolinas between 06-12 UTC on 7 November. During the following 12 hours, this intensifying disturbance would begin interacting with a northern stream shortwave which led to further deepening of the surface low as it neared the 40°N/70°W benchmark (*Fig. 5*).

Further support for intensification existed as a 300 hPa jet streak tracked offshore of the Carolina coast placing the coastal Mid-Atlantic in the favorable left-exit region of the jet. As the low-level circulation continued gathering strength on its approach northward on the morning of 7 November, the 850 hPa moisture transport dramatically picked up strength offshore of southern

New England between 16-21 UTC on 7 November. This region was collocated within an enhanced region of 850 hPa frontogenetic forcing with observations supporting a 14°C (~25°F) gradient across the boundary. At the western fringe of this strong baroclinic zone was an area of weakly negative equivalent potential vorticity (EPV) within the 800-750 hPa layer. In the presence of a saturated lower-to-mid troposphere, the diminished EPV values resulted in considerable conditional symmetric instability (CSI) across the coastal Northeastern U.S.

During this particular timeframe, much of the moderate to heavy snowfall commenced from southern New Jersey north to eastern Massachusetts (*Fig. 6*). During this particular event, snow was the dominant precipitation type given the further offshore low track. This in conjunction with a surface ridge that set up across central Quebec allowed modified Arctic air to advect into the northeastern U.S. Additionally, the tightening pressure gradient over the region (particularly during the 18-00 UTC on 7-8 November timeframe) led to strong wind gusts along coastal New England. Local wind observations suggested gusts up to 76 mph over Buzzards Bay, MA during the height of the event, while 55-65 mph reports were commonplace elsewhere in the region.

2) Impacts

A pair of embedded heavier snowfall amounts of up to 13.5 in. of snow was located across central New Jersey and south-central Connecticut, where mesoscale banding was observed (*Fig. 6*). As this region of the U.S. had just dealt with the impacts of Hurricane Sandy only a week prior, it did not take much damage to further affect local infrastructure. The combination of heavy precipitation, near hurricane force wind gusts, and high seas in excess of 8-ft at local beaches led to over 375,000 additional power outages across New Jersey, New York, and Connecticut. By 14 UTC on 8 November, reports suggested up to 715,000 homes and

businesses over the Northeast were without power due to the combined impacts from these two storms. Further, nearly 2,000 flights were cancelled from local airports; and a number of park and coastal roads were closed. Monetary damages of \$940 thousand were reported for this event, primarily the result of high winds. No deaths or injuries were directly attributed to the winter weather aspect of this event.

c. Western U.S. Heavy Precipitation (29 November – 5 December)

1) Meteorological Overview

During the last week of November, a longwave trough south of the Aleutian Islands moved into the northeastern Pacific while a ridge began to build along the west coast of North America. The long wave trough then evolved into a large cut-off low in the northeastern Pacific and became nearly stationary. A series of low pressure systems developed to the south of this circulation and were directed eastward towards the west coast of the U.S. This general pattern lasted for more than a week before it ended. A total of five low pressure systems moved onshore during this period and delivered considerable amounts of precipitation through the western states.

System #1: Moisture from the first low pressure system rapidly approached the West Coast on 28 November (*Fig. 7a*). Precipitation reached the coast of northern California and the Pacific Northwest early in the morning and overspread these areas during the day. Energy then began to split into two pieces and penetrated rapidly inland. By late in the afternoon, rain and snow began to taper off. Overall, the bulk of the precipitation fell in northern California (*Fig. 7b*).

System #2: As soon as system #1 exited, another frontal system was rapidly moving in from the Pacific. During the morning hours on 29 November, precipitation overspread the same

general regions that were affected by system #1. But unlike system #1, precipitation lingered much longer over the northern half of California well into 30 November (*Fig. 7c*).

System #3: While system #2 was still affecting northern/central California, system #3 was beginning to approach the Pacific Northwest (*Fig. 7c, d*). The bulk of the moisture precipitated from the coastal section of Washington and Oregon eastward into the Cascades throughout the night on the 30 November, and began to spread into northern California by early on 1 December (*Fig. 7d*).

System #4: Just as system #3 began to lose its grip on the West Coast, system #4 was forming off the coast of northern California on 1 December. Much of the precipitation fell along the coast from northern California through Washington and became quite heavy by the evening (*Fig. 7e*). A stronger push of the cold air behind this system advanced a frontal system well inland. The associated precipitation moved into the Great Basin, the Intermountain West, and eventually northern and central Rockies later on 2 December (*Fig. 7f*).

System #5: Behind system #4, a cool high pressure system built across much of the West, allowing a welcome break in the recent spell of active weather on 3 December. However, some light precipitation continued to linger in the Pacific Northwest (*Fig. 7f*). Meanwhile, another low pressure system was strengthening in the Pacific, midway between the Hawaiian Islands and the West Coast. A distinct plume of high moisture from the subtropics, known as an “atmospheric river,” spread rapidly east-northeastward from the Hawaiian Islands into northern California by late in the afternoon on the 3 December (*Fig. 7g*). By the evening hours, widespread heavy precipitation inundated western Oregon and Washington. The intensity of the precipitation began to lessen somewhat during the day on 4 December. However, a reinforcing surge of energy from the Pacific sustained the heavy precipitation in northern California throughout the night on the 4

December (*Fig. 7h*) before this lengthy event finally tapered off during the day on 5 December (*Fig. 7i*).

2) Impacts

The long duration of the entire event from multiple systems resulted in copious amount of precipitation across a wide area of the West. This included reports of snowfall totals greater than 40 inches at a couple of mountainous locations in northern California and Idaho (*Fig. 8*). There were also unconfirmed reports of more than 5 feet of snow in the high Sierra. Some of the lower elevations in northern California received over 20 inches of rain resulting in sudden rise of water in rivers and streams. Over 15 inches of rain fell in parts of Oregon and Washington as well. In addition to heavy precipitation, hurricane force wind gusts up to 150 mph were recorded in the mountainous terrain of California, Montana, Nevada, Oregon, and Utah. Monetary damages of \$402 thousand were reported for this event, primarily the result of high winds. No deaths or injuries were directly attributed to the winter weather aspect of this event.

d. Northern Plains and Upper Midwest Snowstorm (9-10 December)

1) Meteorological Overview

An ideal weather pattern became established over much of South Dakota, Minnesota, and Wisconsin for a significant winter storm. A vigorous 500 hPa shortwave moved from the northern plains into the Upper Midwest on the morning of 9 December, along with significant positive vorticity advection and deep layer ascent. At the surface, a 1035 hPa Arctic high from Canada moved over the Dakotas by the afternoon of 9 December (*Fig. 9*), which provided the cold air necessary for heavy snowfall. To the southeast of this ridge, a surface low began to develop in western South Dakota during the evening of 8 December. The surface low moved northeastward into extreme southern Minnesota with a pressure of 1008 hPa by 18 UTC on 9

December. Most of the snow fell north and east of the surface low before the low reached Minnesota. By 18 UTC on 10 December, the low had moved to southern Quebec and strengthened to 997mb.

2) Impacts

Heavy snow fell over much of South Dakota and the Upper Midwest on 9-10 December, 2012 (*Fig. 10*). The greatest snow amount occurred in the town of Sacred Heart, Minnesota, where 17.3 inches of snow fell. A swath of greater than 10 inches occurred in eastern South Dakota, southern Minnesota, and western Wisconsin, including Minneapolis with 10.5 inches and East Farmington, WI, with 14.0 inches. In addition to the heavy snow that fell with this system, there were also numerous reports of high wind gusts, including 53 mph at Kimball, Nebraska, 52 mph at Ellsworth Air Force Base, South Dakota, and 50 mph at Huron, South Dakota. The heavy snowfall affected transportation throughout the Upper Midwest. There were about 150 flight cancellations at the Minneapolis-St. Paul International Airport. Also in Minnesota, there were about 600 automobile accidents throughout the state during the event, according to the Minnesota State Patrol. In South Dakota, blizzard conditions resulted in the closure of sections of Interstates 29 and 90. Monetary damages reported for this event were minor, amounting to less than \$1 thousand. No deaths or injuries were directly attributed to the winter weather aspect of this event.

e. Pacific Northwest Winter Storm (17 December)

1) Meteorological Overview

The most intense storm of the early 2012-2013 winter season moved ashore as an area of deep low pressure in western Washington early on 17 December. This system was associated with a rapidly moving shortwave trough that moved eastward across the eastern Pacific and was

associated with a 972 hPa surface low that came ashore around 09 UTC on 17 December before heading eastward and weakening over the complex terrain of Washington (*Fig. 11b*).

The main effects of the storm were heavy rain, high winds and high elevation snow. As the storm moved inland, numerous advisories and warnings were issued for much of the western United States, including winter storm and blizzard warnings, storm warnings along the west coast as well as high wind warnings across the Portland, Oregon metropolitan area.

2) Impacts

Some of the high wind reports included 101 mph at Mary's Peak, OR, and 94 mph at Crystal Mountain, WA, at high elevations. Winds also exceeded hurricane force in places along the Oregon and Washington coast, including 84 mph at Cape Disappointment, WA, 81 mph in Lincoln City, OR, 76 mph in Newport, OR and 69 mph in Seattle, WA. Some snowfall totals (*Fig. 11a*) exceeded a foot across northern California and Idaho, 20 inches at Santiam Pass, OR and over 18 inches near Leavenworth, WA, with as much as 2 to 3 feet in the Cascades.

This storm was responsible for generating high waves along the Washington and Oregon coasts, where winds gusted in some areas above hurricane force. Power outages were common across western Washington and Oregon, in and around Seattle and Portland. Travel across the Cascades was dangerous to nearly impossible during the storm. Monetary damages of \$1.1 million were reported for this event, primarily the result of high winds. No deaths or injuries were directly attributed to the winter weather aspect of this event.

f. Plains to Northeast Christmas Storm (25-28 December)

1) Meteorological Overview

A vigorous upper-level shortwave crossed the southern U.S. Rockies on Christmas Eve, and exited into the southern plains on Christmas Day. The shortwave interacted with a

preexisting Arctic frontal zone draped in the lee of the Rockies, across central Texas, and into the lower Mississippi River valley. As this interaction occurred, a surface low developed along the Arctic frontal zone across southeastern Texas on Christmas morning. Snow and freezing rain began to fall north of the developing surface low across Oklahoma early on Christmas morning as Arctic air advected into the region on sustained northerly winds of 20 to 30 kt. Snow began falling as far south as the Dallas metropolitan area Christmas evening as the surface low moved into northern Louisiana. The storm system continued to intensify, and by 00 UTC on 26 December, the low pressure area became closed off below 500 hPa. The surface low tracked northeastward to the Tennessee River valley by 12 UTC on 26 December (*Fig. 12a*), as it deepened to a pressure of 994 hPa and the cyclone began to occlude. During the 12 hours ending at 12 UTC, snow and freezing rain had spread into much of the Ohio River valley. Sustained winds of 30 knots or higher caused blowing snow, with blizzard conditions reported in many areas of the middle Mississippi and Ohio River valleys.

By the afternoon of 26 December, the surface low was centered over Kentucky. The frontal wave had fully occluded and the surface low began to weaken. At the same time, a new surface low developed and intensified over the coastal plain of North Carolina as the upper-level low interacted with a coastal frontal zone, with snow and freezing rain spreading into the northeastern U.S. Through the evening of 26 December and into the morning of 27 December, this surface low tracked northeastward along the Mid-Atlantic coastline (*Fig. 13*) as it continued to deepen. By 12 UTC on 27 December (*Fig. 12b*) the central pressure of the surface low had deepened to 987 hPa, centered just south of eastern Long Island. The surface low continued to move along the New England coastline through the day, reaching the Gulf of Maine by 00 UTC

on 28 December. A swath of moderate to heavy snow accompanied the system across most of New England, with rain along the southern New England coast.

2) Impacts

The storm produced a large swath of 6 to 12 inches of snow from Texas to Maine (*Fig. 13*). Widespread 10 to 18 inch snowfall amounts occurred across northern Pennsylvania, Upstate New York, and northern New England. The highest reported snowfall total from the storm of 27 inches was reported in Woodford, VT. Freezing rain accumulations of up to 0.50 inch occurred over areas of Pennsylvania and West Virginia. Wind gusts in excess of 60 mph occurred across much of the coastal Mid-Atlantic region, with a hurricane force wind gust of 74 mph measured near Milton, MA. The high winds were associated with the intense pressure gradient between the deepening Mid-Atlantic/Northeast coastal low and an expansive area of high pressure across Ontario into the western Great Lakes.

The storm left hundreds of thousands of residents without power for several days in the swath of heavy snow. Some of the worst power outages occurred in Arkansas where over 100 thousand residents were without power for days due to heavy snow and freezing rain.

Additionally, thousands of flights were delayed or cancelled due to the extreme winter weather conditions. Monetary damages of nearly \$120 million were reported for this event, from a combination of heavy snow, high winds, and coastal flooding. Four fatalities were directly attributed to the event, including three resulting from exposure/hypothermia and one as a result of a fallen tree in strong wind.

g. Lower Mississippi River Valley to Northeast Winter Storm (16-18 January)

1) Meteorological Overview

From 16-18 January, 2013, as a deep upper-level low moved across the southern U.S., snow spread from Louisiana to southern Virginia (*Fig. 14a*). Long Island and southeastern New England also received some light snow as the system moved offshore (*Fig. 14b*). This occurred as moisture and a series of shortwave troughs propagated northeastward along the leading edge of a large scale trough that extended from the northern plains into the Southwest.

On the evening of 15 January, a cutoff upper low developed in the base of the trough as it moved east from the Southwest across the southern Rockies into the adjacent high plains. By the morning of 16 January, a deep closed low developed and moved over central Texas, rotating into the eastern parts of the state by that evening (*Fig. 15*). Snow fell across portions of the lower Mississippi into the Tennessee valleys as moisture was lifted from the Gulf of Mexico. The trough began to assume a slight negative tilt as it swung progressively from the lower Mississippi valley to the southern Appalachians on 17 January. A frontal boundary that represented the leading edge of the Arctic air mass that had moved into place earlier in the week, lingered across the Carolinas into the central Gulf of Mexico. A surface low positioned along the boundary began to strengthen over northern Georgia before tracking east-northeastward into the Carolinas. In addition to strong upper divergence afforded by favorable upper jet dynamics, strong low-level frontogenesis coinciding with an area of negative geostrophic equivalent potential vorticity (EPVg) was noted across western North Carolina into far southern West Virginia (*Fig. 16*). Interacting with moisture that continued to stream north from the Gulf of Mexico, these ingredients are thought to have contributed to the heaviest snow accumulations that occurred during this event. This precipitation was relatively short-lived however, with the back edge of the precipitation shield progressing steadily across North Carolina and southern Virginia, then moving off of the middle Atlantic coast during the early morning of hours of 18

January behind the departing low. As the system moved offshore, the northern edge of the precipitation shield brushed Long Island and southern New England during the overnight hours.

2) Impacts

Up to 4 inches of snow fell across portions of central and northern Mississippi and northern Alabama, an area unaccustomed to frequent snows, and resulted in several new daily snowfall records. Snow accumulations of up to 6 inches were reported over far eastern Kentucky and Tennessee. The heaviest amounts of the event fell across far northwestern North Carolina, southwestern Virginia and far southern West Virginia, where accumulations of 12 to 15 inches were reported, breaking numerous daily snowfall records, and resulting in numerous power outages across the region. Monetary damages of \$2 million were reported for this event, from a combination of heavy snow, ice, and strong winds. No deaths or injuries were directly attributed to the winter weather aspect of this event.

h. Great Lakes to Northeast Winter Storm (7-9 February)

1) Meteorological Overview

A major winter storm affected the Great Lakes with up to a foot of snow and the Northeast with 1-3 feet of snow on 7-9 February (*Fig. 17a*). The storm underwent “bomb” cyclogenesis, deepening 24 hPa in 24 hours from 994 hPa at 12 UTC on 8 February to 970 hPa at 12 UTC 9 February (*Fig. 17b*). The main culprit for the rapid intensification was the phasing of the northern and southern stream jets and merging of their respective mid-level energy. The state of the atmosphere on the days leading up to the intense cyclogenesis was characterized by zonal flow, but an anomalous ridge in place in the North Atlantic and an upstream digging trough over California led to a rapid amplification of the flow pattern across the U.S. from 6-9 February (*Fig. 18*).

Southern stream energy over the Mexican Plateau moved into the Gulf of Mexico by 06 UTC on 7 February, leading to the development of a surface cyclone off the Texas coast. The northern stream energy originated in the Gulf of Alaska and crossed the northern Rockies before a surface cyclone developed in Montana by 12 UTC on 7 February. A trough digging into the southwest U.S. led to upstream amplification, including the simultaneous amplification of both the southern and northern stream troughs moving into the eastern U.S. With downstream blocking in place, the troughs were forced to phase along the Eastern Seaboard. The merging of the two systems took place from roughly 00 to 06 UTC on 9 February and coincided with the period of most intense snowfall rates and rapid deepening of the surface low in the Atlantic. The confluence of the southern and northern stream 250 hPa jets began around 00 UTC on 9 February. By this time, the amplification of the flow pattern had turned the surface low northeastward up the Mid-Atlantic coast to a position south of Cape Cod. The merging of the mid-level vorticity maxima occurred between 00-06 UTC on 9 February with the strengthening southern stream storm absorbing the northern stream energy. Another factor that led to the rapid intensification at this time was strong upper-level divergence due to the coupled entrance/exit regions of the jet streaks immediately upstream and downstream of the consolidating vorticity center.

Strong surface frontogenesis created a low-level lifting mechanism for heavy snowfall to develop. Anomalous high pressure in place across eastern Canada allowed the sub-freezing surface temperatures to stay in place as the storm advected the warmer marine layer toward the New England coast, allowing a strong front to set up in a north-south orientation along the coast. At 850 hPa, a very strong easterly jet developed in response to the strong baroclinicity at the surface. Easterly 850 hPa winds of 70 kt observed at Chatham, MA indicated a strong low-level

jet supplying Atlantic moisture westward into the cold sector of the storm. A strong mesoscale banding feature set up across central Long Island and central Connecticut just west of the strong surface frontal zone and at the nose of the 850 hPa jet. Snowfall rates of 3-4 inches per hour were observed in this band, with one report of 6 inches in one hour in central Connecticut.

2) Impacts

Major impacts were felt across the Northeast where 1-3 feet of snow fell (*Fig. 17a*). Portland, Maine had a record snowfall with 31.9 in., and Boston received its fifth highest total with 24.9 in. Hartford received its second highest total with 22.8 in. Hamden, CT received 40 in. of snow, which was the highest reported total of the storm. Hurricane-force winds along the coast caused coastal flooding in Massachusetts; and Boston received its fourth highest storm surge of 4.2 feet. Over 600,000 people lost power during the storm and over 6,000 flights were cancelled. Monetary damages of \$54 million were reported for this event, resulting primarily from a combination of heavy snow/blizzard and coastal flooding. Seven fatalities were directly attributed to the blizzard conditions that occurred during this event, making this the deadliest winter storm of the season.

i. Northern Plains and Upper Midwest Winter Storm (10-11 February)

1) Meteorological Overview

A powerful winter storm moved through the north central U.S., bringing heavy snow, gusty winds, and icing to portions of the northern plains and Upper Midwest. A mid-level trough triggered the event as it lifted out of the Southwest and initiated surface cyclogenesis in the lee of the Colorado Rockies beginning 00 UTC on 10 February (*Fig. 19*). The surface low deepened as it tracked steadily northeastward through the central plains on 10 February, beneath the favorable left exit region of an upper jet streak extending from the southern Rockies into Kansas (*Fig. 20*).

Cold (warm) advection west (east) of the surface low sharpened the 500 hPa trough and allowed the surface low to continue to deepen while it moved into the Upper Midwest Sunday evening.

While the storm continued with its development cycle, surface winds increased as the pressure gradient surrounding the low increased, and moisture from the Gulf of Mexico feeding northward into the storm allowed for heavy rain and snow within the expansive precipitation shield. The warm Gulf air overrunning a sub-freezing air mass in place led to pockets of freezing rain and sleet across southern Minnesota and eastward into portions of the Upper Great Lakes. As the sharpening 500 hPa trough became closed off over Nebraska, a band of intense snow developed within a deformation zone over the eastern Dakotas and Minnesota. The mid-level trough quickly became negatively tilted, and the surface low migrated into the cold air as the system became vertically stacked. By 12 UTC on 11 February, the storm started to track across southern Ontario, and the deep area of low pressure began to fill and weaken.

2) Impacts

This storm left a wide swath of greater than 4 inch snowfall accumulations stretching from north-central Nebraska to northern Wisconsin and the Minnesota arrowhead (Fig. 3). Several reports exceeding a foot of snow were recorded in the narrow deformation axis that set up over the eastern Dakotas and Minnesota (Fig. 21). Strong sustained winds, with gusts in excess of 50 mph, surrounded the deep surface cyclone. The high winds, combined with the heavy snow, created dangerous whiteout conditions. Periods of freezing rain and sleet also made for hazardous travel conditions over southern Minnesota eastward into the Upper Great Lakes. Numerous roads and highways were forced to shut down across the region, including portions of Interstate 90 and 29 in North and South Dakota. Monetary damages of \$53 thousand were reported for this event from a combination of the winter weather and high wind. One fatality was

directly attributed to the event, the result of exposure after a motorist left a vehicle after becoming stranded in blizzard conditions.

j. Central U.S. Winter Storm (20-22 February)

1) Meteorological Overview

A multi-day winter storm brought wintry precipitation across a large portion of the Great Plains through the Middle and Upper Mississippi valley and into the Great Lakes region. Early in the period (12 UTC on 20 February), the synoptic pattern featured a highly amplified 500-hPa flow with a ridge centered over the middle of the U.S., a closed low anchored the lower Great Lakes, and a strong shortwave located over southern California (*Fig. 22a*). The progressive nature of the mid-latitude flow allowed the California shortwave to reach the Texas/Oklahoma panhandle within 24 hours while becoming negatively-tilted (*Fig. 22b*). At this point, radar imagery indicated an expansion in the moderate to heavy precipitation as the 300 hPa flow became increasingly diffluent over the central plains.

During this synoptic-scale deepening process, low-to-mid level frontogenetic forcing increased significantly, and was vertically collocated with an axis of slightly negative equivalent potential vorticity (EPV) values. RADAR and surface observations suggested a large axis of banded precipitation with temperatures well below freezing, thus supporting snow as the dominant hydrometeor type. As the broad shield of precipitation moved toward Missouri and Arkansas, the storm transitioned into a mixed precipitation event. A large flux of above freezing air between 900-650 hPa overrode a subfreezing boundary layer, resulting in widespread freezing rain and sleet reports. Sufficient mid/upper-level instability resulting from steep vertical lapse rates caused some of the precipitation to become convective in nature. Within this

convective precipitation, widespread ice accumulations of 0.25 to 0.50 inches were reported, with isolated higher amounts (*Fig. 23a*).

Ahead of the intensifying shortwave, low-level moisture continued to overrun a surface warm front near the Gulf Coast (*Fig. 24*), with mixed precipitation reported over much of the Ohio valley. Farther north, across the middle Mississippi valley and Upper Great Lakes, vertical temperature profiles were completely below freezing, thus maintaining snow throughout the event. While 6 to 12 inches of snow was common over this region, a heavier band associated with the deformation zone/comma-head set up across central Kansas. As the parent upper-level low rapidly strengthened and became more negatively-tilted over Oklahoma and Kansas during the afternoon of 21 February, mesoscale banding resulted in snowfall rates nearing 3 inches per hour. There were also numerous reports of thundersnow. This heavier snow band occurred just north and west of the surface low (*Fig. 24*) in association with the strongest mesoscale ascent. Local snowfall measurements indicated a broad region of one foot across central Kansas, with a maximum ranging from 19 to 22 inches just north and south of interstate 70 between Hays and Russell, KS (*Fig. 23b*). Some locations reported near record amounts with Mid-Continent Airport in Wichita, KS measuring 14.2 inches of snow, which ranked second highest from an individual storm.

2) Impacts

Widespread snow and ice impacted a significant portion of the central U.S. and caused numerous societal impacts. Reduced visibility within heavier snow bands caused sections of Interstate 70 to be closed in Kansas and Missouri on 21 February. Many other roads were littered with stalled/abandoned vehicles as the intense snowfall rates led to very hazardous driving conditions. Additional impacts included the closure of Kansas City International Airport and

states of emergency issued for Kansas and Missouri. Monetary damages of \$1.7 million were reported for this event, largely the result of the freezing rain/ice storm component of the storm. No deaths or injuries were directly attributed to the winter weather aspect of the event.

k. Plains to Northeast Winter Storm (25-28 February)

1) Meteorological Overview

During the period of 25-28 February, snow and blizzard conditions occurred in the plains and the Northeast while the Gulf Coast experienced heavy rainfall. In the week prior to this event, much of the plains and the middle Mississippi valley had already received impressive snowfall amounts. This low-pressure system brought additional paralyzing snow to the middle Mississippi valley and white-out blizzard conditions to the Texas Panhandle.

On the morning of 25 February, a closed and deeply layered 500-hPa low was located over the Texas Panhandle and moved toward the middle and lower Mississippi valley. The mid-level low followed a southern track and intensified as it moved over the southern plains. As the surface low tracked to the south and southeast of Amarillo, it brought blizzard conditions, including heavy snow and strong winds. The National Weather Service Weather Forecast Office in Amarillo, TX reported 19 inches of snow on site with nearly 6 foot drifts; in addition, 75 mph wind gusts and 50 feet visibilities were reported.

Once the 500 hPa low turned northeast toward the middle Mississippi valley, it gradually began to weaken. Despite the weakening, a vorticity maximum assisted in producing up to 10 inches of snow. Thus, two snowfall maxima occurred northwest of the surface low in the Texas Panhandle and Western Missouri (*Fig. 25*). In addition, a surface low also developed along the Mid-Atlantic coast; this set up a freezing rain event along the Appalachians from Pennsylvania to North Carolina. On 27 February, the 500 hPa low continued to weaken and the primary surface

low moved north from Virginia to northern Maine. Nonetheless, some snow fell in the interior of the Northeast (*Fig. 26*).

2) Impacts

With such a historic event for the Texas and Oklahoma Panhandle, the public felt the effects of such a significant system. This was the third largest snowfall event in Amarillo. Interestingly, NWS Amarillo did not set a record for a calendar date. Although they received 19 inches of snow on that day, the record was 19.3 inches on 25 March, 1934. Thousands of people lost power in both Texas and Oklahoma, hundreds of motorists were stranded on interstates, and flights were cancelled at both Dallas-Fort Worth International Airport and Oklahoma City Airport. By the time this system moved out of the Midwest and headed for the Northeast, over 1,000 flights were grounded at the Chicago O'Hare International Airport. Monetary damages of \$15.5 million were reported for this event, primarily the result of the blizzard conditions. Two fatalities were directly attributed to the event, one the result of exposure to cold/wind chill and the other the result of a tree falling on a vehicle in strong gradient winds behind the system.

1. Upper Midwest to Mid-Atlantic Winter Storm (5-8 March)

1) Meteorological Overview

A winter storm developed over the Upper Midwest on the morning of 5 March that eventually traveled to the East Coast by the 7 March. The storm originated from an eastern Pacific shortwave that moved across British Columbia and then tracked into the northern plains. Around the same time as the surface low was producing wintry precipitation over the Upper Midwest, lee cyclogenesis led to the development of a southern stream low that tracked from the central plains and eventually merged with the northern stream disturbance. As a result, a strong

coastal low developed near the Virginia coast, and tracked slowly out to sea (*Fig. 27*). However, the northern edge of the storm affected eastern parts of New England.

This storm proved difficult to forecast along the East Coast for a few reasons. Along the Interstate 95 corridor, boundary layer temperatures proved to be the greatest factor in the amount of snow that fell. Model forecasts depicted 850 hPa and 925 hPa temperatures cold enough for snow in these areas, but they had difficulty resolving the warmer marine layer temperatures below 925 hPa from the Atlantic Ocean. Similar precipitation type forecasting concerns arose in coastal areas of New England as milder air from the Atlantic overspread the limited amount of cold air already in place. Another forecast problem for the Northeast U.S. was the strength of the downstream ridging and the ultimate track of the surface low. Most model guidance forecasted a more eastward track, farther away from New England owing to a stronger-than-expected ridge. These forecasts did not verify, as the ridge was weaker and allowed the storm to track farther west.

2) Impacts

This winter storm had a significant impact on much of the Midwest, Ohio valley, Mid-Atlantic, and eastern New England. There were numerous reports of at least 12 inches of snow in northwestern Virginia, with some in excess of 20 inches. Another area of very heavy snow occurred over eastern Massachusetts, where amounts on the order of 2 feet were observed (*Fig. 28*). Most of this snow was heavy and wet with low snow-to-liquid ratios. The weight of this snow was enough to damage trees and power lines, resulting in numerous power outages. Along the coast of Maine and Massachusetts, beach erosion from the strong onshore winds and high waves damaged or destroyed many waterfront houses. Total monetary damages of \$3.58 million were reported for this event, the result of a combination of heavy snow/blizzard conditions and

coastal flooding. One fatality, the result of exposure to cold/wind chill in Wisconsin, was directly attributed to the event.

m. New England Winter Storm (18-20 March)

1) Meteorological Overview

A split flow upper-level pattern was in place across the CONUS in mid-March 2013. On 18 March, a vigorous upper-level trough in the Polar jet and the associated occluded surface low pressure system were moving across the Great Lakes. Meanwhile, a coastal “Miller-B” low-pressure system developed along the Mid-Atlantic coastline late on 18 March as a shortwave in the Subtropical jet interacted with a coastal baroclinic zone associated with cold air damming east of the Appalachians (Miller 1946). At 12 UTC on 19 March the strengthening coastal surface low was centered just south of Long Island, NY with a central pressure of 1004 hPa. By this time, snow was already falling across much of southern and central New England. The most intense snow fell during the day on 19 March as the surface low moved northward and continued to deepen as the Polar and Subtropical systems partially phased. By 00 UTC on 20 March, the low had moved northward to near Provincetown, MA with a central pressure of 998 hPa. During the initial development of the surface low, deepening may have been inhibited by unfavorable upper-level jet dynamics. Through late in the day on 19 March, the surface cyclone remained in the right exit region of the 300-hPa jet. However, by the early morning hours of 20 March, the surface cyclone was positioned in the divergent left exit region of the upper-level jet. The surface low deepened 11 hPa in the 24 hours prior to 00 UTC on 20 March; and deepened an additional 13 hPa (to a central pressure of 986 hPa) in the following 12 hours, by 12 UTC on 20 March. The rapid deepening was presumably aided by the enhanced upper-level divergence.

The heaviest snow fell within a band of strong 850 hPa frontogenetic forcing (*Fig. 29*). This frontogenetic band slowly shifted north across New England from the early morning hours of 20 March through much of the day as moderate to heavy snow fell. The frontogenetic band persisted across Maine into the day on 20 March, much longer than across southern New England, as the cyclone strengthened offshore and a well-defined “comma-head” feature developed.

2) Impacts

Snowfall totals of greater than 4 inches were numerous across New England with the event (*Fig. 30*). The heaviest snow fell across an area including portions of northern Vermont, New Hampshire, and Maine where snowfall amounts averaged to 10 to 18 inches. Additionally, freezing rain accumulations of up to 0.30” occurred over portions of northeastern Pennsylvania. The most significant impacts of the storm remained north of Boston, which only received 1 to 3 inches of snow. Nonetheless, Boston public schools were closed during the event. Numerous flights were cancelled at airports across the northeastern U.S. Total monetary damages of \$364 thousand were reported for this event, primarily the result of heavy snow, high winds, and coastal flooding. No fatalities or injuries were directly attributed to the winter weather component of this event.

n. Central and Eastern U.S. Winter Storm (23-26 March)

1) Meteorological Overview

This late-March snow event occurred during a period of an anomalously low negative North Atlantic Oscillation index when a large upper-level low remained anchored in southeastern Canada. On 22 March, a shortwave embedded within a broad trough in western Canada began to amplify and move southward into the western U.S. The best lifting mechanism began to set up

over the central Rockies where a surface low pressure center formed in the foothills of central Colorado. On 23 March, snow developed quickly during the evening in northeastern Colorado and expanded in coverage across Nebraska and Kansas. Meanwhile, low-level cold air continued to advect southward into Colorado. Replenishing shortwave energy associated with the broad upper-level trough acted to sustain the heavy snow in Colorado throughout much of the day on 23 March. Snow finally tapered off in the evening of 23 March after producing accumulations of 10 to 20 inches in northeastern Colorado. Late on 24 March, the last piece of shortwave energy began to move around the base of the upper-level trough and exited the central Rockies. In response, the surface low and associated precipitation accelerated eastward across the central plains.

Early on 24 March, upper-level divergence ahead of the system began to induce the formation of a secondary surface low pressure center near the border of Missouri and Arkansas. An area of light to moderate snow developed and remained anchored to the northwest of the low center. Meanwhile, the primary low pressure center over the central Gulf coast moved eastward along the warm front. Widespread showers and thunderstorms developed as southerly flow advected moisture from the Gulf of Mexico and instability increased in the vicinity of the warm front. As a result, widespread heavy rain and thunderstorms swept across the Southeast on the morning of 24 March. The moisture also spread northward over the cold air in Virginia where a period of moderate snow fell in the afternoon over the central Appalachians. By the evening hours, snow was exiting Virginia while mixed snow and sleet overspread the Mid-Atlantic States. As the wide swath of precipitation swept across the Eastern Seaboard, the secondary low in the middle Mississippi valley intensified rapidly and became the primary low pressure center later on 24 March. The area of moderate to heavy snow on the northwestern quadrant of the low

expanded across the Midwest and into the Ohio valley. The heaviest snow fell near a surface inverted trough located to the northwest of the low center (i.e. under the “trowal”). Thundersnow was also observed during the height of the storm. The high snowfall rates broke 24-hour snowfall records in central Illinois.

The intensification of this low was rather unusual, as it occurred within the polar air mass without a preexisting surface frontal zone. It appeared that cyclogenesis commenced as an upper-level front associated with the energized shortwave trough began to build down to the surface. Surface analyses show that frontogenesis was most apparent to the south of the intensifying surface low as the upper-low approached from the west.

The anomalous intensification of the secondary low was relatively short-lived as the surface low center suddenly tracked northward into Ohio whereas the upper low center continued to track eastward towards the Mid-Atlantic States during the night of 24 March (*Fig. 33*). The sudden change of vertical tilt of the storm led to its rapid dissipation during the morning of 25 March. Meanwhile, the upper-level low continued to move eastward into the Mid-Atlantic region and began to tap into Atlantic moisture. The antecedent primary surface low in the Southeast began to intensify off the coast of North Carolina during the night of 24 March and early on 25 March as the Ohio valley low weakened (*Fig. 31a*). As this transfer of energy occurred, wet snow started to develop in the Mid-Atlantic region before sunrise on 24 March with temperatures hovering at or slightly above freezing under northwesterly winds. The snow then spread farther north into New Jersey and Long Island during the day (*Fig. 31b*) and into the evening hours before tapering off during the overnight hours as the storm deepened just off the Mid-Atlantic coast (*Fig. 33*).

2) Impacts

The storm brought widespread significant snowfall across the country from the Rockies to the East Coast with three distinct snowfall maxima (*Figs. 32 and 33*). In northeastern Colorado, near-blizzard conditions prompted highway closures during the height of the storm. To the north of Denver, a crash on Interstate 25 resulted in a pile-up with as many as 50 vehicles involved. One positive aspect with the snow was that it brought much-needed precipitation to a drought-stricken Colorado. Snow accumulations of more than 20 inches were observed in the Foothills; up to about 18 inches were measured in the High Plains of northeastern Colorado. In central Illinois, 18.5 inches of snow fell in Springfield, establishing a new 24-hour snowfall record for the city. Schools were closed for the first time in two years due to snow. Over extreme western Maryland and nearby West Virginia, a total of 16 inches was observed on the western slopes of the central Appalachians. Lastly, Washington D.C. received its first one inch snowfall on 25 March in the entire winter with 1.4 inches measured at Reagan National Airport. This ended a recording-breaking streak of 788 days without an inch of snow on the ground at the airport. Total monetary damages of \$1.46 million were reported for this event, primarily the result of high wind. No fatalities or injuries were directly attributed to the winter weather component of the event.

o. Northern and Central Plains Winter Storm (8-12 April)

1) Meteorological Overview

A major spring snowstorm affected the northern and central plains April 8-12. A strong cold front diving out of Canada created a strong thermal gradient in vicinity of the High Plains. Temperatures ahead of the front reached the 60's and low 70's Fahrenheit across portions of Colorado before falling into the 20's within a few hours. The strong thermal gradient combined

with coupled upper level jets and a deep mid-level trough provided the forcing for heavy snowfall across a large region.

On 8 April at 1200 UTC, a trough at 250 hPa was digging into the western U.S. The jet maximum quickly rounded the base of the trough and by 00 UTC on 9 April the downstream jet began to intensify. The High Plains was situated in the left exit region of the jet maximum exiting the trough, and the downstream jet's right entrance region. The heaviest snowfall occurred from approximately 00 UTC on 9 April through 00 UTC on 10 April. This time period coincides with the best upper-level dynamics due to the coupled jets (*Fig. 34a*). Heavy snow continued to fall across portions of the Upper Midwest as the coupled jet region pushed northeastward. A shortwave trough at 500 hPa digging into the southwestern U.S. on 8 April deepened to a 548 dm closed low over the southwest by 1200 UTC on 9 April. Strong diffluent flow was evident at this time over the High Plains downstream of the closed low, likely aiding in initiating strong vertical ascent over the region. The closed low slowly progressed northeastward, tracking across the High Plains. A cold winter-like air mass moving southward out of Canada collided with a warm and moist air mass from the southern plains. This resulted in a very strong baroclinic zone over the central High Plains by 12 UTC on 9 April (*Fig. 34b*). Heavy precipitation fell in the cold sector from northern Colorado to South Dakota where a strong north northeasterly low-level jet of up to 40 knots was set up. As the 850 hPa low progressed into the Upper Midwest, the strong baroclinic zone was oriented north/south from the low in Iowa and then east/west extending into the Great Lakes. Heavy precipitation was observed along both baroclinic zones. By 12 UTC on 10 April, the system became vertically stacked, and ceased deepening. The mid-level trough took on a negative tilt and began to fill by 12 UTC on 11 April. Heavy snow was still falling across the Upper Midwest along the TROWAL (Trough of warm

air aloft) feature that was evident by 12 UTC on 11 April. Without the aid of upslope flow, snowfall totals only reached around a foot across the upper Midwest.

2) Impacts

More than a foot of snow fell across seven states with a maximum of 30 inches in South Dakota (*Fig. 35*). Favorable conditions for heavy precipitation at each level of the atmosphere were collocated in the same region and combined with upslope enhancement to produce impressive snowfall totals. Major metropolitan areas affected included Denver and Minneapolis, where 4 to 8 inches of snow fell. High winds, with gusts over 60 mph, were observed behind the cold front as it cross the central U.S. A strong pressure gradient associated with the strong winds was evident at 12 UTC on 9 April. Monetary damages of \$208 million were reported for this event, primarily the result of heavy snow, ice, and high winds. One fatality, in Nebraska, was directly attributed to this event.

p. Northern Plains and Upper Midwest Winter Storm (13-15 April)

1) Meteorological Overview

From 13-15 April a deep upper level low developed and moved eastward across the northern plains and the Upper Midwest, producing late-season, anomalous snow accumulations across parts of the region (*Fig. 36*).

On 13 April a deep upper-level trough moved across western Canada and the northwestern U.S. with a strong upper jet extending from the eastern Pacific into the Great Basin. That evening an upper-level low within the trough began to weaken as it moved across southern Alberta. Meanwhile, a second low center began to develop to its southeast (*Fig. 37a*). By the morning of 14 April this newly formed center had rotated into southeastern Montana (*Fig. 37b*). Moisture converging on the northwest side of this newly formed system fell as heavy snow

across portions of central and eastern Montana. Meanwhile, strong southerly flow ahead of the low advected deep moisture into a region of strong low-level convergence and upper-level divergence, which contributed to the development of heavy snows across parts of North Dakota and northern South Dakota.

The upper low continued to deepen as it moved into the central Dakotas by the evening of 14 April (*Fig. 37c*). Snow moved east across Minnesota, Wisconsin and the Upper Peninsula of Michigan along an axis of strong low-level frontogenesis, while support for heavy snow continued across portions of the central and eastern Dakotas. The low moved east-northeastward into northern Minnesota by the morning of 15 April (*Fig. 37d*). Precipitation ahead of the low continued to move north through the upper Great Lakes region into southern Canada, while precipitation to the west was reduced to some scattered light snows across eastern North Dakota.

2) Impacts

Up to 14 inches of snow fell across portions of northeastern Montana. Several new daily snowfall records were set, including Glasgow International Airport which received 6.4 inches on 14 April. Widespread accumulations of over 12 inches, with local amounts of up to 22 inches, were reported across North Dakota and northern South Dakota, breaking numerous snowfall records there as well. At Bismarck Municipal Airport, the record snowfall amount for any day of the year was set when 17.3 inches fell on 14 April, breaking a previous record that stood for nearly 50 years. Blizzard conditions were reported in Bismarck, with visibilities dropping to 0.25 mile, while winds gusted to over 35 mph on the morning of 14 April. A wintry mix fell further to the south, with up to 0.25 inch ice accumulations reported over northeastern South Dakota. While snow accumulations to the east were generally lighter, numerous daily snowfall records were set across Minnesota and Wisconsin. The heaviest amounts across the region centered from the

southern Red River valley to the Arrowhead region of Minnesota, where widespread accumulations of 4 to 8 inches were reported. Monetary damages reported for this event were low, with less than \$1 thousand. No fatalities or injuries were directly attributed to the event.

q. Western and Central U.S. Winter Storm (16-19 April)

1) Meteorological Overview

This storm was one of several that contributed to an exceptionally snowy April for portions of the Rockies and Upper Midwest. An upper level trough amplified over the western United States on 16 April as low pressure moved eastward from the Great Basin to southwestern Colorado (*Fig. 38a*). An area of cold high pressure remained north of the Canadian border but cold air spilled southward along the eastern slopes of the Rocky Mountains, allowing heavy snow to fall especially heavily across Wyoming as temperatures fell from the 20s into the teens Fahrenheit.

By early morning on 17 April the area of low pressure had moved southeastward across northeastern New Mexico as snow continued from Colorado northward across Wyoming and eastward into Nebraska and South Dakota. The upper-level trough continued to move very slowly eastward while the surface low only moved slowly into northern Texas. A tremendous temperature gradient was found across Texas as the front east of the low separated temperatures in the 90s across western Texas from temperatures in the 30s across the northern Texas Panhandle and temperatures in the teens and 20s from Colorado and the central plains into Wyoming.

By the morning of 18 April the upper-level trough finally began to lift northeastward while low pressure redeveloped northeastward along the strong front separating temperatures in the 60s and 70s across the Ohio valley from much colder air behind the front. Low pressure

along the front began to consolidate northeastward toward Chicago with a pressure of around 1000 hPa. During the day, this low continued to intensify as the upper-level trough lifted northeastward, deepening to 992 hPa over southern Wisconsin at 00 UTC on 19 April and then to 982 hPa over the Upper Peninsula of Michigan by the morning of 19 April (*Fig. 38b*). During this period of more rapid surface development, snowfall rates increased across the Upper Mississippi valley to the Upper Midwest before the system moved into Canada later on 19 April and into 20 April.

2) Impacts

Snow initially fell across the higher elevations of the Great Basin, especially across Nevada into the Wasatch Range in Utah, leaving up to 20 inches in northern Nevada and 13 inches in Utah. However, the heaviest snow developed from northern Colorado into Wyoming, where blizzard conditions and very heavy snowfall amounts crippled many of the area highways. Fort Collins received over 23 inches of snow while Boulder received more than 19 inches. Denver recorded slightly less than 10 inches. Snowfall totals were highest across Wyoming, where up to 3 feet of snow was reported, including 36 inches at Centennial and between 17 and 19 inches at Casper, Cheyenne, Laramie and Landers.

Snowfall amounts (*Fig. 39*) were significant but not nearly as great over Nebraska and South Dakota, where up to a foot of snow fell, with 8 inches at Rapid City (after 28 inches on 8-10 April) and nearly 10 inches at Scottsbluff, Nebraska. However, once the surface low began to redevelop northward along the advancing front, snows again became quite heavy, especially across Minnesota into northwestern Wisconsin, where up to 2 feet of snow fell. While 7.3 inches were measured at Minneapolis-St. Paul, snowfall amounts increased north of the city. St. Cloud measured more than 12 inches while Duluth reported 17.7 inches, the heaviest 24 hour snowfall

ever in the month of April during the snowiest month of record, when 50.8 inches were totaled by the end of April 2013. Monetary damages of \$35 thousand were reported for this event, primarily the result of high winds. No fatalities or injuries were directly attributed to the event.

r. Central Rockies to Upper Midwest Winter Storm (1-3 May)

1) Meteorological Overview

A late season snow storm occurred on 1-3 May, and was noteworthy both for producing impressive snowfall in parts of the plains and Midwest, as well as producing measureable snow across parts of the South at a time of the year when snow has typically long since ended for the season. Three separate regions of the United States were significantly impacted from this system, all receiving snowfall accumulations uncommon for early May. The higher elevations of the Wyoming and the Colorado Rockies received over a foot of snow, followed by 4 to 8 inches into the central High Plains, well removed from mountain influences (*Figs. 40, 41*). The second region impacted was the Upper Midwest 24 to 36 hours, where a narrow band of snow helped to blanket portions of Iowa into Wisconsin with 12 to 18 inches. Light to moderate accumulations of freezing rain were also recorded across parts of the Midwest, a precipitation type which is rare to see in May. Lastly, measurable snow was reported as far south as Oklahoma and Arkansas, a first for Arkansas during the month of May since record-keeping began.

The storm began early on 1 May when a deep mid/upper-level trough began to evolve over the northwestern U.S. as a north-northwesterly upper-level jet of 140 kt entered the Pacific Northwest. The trough amplified as it reached the central U.S., with a closed low developing over the central plains by 3 May. Bitter cold temperatures for early spring filtered southward into the central High Plains behind a strong cold front on 1 May, with low level winds turning to an upslope direction in the central High Plains, leading to the onset of precipitation. The strong

change in air mass caused temperature swings of 55 to 65 degrees Fahrenheit at many locations in the central and southern plains over roughly a 36 hour period. A combination of favorably oriented low-level upslope flow, a moisture source initially from the Gulf of Mexico and strong low/mid-level frontogenesis was present during the heaviest snowfall across Wyoming, Colorado, Nebraska and Kansas.

As the slow moving cold front progressed eastward through the Plains on 2-3 May, rain was the initial precipitation type in the post-frontal environment, but a changeover to snow occurred as cold air continued to filter in from the north. An axis of relatively high equivalent potential temperature advected northward across the plains, overrunning the shallow cold air near the surface. Rare accumulations of sleet and freezing rain were reported in Iowa, Wisconsin and the Upper Peninsula of Michigan. The heaviest snow in the Upper Midwest developed early on 2 May, collocated with a layer of very strong frontogenesis near 850 hPa, with 10 to 18 inches falling in a narrow corridor from the central Iowa-Minnesota border into northwestern Wisconsin. A tight snowfall gradient was evidenced by only a trace of snow being measured at Minneapolis-St. Paul International Airport compared to locations less than 50 miles away (to the south and east), which received as much as 18 inches.

2) Impacts

The impacts from this storm were numerous and widespread, breaking many records. Almost every state that received snowfall from this storm contained cities that broke all-time records for storm total snowfall for the month of May. For example, Dodge Center, MN received 15.4 inches on 2 May, establishing a new state record for a 1-day snowfall, breaking the previous record of 12 inches set back in both 1954 and 1938. In Arkansas, measureable snow had never been reported since record-keeping began back in 1819 for the month of May until this storm,

with Decatur picking up 5 inches. Heavy snow was responsible for numerous accidents, road closures, the closing of schools and businesses as well as power outages from fallen trees and power lines. Closures and power outage reports were widespread from Colorado to the Upper Midwest, but numbered greatest from southeastern Minnesota into northwestern Wisconsin within a narrow band of heavy snow resulting in 10 to 18 inches. Lastly, due to the anomalous cold, characterized by 850 hPa temperature anomalies of -10 to -16 degrees C across the plains, temperatures at the surface were more representative of mid-winter than early May. Record low minimum and maximum temperatures for the month of May were set in locations from Wyoming to Texas and as far east as Tennessee. Monetary damages of \$444 million were reported for this event, primarily the result of heavy snow and strong winds. No fatalities or injuries were directly attributed to the event.

5. Summary

The winter weather season of 2012-2013 was a very active one. The events described in this seasonal review directly resulted in a total of 17 fatalities and at least \$444 million in damages (*Table 1*). Both of these numbers were a significant increase over the previous winter weather season of 2011-2012. The 2012-2013 winter weather season got off to an early start with the winter storm component of Hurricane/Post-Tropical Storm Sandy, and ended late, with significant snows impacting large parts of the country into early May. Overall, areas of the northern plains and Midwest received significantly above average snowfall for the season, while the central Rockies and portions of the Northeast received below average snowfall.

6. Acknowledgements: The authors would like to thank Wallace Hogsett and Mark Klein for invaluable input and guidance throughout this project.

7. References

- Barnston, A.G., R.E. Livezey, 1987: Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. *Mon. Wea. Rev.*, **115**, 1083-1126.
- Blake, E.S., T.B. Kimberlain, R.J. Berg, J.P. Cangialosi, J.L. Beven II, 2013: Tropical Cyclone Report, Hurricane Sandy (AL182012), 22-29 October, 2012.
- Kalnay, E. and Coauthors, 1996: The NCEP/NCAR Reanalysis 40-year project. *Bull. Amer. Meteor. Soc.*, **77**, 437-471.
- Miller, J.E., 1946: Cyclogenesis in the Atlantic coastal region of the United States. *J. Met.*, **3**, 31-44.
- NOHRSC Interactive Snowfall Maps, NOAA/NWS/OCWWS, 2005 (www.nohrsc.noaa.gov/technology/pdf/Snowfall_Maps.pdf)
- NWS Natural Hazard Statistics, 2013 (http://www.nws.noaa.gov/om/hazstats/resources/weather_fatalities.pdf)
- NWS Ridge II Snowfall Analysis (<http://www.srh.noaa.gov/ridge2/snow>)
- Storm Data and Unusual Weather Phenomena (www.ncdc.noaa.gov/oa/climate/sd)
- Thompson, D.W.J., J.M. Wallace, 1998: The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. *Geo. Res. Lett.*, **25**, 1297-1300.

8. Figures

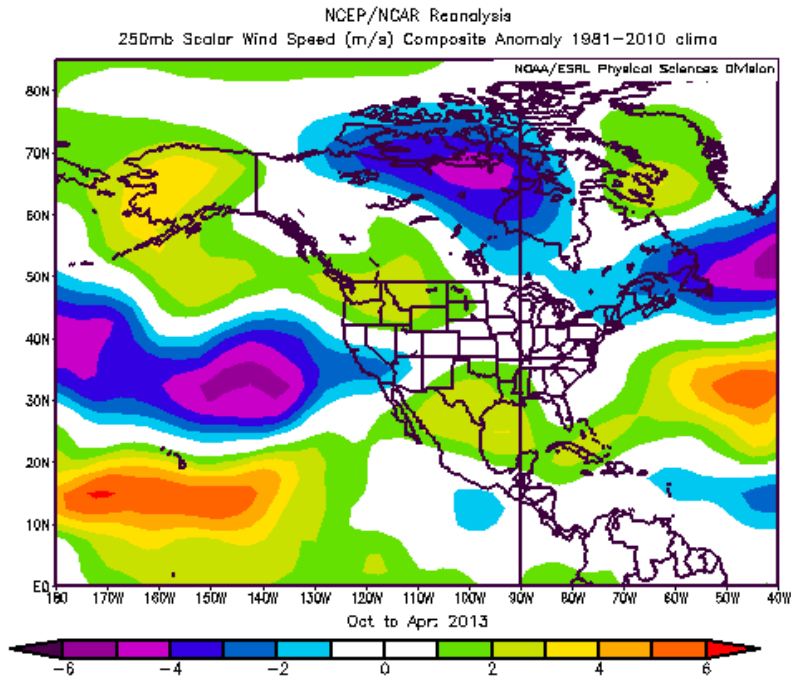


Figure 1: Mean 250 hPa wind speed composite anomalies from October 2012 to April 2013 (NCEP/NCAR Reanalysis).

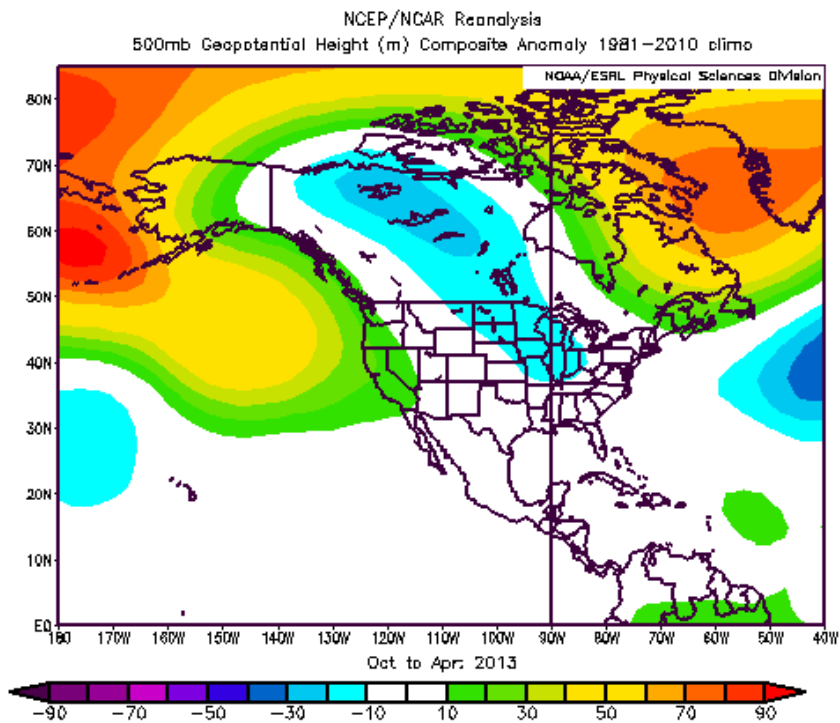


Figure 2: Mean 500 hPa geopotential height (m) composite anomalies from October 2012 to April 2013 (NCEP/NCAR Reanalysis).

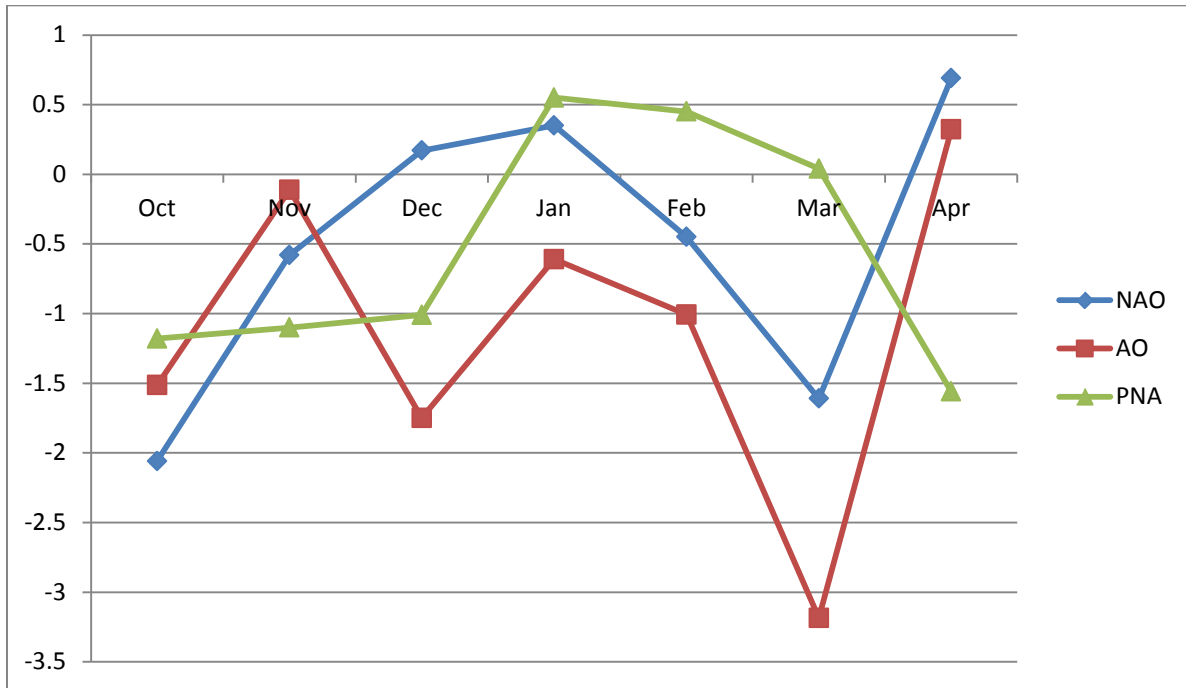


Figure 3: The North Atlantic Oscillation (NAO), Arctic Oscillation (AO), and Pacific-North America (PNA) indices during the 2012-2013 cold season (October to April).

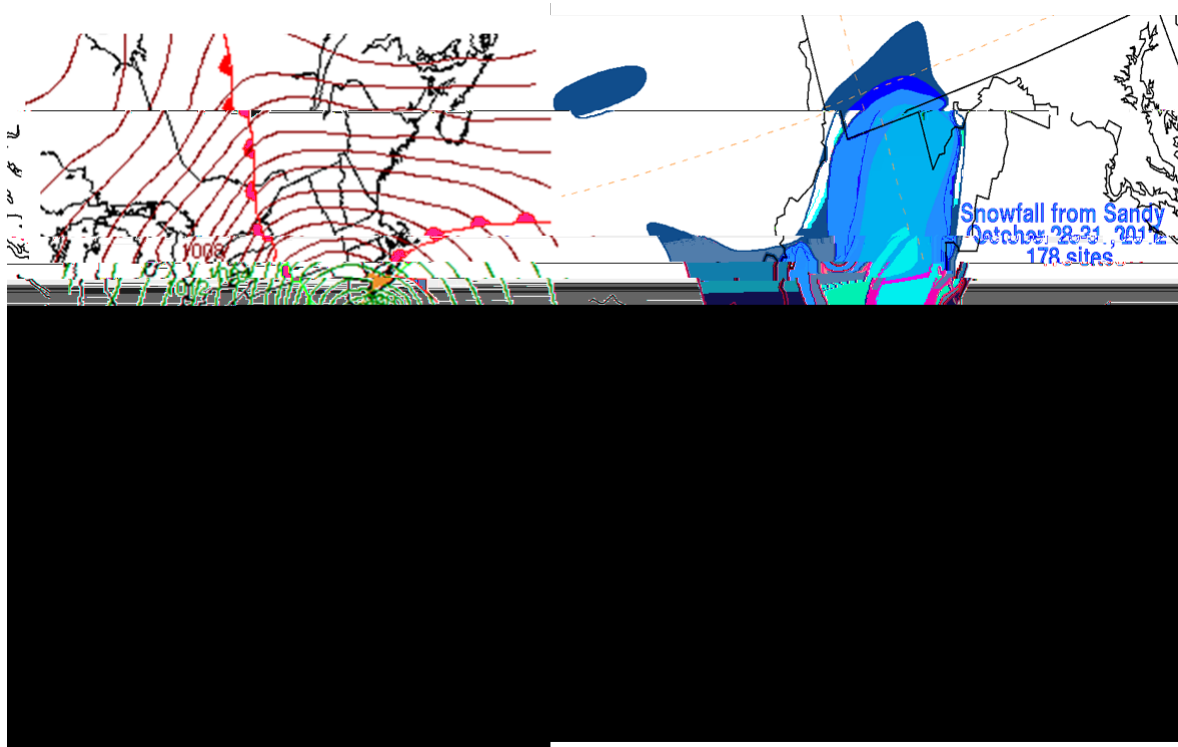


Figure 4: Analyzed surface pressures (isobars every 4 mb) and fronts at 00 UTC on 30 October, 2012 (a) and observed snowfall from Post-Tropical Storm Sandy (b) (WPC).

Figure 5: WPC surface analyses for 12 UTC on 7 November, 2012 (a), 00 UTC on 8 November (b), and 12 UTC on 8 November (c).

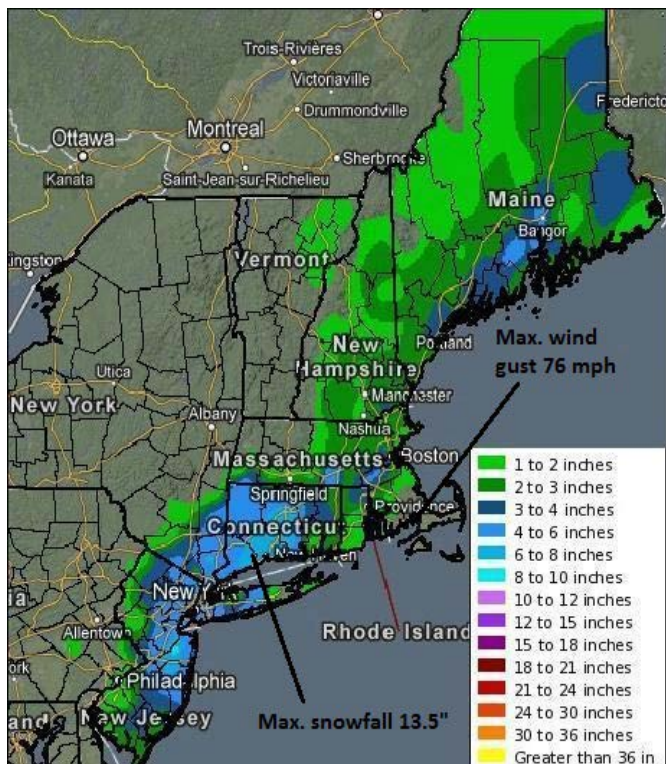


Figure 6: Snowfall analysis from 6-7 November, 2012 with maximum snowfall and wind gust indicated (Snowfall image courtesy of NWS Southern Region).

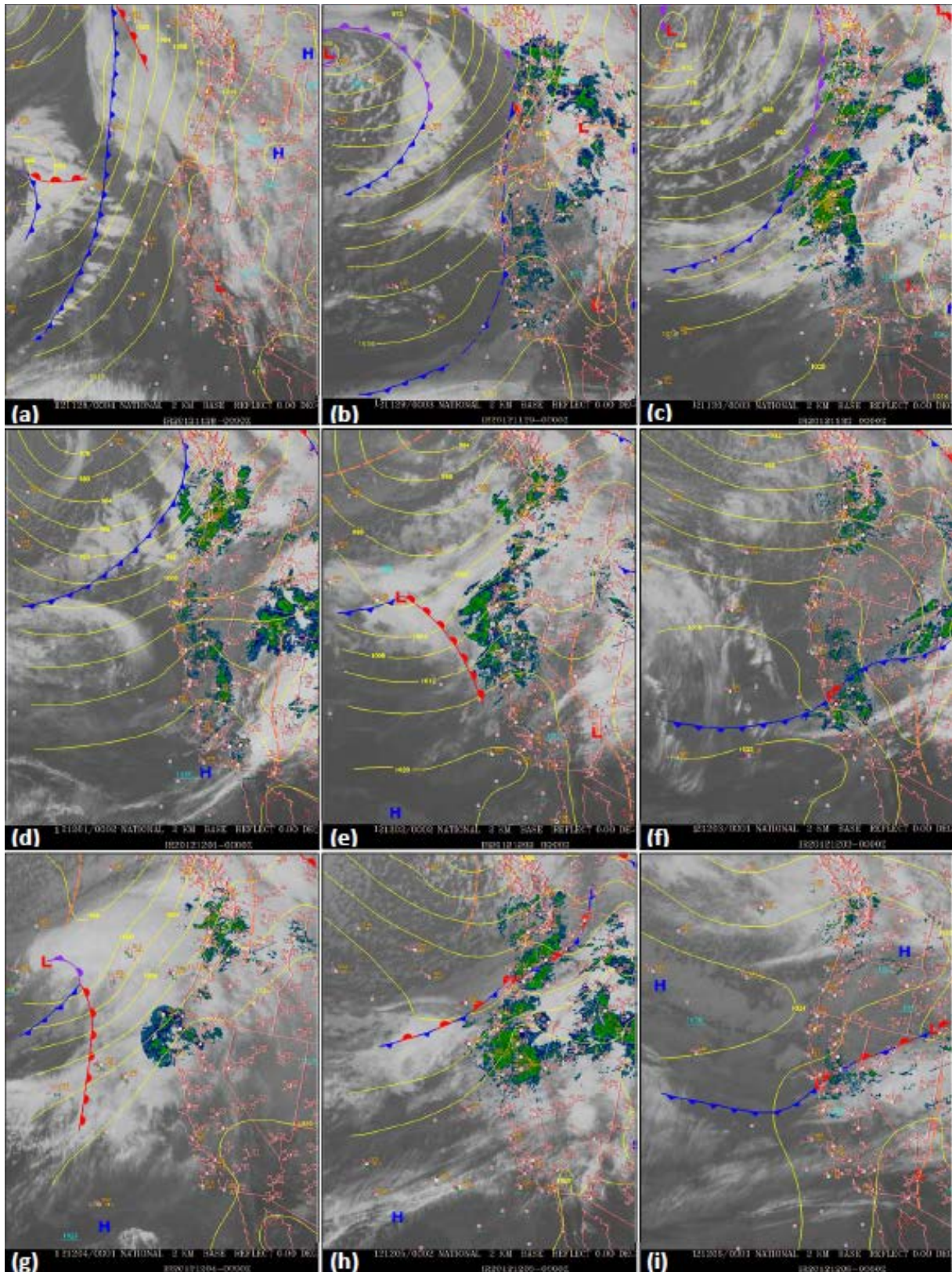


Figure 7: WPC surface analyses overlaid on GOES-WEST infrared and radar composites at (a) 00Z on Nov. 28, (b) 18Z on Nov. 28, and 00Z on (c) Nov. 30, (d) Dec. 1, (e) Dec. 2, (f) Dec. 3, (g) Dec. 4, (h) Dec. 5, and (i) Dec. 6.



Figure 8: Map of maximum snowfall locations and amounts in each of the affected states from 29 November to 5 December, 2012.

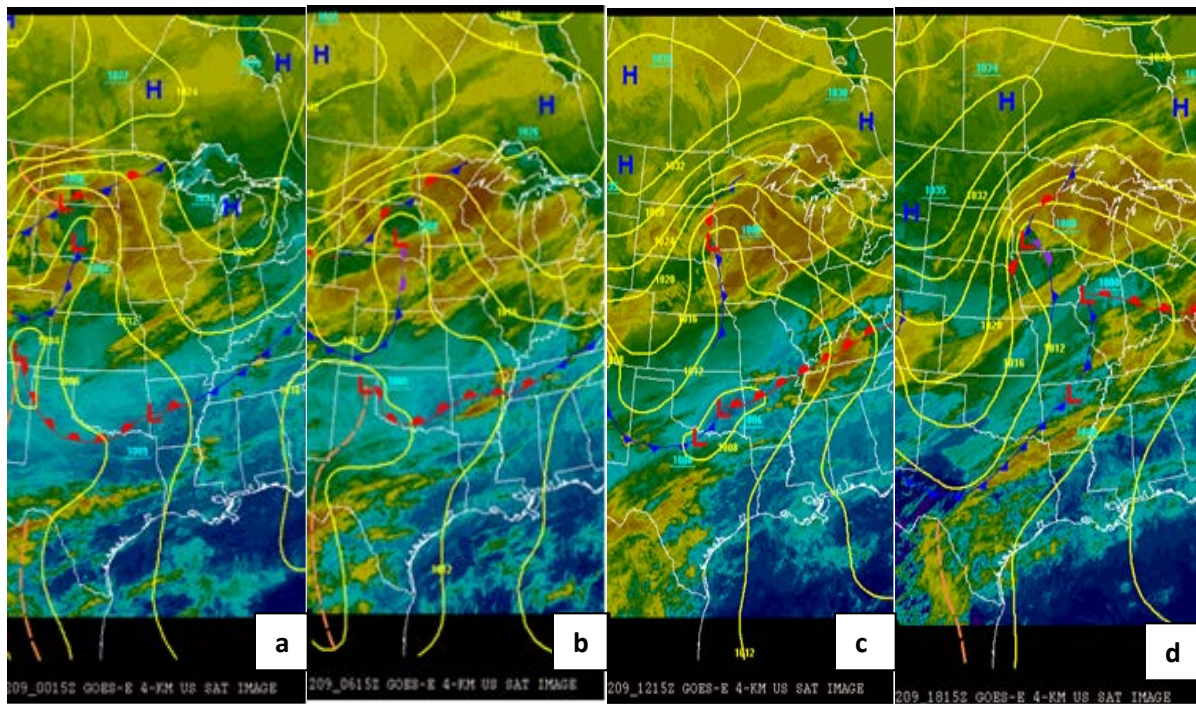


Figure 9: Surface analyses and infrared satellite imagery at a) 00 UTC December 9, 2012, b) 6 UTC December 9, 2012, c) 12 UTC December 9, 2012, and d) 18 UTC December 9, 2012.

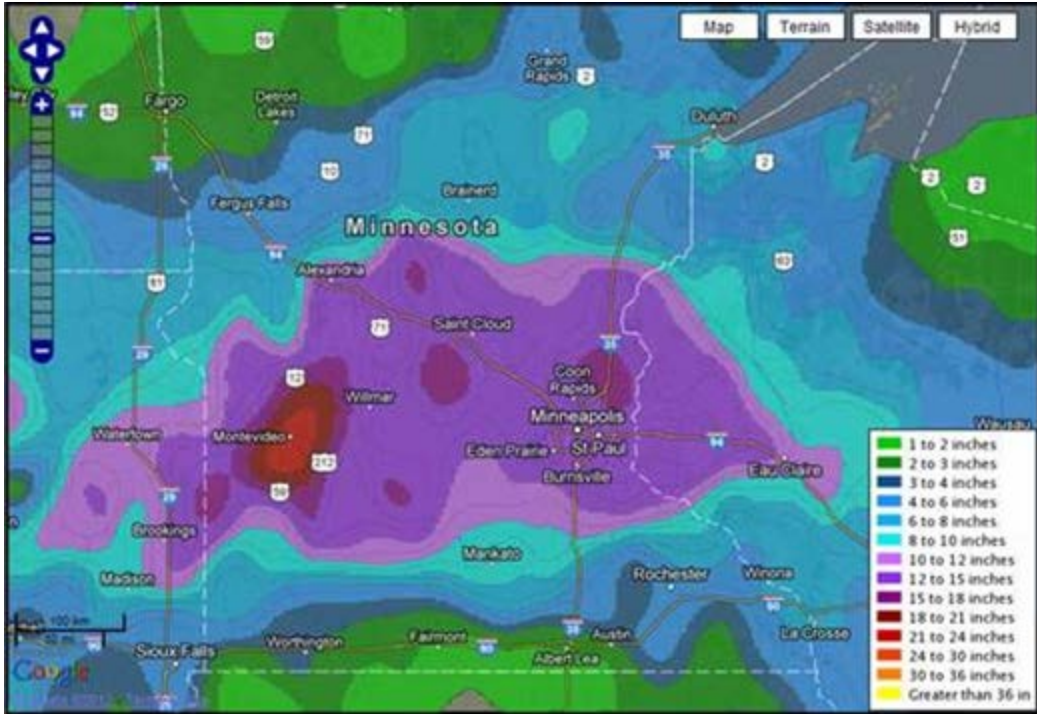


Figure 10: Snowfall accumulations across the Upper Midwest and eastern Dakotas on 9-10 December 2012 (Image courtesy of NWS Southern Region).

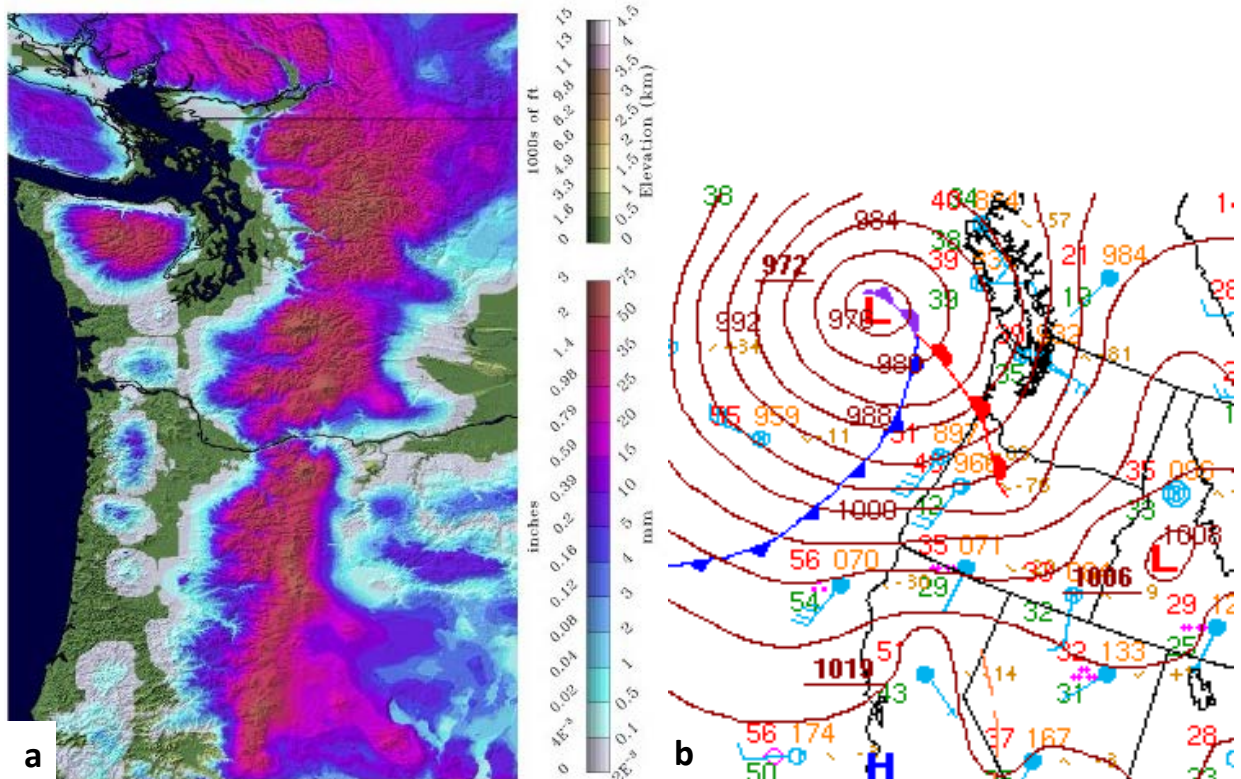


Figure 11: Snowfall accumulations (a) for the 24-hour period ending at 06 UTC on 18 December, 2012 (NOHRSC). WPC surface analysis valid at 00 UTC on 17 December, 2012 (b).

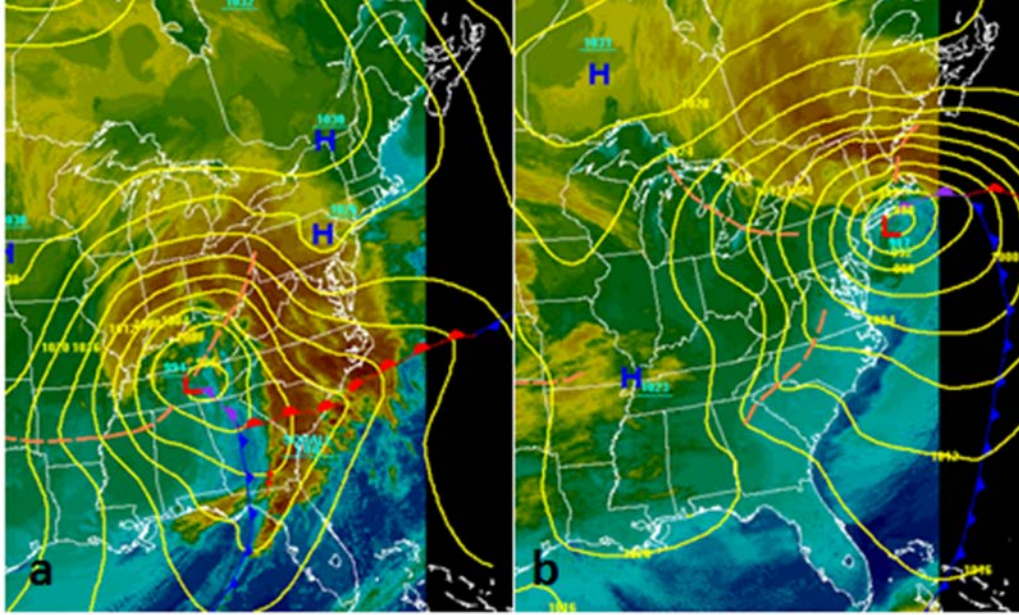


Figure 12: WPC surface analyses overlaid on infrared satellite imagery from 12 UTC on (a) 26 December and (b) 27 December, 2012.

Figure 13: Snowfall totals from 25-28 December, 2012, with the tracks of the primary low and coastal low shown (Snowfall totals in this image courtesy of NWS Southern Region, low tracks taken from WPC Surface Analyses).

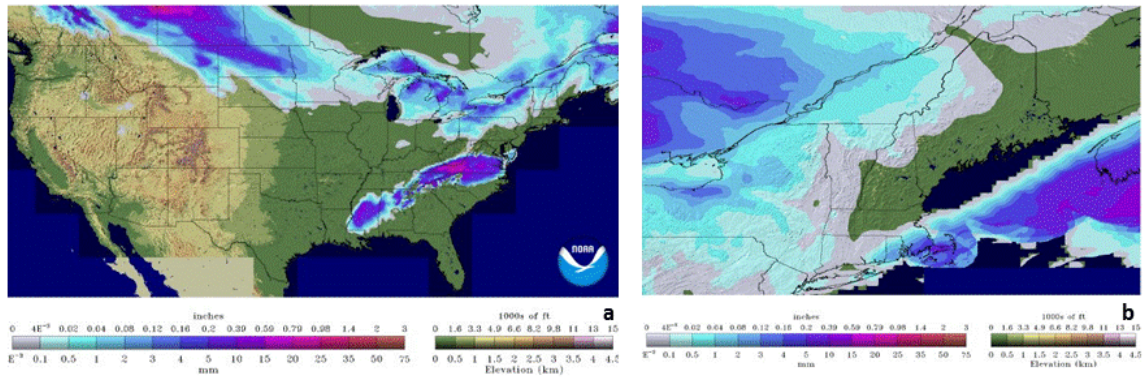


Figure 14: Scaled snow precipitation from 06 UTC on (a) 18 Jan 2013 and (b) 19 Jan 2013 (NOHRSC).

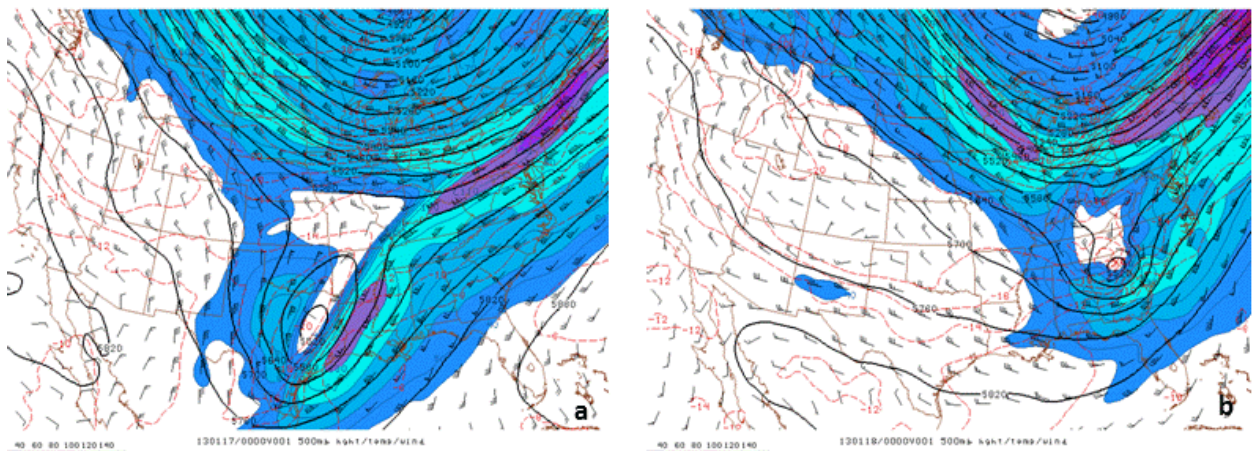


Figure 15: 500 hPa analysis, wind bards, wind speed (shaded) from 00 UTC on (a) 17 Jan 2013, (b) 18 Jan 2013 (SPC).

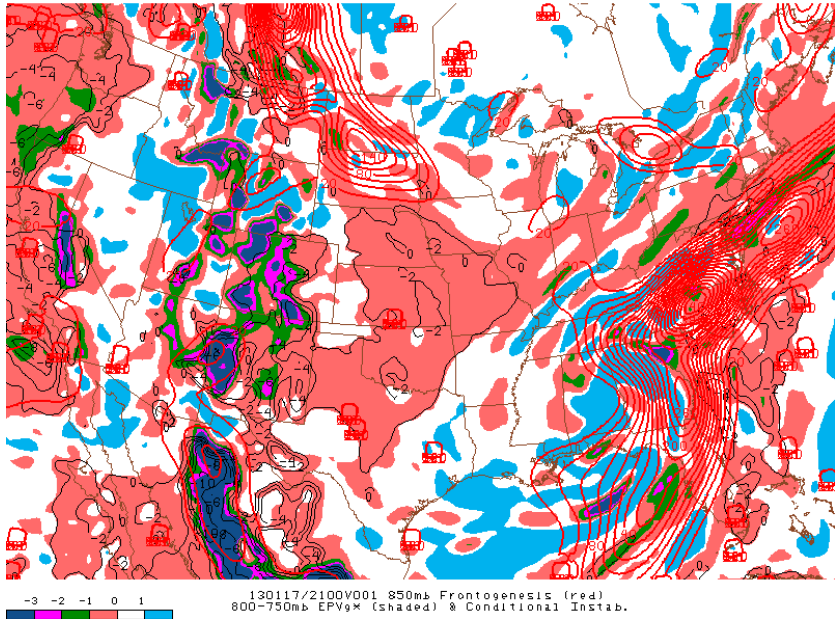


Figure 16: 850 hPa frontogenesis (red), 800-700 hPa EPVg* (shaded) and conditional instability on 21 UTC 17 Jan 2013 (SPC).

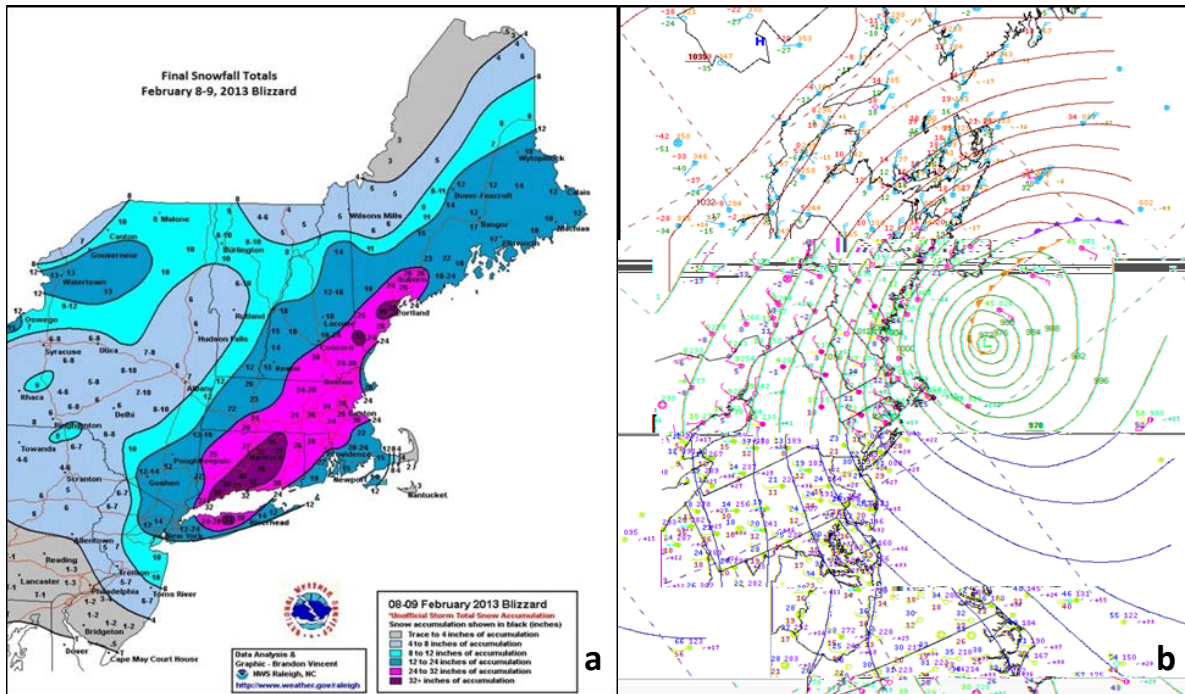


Figure 17: (a) Snow totals for February 8-9, 2013 (Courtesy NWS Raleigh, NC); (b) WPC Surface Analysis from 9 February, 2013 at 1200 UTC.

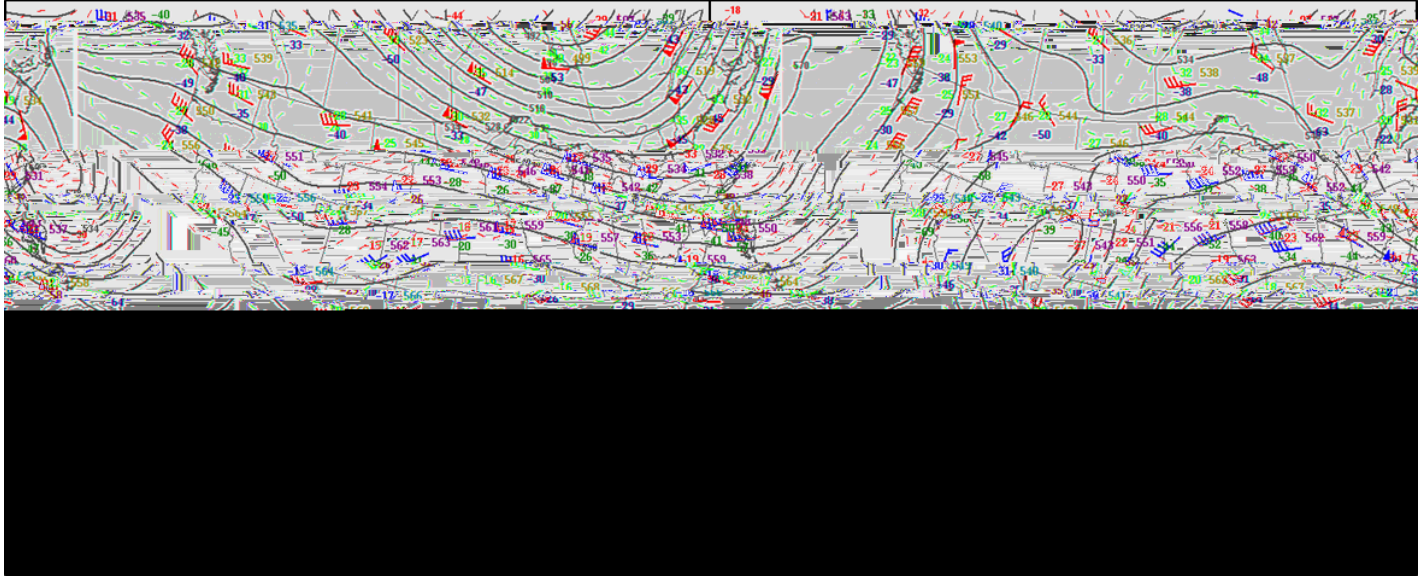


Figure 18: February 6, 2013 1200 UTC and February 9, 2013 1200 UTC (SPC).

Figure 19: 500 hPa heights (dm) and absolute vorticity (a) and analyzed surface pressures (isobars every 4 mb) and fronts (b) from 00 UTC on 10 February, 2013 (Images courtesy of UCAR and WPC).

Figure 20: 300 hPa isotachs, streamlines, and divergence (a) and analyzed surface pressures (isobars every 4 mb) and fronts (b) from 12 UTC on 10 February 2013 (Images courtesy of SPC and WPC).

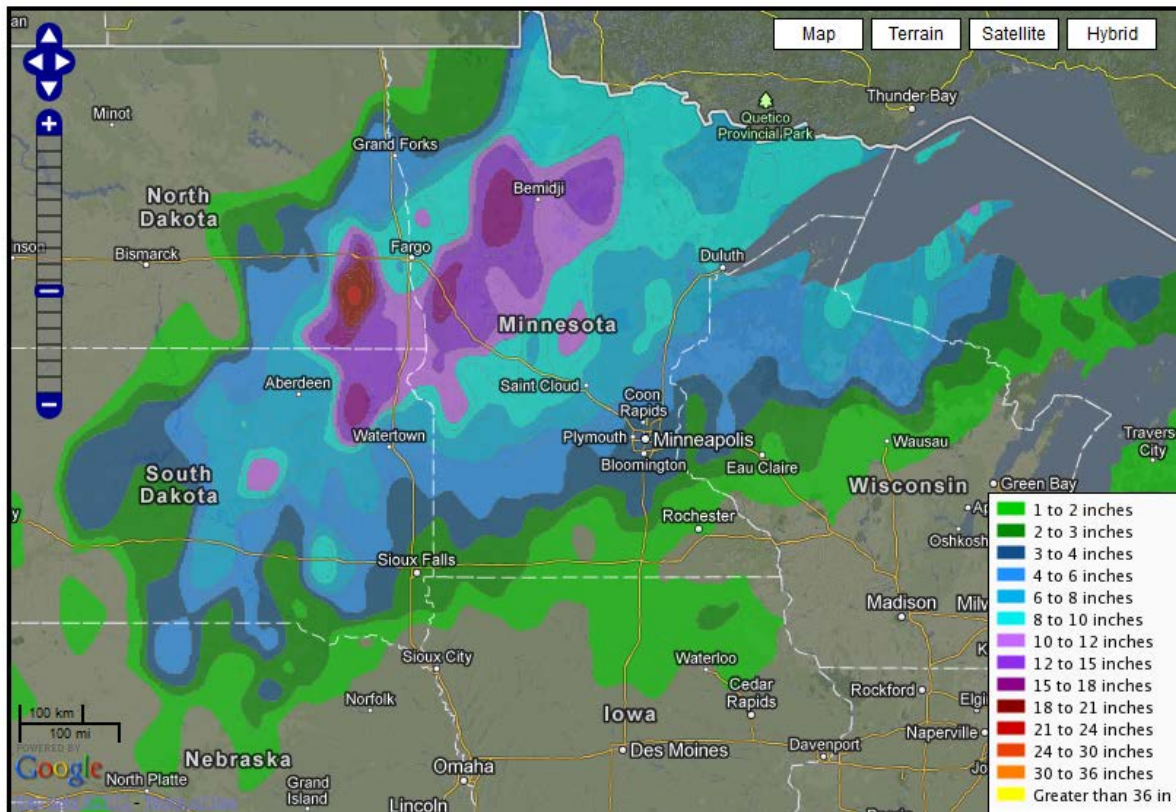


Figure 21: Observed 48 hour snowfall analysis ending at 12 UTC on 12 February, 2013 (Image courtesy of NWS Southern Region).

Figure 22: 500 hPa heights (black contours), temperatures (red contours), and wind barbs at 12 UTC on 20 February, 2013 (a), and 12 UTC on 21 February, 2013 (b). (Images courtesy of SPC)

Figure 23: (a) Ice accumulation (inches) and (b) snowfall analysis from 20-22 February, 2013 (Ice accumulation image courtesy of WPC, snowfall image courtesy of NWS Southern Region).

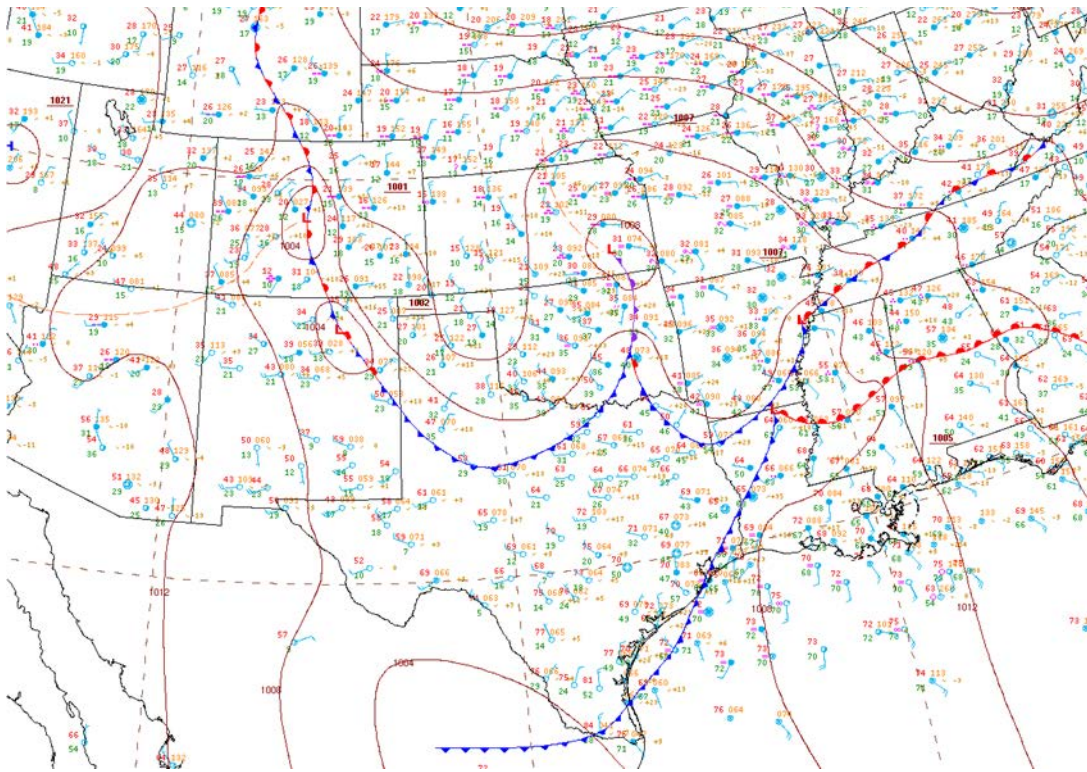


Figure 24: Surface analysis from 00 UTC on 22 February, 2013. (WPC)

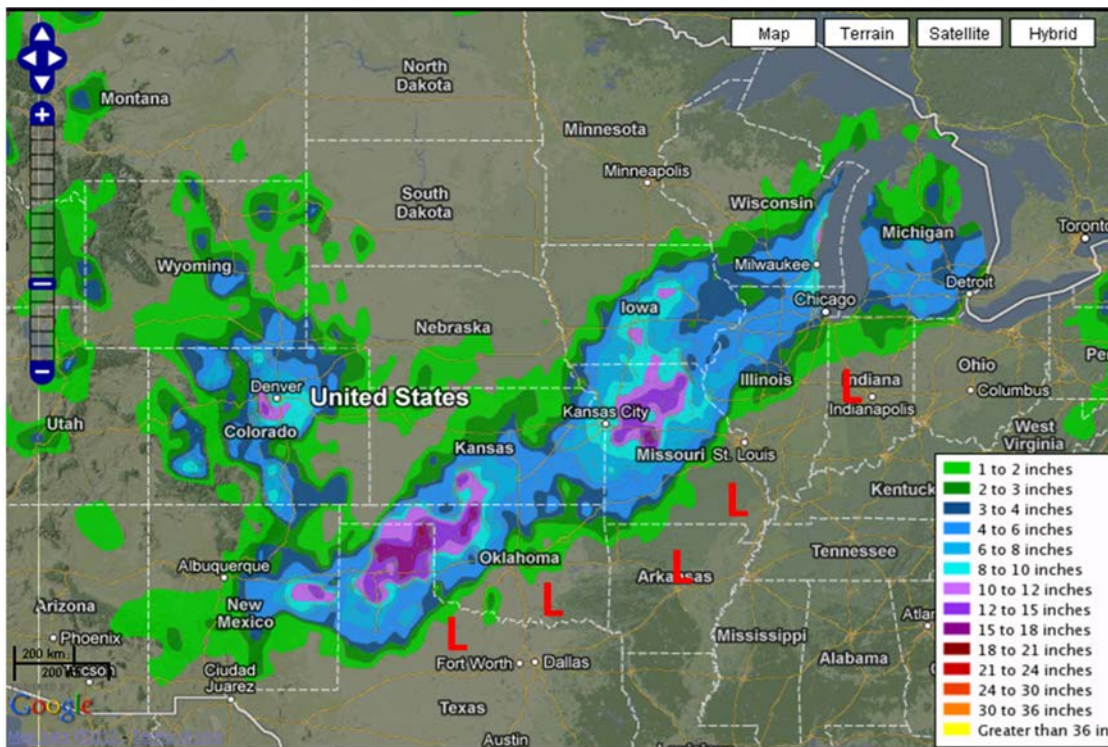


Figure 25: Total accumulated snowfall from 25-28 February, 2013, with surface low track overlaid. (Snowfall graphic courtesy of NWS Southern Region Headquarters)

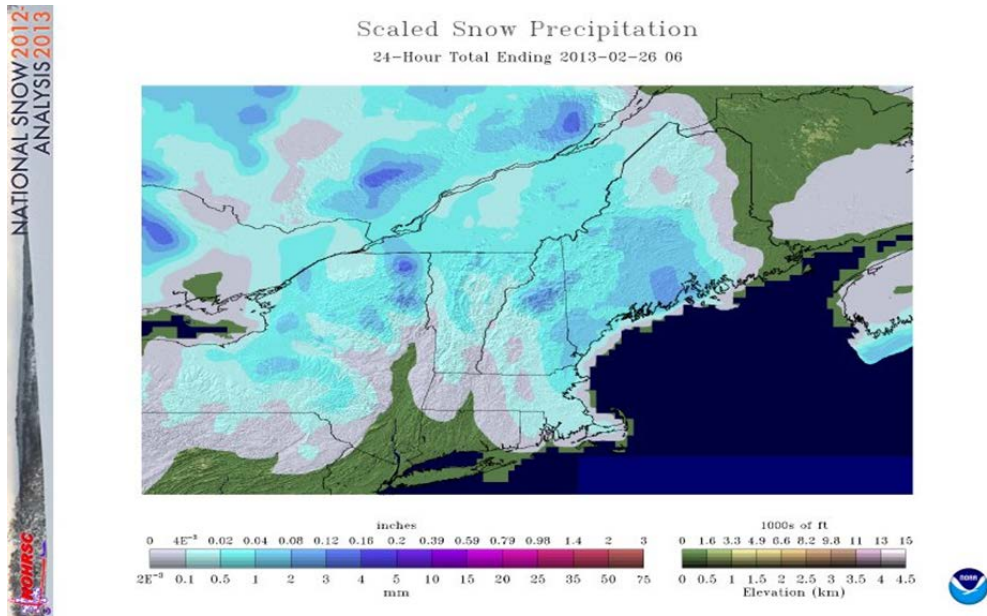


Figure 26: 24-hour snowfall for the northeastern U.S. ending at 06 UTC on 26 February, 2013. (NOHRSC)

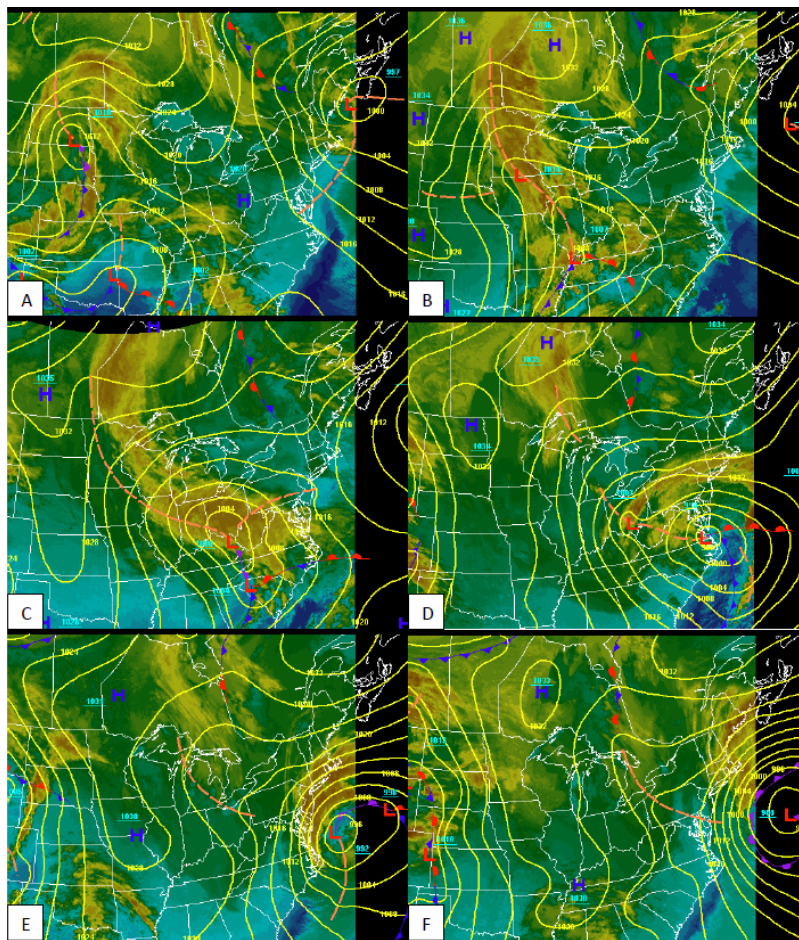


Figure 27: Surface analysis (WPC) overlaid with infrared satellite imagery at (a) 00 UTC on 5 March, (b) 12 UTC on 5 March, (c) 00 UTC on 6 March, (d) 12 UTC on 6 March, (e) 00 UTC on 7 March, (f) 12 UTC on 7 March, 2013.

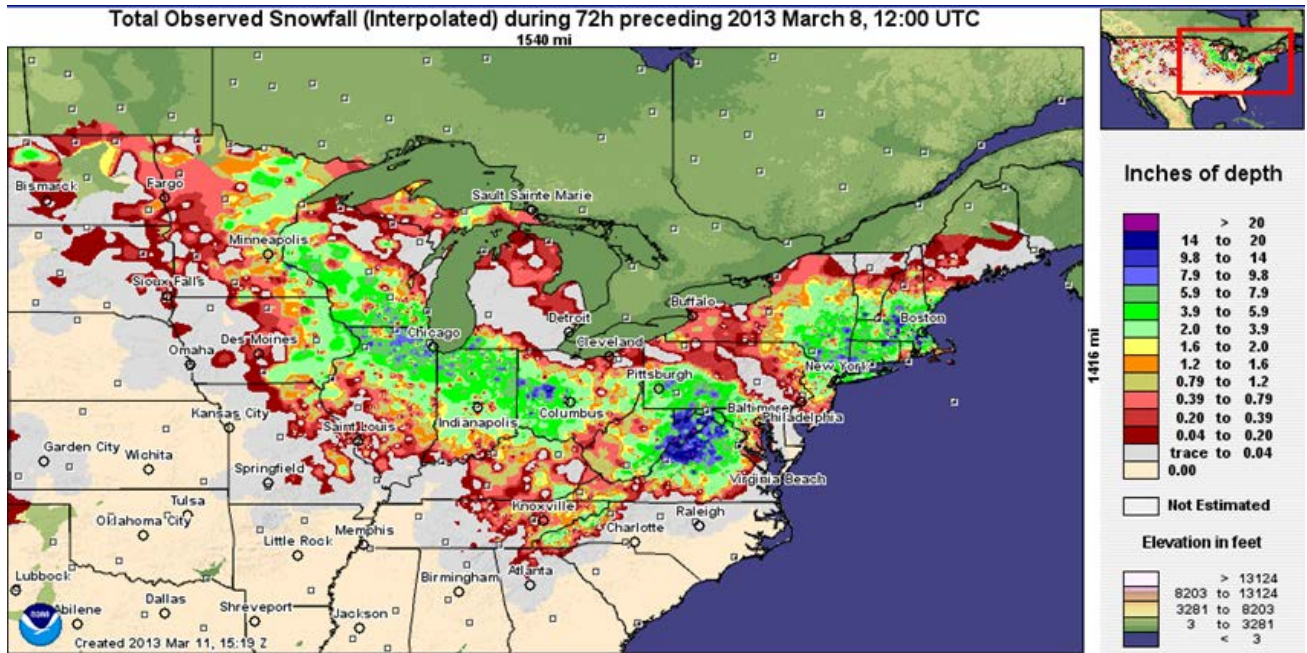


Figure 28: Total snowfall accumulation for the 72 hour period ending at 12 UTC on 8 March, 2013 (NOHRSC).

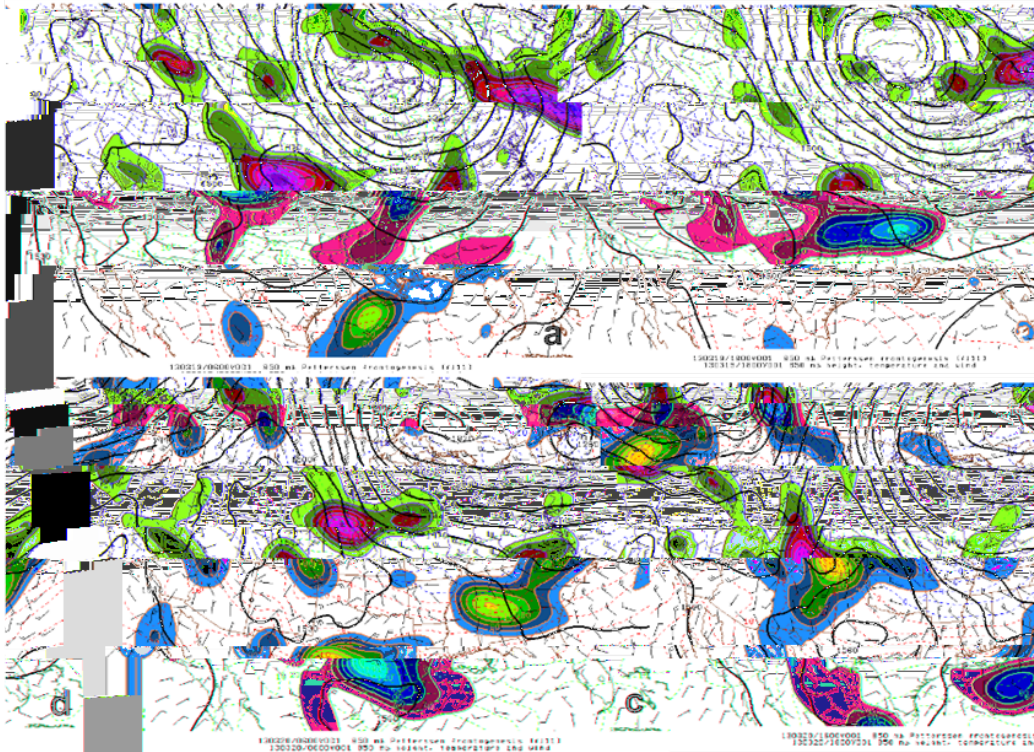


Figure 29: 850 hPa heights (contours), winds (barbs) and Petterssen frontogenesis (shaded) for 06 UTC on 19 March (a), 18 UTC on 19 March (b), 06 UTC on 20 March, and 18 UTC on 20 March, 2013.

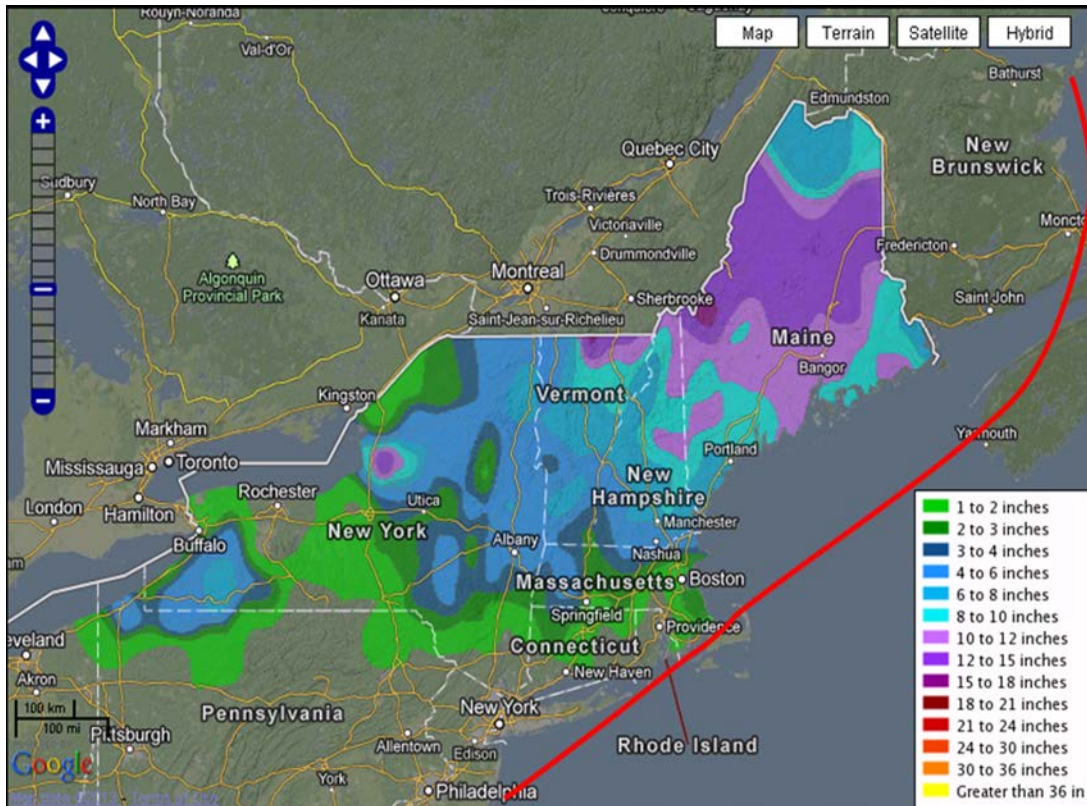


Figure 30: Total snowfall accumulation on 19-20 March, 2013. (Snowfall image courtesy of NWS Southern Region Headquarters, low track taken from WPC Surface Analyses)

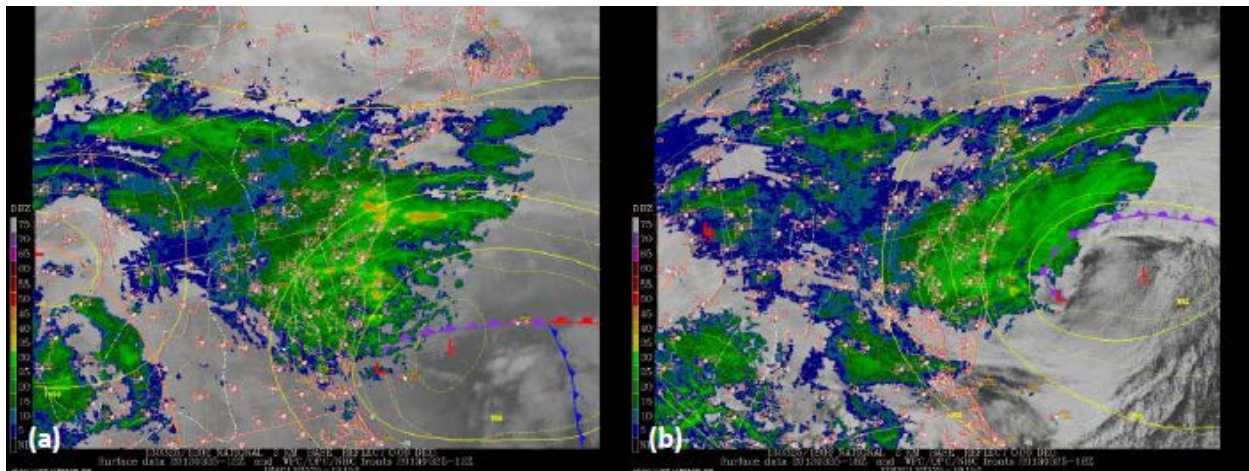


Figure 31: WPC surface analyses overlaid on radar and GOES-E infrared images at around 12 UTC on 25 March, 2013, and (b) radar and GOES-E visible image at around 18 UTC on 25 March, 2013 for the Mid-Atlantic region.

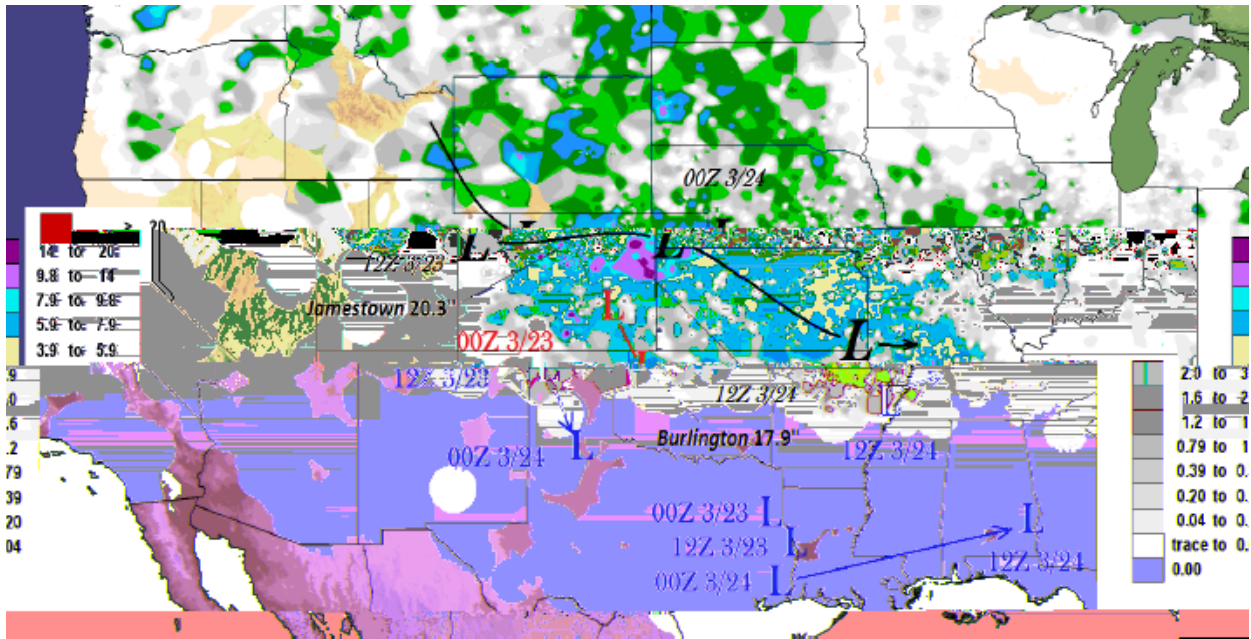


Figure 32: 72-hour snowfall accumulation ending at 12 UTC on 24 March, 2013, with total observed snowfall at Jamestown and Burlington, CO. The 500 hPa (black) and surface (red) low tracks are also shown (Snowfall data courtesy of NOHRSC, low tracks taken from WPC Surface Analyses).

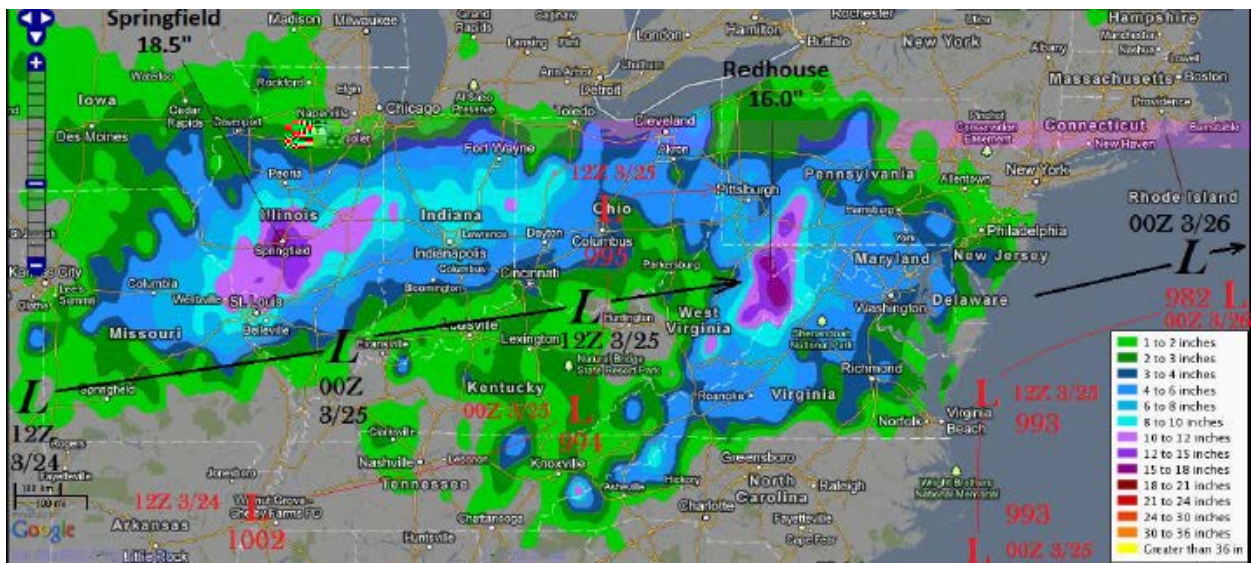


Figure 33: 72-hour snowfall accumulations ending at 12 UTC on 27 March, 2013 along with total observed snowfall at Springfield, IL and Redhouse, WV. The tracks of 500mb low centers (black), surface low pressure centers and their estimated central pressures (red) are also shown. (Snowfall image courtesy of NWS Southern Region, low tracks taken from WPC Surface Analyses).

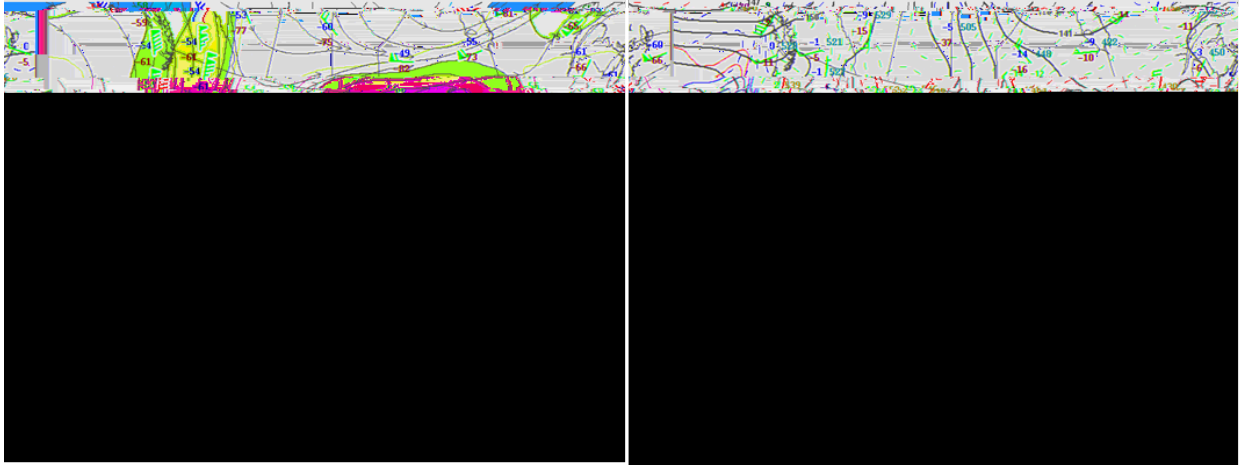


Figure 34: (a) 250 hPa heights and winds and (b) 850 hPa heights, temperatures, and winds for 12 UTC on 9 April, 2013 (SPC).

Figure 35: Total snowfall accumulation for the 72 hour period ending at 12 UTC on 12 April, 2013 (NOHRSC).

Figure 36: Scaled snow precipitation from 06 UTC on 15 Apr 2013 (NOHRSC).

Figure 37: 500 hPa analysis, wind bards, wind speed (shaded) from (a) 00 UTC on 14 Apr 2013, (b) 12 UTC on 14 Apr 2013, (c) 00 UTC on 15 Apr 2013 and (d) 12 UTC on 15 Apr 2013 (SPC).

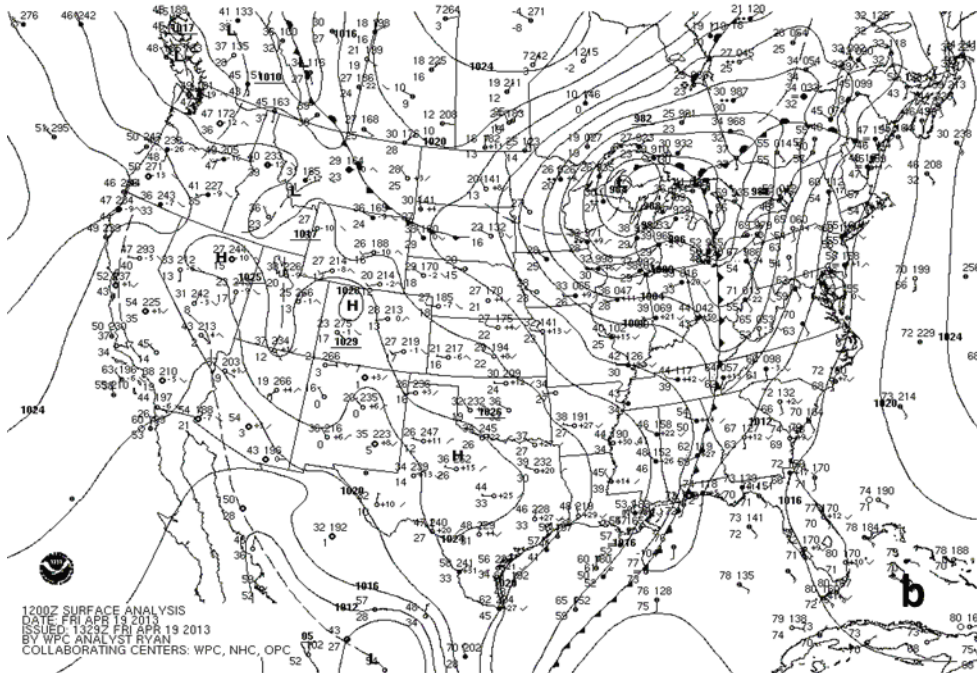
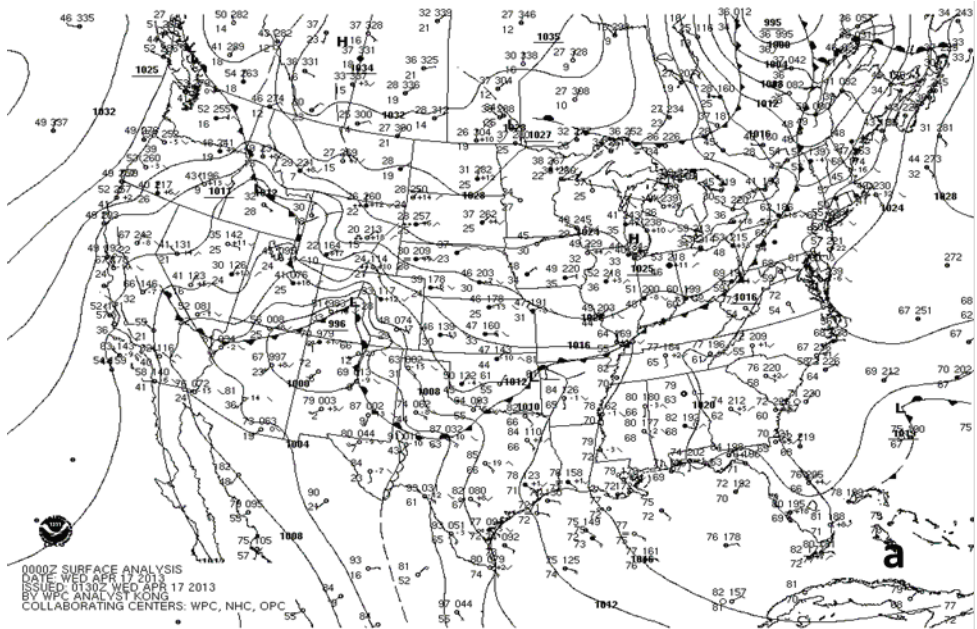


Figure 38: WPC surface analyses from 00 UTC on 17 April (a) and 12 UTC on 19 April (b), 2013.

Figure 39: Total snowfall accumulation for three days ending at 12 UTC on 19 April, 2013 (NOHRSC).

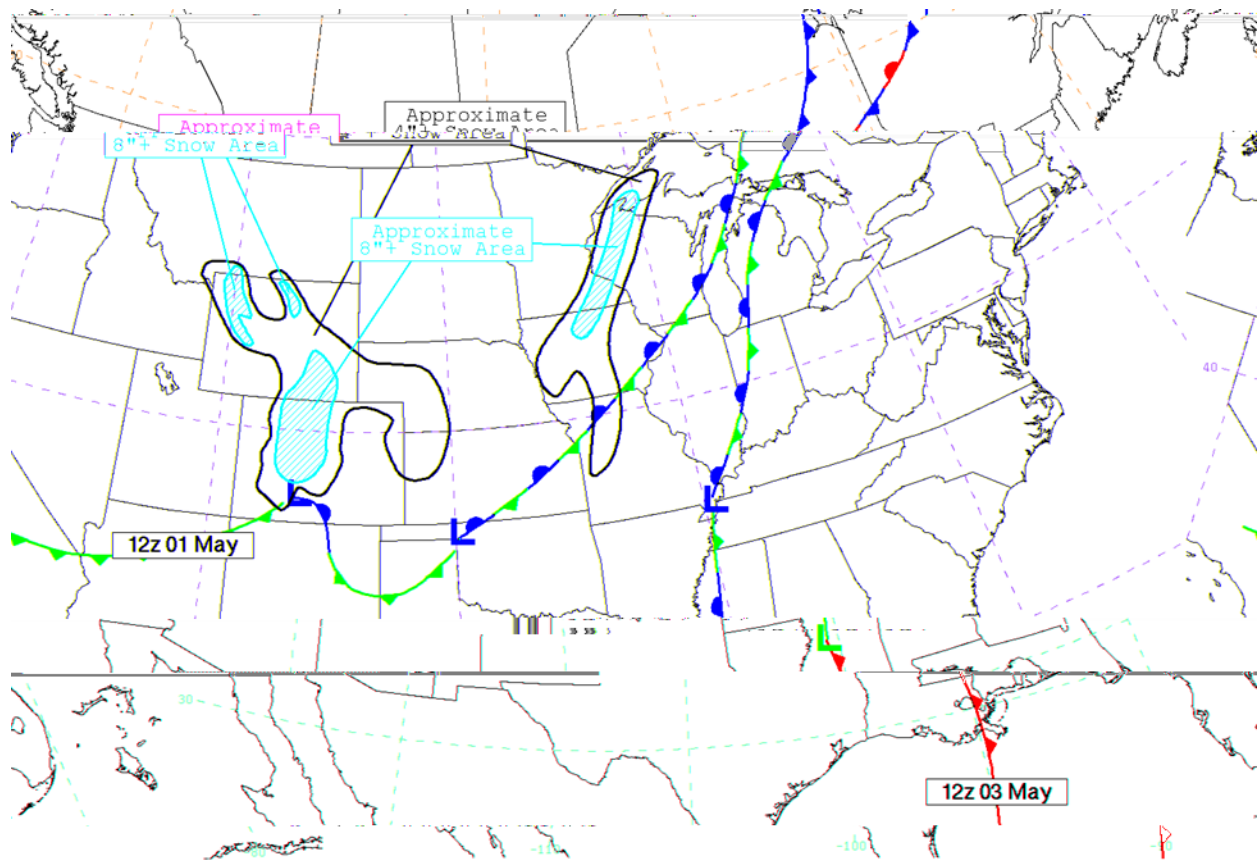


Figure 40: Approximate 72 hour snowfall isopleths of 4 and 8 inches from 0600 UTC 30 April – 0600 UTC 03 May, 2013. Also shown are the locations of a slow moving front at two separate times, 1200 UTC 01 May and 1200 UTC 03 May, 2013.

Figure 41: Total snowfall accumulation for the three days ending at 06 UTC on 3 May, 2013 (NOHRSC).

Table 1:

Date	Event	Impacts	Deaths/Injuries	Damage (\$)
28-31 October, 2012	Post-Tropical Storm Sandy	Winter Storm/Blizzard, Wind	1/0*	31.3 M*
6-7 November, 2012	Early Season Nor'easter	Winter Storm/Heavy Snow, Wind	0/0	940 K
29 November – 5 December, 2012	Western U.S. Heavy Precipitation	Winter Storm/Heavy Snow, Wind	0/0	402 K
9-10 December, 2012	Northern Plains/Upper Midwest Snowstorm	Winter Storm/Heavy Snow, Wind	0/0	0.5 K
17 December	Pacific Northwest Winter Storm	Winter Storm/Heavy Snow, Wind	0/0	1.11 M
25-28 December, 2012	Plains to Northeast Christmas Storm	Winter Storm/Blizzard/Heavy Snow, Wind, Cold/Wind Chill, Coastal Flooding	4/0	119.8 M
16-18 January, 2013	Lower Mississippi River Valley to Northeast Winter Storm	Winter Storm/Heavy Snow/Ice Storm, Wind	0/0	2.04M
7-9 February, 2013	Great Lakes to Northeast Winter Storm	Winter Storm/Blizzard, Wind, Coastal Flood	7/0	54.0 M
10-11 February, 2013	Northern Plains and Upper Midwest Winter Storm	Winter Storm, Wind	1/0	53K
20-22 February, 2013	Central U.S. Winter Storm	Winter Storm/Ice Storm	0/0	1.70 M
25-28 February, 2013	Plains to Northeast Winter Storm	Winter Storm/Heavy Snow/Blizzard/Ice Storm, Wind	2/0	15.5 M
5-8 March, 2013	Upper Midwest to Mid-Atlantic Winter Storm	Winter Storm/Heavy Snow, Wind, Coastal Flood, Cold/Wind Chill	1/0	3.58 M
18-20 March, 2013	New England Winter Storm	Winter Storm/Heavy Snow, Wind	0/0	364 K
23-26 March, 2013	Central and Eastern U.S. Winter Storm	Winter Storm, Wind	0/0	1.46 M
8-12 April, 2013	Northern and Central Plains Winter Storm	Winter Storm/Ice Storm, Wind	1/0	207.6 M
13-15 April, 2013	Northern Plains and Upper Midwest Winter Storm	Winter Storm, Wind	0/0	0.5 K
16-19 April, 2013	Western and Central U.S. Winter Storm	Winter Storm, Wind	0/0	35 K
1-3 May, 2013	Central Rockies to Upper Midwest Winter Storm	Winter Storm/Heavy Snow, Wind	0/0	4.00 M
		Total	17/0	443.9 M

*Damage and deaths/injuries from Post-Tropical Storm Sandy included here are only those caused by the winter storm aspect of the event. The totals do not include damage/casualties from storm surge or from the hurricane force winds near the center of the storm. Damage/casualties from high winds associated with the blizzard conditions over the Appalachians are included in the total.