Weather and Forecasting

Investigating synoptic, mesoscale features SNOW six events

--Manuscript Draft--

Manuscript Number:	
Full Title:	Investigating synoptic, mesoscale features SNOW six events
Article Type:	Article
Corresponding Author:	Ralph Wade Johnson, Ph.D. program University Of Missouri Columbia, Missouri UNITED STATES
Corresponding Author's Institution:	University Of Missouri
First Author:	Ralph Wade Johnson, Ph.D. program
Order of Authors:	Ralph Wade Johnson, Ph.D. program
Abstract:	This investigative study evaluates phenomena that that contributed to the heavy snowfall during six selected events - four mainly central United States and two Southeast, Middle Atlantic, Northeastern/New England. The physical and dynamical processes emphasized for their respective roles include 700hPa vertical motions or omega ω≥-0.60 pa/s, cyclogenesis and cyclone tracks, jet streak induced ageostrophic circulations, 850hPa temperature gradients, 850hPa warm and cold advection, latent heat release, 850hPa frontogenesis, 850hPa low level jet, 700hPa relative humidity (RH), 850hPa meridional and zonal wind, 700hPa v-component of storm motion, 700hPa heights and zonal winds, 300hPa heights and zonal winds. This research compares and analyzes 700hPa omega, pressure at mean sea level, 850hPa temperature along with other variables mentioned above that made contributions to the event physical and dynamical processes. This focus is on the physical and dynamical processes individually or collectively contributed to produce the heavy snowfall that occurred that occurred during these events. This study compares the role pf latent and sensible heat fluxes over ocean and land in cyclone development. In addition, while development of the heavy snow event represents complex interaction among many physical processes that occur on the synoptic and mesoscales, ENSO and teleconnections provide an important framework within which the winter storm evolves.
Suggested Reviewers:	Paul Markowski, PhD Chief Editor, American Meteorological Society markowski.waf@ametsoc.org DR Paul Markowski, along with DR Anthony Lupo are aware submit a manuscript that meets the AMS standards for publishable work!!!!
	Lynn McMurdie, PhD Editor McMurdie.WAF@ametsoc.org DR Lynn McMurdie, along with DR Paul Markowski and DR Anthony Lupo - University of Missouri are well aware of my efforts to submit a manuscript that meets the AMS standards for publishable work.

Click here to access/download

Cost Estimation and Agreement Worksheet

Cost Estimation and Agreement Worksheet (7c).pdf

Response to Reviewers – 2/03/2017 Update

"Investigating the synoptic and mesoscale features in six selected heavy snow events" has been revised to "Investigating the synoptic and mesoscale features in six selected heavy snow events – Jet Streak Circulations and Latent, Sensible Heat Fluxes" Ralph Wade Johnson - Author

Manuscript does not identify a "gap" in scientific knowledge to and add new knowledge to the body of scientific work.

RE: Discussion of analyses that compares or contrast the contribution of latent, sensible heat fluxes during mainly continental heavy snow events with mainly ocean heavy snow events is presented for each of the six events studied. Since most of the emphasis has been on the contribution of oceanic latent, sensible heat fluxes to heavy snow events, this bridges the "gap" by recognizing that although the roles are different they are equally important whether the event is mainly over land or ocean (coastal).

Also, this study identifies a possible "gap" in scientific knowledge between scientific knowledge between heavy rain and heavy snow events. The use of SPC Hourly Mesoscale Analysis Archive parameters to diagnose the 25-26 December 2010 and 1-2 February 2011 events partially fills this "gap", in particular 850hPa convergence, 250-850hPa differential divergence and 250hPa divergence.

The arguments presented in the manuscript should be free of errors in logic and the conclusions should follow from the original evidence presented.

RE: Since there is no relationship between the ENSO phase and the occurrence of snowstorms, it has been shown for all six events that heavy snow is a “manifestation of complex interactions or contributions of many physical processes that occur on the synoptic and mesoscales.

For all events, 850hPa temperature, meridional wind, zonal and the 700hPa v-component of storm variables have been changed to only as variables that interacted or contributed to heavy snow during each of the six events.

Zonal winds crossing geopotential height contours, as an indication jet streak ageostrophic circulations has been REMOVED from the manuscript. Jet streak ageostrophic circulations are represented by SPC Hourly Mesoscale Analysis Archive images of 300hPa isotachs, height and ageostrophic wind.

The transition from a closed circulation at 900hPa to a trough at 600hPa and subsequent latent heat release are primary synoptic and mesoscale processes statement(s) have been removed from the manuscript.

Latent Heat Release for the 25-26 December 2010 and 1-2 February 2011 events has been explored by SPC Hourly Mesoscale Analysis Archive images of 700-500hPa mean RH and 700-500hPa layer – average omega.

Previous work and current understanding must to cited and represent correctly.

RE: Quote marks, as proper acknowledgement of literature references, have placed around Martin 1998 source used in 19 January 1995 event discussion and Kocin and Uccellini 2004 source used in manuscript Summary.

RE: Editing this manuscript, according Lynn McMurdie, Ph.D. Editor – AMS Weather and Forecasting has indeed been a learning experience!! If further editing is needed prior to recommendation for publication, PLEASE inform me!! There may be other standards that need to be met?! I am ready to be "refreshed" and learn more!!

I plan to use the standards that you have taught while editing my final AMS 28th Conference on Weather Analysis and Forecasting manuscript.

THANKS again, Ralph Wade Johnson – Author

Investigating synoptic, mesoscale features six events

Ralph Wade Johnson*

Department of Soil, Environmental and Atmospheric Sciences

302 Anheuser Busch Natural Resources Building

University of Missouri

Columbia MO 65211 USA

Submitted to:

Weather and Forecasting

December 2016

*Corresponding Author: Ralph Wade Johnson

Department of Soil, Environmental and Atmospheric Sciences, 302 Anheuser Busch Natural Resources Building, Columbia MO 65211 rwjb75@mail.missouri.edu

ABSTRACT

This investigative study evaluates meteorological phenomena that played roles in the heavy snowfall during six selected events – four mainly central United States and

two Southeast, Middle Atlantic, Northeast/New England. The physical and dynamical processes emphasized for their respective roles include 700hPa vertical motions or omega (ω) ≥-0.60 pa s^{-1}, Cyclogenesis and cyclone tracks, Jet streak-induced ageostrophic circulation, 850hPa temperature gradients, 850hPa warm air advection (WAA), latent heat release (LHR), 850hPa cold air advection, 850hPa frontogenesis, 850hPa low level jet (LLJ), 700hPa relative humidity (RH) ≥80%, 850hPa meridional wind, 850hPa zonal wind, 700hPa v-component of storm motion, 700hPa heights and zonal winds, 300hPa heights and zonal winds.

This research compares and analyzes 700hPa omega, pressure at mean sea level, 850hPa temperature along with other variables mentioned above that made contributions to the event physical and dynamical processes. The focus is on how the physical and dynamical processes individually or collectively contributed to produce the heavy snowfall that occurred during these events. This study compares the role of latent and sensible heat fluxes over ocean and land in cyclone development. In addition, while development of the heavy snow event represents complex interaction among many physical processes that occur on the synoptic and mesoscales, ENSO and teleconnections provide an important framework within which the winter storm evolves.

1. Introduction

The six events included in this investigative study are 30-31 January 1982, 14-15 December 1987, 19 January 1995, 1-2 February 2011, 13-14 March 1993 and 25-26 December 2010. The events were compared according to the region(s) that they impacted and the physical and/or dynamical processes that were analyzed and/or documented during periods of heaviest snowfall. The 30-31 January 1982 event was compared with 14-15 December 1987, since they both produced heavy snowfall over the central United States, in particular from southwest Missouri to northeast Illinois/southeast Wisconsin/northern Indiana. The 19 January 1995 event was compared with 1-2 February 2011, since they both produced a similar pattern of heavy snowfall from southwest Missouri to northeast Missouri/southeast Iowa, central/northeast Illinois to southeast Wisconsin. The 13-14 March 1993 event was compared with 25-26 December 2010, since they both produced heavy snowfall over parts of the southeast United States, the Middle Atlantic States, northeast and New England.

The main focus of this research is to show that heavy snow events, regardless of development region, are result of a "manifestation of a complex interaction" (Kocin and Uccellini 2004 Volume I) or contribution(s) of among many synoptic and mesoscale phenomena. The variables and physical/dynamical processes include 700hPa maximum negative omega, 700hPa RH ≥80%, pressure at mean sea level, 850hPa temperature (gradients), 850hPa meridional wind, 850hPa zonal wind, 700hPa v-component of storm motion. Emphasis is on how they contributed to produce latent heat release (LHR), 850hPa frontogenesis, 850hPa warm and cold advection, cyclogenesis and the event regional distribution of snowfall. Also, 700hPa heights and zonal winds, 300hPa heights and zonal winds are included to diagnose the contribution of this vertical plane to the snowfall during the selected six events.

A goal of this research is to show that latent and sensible heat fluxes at surface "complex interact" or contribute with the variables, synoptic and mesoscale processes mentioned above during cyclone development associated with heavy snow during each of the six events. However, the role of latent and sensible heat fluxes in cyclone development associated with heavy continental snows is less notable than one associated with Middle Atlantic and Northeast events. Another goal is to provide an indication of latent heat release by showing 700hPa relative humidity and 700hPa omega images during periods of maximum snow accumulation for each of the six events.

(Kocin and Uccellini 2004 Volume I) discuss the large-scale circulation patterns, (variables, synoptic and mesoscale processes) that contribute to episodes of Middle Atlantic and Northeast heavy snow events. However, the central purpose or focus of this research analyzes ENSO, teleconnections, variables, synoptic and mesoscale processes that contribute to episodes of central United States heavy snow events. This objective is accomplished in the figure presentation section.

2. Data sources and analysis methods

a. Data

NCEP North American Regional Reanalysis (NARR) 3-Hourly Composite Mean Archives[1] were used to download pressure at mean sea level, 700hPa omega and categorical snow at surface panels representative of dates and hours when most intense snowfall occurred during selected cases, in particular those 1

January 1979 through 31 July 2015. **NCEP NARR 3-Hourly Composite Mean Archives** were also used to download 700hPa omega (maximum), pressure at mean sea level, 850hPa temperature, categorical snow at surface, 850hPa meridional wind, 850hPa zonal wind, 700hPa v-component of storm motion for selected events listed above. Since it was unavailable from NCEP NARR 3-Hourly, 700hPa RH≥80% data was downloaded from **NCEP NCAR 6-Hourly composite mean archives**[3]

Additional NCEP 3-Hourly Composite Mean Archive synoptic and mesoscale phenomena variables are downloaded for events that impacted more than one region during their development and maturity. These include the 700hPa heights and zonal winds and 300hPa heights and zonal winds. For 13-14 March 1993, event latent, sensible heat fluxes at surface and event pressure at mean sea level at six hour intervals during most intense cyclogenesis are included.

b. Analysis

Analysis are done for NCEP NARR 3-Hourly Composite Mean 700hPa maximum negative omega, pressure at mean sea level, 850hPa temperatures, 850hPa meridional and zonal wind, 700hPa v-component of storm motion, sensible and latent heat fluxes at surface, 700hPa and 300hPa heights, 700hPa and 300hPa zonal winds to determine how they contributed to cyclogenesis, jet streak-induced ageostrophic circulation, latent heat release (LHR), 850hPa warm air and cold air advection, 850hPa temperature gradients, 850hPa frontogenesis, 850hPa low level jet (LLJ) in the selected events. NCEP NARR 3-Hourly Composite Mean 900hPa analyses (lower troposphere closed circulation) and 600hPa analyses (middle troposphere trough) have been used to diagnose LHR during each of the six events. **The Storm Prediction Center[2] (SPC)** uses 850hPa frontogenesis, 850hPa temperature advection and differential vorticity advection in their analyses. As mentioned above, comparison of the above parameters as indicators of the physical and dynamical processes has been done by regions impacted by the heavy snowfall during the winter storms. The selection of dynamical and physical processes has been in accord with Kocin and Uccellini Volume II (2004) analyses of thirty-two selected major snowstorms.

Relevant higher resolution image patterns from the SPC Hourly Mesoscale Analysis Archive are included to provide emphasis of the contribution of these parameters to snowfall during the selected events. These are: Group (1) is 700hPa height, wind, temperature, 700-500hPa mean RH (fill). Group (2) is 300hPa isotachs (fill), height and ageostrophic wind and 700-500hPa layer-average omega (magenta – up). Group (3) is 850hPa Pettersen frontogenesis (fill), 850hPa height, temperature and wind. Group (4) is 850hPa temperature advection (fill), 850hPa height, temperature and wind. Group (5) is 850hPa convergence (red), 250-850hPa differential divergence (fill), 250hPa divergence (purple). Group (6) is Surface temperature, dewpoint and pressure mean sea level. Group (7) Near freezing surface wet bulb temperature, sea level pressure and wind. The SPC Hourly Mesoscale Analysis Archive for these parameters is available 1800 UTC 1 February 2011, 2100 UTC 1 February 2011, 0000 UTC 2

February 2011. (According to surface observations, this is the 6-hour increment period of maximum 1-2 February 2011 event snow accumulation.) Also, the SPC Hourly Mesoscale Analysis Archive for these parameters is available 0600 UTC 26 December 2010, 0900 UTC 26 December 2010, 1200 UTC 26 December 2010. (According to surface observations, this is the 6-hour increment period of maximum 25-26 December 2010 event snow accumulation.)

Commented [JRW(1]: um

Other parameter images from the SPC Hourly Mesoscale Analysis Winter Weather Archive that are relevant to the 1-2 February 2011 and 25-26 December 2010 maximum events snow accumulation are 800-750hPa EPVg (shaded) and Conditional Instability which includes 850hPa frontogenesis (red), 650-500hPa EPVg (shaded) and Conditional Instability which includes 700hPa frontogenesis (red) and Critical Thickness – 1000-500hPa (red), 1000-700hPa (green), 1000-850hPa (blue), 850-700hPa (yellow) and surface temperature 0°C (magenta). According to surface observations, the 6-hour increment period of maximum 1-2 February 2011 event snow accumulation for 800-750hPa EPVg, 650-500hPa EPVg and Critical Thickness includes 2100 UTC 1 February 2011. According to surface observations, the 6-hour increment period of maximum 25-26 December 2010 event snow accumulation 800-750hPa EPVg, 650-500hPa EPVg and Critical Thickness includes 0800 – 0900 UTC 26 December 2010.

Comparison of parameters, physical and dynamical processes are done by region(s) in which the selected events occurred. This is shown in Tables 1, 2 and 3 that also include surface, 850hPa and 700-500hPa frontogenesis, [EPVg and CI (850-750hPa) (650-500hPa)] used in SPC analyses. Also, NCEP NARR 3-

Hourly and NCEP NCAR 6-Hourly variables are included in the tables. The tables depict which variables, physical and dynamical processes that are common, as well as unique to the events compared and hence unite understanding of the case studies. Also, this research, including tables, has been done to show specific contributions for jet streak circulations, including ageostrophic, latent, sensible heat fluxes (ocean, gulf and continent) and latent heat release that produced heavy snowfall during each of the selected events. However, a main goal of this research is not to analyze the variables, physical, dynamical processes and SPC Hourly Mesoscale Analysis Archive parameters but emphasize their contributions to the regional distribution of snowfall and areas of heavy snow in each of the six events. Unfortunately, SPC Hourly Mesoscale Analysis Archive parameters-24 hour are available 18 October 2005 to present which only includes the 25-26 December 2010 and 1-2 February 2011 events.

[1]www.esrl.noaa.gov/psd/cgi-bin/narr/plothour.pl

[2]www.spc.noaa.gov

[3]www.esrl.noaa.gov/psd/data/composites/hour

3. Synoptic and Mesoscale Analyses – Central United States

a. 30-31 January 1982 Event

i. Overview

This event was chosen since it was associated with cyclogenesis that produced notable rains prior to heavy snows over the middle Mississippi valley. Also, extensive elevated convection was recorded during moderate/heavy snowfall. The storm regional distribution of snowfall was primarily central United States, including Great Lakes.

Moore and Blakley (1988) documented that moderate/heavy snowfall accompanied by lightning and thunder occurred between 0100UTC 31 January 1982 and 1400UTC 31 January 1982 at Lambert Saint Louis International Airport. According to Moore and Blakley (1988), surface observations for Saint Louis Lambert Airport 2200-1400UTC 30-31 January 1982 indicated large pressure fluctuations throughout the period with a periodicity of several hours, most likely related to thunderstorm activity. Such pressure fluctuations may also indicate mesoscale gravity waves during this event (Schneider 1990a). The banded structure of moderate-to-heavy snowfall from east-central Missouri through northeast-to-east Illinois into north-central Indiana were accompanied by 700hPa $\omega \leq -1.2$ pa s^{-1} over east-central Missouri and west central Illinois (indicated Figure 1C) and possible mesoscale gravity wave activity during this event. The presence of these vertical motions, heavy snow along relatively narrow band north-northwest of inverted trough, and a marked warm front extending across south-central Missouri-central and southern Illinois-central and southern Indiana 0000-1200UTC 31 January 1982 indicate that thunder-snow was elevated. Thunder-snow ~400 km north of surface cyclone over east-central

Arkansas at 0600UTC 31 January 1982 (Moore and Blakely 1988) is indication of the presence of elevated convection during this event (Market et al. 2002).

II. Analyses of variables and synoptic, mesoscale processes

Figure 2 Images [A], [B], [D] show how 850hPa temperature, 850hPa meridional wind and 850hPa zonal wind interacted during this event. Figure 2 Image [C] indicates how the 700hPa v-component of storm motion contributed along with [A], [B] and [D] to produce the regional distribution of snowfall shown in Figure 1 Image D.

Figure 2 Images [B], [C] indicate an advection role of the 850hPa low level jet (LLJ) during this event. Figure 2 [A], [B], [C] indicate how the 850hPa LLJ contributed along with 850hPa temperature (gradients) – [A] and v-component of storm motion – [C] to produce heavy snowfall during this event. Figure 1 Images B and C provide an indication of latent heat release during this event.

The complex interactions or contributions include 700hPa trough–ridge systems [Figure 18 Image A] provide divergence and ascent (700hPa maximum negative omega) [Figure 1 Image C] for cyclogenesis [shown Figure 1 Image A]. Jet streak circulations embedded within this trough-ridge system [indicated Figure 18 Images A, B, C, D] help focus ascent patterns [Figure 1 Image C], transport potential vorticity (Kocin and Uccellini 2004 Volume I – their Figure 7.1c) toward the developing cyclonic circulation (Figure 1 Image A), enhance low-level temperature gradients, for example 850hPa [shown Figure 2 Images A and B] and middle level moisture transports [shown Figure 1 Image B and Figure

2 Image C] that are required heavy snowfall (Kocin and Uccellini 2004 Volume I).

Since 700hPa and 300hPa zonal winds (Figure 18 Images B and D) are available, convergence and divergence, vorticity advection and the presence of jet streak circulation can be diagnosed from 700hPa–300hPa vertical plane geopotential height fields during this event (Figure 18 Images A and C).

Figure 23 [Images A, B] show the role of sensible and latent heat fluxes in development of cyclones associated with heavy continental snow events is somewhat less defined than those associated with middle Atlantic and northeast events. However, notable contributions of latent and sensible fluxes can be seen in vicinity of the cyclone [Image C] associated with this event. Also, Image [C] indicates role of the “cold” anticyclone over western Minnesota during this event.

b. 14-15 December 1987 Event

I. Overview

This event was chosen because of the observed and documented presence of mesoscale gravity wave interaction during the event. Again, elevated convection was recorded during moderate/heavy snowfall. The storm regional distribution of snowfall was primarily central United States, including Great Lakes.

There is considerable interest for including this previously studied event here. First, Moore and Lambert (1993) found EPV, CSI, convective instability and elevated convection were important processes during 14-15 December 1987 winter storm. Second, Pokerandt et al. (1996) document that within this event, a series of mesoscale gravity waves that formed and lasted for over 10 hours within a rapidly developing mid-latitude cyclone. According to Schneider 1990a, the large-amplitude mesoscale wave disturbances had a maximum surface pressure perturbation of ~10hPa and produced severe winter weather including wind gusts to 30 m s^{-1}, cloud to ground lightning and much localized periods of heavy snow.

Near the time when observed mesoscale waves had large amplitude, many mesoscale surface pressure perturbations were evident in the Pokerandt el al. (1996) model. When observed waves had just entered west-central Illinois (0600-0800UTC 15 December 1987), their model had a wave from southwest WI into northeast IL, another with amplitude ~4hPa from east-central IA into west-central IL, several others from southern MI southwest to southern MO. So, 0300 – 0900UTC 15 December1987 NCEP/NARR $\omega \leq -0.90$ pa s^{-1} (shown Figure 3C) fields have observational relationship to mesoscale gravity waves at mature stage of this event.

II. Analyses of variables and synoptic, mesoscale processes

Figure 4 Images [A], [B], [D] show how 850hPa temperature, 850hPa meridional wind and 850hPa zonal interacted during this event. Image [C] shows how the 700hPa v-component of storm motion contributed along with [A], [B] and [D] to produce the regional distribution of snowfall shown in Figure 3 Image D. Figure 3 Images B and C provide an indication of latent heat release during this event.

Figure 4 Images [B], [C] an advection role of the 850hPa low level jet (LLJ) during this event. Images [A], [B], [C] show how the 850hPa LLJ “complexly interacted” or contributed along with 850hPa temperature (gradients) – [A] and v-component of storm motion – [C] to produce heavy snowfall during this event.

The complex interactions or contributions include 700hPa trough-ridge systems [Figure 19 Image A] that provide divergence ascent (700hPa maximum negative omega) [Figure 3 Image C] for cyclogenesis [indicated Figure 3 Image A]. Jet streak circulations embedded within this trough-ridge system [indicated Figure 19 Images A, B, C, D] help focus ascent patterns [Figure 3 Image C], transport potential vorticity (Kocin and Uccellini 2004 Volume I – their figure 7.1c) toward the developing cyclonic circulation [Figure 3 Image A], enhance low-level temperature gradient, for example 850hPa [indicated Figure 4 Images A and B] and middle level moisture transports [indicated Figure 3 Image B and Figure 4 Image C] that are required for heavy snowfall (Kocin and Uccellini 2004 Volume I).

Since 700hPa and 300hPa zonal winds (Figure 19 Images B and D) are available, convergence and divergence, vorticity advection and the presence of jet streak circulations can be diagnosed from 700hPa – 300hPa vertical plane geopotential height fields during this event (Figure 19 Images A and C).

Figure 24 [Images A, B] show the contributions of sensible and latent heat fluxes in development of cyclones associated with heavy continental snow events is somewhat less defined than those associated with middle Atlantic and northeast events. However, notable contributions of latent and sensible heat fluxes can be seen in vicinity of the cyclone [Image C] associated with this event. Similar to middle Atlantic and northeast events, notable latent and sensible heat fluxes are associated with the succeeding anticyclone over the Gulf of Mexico [Images A, B].

Table 1 has been done to show common or unique variable, physical/dynamical processes that produced the regional distribution snowfall and areas of heavy snowfall during the 30-31 January 1982 and 14-15 December 1987 events. Since both of these events were central United States, Table 1 compares variables, physical/dynamical processes documented or observed/analyzed that contributed during 30-31 January 1982 that were also documented or observed/analyzed during 14-15 December 1987. The exceptions were 850hPa **Q** vector/isotherm fields (30-31 January 1982) and mesoscale gravity wave interaction (14-15 December 1987).

c. 19 January 1995 Event

I. Overview

This event was chosen due to the “sharp” gradient of regional snowfall intensity, for example, heavy southwest – central Missouri and light/very light east central Missouri/west central Illinois. Again, elevated convection was observed and recorded, in particular central – southwest Missouri, although lesser extent than 30-31 January 1982 and 14-15 December 1987 events. The storm regional distribution of snowfall is over central United States, in particular middle Mississippi valley.

“Martin 1998 model analyses of the 19 January 1995 event found that saturated regions of CSI did not appear in the simulated frontal environment, suggesting it may not have been an important factor. Instead frontogenesis in the presence of “across-front” differences in the effective static stability [as measured in terms of equivalent potential vorticity (EPV) was found to be the circumstance responsible for the intensity and dimensions of the snow band. Martin 1988 determined that release of convective instability in the ascending branch of the thermally direct frontal circulation provided the convective component to the band, manifested in cloud-to-ground lightning and occasional bursts of 5 cm h^{-1} snowfall rates.” Figure 5C shows 700hPa omega did indeed interact or contribute with the thermally direct frontal circulation to provide the convective components that produced categorical snow at the surface.

The results of Martin 1998 further revealed: Ascent of warm, moist air in the trowel portion of the warm-occluded structure that developed in this case was shown to contribute to the heavy snowfall. Frontogenesis along the warm-frontal portion of the warm-occluded structure forced the lifting of air into and through the trowel. Also, it is suggested that the trowel, which was a focus of frontogenesis to the northwest of the cyclone center in this case, is easily identifiable given emerging visualization technologies, that is, 1998 and current advances in radiosonde observations.

II. Analyses of variables and synoptic, mesoscale processes

Figure 6 Images [A], [B], [D] indicate how 850hPa temperature, 850hPa meridional wind and 850hPa zonal wind interacted during this event. Image [C] indicates how the 700hPa v-component of storm motion contributed along with [A], [B] and [D] to produce the regional distribution of snowfall shown in Figure 5 Image D.

Figure 6 Images [B], [C] show the advection role of the low level jet (LLJ) during this event. Images [A], [B], [C] show how the 850hPa LLJ “complexly interacted” or contributed along with 850hPa temperature (gradients) – [A] and v-component of storm motion – [C] to produce heavy snowfall during this event. Figure 5 Images B and C provide an indication of latent heat release during this event.

The complex interactions or contributions include 700hPa trough-ridge systems [Figure 20 Image A] that provide divergence and ascent (700hPa maximum negative omega) [Figure 5 Image A]. Jet streak circulations embedded within this trough-ridge system [shown Figure 20 Images A, B, C, D] help focus ascent patterns [Figure 5 Image C], transport potential vorticity (Kocin and Uccellini 2004 Volume I – their Figure 7.1c) toward the developing cyclonic circulation [Figure 5 Image A], enhance low-level temperature gradients, for example 850hPa [shown Figure 6 Images A and B] and middle level moisture transports [shown Figure 5 Image B and Figure 6 Image C] that are required for heavy snowfall (Kocin and Uccellini 2004 Volume I).

Since 700hPa and 300hPa zonal winds (Figure 20 Images B and D) are available, convergence and divergence, vorticity advection and the presence of jet streak circulations can be diagnosed from 700hPa – 300hPa vertical plane geopotential height fields during this event (Figure 20 Images A and C).

Figure 25 [Images A, B] show the contribution of sensible and latent heat fluxes in development of cyclones associated with heavy continental snow events is somewhat less defined than those associated with middle Atlantic and northeast events. However, notable contributions of latent and sensible heat fluxes can be seen in vicinity of the cyclone [Image C] associated with this event.

d. 1-2 February 2011 Event

I. Overview

This event was chosen for its cyclone intensity that brought a variety of precipitation to the central United States; types included heavy snow – west, southwest/central Missouri/east Iowa/central-northeast Illinois, southeast Wisconsin, snow/ice pellets (sleet), freezing rain – east central Missouri/west central Illinois, freezing rain/extensive “glazing” – central/southern Indiana. There was observed and documented elevated convection, in particular southwest/central Missouri (compare to 14-15 December 1987 and 19 January 1995), central Illinois. The regional distribution of storm snowfall was not only central United States, including lakes Michigan, Superior, Huron, but lakes Erie and Ontario and Northeast United States.

HPC surface analysis – 0000 UTC 2 February 2011, along with upper air analysis indicated “comma head” region associated with a 996hPa cyclone. Referring to Rauber et al. 2014 and Rosenow et al. 2014, an upper-tropospheric dry air stream associated with a cyclone’s dry slot frequently intrudes over lower-level Gulf of Mexico air in the comma head of strong cyclones. This creates two zones of precipitation within the comma head: a northern zone characterized by deep stratiform clouds and topped by “cloud-top generating” cells, and a southern zone marked by elevated convection. The Rauber et al. 2014 research found that 1049 total lightning flashes occurred within the comma head region of the 1-2 February 2011 cyclone from 1850 UTC 1 February to 1104 UTC 2 February 2011, providing evidence that elevated convection (see Table 2 – 1-2 February 2011 event column) was dominant in the region of moderate to heavy snowfall associated with this winter storm.

Figures 35 through 42 show relevant SPC Hourly Mesoscale Analysis Archive parameters that contributed to regional maximum observed snowfall accumulation during the selected time increment 1800 UTC 1 February – 0000 UTC 2 February 2011. These include [700-500hPa mean RH], [300hPa isotachs, ageostrophic wind, 700-500hPa layer-average omega], [850hPa Pettersen frontogenesis], [850hPa temperature advection], [850hPa convergence, 250-850hPa differential divergence, 250hPa divergence], [surface temperature, dewpoint], [near freezing surface wet bulb temperature], [800-750hPa EPVg-conditional instability], [650-500hPa EPVg-conditional instability] and [critical thickness].

II. Analyses of variables and synoptic, mesoscale processes

Figure 8 Images [A], [B], [D] indicate how 850hPa temperature, 850hPa meridional wind and 850hPa zonal interacted during this event. Image [C] shows how 700hPa v-component of storm motion contributed along with [A], [B] and [D] to produce the regional distribution of snowfall shown Figure 7 Image [D].

Figure 8 Images [B], [C] indicate an advection role of the 850hPa low level jet (LLJ) during this event. Images [A], [B], [C] show how the 850hPa LLJ contributed along with 850hPa temperature (gradients) – [A] and v-component of storm motion – [C] to produce heavy snowfall during this event. Figures 35 and 36 provide an indication of latent heat release during this event.

The complex interactions or contributions include 700hPa trough-ridge systems [Figure 9 Image A] that provide divergence and ascent (700hPa maximum negative omega) [Figure 7 Image C] required for cyclogenesis [shown Figure 7 Image A]. Jet streak circulations embedded within this trough-ridge system [shown Figure 9 Images A, B, C, D] help focus ascent patterns [Figure 7 Image C], transport potential vorticity (Kocin and Uccellini 2004 Volume I-their Figure 7.1 c) toward the developing cyclonic circulation [Figure 7 Image A], enhance low-level temperature gradients, for example 850hPa [shown Figure 8 Images A and B] and middle level moisture transports [shown Figure 7 Image B and Figure 8 Image C] that are required for heavy snowfall (Kocin and Uccellini 2004 Volume I). Since 700hPa and 300hPa zonal winds (Figure 9 Images B and D) are available, convergence and divergence, vorticity advection and the presence of jet streak circulations can be diagnosed from the 700hPa – 300hPa vertical plane geopotential height fields during this event (Figure 9 Images A and C).

Also, mesoscale processes such as 850hPa frontogenesis and LLJ [shown Figure 8 Images A, D and B] contribute to enhancing the baroclinic environment for cyclogenesis and focus moisture transports and ascent that enhance the snowfall rate(s). Cold anticyclones (synoptic scale) generally have to be positioned to the north of the developing cyclone to sustain the source of level cold air required for snow (Kocin and Uccellini 2004 Volume I). For the 1-2 February 2011 event, this is shown in Figure 7 Image A, as a (105000 Pa High) over west North Dakota, northwest South Dakota, northeast Wyoming and east Montana.

Figure 26 [Images A, B] show the contribution of sensible and latent heat fluxes in development of cyclones associated with heavy continental snow events is somewhat less defined than those associated with middle Atlantic and northeast events. However, notable contributions of latent and sensible heat fluxes can be seen in vicinity of the cyclone [Image C] associated with this event, in particular Lakes Superior, Michigan and Huron.

Table 2 was done to show variables, physical/dynamical processes common and unique to 19 January 1995 and 1-2 February 2011 events. Since mesoscale gravity wave interaction was only indicated from surface analysis during 1-2

February 2011, the only unique documented physical/dynamical process was cyclonic advection of θe (19 January 1995).

4. Synoptic and Mesoscale Analyses – middle Atlantic and northeast US events

a. 13-14 March 1993

I. Overview

This event was chosen for the contribution that latent, sensible heat fluxes and latent heat release played in cyclone development during various stages of the storm. Again, the extent and intensity of elevated convection, respect to snowfall, was of considerable interest (compare to other selected events). The storm regional snowfall distribution (contrast to other selected events) included not only lakes Superior, Michigan and Huron, but Erie and Ontario, sections of the southeast United States, east Tennessee – central Alabama, the Appalachians, Middle Atlantic and Northeast United States, plus sections of New England.

Reference Kocin and Uccellini 2004 Volume II, the 850hPa isotherm pattern had taken on the classic “S” on 13 March, as warm-air advection (WAA) was concentrated north and east of the surface low and cold-air advection (CAA) occurred to the south and west. These areas of WAA and CAA occur over a region of “strong” upward vertical motion ($\omega \leq -1.3$) from southeast Virginia to southern New England [indicated Figure 10C] and correspond to heavy snow and ice pellets over this same region during the same time period [indicated

Figure 10D]. As indicated Figure 10A, intense cyclogenesis played an important role in the 700hPa ω≤-1.3 region depicted by Figure 10C.

Kocin et al. 1995 provide additional information that indicates the interaction of parameters listed in Table 3 and their role during the 13-14 March 1993 event: The 850hPa analysis at 1200UTC 13 March shows that a “massive circulation” developed in the lower troposphere over the southern United States, accompanied by an increase in temperature gradients along the baroclinic zone in northern Florida, eastern Georgia and the Carolinas, plus an increase of observed wind speeds (for those stations still reporting winds) surrounding the cyclone. In addition, the 850hPa low center became collocated with the 0°C isotherm with strong WAA located northeast of the center and strong CAA to the south. The 0°C to -2°C isotherm corresponds closely to the rain/snow line, with the greatest manually digitized radar video integrator and processor (VIP) echo levels found in the southeasterly 850hPa flow from the Atlantic Ocean to North Carolina and into the Middle Atlantic States as moisture-laden air in the warm sector of the cyclone ascends over the colder air west of the coast-line.

. **Analyses of variables and synoptic, mesoscale processes**

Figure 11 Images [A], [B], [D] indicate how 850hPa temperature, 850hPa meridional wind and 850hPa zonal wind interacted during this event. Image [C] shows how the 700hPa v-component of storm motion contributed along with [A], [B] and [D] to produce the regional distribution of snowfall shown in Figure 10 Image D.

Figure 11 Images [B], [C] an advection role of the low level jet (LLJ) during this event. Images [A], [B], [C] show how the 850hPa low level jet (LLJ) “complexly interacted” or contributed with 850hPa temperature (gradients) – [A] and v-component of storm motion – [C] to produce heavy snowfall during this event. Figure 10 Images B and C provide an indication of latent heat release during this event.

Sensible and latent heat fluxes over the Gulf of Mexico and Atlantic Ocean vicinity of the developing cyclone act to contribute to the cyclone’s rapid intensification (Kocin and Uccellini 2004 Volume I). Figures 12, 13, 14, 15 [Images A, B and C 1200 – 1800 UTC 13 March 1993, 1800 UTC 13 March - 0000 UTC 14 March 1993, 0000 – 0600 UTC 14 March 1993, 0600 - 1200 UTC 14 March 1993] clearly show how these ≤meso-α scale phenomena contributed to the cyclone’s rapid intensification. This intensification was associated with the heavy snowfall over the Appalachians and western New York during this event.

The complex interactions or contributions include 700hPa trough-ridge systems [Figure 21 Image A] that provide divergence and ascent (700hPa maximum negative omega) [Figure 10 Image C] for cyclogenesis [shown Figure 10 Image A]. Jet streak circulations embedded within this trough-ridge system [shown Figure 21 Images A, B, C, D] help focus ascent patterns [Figure 10 Image C], transport potential vorticity (Kocin and Uccellini 2004 Volume I – their Figure 7.1c) toward the developing cyclonic circulation [Figure 10 Image A], enhance low-level temperature gradients, for example 850hPa [shown Figure 11 Images A and B] and middle level moisture transports [indicated Figure 10 Image

B and Figure 11 Image C] that are required for heavy snowfall (Kocin and Uccellini 2004 Volume I).

Since 700hPa and 300hPa zonal winds (Figure 21 Images B and D) are available, convergence and divergence, vorticity advection and the presence of jet streak circulations can be diagnosed from 700hPa-300hPa vertical plane geopotential height fields during this event (Figure 21 Images A and C).

II. Latent Heat Release – real time

The transition from a closed circulation (1200 – 1800 UTC 13 March 1993) at 900hPa (Figure 28 Image A) to a trough (1200 – 1800 UTC 13 March 1993) at 600hPa (Figure 28 Image B) is a synoptic-scale process that can possibly result in latent heat release and development of (1200 – 1800 UTC 13 March 1993) cyclone (Figure 28 Image C). It is the intent of Figure 28 Images A, B, C and reference Kocin and Uccellini (2004) Volume I to provide an indication of latent heat release during cyclone development (1200 – 1800 UTC 13 March 1993).

The transition from a closed circulation (1800 UTC 13 March – 0000 UTC 14 March 1993) at 900hPa (Figure 29 Image A) to trough (1800 UTC 13 March – 0000 UTC 14 March 1993) at 600hPa (Figure 29 Image B) is a synoptic-scale process that can possibly result in latent heat release and development of (1800 UTC 13 March – 0000 UTC 14 March 1993) cyclone (Figure 29 Image C). It is the intent of Figure 29 Images A, B, C and reference Kocin and Uccellini (2004) Volume I to provide an indication of latent heat release during cyclone development (1800 UTC 13 March – 0000 UTC 14 March 1993).

The transition from a closed circulation (0000 – 0600 UTC 14 March 1993) at 900hPa (Figure 30 Image A) to trough (0000 – 0600 UTC 14 March 1993) at 600hPa (Figure 30 Image B) is a synoptic-scale process that can possibly result in latent heat release and subsequent development of (0000 – 0600 UTC 14 March 1993) cyclone (Figure 30 Image C). It is the intent of Figure 30 Images A, B, C and reference Kocin and Uccellini (2004) Volume I to provide an indication of latent release during cyclone development (0000 – 0600 UTC 14 March 1993).

The transition from a closed circulation (0600 – 1200 UTC 14 March 1993) at 900hPa (Figure 31 Image A) to trough (0600 – 1200 UTC 14 March 1993) at 600hPa (Figure 31 Image B) is a synoptic-scale process that can possibly result in latent heat release and subsequent development of (0600 – 1200 UTC 14 March 1993) cyclone (Figure 31 Image C). It is the intent of Figure 31 Images A, B, C and reference Kocin and Uccellini (2004) Volume I to provide an indication latent heat release during cyclone development (0600 – 1200 UTC 14 March 1993). Although not high resolution patterns, Figure 10 Image B (700hPa RH ≥80%) and Image C (700hPa Omega ≤-1.3 pa s^{-1}) are can be considered as indicators of latent heat release during this event.

b. 25 – 26 December 2010

I. Overview

Also, this event was chosen for the role that latent, sensible heat fluxes and latent heat release played in storm cyclone development off the middle Atlantic and Northeast United States coasts. However, contrast to 13-14 March 1993 event, the minimum pressure at mean sea level is about 13hPa higher and the latent, sensible heart fluxes were about half the magnitude. Again, elevated convection was of interest during this event, although to a lesser extent than 13-14 March 1993. The storm regional distribution of snowfall is of interest, as east central Missouri, northeast/east Illinois, north Alabama, middle/east Tennessee, west North Carolina, Virginia, Middle Atlantic/Northeast states and New England received notable accumulations.

Figures 43 through 50 show relevant SPC Hourly Mesoscale Analysis Archive parameters that contributed to the regional maximum snowfall observed during the selected time increment 0600 – 1200 UTC 26 December 2010. These include [700-500hPa mean RH], [300hPa isotachs, ageostrophic wind, 700-500hPa layer- average omega], [850hPa Pettersen frontogenesis], [850hPa temperature advection], [850hPa convergence, 250-850hPa differential divergence, 250hPa divergence], [surface temperature, dewpoint], [near freezing surface wet bulb temperature], [800-750hPa EPVg-conditional instability], [650-500hPa EPVg-conditional instability] and [critical thickness].

II. Analyses of variables and synoptic, mesoscale processes

Figure 17 Images [A], [B], [D] indicate how 850hPa temperature, 850hpa meridional wind and 850hPa zonal wind interacted during this event. Image [C] shows how the 700hPa v-component of storm motion contributed along with [A],

[B] and [D] to produce the regional distribution of snowfall shown in Figure 16 Image D.

Figure 17 Images [B], [C] indicates an advection role of the 850hPa low level jet (LLJ) during this event. Images [A], [B], [C] show how the 850hPa LLJ contributed with 850hPa temperature (gradients) – [A] and v-component of storm motion – [C] to produce heavy snowfall during this event. Figures 43 and 44 are synoptic, mesoscale indicators of latent heat release.

The complex interactions or contributions include 700hPa trough-ridge systems [Figure 22 Image A] that provide divergence and ascent (700hPa maximum negative omega) [Figure 16 Image C] for cyclogenesis [shown Figure 16 Image A]. Jet streak circulations embedded within this trough-ridge system [shown Figure 22 Images A, B, C, D] help focus ascent patterns [Figure 16 Image C], transport potential vorticity (Kocin and Uccellini 2004 Volume I – their Figure 7.1c) toward the developing cyclonic circulation [Figure 16 Image A], enhance low-level temperature gradients, for example 850hPa [indicated Figure 17 Images A and B] and middle level moisture transports [shown Figure 16 Image B and Figure 17 Image C] that are required for heavy snowfall (Kocin and Uccellini 2004 Volume I).

Since 700hPa and 300hPa zonal winds (Figure 22 Images B and D) are available, convergence and divergence, vorticity advection and the presence of jet streak circulations can be diagnosed from 700hPa-300hPa vertical plane geopotential height fields during this event (Figure 22 Images A and C).

Figure 27 indicates the role of sensible and latent heat fluxes similar to 13-14 March 1993 where such ≤meso α scale phenomena contributed to the cyclone's intensification during this event. Although only about half the intensity, the 25-26 December 2010 sensible and latent heat fluxes [Images A, B] are located vicinity and southwest of the event cyclone over the Atlantic Ocean and Gulf of Mexico [Image C].

Table 3 was done to show variables, physical/dynamical processes common and unique to 13-14 March 1993 and 25-26 December 2010 events. Although both these storms were primarily Middle Atlantic and Northeast United States coasts, there were variables, physical/dynamical processes unique to each. These are differential positive vorticity advection (700-450hPa), EPVg and CI (850hPa-750hPa) (650-500hPa) (25-26 December 2010) and Isentropic Potential Vorticity, Potential Vorticity Advection into cyclone center (13-14 March 1993).

5. Summary

This research has analyzed and compared six major heavy snow events. The four from the central United States are 30-31 January 1982, 14-15 December 1987, 19 January 1995 and 1-2 February 2011. The other two are 13-14 March 1993 and 25-26 December 2010 which impacted parts of the Southeast, Middle Atlantic and Northeast United States regions. Although the events were analyzed individually, they were compared 30-31 January 1982 – 14-15 December 1987, 19 January 1995 – 1-2 February 2011 and 13-14 March 1993 and 25-26 December 2010 (Tables 1, 2, 3), according to the regions impacted by heavy snowfall.

Analysis of maximum negative 700hPa omega areas, 700hPa RH≥80% areas, minimum pressure at mean sea level areas, regional categorical snow at surface, 850hPa temperature (gradient) areas, 850hPa meridional and zonal wind areas, 700hPa v-component of storm motion areas for all six events. Reference Kocin and Uccellini (2004) Volume 1, this research has shown that a major winter storm, regardless of region, is “manifestation” of a complex interaction or contributions among variables that indicate several physical and/or dynamical processes, which occur on the synoptic to mesoscales. These meteorological phenomena are: 1) Upper-level trough-ridge systems provide divergence and ascent required for cyclogenesis. 2) Jet streaks embedded within this trough-ridge system help focus the ascent patterns, and enhance low-level temperature gradients and moisture transports that are required for heavy snowfall (1-2 February 2011). 3) “Cold” anticyclones generally have to be positioned to the north or northwest of the developing cyclone to sustain the source of low-level arctic or polar continental air required for heavy snow (1-2 February 2011).

4) Referring to Kocin and Uccellini (2004) Volume I, surface cyclogenesis associated with Northeast snowstorms, for example 13-14 March 1993, involves either a primary low pressure center that develops near the Gulf of Mexico or a secondary low pressure that develops along the Southeast or middle Atlantic coast and tracks north/northeast along to approximately 200 kilometers offshore (Figure 12, 13, 14, 15 - Image C). These cyclone systems encompass a wide range of processes throughout the depth of the troposphere that promote interactions of relatively warm and cold air, in particular 850hPa (Figure 11 Images A, B, D),

entrain large amounts of water vapor into regions of precipitation, in particular 700hPa (Figure 10 Image B), organize, focus and enhance ascent, in particular 700hPa (Figure 10 Image C). All of which are necessary for the production of heavy snow during this event.

5) “The evolution of the cyclones that produce these snowstorms is linked to upper level trough-ridge and embedded jet streak patterns that evolve in a manner consistent with baroclinic instabilities and self-development concept(s) (Kocin and Uccellini 2004 Volume I). Self-development depends on the following conditions that have been analyzed for the selected events of this study: a) the existence of an upper level trough-ridge system and jet streaks focus on the divergence aloft, a necessary condition for maximizing mass divergence and ascent immediately downstream of the developing surface low; b) an asymmetrical distribution of clouds and precipitation to focus latent heat release and associated dynamic feedbacks on the downstream ridge and polar jet streak, both factors that can enhance the middle troposphere divergence north and east of the storm center; c) warming is due to an enhanced low level jet and warm air advection pattern immediately north and east of the developing coastal or continental cyclone.” The concept accounts for the adiabatic, quasi-geostrophic framework that has been applied to cyclogenesis (Holton and Hakim 2013, chapter 6) and also for the various interactions among dynamical and diabatic processes indicated for each of the selected events analyzed.

6) The influence of curvature effects in minimizing the contribution of jet streaks to upper-level ageostrophic winds and divergence, and their associated

vertical motion fields, is discussed in studies by Kocin et al. (1986), Uccellini and Kocin (1987), Moore and Vanknowe (1992) and Loughe et al. (1995). These studies indicate that curvature complicates the simple two-dimensional relationship(s) (as shown by Kocin and Uccellini 2004 Volume I – their Figure 7.1b) between the ageostrophic wind field associated with jet streaks and divergence. Diabatic processes especially those related to latent heat release, can also enhance the vertical motions associated with jet streak circulations (Uccellini et al. 1987). Despite the complications introduced by curvature and diabatic processes, Loughe et al. (1995) demonstrates that these transverse circulations make a significant contribution to the divergence aloft and resultant vertical motion patterns in the entrance and exit region of the jet streak.

Mesoscale (≤α) processes such as 850hPa frontogenesis, low level jet (LLJ) contribute to enhancing the baroclinic environment for cyclogenesis and focus the middle troposphere moisture transports and ascent (maximum negative omega) that enhance snowfall rates (30-31 January 1982, 14-15 December 1987, 19 January 1995, 1-2 February 2011, 13-14 March 1993 and 25-26 December 2010 events). Sensible and latent heat fluxes over the Gulf of Mexico and Atlantic Ocean (13-14 March 1993 event) and latent heat release (LHR) within the developing cyclone (30-31 January 1982, 14-15 December 1987, 19 January 1995, 1-2 February 2011, 13-14 March 1993 and 25-26 December 2010 events) all act to contribute to the cyclone's "rapid" intensification. When all these physical and/or dynamical processes are combined during cyclogenesis in such a manner to maximize the low/middle troposphere thermal advections and moisture transports, enhance ascents (maximum negative omega), yet still maintain a deep enough layer of (surface to 850hPa) ≤0°C, heavy snow will, likely, be the outcome, regardless of event region. However, these processes do not indicate a specific contribution for LHR in the selected event cyclogenesis.

6. Conclusions

The selected case results further indicate the deepening rates of extratropical cyclones are related to "complex interactions" (Kocin and Uccellini 2004 Volume I) or contributions between thermodynamic and dynamic processes which are dependent on the horizontal and vertical distributions of the pressure gradient force especially as it relates to the transition from a closed circulation to a trough between 900 and 600hPa and subsequent latent heat release. Again, referring to Kocin and Uccellini (2004) Volume I, within the transition layer between a closed circulation in the lower troposphere and trough aloft, the release of latent heat poleward and east the developing cyclone would be especially important for enhancing the parcel accelerations, divergent airflow (shown in Figures 28 – 36 Image B), surface pressure tendency and associated "rapid" development of the cyclone (shown in Figures 28 – 36, in particular 28 – 31, Image C).

This study provides evidence of how latent heat release is involved in storm cyclogenesis during each of the 25-26 December 2010 and 1-2 February 2011 events. For the other events, although not high resolution, NCEP/NARR images of 700hPa RH and 700hPa omega provide an indication latent release. For the 13-14 March 1993 event, air parcels ascending from the lower troposphere to the middle troposphere, for example 900hPa to 600hPa, can possibly provide an indication of latent heat release.

This study identifies a possible “gap” in scientific knowledge between heavy rain and heavy snow events. The use of SPC Hourly Mesoscale Analysis Archive parameters to diagnose the 25-26 December 2010 and 1-2 February 2011 events partially fills this “gap”, in particular 850hPa convergence, 250-850hPa divergence and 250hPa divergence.

A novel result of this study is that it shows large-scale circulation pattern(s) which includes ENSO and teleconnections, (variables, synoptic and mesoscale processes) contribute to episodes of regional snowfall distribution and areas of heavy snow during six selected events. Although Kocin and Uccellini (2004) Volume I schematically show how synoptic and mesoscale processes, including LHR (their Figure 8.1 Images A and B) contribute to heavy snowfall along the Northeast urban corridor, this research has shown that such processes, including LHR, can contribute to heavy snowfall over the central United States. It is through understanding the large-scale circulation pattern(s), (variables, synoptic and mesoscale processes) contributing to episodes of central United States winter storms that further advances in the prediction of these events can be made.

Danard (1964) recognized that the inability of the first numerical models to accurately predict cyclogenesis was partially due to the neglect of latent heat release. He found that it was necessary to include latent heat release in model simulations to account for the distribution and magnitude of the vertical motion or omega patterns during cyclogenesis and its observed deepening rates. Krishnamurti's (1968) application of the quasi-geostrophic omega equation to the life cycle of a rapidly developing cyclone demonstrates that latent heat release is a major contributor to vertical motions or omega. Throughout this research study, focus has been on maximum negative 700hPa omega patterns, their contribution to intense cyclogenesis due to latent heat release (lower level closed circulation to middle level trough) and other physical/dynamical processes, using NARR variable archives. Although Kocin and Uccellini (2004) Volume I acknowledges that assessing the relative importance of sensible and latent heat processes is difficult, if not counterproductive, an objective of this research is to encourage NOAA/NWS forecasters that being more aware of the contributions of latent heat release and the other synoptic to mesoscale physical processes could definitely improve heavy snowfall forecasts which are dependent on the large-scale circulation pattern(s).

Another important goal of this research is to focus as much on the synoptic and mesoscale physical processes, including LHR, as on the forecast parameter or variable. This emphasis is likely to increase the confidence of snowfall amount forecast(s) associated with a major winter storm. Study has reached this goal through presentation analyses, including tables, for each of the six events.

Uccellini et al. 1987 use the phrase “full physics” to refer to model simulation that includes planetary boundary layer or sensible, latent heat fluxes and latent heat release. This research has shown that both latent, sensible heat fluxes at surface and latent heat release (lower to middle levels of troposphere) “complex interact” (Kocin and Uccellini 2004 Volume I), “synergistic interact” (Uccellini et al

1987) or contributed along with other variables synoptic and mesoscale processes to provide a more “realistic” rate of cyclone development that is prerequisite for accurate model prediction of the storm regional snowfall distribution and heavy snow areas.

While the large-scale circulation (ENSO and teleconnections) which provides an important framework on which each of the six events evolve is unique for each event, there are some common patterns. The ENSO patterns are moderate La Nina for 25-26 December 2010 and 1-2 February 2011 events, neutral conditions for 13-14 March 1993 and 30-31 January 1982, weak to moderate El Nino for 19 January 1995 and 14-15 December 1987 events. The teleconnection patterns are weak negative AO for 19 January 1995, 30-31 January 1982 and 14-15 December 1987 events. However, 13-14 March 1993, both AO and NAO were weak positive. For 1-2 February 2011, January 2011 moderate negative AO became moderate positive February 2011 AO. Reflecting 25-26 December 2010, AO was strong negative and NAO was moderate negative. So, central purpose or theme that unites each of the six cases is the heavy snow that developed during these events was a “manifestation of a complex interaction” or contribution among the many or several physical processes that occur on the synoptic and mesoscales. This has been shown by presentation analyses throughout this study.

REFERENCES

Danard, M.B., 1964: On the influence of released latent heat on cyclone development. *J. Appl. Meteor.* **3,** 27-37.

Holton, J.R. and G.J Hakim, 2013: *An Introduction to Dynamic Meteorology.* 5th ed. Academic Press, 532 pp.

Kocin, P.J., L.W. Uccellini and R.A. Petersen, 1986: Rapid evolution of a jet stream circulation in a pre-convective environment. *Meteor. Atmos. Phys.,* **35,** 103-138.

_________, P.N. Schumacher, R.F. Morales Jr. and L.W. Uccellini, 1995: Overview of the 12-14 March 1993 Superstorm. *Bull. Amer. Meteor. Soc.,* **76,** 165-182.

Kocin, P.J and L.W. Uccellini, 2004: Northeast Snowstorms: Volume I: Overview: *Amer. Meteor. Soc.,* 296 pages.

________ and___________, 2004: Northeast Snowstorms: Volume II: The Cases. *Amer. Meteor*. Soc., 821 pages.

Krishnamurti, T.N., 1968: A study of a developing wave cyclone. *Mon. Wea. Rev.,* **96,** 208-217.

Loughe, A., C.-C. Lai and D. Keyser, 1995: A technique for diagnosing three-dimensional circulations in baroclinic disturbances on limited area domains. *Mon. Wea. Rev.,* **123,** 1476-1504.

Market, P.S., C.E. Halcomb and R.L. Ebert, 2002: A climatology of thunder-snow events over the contiguous United States. *Wea. Forecasting,* **17,** 1290-1295.

Martin, J.E., 1998: The structure and evolution of a continental winter cyclone. Part II: Frontal forcing of an extreme snow event. *Mon. Wea. Rev.,* **126,** 329-348.

Moore, J. T. and P. D. Blakely, 1988: The Role of Frontogenesis Forcing and Conditional *S*ymmetric instability in the Midwest Snowstorm of 30-31 January 1982. *Mon. Wea. Rev.,* ***116*,** 2155-2171.

__________and G.E. Vanknowe, 1992: The effect of jet-streak curvature on kinematic fields. *Mon. Wea. Rev.,* **120,** 2429, 2432.

__________and T. E. Lambert, 1993: The use of equivalent potential vorticity to diagnose regions of conditional symmetric instability. *Wea. Forecasting,* **8,** 301-308.

Pokrandt, P.J., G.J. Tripoli and D.D. Houghton, 1996: Processes leading to the formation of mesoscale waves in the Midwest cyclone of 15 December 1987. *Mon. Wea. Rev.,* **124,** 2726-2752.

Rauber et al. 2014: Stability and charging characteristics of the comma head Region of continental winter cyclones. *J. Atmos. Sci.,* **71,** 1559-1582.

Rosenow et al 2014: Vertical motions within generating cells and elevated convection in the comma head of winter cyclones. *J. Atmos. Sci.* **71,** 1538-1558.

Schneider, R.S., 1990a: Large-amplitude mesoscale wave disturbances within the intense Midwest extratropical cyclone of 15 December 1987. *Wea.Forecasting,* **5,** 533-558.

___________, and G. Vaughan, 2011: Occluded fronts and the occlusion process: A fresh look at conventional wisdom. *Bull. Amer. Meteor. Soc.,***92,** 443-466.

Uccellini, L.W. and P.J. Kocin, 1987: An examination of vertical circulations associated with heavy snow events along the East Coast of the United States. *Wea. Forecasting,* **2,** 289-308.

___________, L.W., R.A. Petersen, K.F. Brill, P.J. Kocin and J.J. Tuccillo, 1987: Synergistic interactions between an upper-level jet streak and diabatic processes that influence the development of a low-level jet and secondary coastal cyclone. *Mon. Wea. Rev.,* **115,** 2227-2261.

Weather Prediction Center (WPC) Event Review: 25-27 December 2010 Winter Storm, Eastern United States.

30–31 January 1982 Event	**14–15 December 1987 Event**
Variable or Parameter (documented or observation/analysis)	Variable or Parameter (documented or observation/analysis)
850hPa Low Level Jet (LLJ)	850hPa LLJ
850hPa Warm Air Advection (WAA)	850hPa WAA
850hPa Cold Air Advection (CAA)	850hPa CAA
Latent Heat Release (LHR)	Latent Heat Release (LHR)
$\omega \leq -1.2$ pa s^{-1} 700hPa	$\omega \leq -0.90$ pa s^{-1} 700hPa
Frontogenesis (Surface, 850hPa, 700- 500hPa)	Frontogenesis (Surface, 850hPa, 700-500hPa)
CSI/MSI and EPV	CSI/MSI and EPV
Cyclone tracks and Cyclogenesis	Cyclone tracks and Cyclogenesis
Elevated Convection	Elevated Convection
700hPa RH≥80%	Mesoscale Gravity Wave Interaction
Jet streak-induced Ageostrophic circulation	EPVg and CI (800-750hPa) (650-500hPa)
850hpa Temperature Gradients	Jet streak-induced Ageostrophic circulation

Enhanced IR Satellite Imagery	700hPa RH≥80%
850hPa **Q** vector/isotherm fields	Enhanced Satellite Imagery

Table 1. Comparison of variables most relevant to the 30-31 January 1982 event with variables most relevant to the 14-15 December 1987 event

19 January 1995 Event	**1 - 2 February 2011 Event**
Variable or Parameter (documented and/or indicated from surface/upper air analyses)	Variable or Parameter (documented and/or indicated from surface/upper air analyses)
$\omega \leq -0.90$ pa s^{-1} 700hPa	$\omega \leq -1.2$ pa s^{-1} 700hPa
TROWAL	850hPa Temperature (°K)
Frontogenesis (850hPa, 700-500hPa)	850hPa Temperature Gradients (°K)
Elevated Convection	TROWAL and CSI (Cross-sectional analyses), EPV
EPVg and CI (800-750hPa) (650-500hPa)	Frontogenesis (850hPa, 700-500hPa)
Latent Heat Release (LHR)	Latent Heat Release (LHR)
700hPa RH≥80%	700hPa RH≥80%
Cyclonic Advection of θe	Elevated Convection
Cyclone tracks and cyclogenesis (indicated from surface analyses)	Cyclone tracks and cyclogenesis (indicated from surface analyses)
Jet streak-induced Ageostrophic circulation (indicated from literature)	Jet streak-induced Ageostrophic circulation (indicated from literature)
Low Level Jet (LLJ) (indicated from literature)	Low Level Jet (LLJ) (indicated from literature)
Warm Air Advection (WAA) (indicated from literature)	Warm Air Advection (WAA) indicated from literature)
Cold Air Advection (CAA) (indicated from literature)	Cold Air Advection (CAA) (indicated from literature)
	Mesoscale Gravity Wave Interaction (indicated from surface analyses)

Table 2. Parameters relevant to 19 January 1995 event comparison to parameters relevant to 1-2 February 2011 event

13 - 14 March 1993 Event	**25 – 26 December 2010 Event**
Variable or Parameter	Variable or Parameter
$\omega \leq -1.3$ pa s^{-1} 700hPa	$\omega \leq -0.90$ pa s^{-1} 700hPa

Enhanced IR Satellite Imagery	Frontogenesis (Surface, 850hPa, 700-500hPa)
850hPa Low Level Jet (LLJ)	Cyclone tracks and Cyclogenesis
CSI/MSI and EPV	Elevated Convection
Frontogenesis (Surface, 850hPa, 700-500hPa)	EPVg and CI (850hPa-750hPa) (650-500hPa)
Cyclone tracks and Cyclogenesis	Differential Positive Vorticity Advection (700-450hPa)
LHR	TROWAL
Elevated Convection	700hPa RH≥80%
TROWAL	LHR
700hPa RH≥80%	850hPa WAA
850hPa convergence and 250hPa divergence	850hPa CAA
850hPa Warm Air Advection (WAA)	Jet streak-induced Ageostrophic circulation
850hPa Cold Air Advection (CAA)	850hPa LLJ
Isentropic Potential Vorticity	850hPa Temperature Gradients
Latent and Sensible Heat Fluxes at Surface (Gulf of Mexico and Atlantic Ocean)	Latent and Sensible Heat Fluxes at Surface (off middle Atlantic and northeast coasts)
Jet streak-induced Ageostrophic circulation	
Potential Vorticity Advection into cyclone center	
850hPa Temperature Gradients	

Table 3. Parameters relevant to 13-14 March 1993 event comparison to parameters relevant to 25-26 December 2010 event

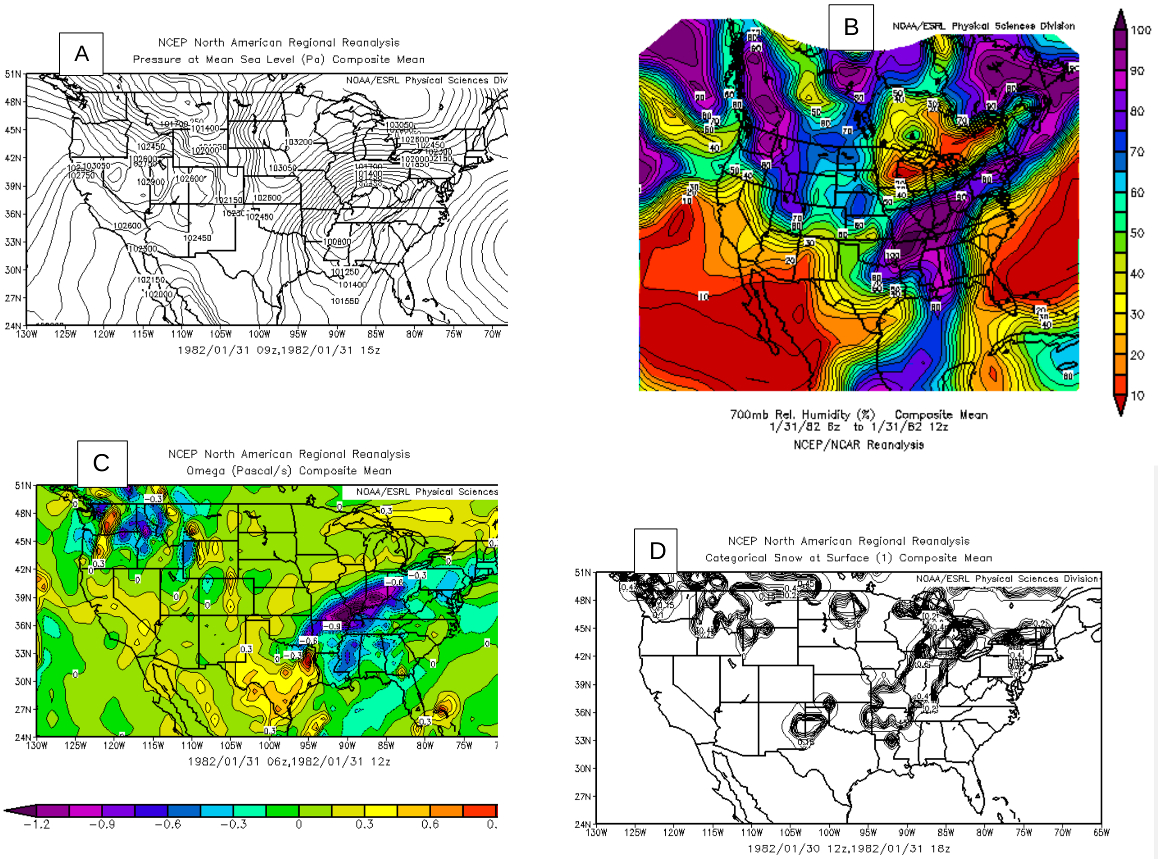


Figure 1. 30-31 January 1982 - Image [A] is event Pressure at Mean Sea Level≤100400. Image [B] is event 700hPa RH≥80%. Image [C] is event 700hPa Omega≤-1.2. Image [D] is event Categorical Snow at Surface<1. Images [A], [B], [C] indicate complex interaction of these variables to produce the regional distribution of snowfall shown in Image [D] and focus on the patterns of middle level moisture and ascent north-northeast of the cyclone center that enhance snowfall rates, subsequently increase accumulations.

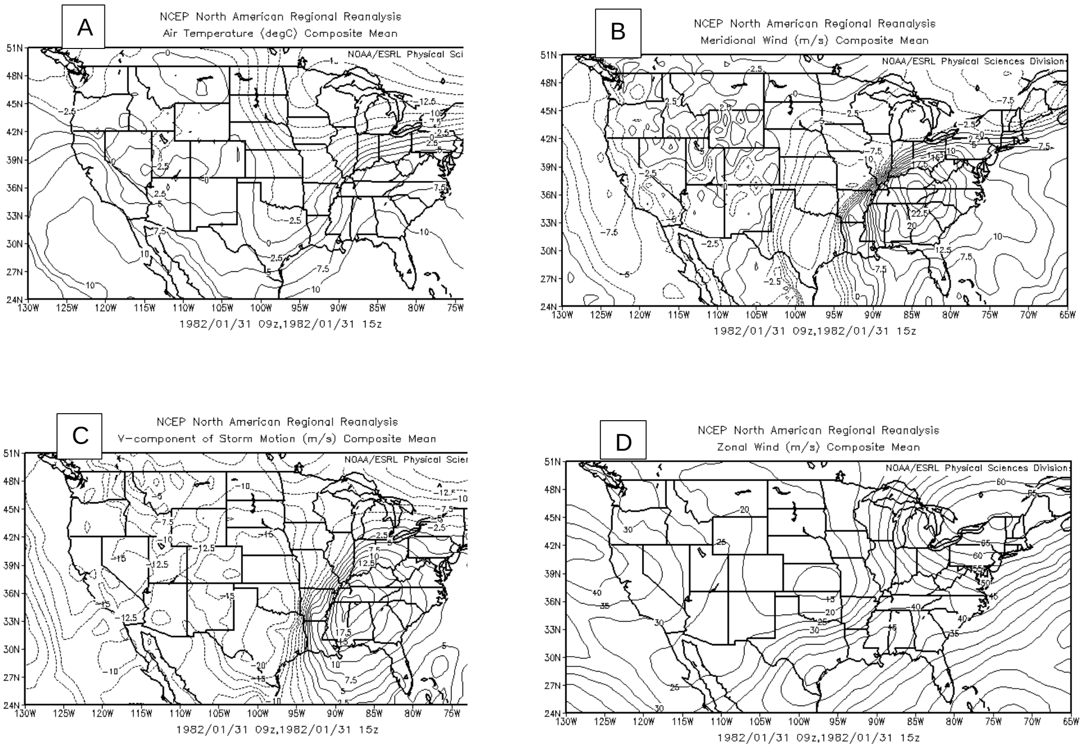


Figure 2. 30-31 January 1982 – Image [A] is event 850hPa Temperature. Image [B] is event 850hPa Meridional Wind. Image [C] is event 700hPa V-Component of Storm Motion. Image [D] is event 850hpa Zonal Wind. Images [A], [B], [C], [D] indicate a complex interaction of these variables to produce the regional distribution of snowfall shown in Figure 1 Image [D].

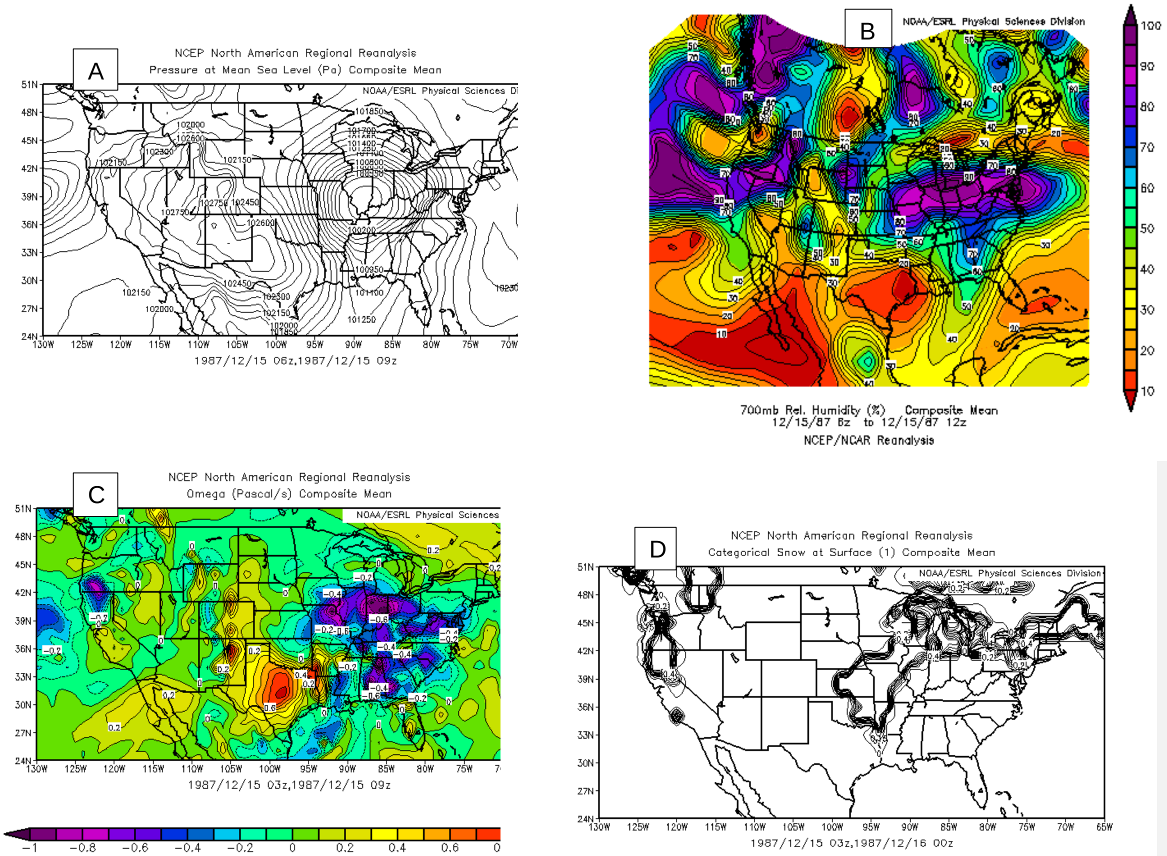


Figure 3. 14-15 December 1987 – Image [A] is event Pressure at Mean Sea Level≤100000. Image [B] is event 700hPa RH≥80%. Image [C] is event 700hPa Omega≤-0.9. Image [D] is event Categorical Snow at Surface<1. Images [A], [B], [C] indicate a complex interaction of these variables to produce the regional distribution of snowfall shown in Image [D] and focus on the patterns of middle level moisture and ascent north-northeast of the cyclone center that enhance snowfall rates, subsequently increase accumulations.

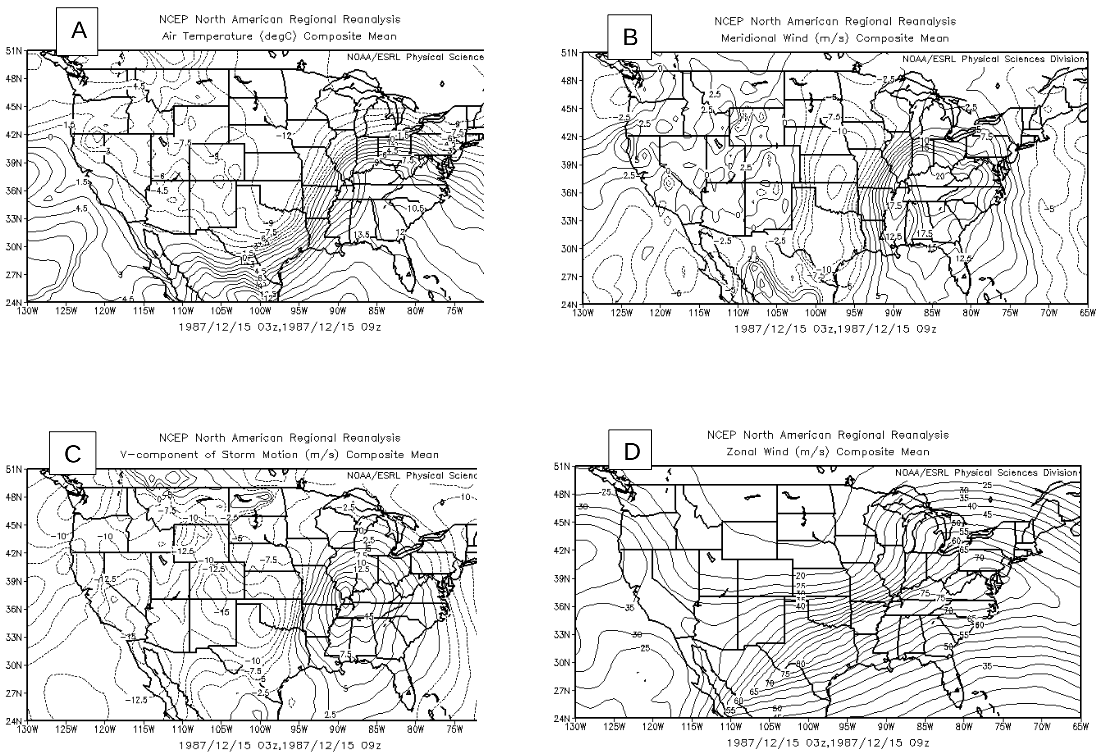


Figure 4. 14-15 December 1987 – Image [A] is event 850hPa Temperature. Image [B] is event 850hPa Meridional Wind. Image [C] is event 700hPa V-Component of Storm Motion. Image [D] is event 850hPa Zonal Wind. Images [A], [B], [C], [D] indicate a complex interaction of these variables to produce the regional distribution of snowfall shown in Figure 3 Image [D].

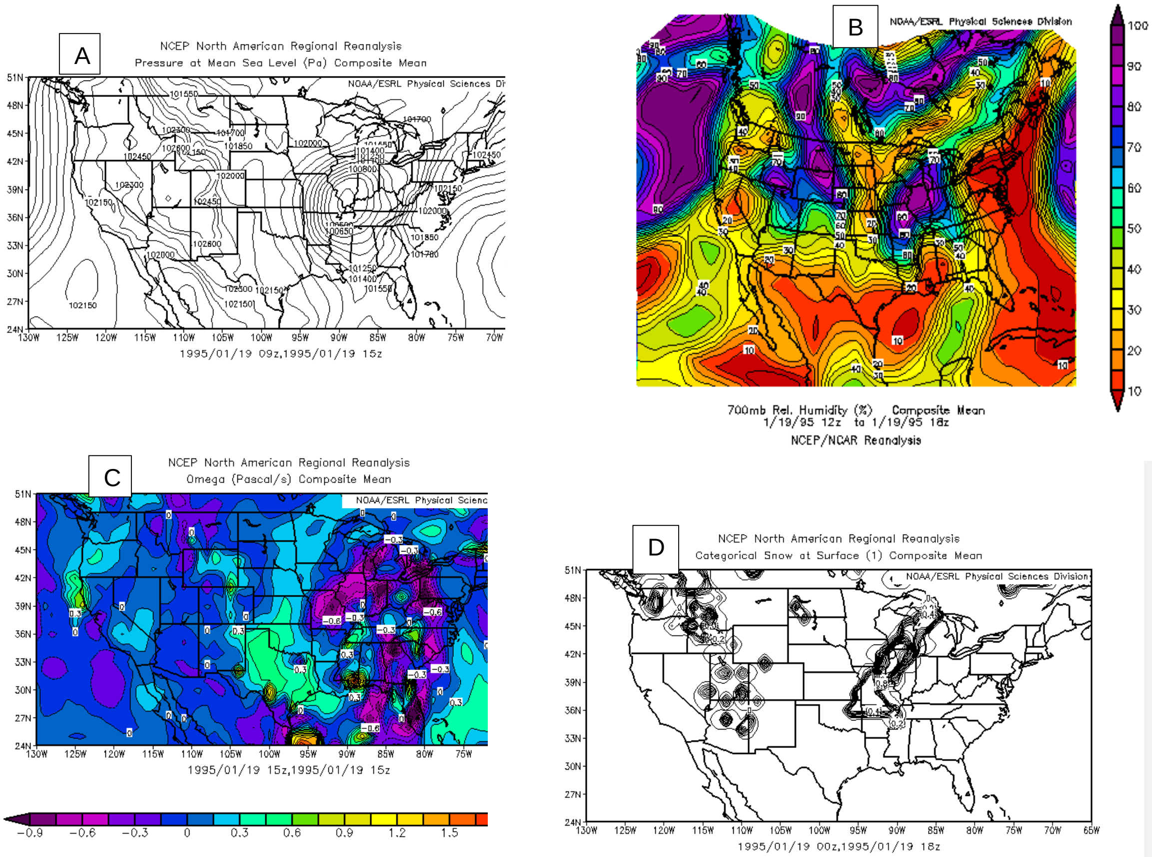


Figure 5. 19 January 1995 – Image [A] is event Pressure at Mean Sea Level≤100350. Image [B] is event 700hPa RH≥80%. Image [C] is event 700hPa Omega≤-0.9. Image [D] is event Categorical Snow at Surface<1. Images [A], [B], [C] indicate a complex interaction of these variables to produce the regional distribution of snowfall shown in Image [D] and focus on the patterns of middle level moisture and ascent north-northeast of the cyclone center that enhance snowfall rates, subsequently increase accumulations.

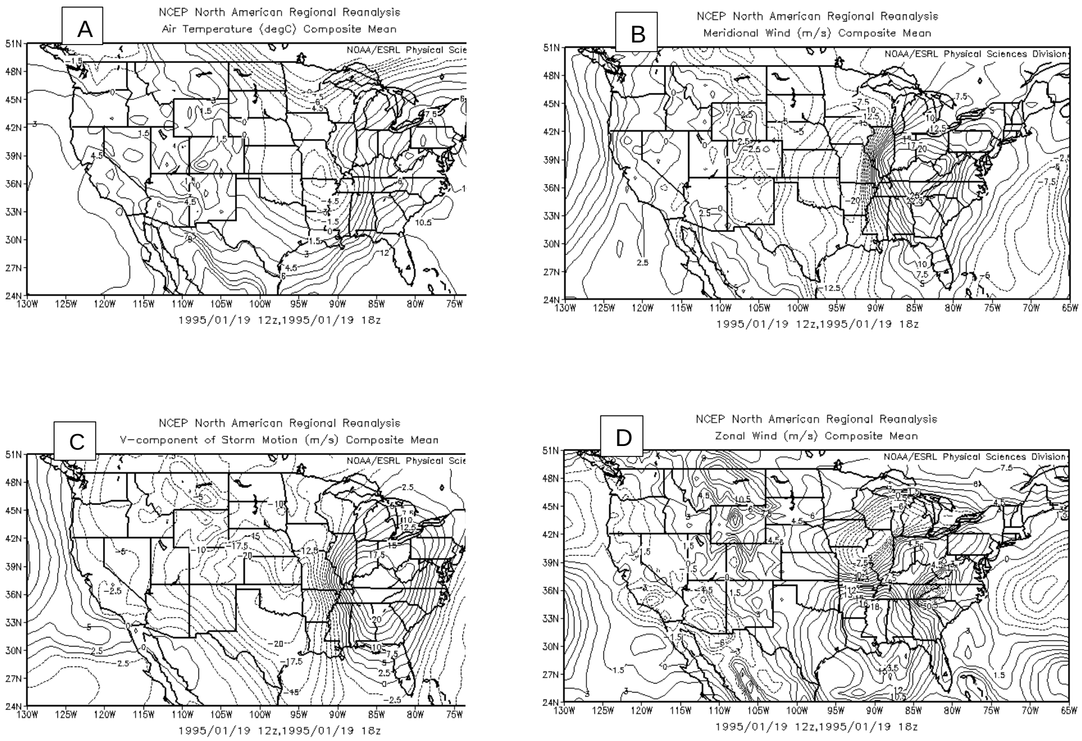


Figure 6. 19 January 1995 – Image [A] is event 850hPa Temperature. Image [B] is event 850hPa Meridional Wind. Image [C] is event 700hPa V-Component of Storm Motion. Image [D] is event 850hPa Zonal Wind. Images [A], [B], [C], [D] indicate a complex interaction of these variables to produce the regional distribution of snowfall shown in Figure 5 Image [D].

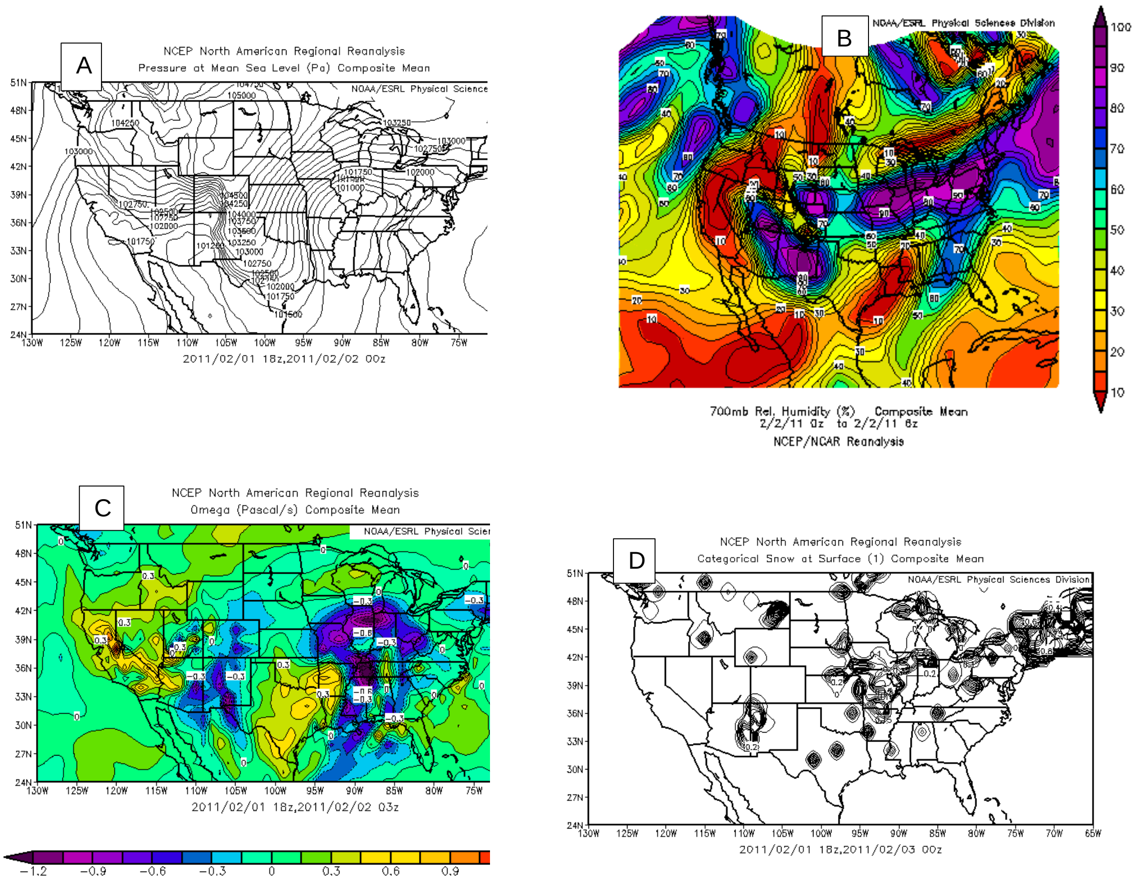


Figure 7. 1-2 February 2011 – Image [A] is event Pressure at Mean Sea Level ≤100850. Image [B] is event 700hPa RH≥80%. Image [C] is event 700hPa Omega≤-1.2. Image [D] is event Categorical Snow at Surface<1. Images [A], [B], [C] indicate a complex interaction of these variables to produce the regional distribution of snowfall shown in Image [D] and focus on the patterns of middle level moisture and ascent to north-northeast of the cyclone center that enhance snowfall rates and subsequently increase accumulations.

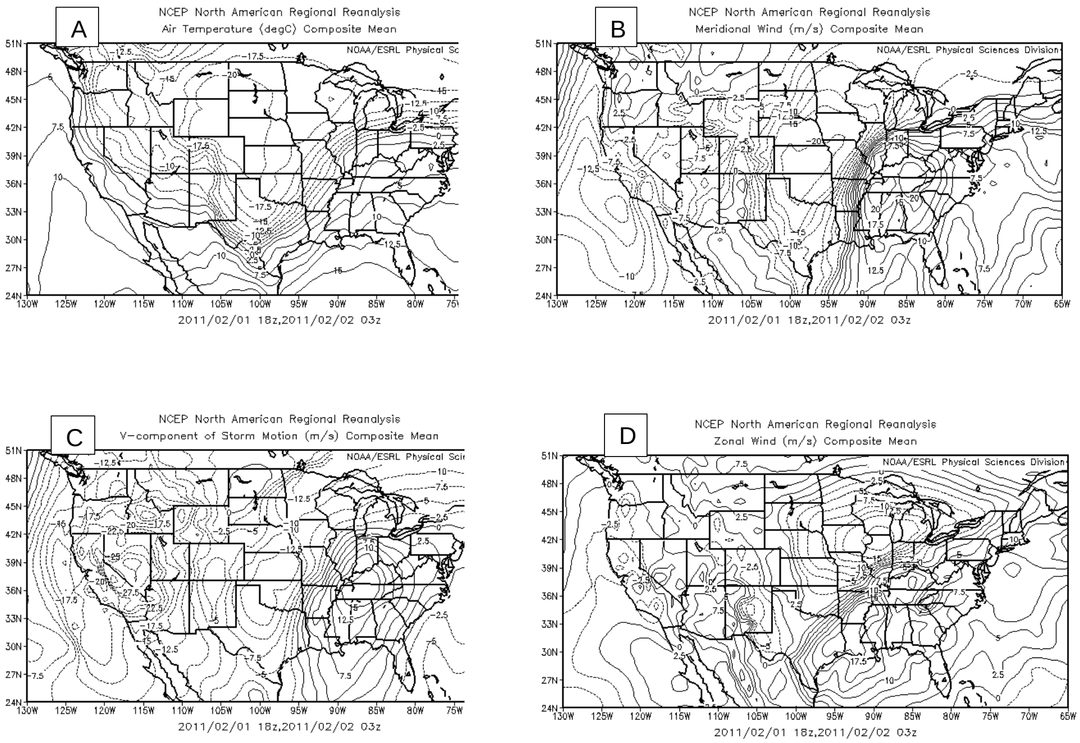


Figure 8. 1-2 February 2011 – Image [A] is event 850hPa Temperature. Image [B] is 850hPa Meridional Wind. Image [C] is event 700hPa V-Component of Storm Motion. Image [D] is event 850hPa Zonal Wind. Images [A], [B], [C], [D] indicate a complex interaction of these variables to produce the regional snowfall distribution shown in Figure 7 Image [D].

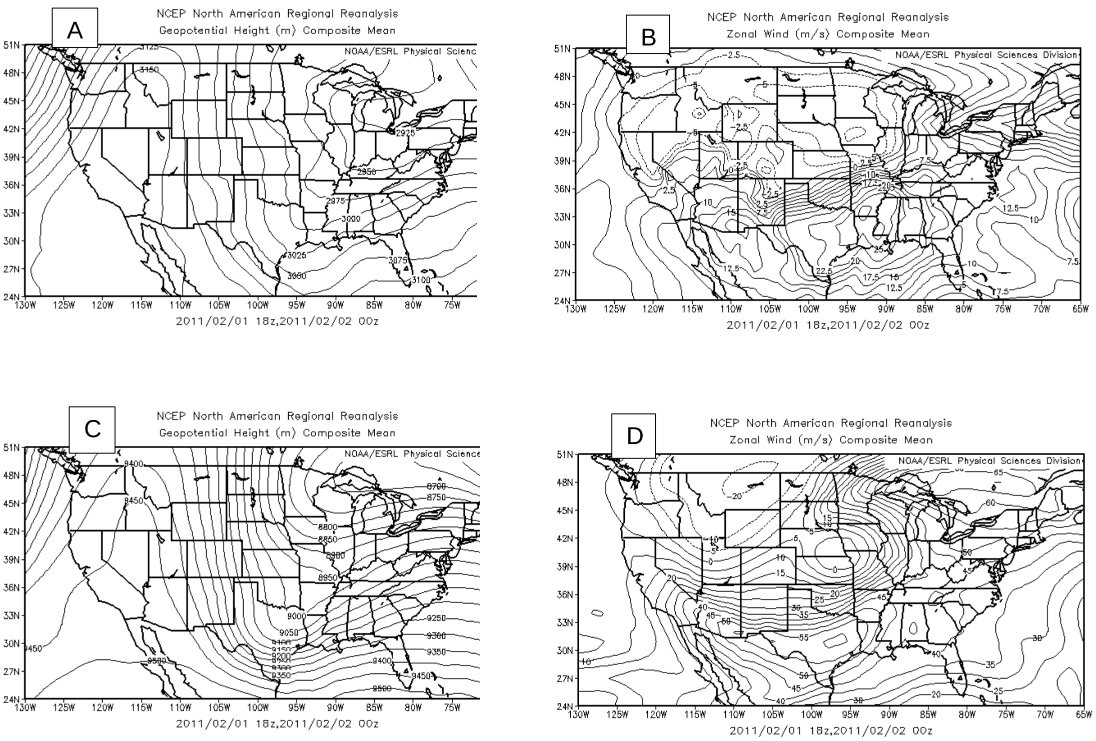


Figure 9. 1-2 February 2011 – Image [A] is event 700hPa Height. Image [B] is event 700hPa Zonal Wind. Image [C] is event 300hPa Height. Image [D] is event 300hPa Zonal Wind. Images [A], [B], [C], [D], also, indicate a complex interaction of these variables to produce the regional distribution of snowfall shown in Figure 7 Image D.

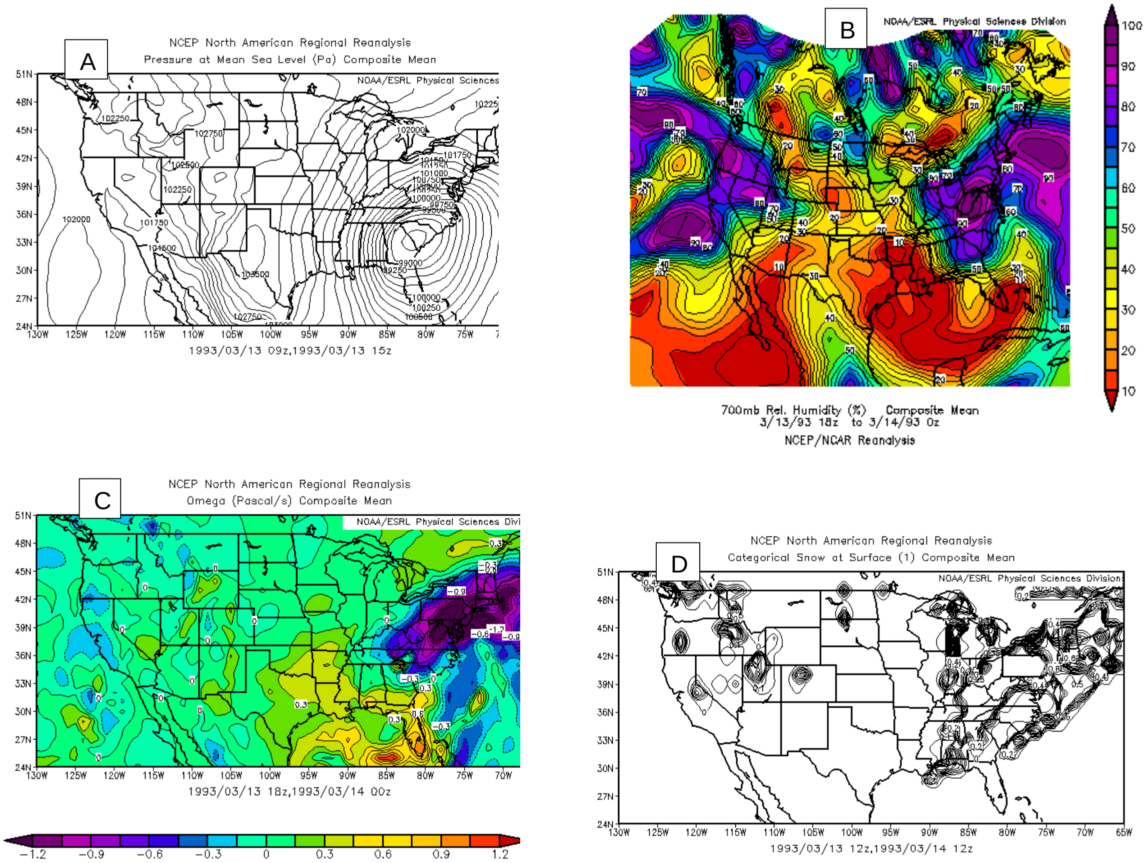


Figure 10. 13-14 March 1993 – Image [A] is event Pressure at Mean Sea Level≤98750. Image [B] is event 700hPa RH≥80%. Image [C] is event 700hPa Omega≤-1.3. Image [D] is event Categorical Snow at Surface<1. Images [A], [B], [C] indicate a complex interaction of these variables to produce the regional distribution of snowfall shown in Image [D] and focus on the patterns of middle level moisture and ascent north-northeast of the cyclone center that enhance snowfall rates, subsequently increase accumulations.

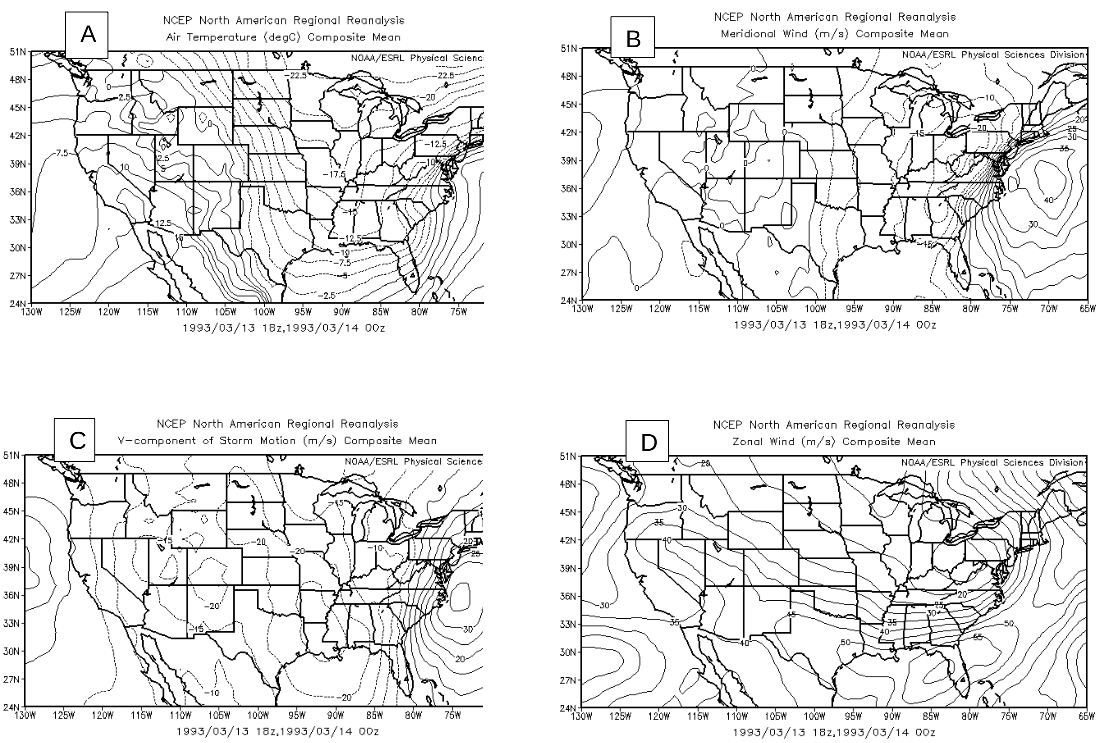


Figure 11. 13-14 March 1993 – Image [A] is event 850hPa Temperature. Image [B] is event 850hPa Meridional Wind. Image [C] is event 700hPa V-Component of Storm Motion. Image [D] is event 850hPa Zonal Wind. Images [A], [B], [C], [D] indicate a complex interaction of these variables to produce the regional distribution of snowfall shown in Figure 9 Image [D].

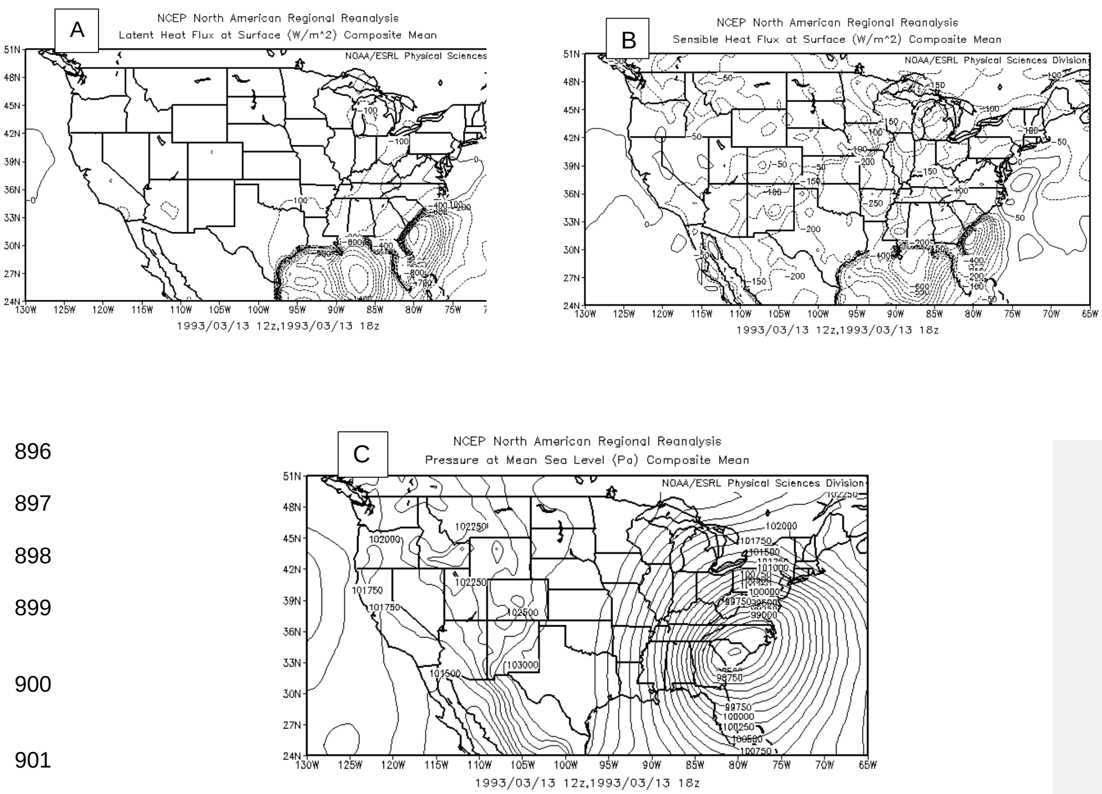


Figure 12. 13-14 March 1993 – Image [A] is event Latent Heat Flux at Surface 1200 – 1800 UTC 13 March 1993. Image [B] is event Sensible Heat Flux at Surface 1200 – 1800 UTC 13 March 1993. Image [C] is event Pressure at Mean Sea Level 1200 – 1800 UTC 13 March 1993.

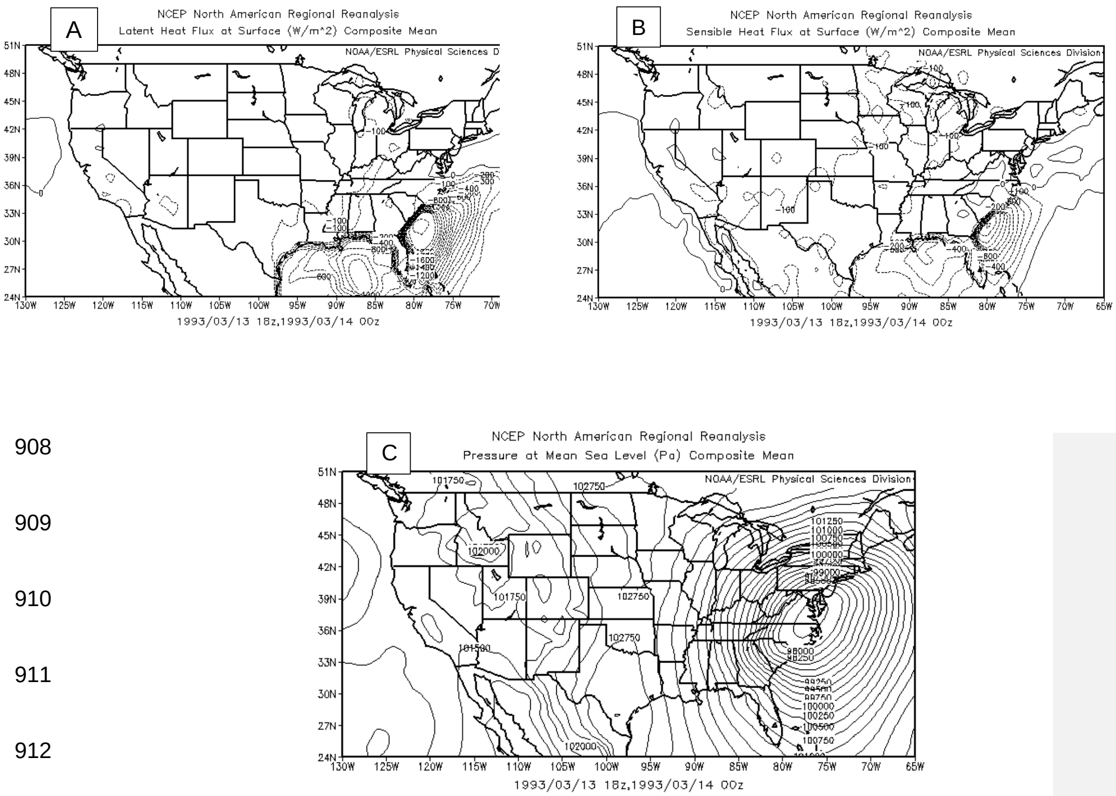


Figure 13. 13-14 March 1993 – Image [A] is event Latent Heat Flux at Surface 1800 UTC 13 March – 0000 UTC 14 March 1993. Image [B] is event Sensible Heat Flux at Surface 1800 UTC 13 March – 0000 UTC 14 March 1993. Image [C] is event Pressure at Mean Sea Level 1800 UTC 13 March – 0000 UTC 14 March 1993.

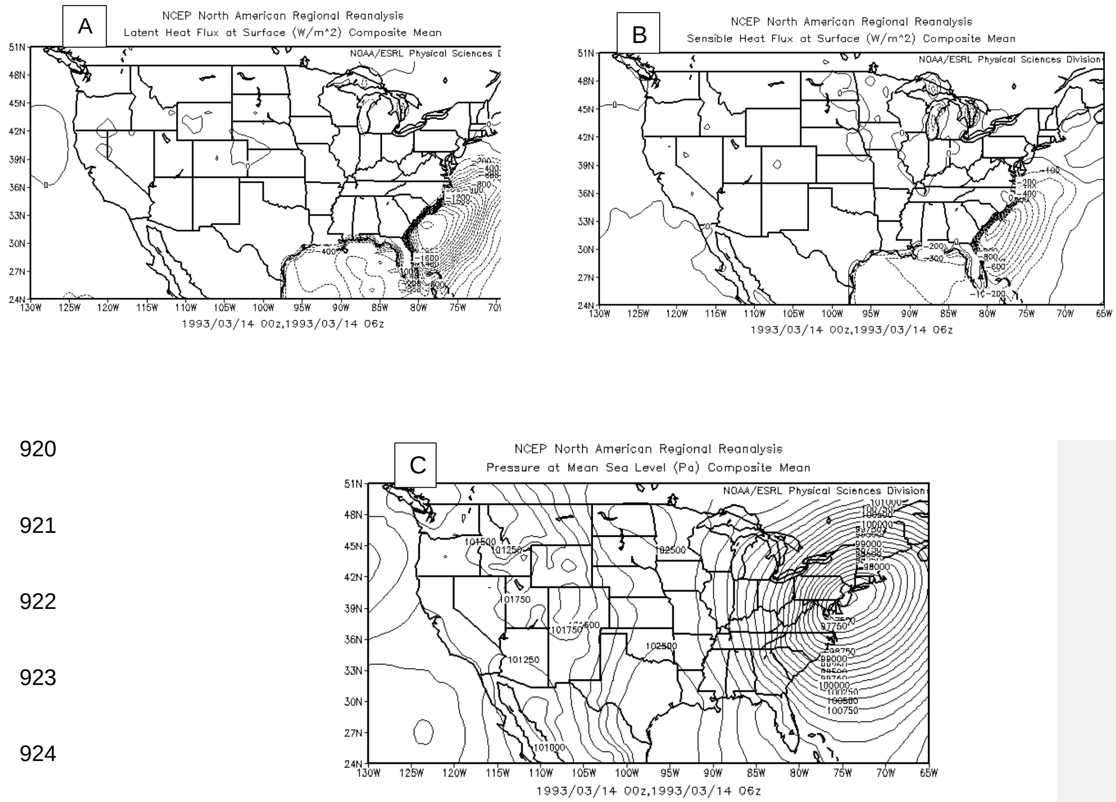


Figure 14. 13-14 March 1993 – Image [A] is event Latent Heat Flux at Surface 0000 – 0600 UTC 14 March 1993. Image [B] is event Sensible Heat Flux at Surface 0000 – 0600 UTC 14 March 1993. Image [C] is event Pressure at Mean Sea Level 0000 – 0600 UTC 14 March 1993.

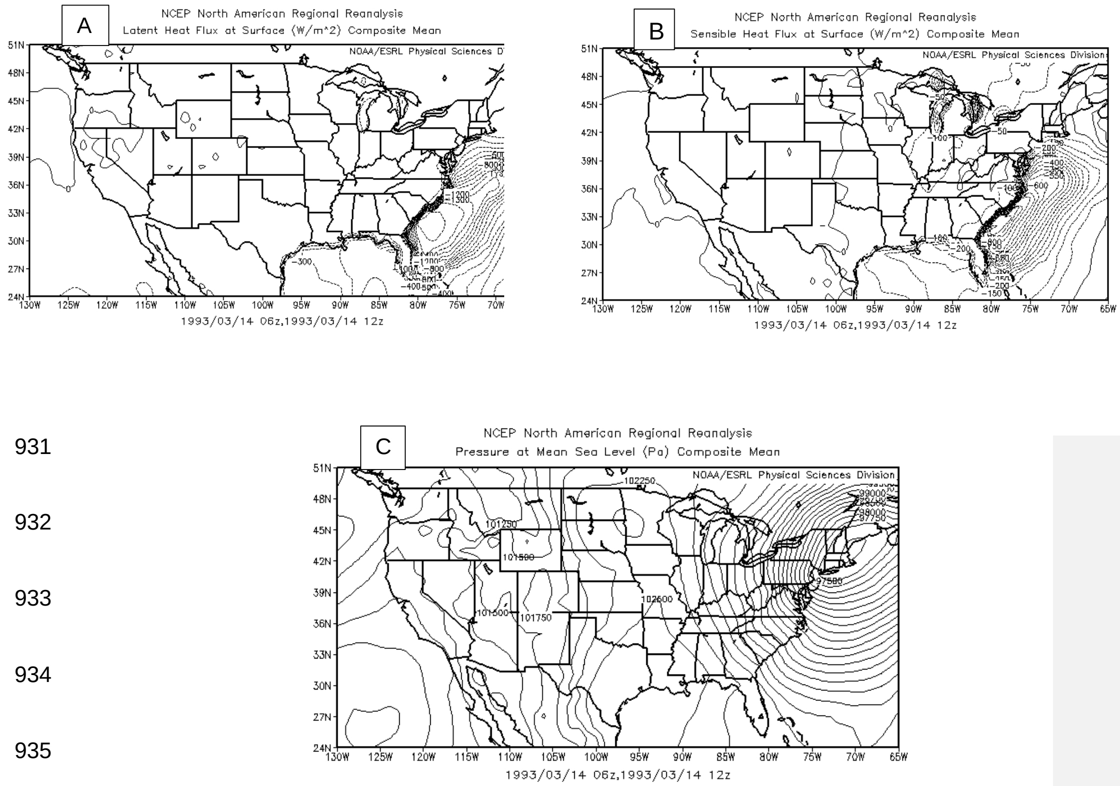


Figure 15. 13-14 March 1993 – Image [A] is event Latent Heat Flux at Surface 0600 – 1200 UTC 14 March 1993, Image [B] is event Sensible Heat Flux at Surface 0600 – 1200 UTC 14 March 1993. Image [C] is event Pressure at Mean Sea Level 0600 – 1200 UTC 14 March 1993.

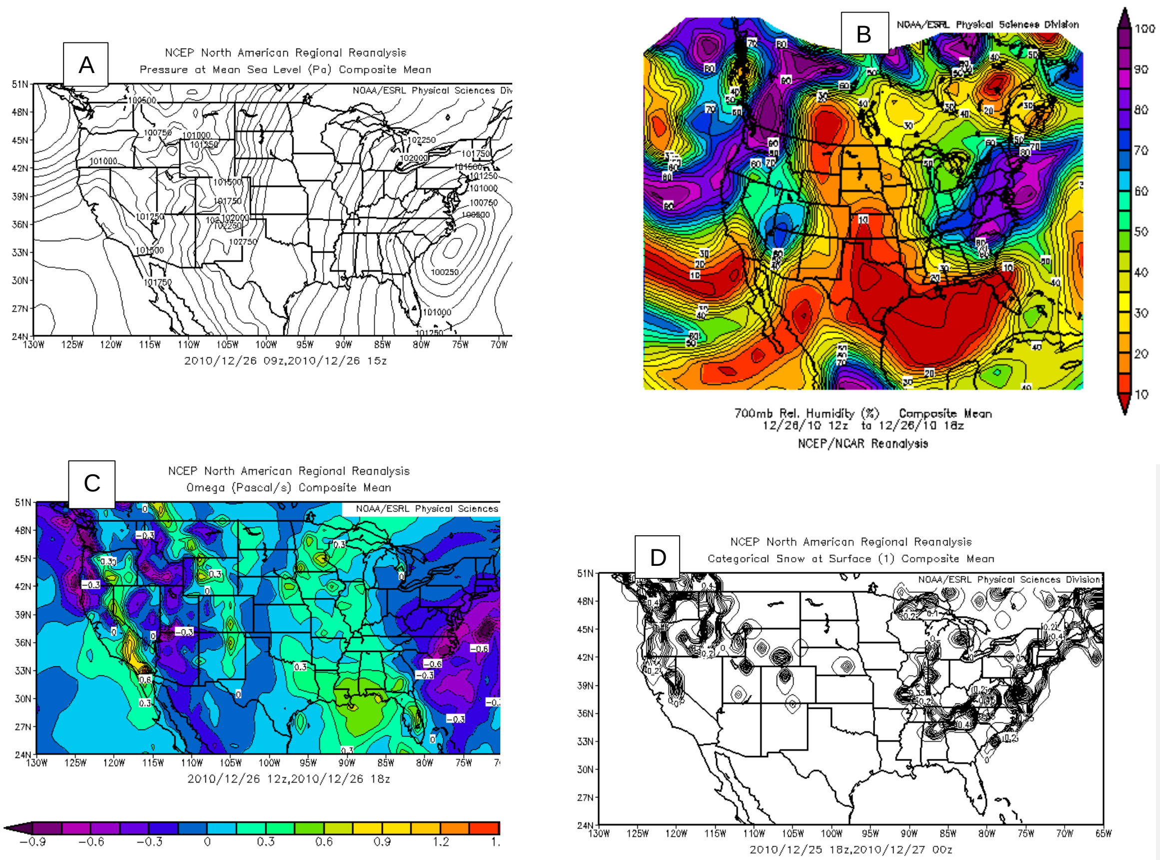


Figure 16. 25-26 December 2010 – Image [A] is event Pressure at Mean Sea Level≤100000. Image [B] is event 700hPa RH≥80%. Image [C] is event 700hPa Omega≤-0.90. Image [D] is event Categorical Snow at Surface<1. Images [A], [B], [C] indicate a complex interaction of these variables to produce the regional distribution of snowfall shown in Image [D] and focus on the patterns of middle level moisture and ascent north-northeast of the cyclone center that enhance event snowfall rates, subsequently increase accumulations.

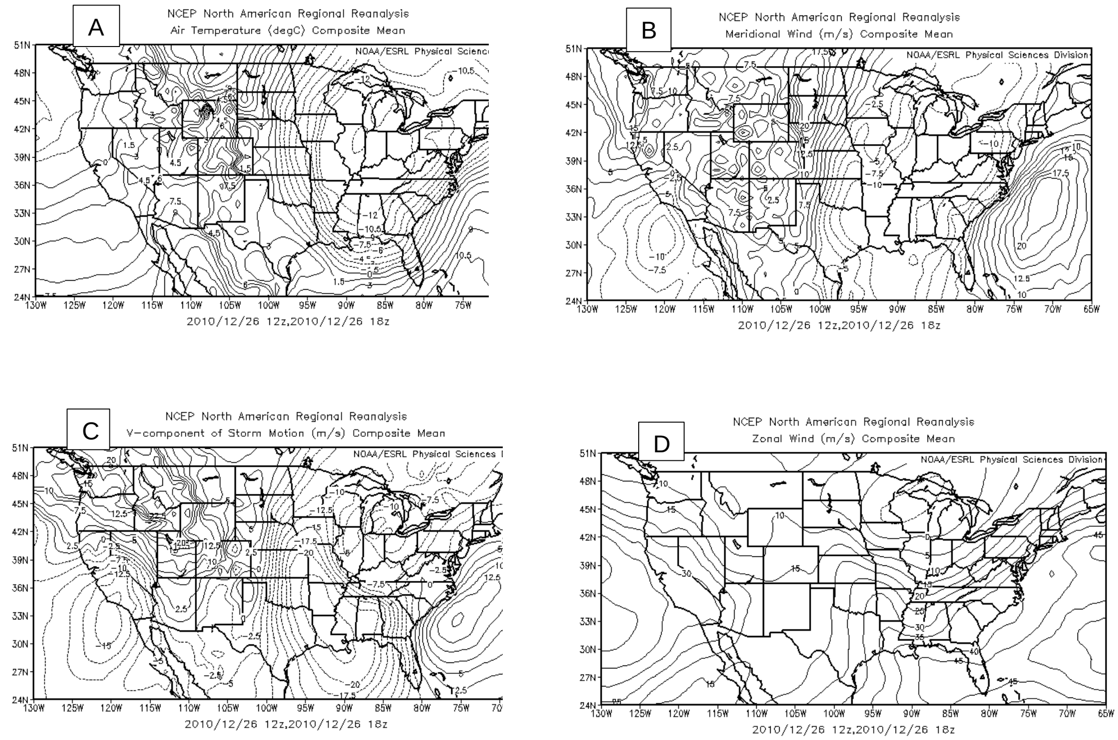


Figure 17. 25-26 December 2010 – Image [A] is event 850hPa Temperature. Image [B] is event 850hPa Meridional Wind. Image [C] is event 700hPa V-Component of Storm Motion. Image [D] is event 850hPa Zonal Wind. Images [A], [B], [C], [D] indicate a complex interaction of these variables to produce the regional distribution of snowfall shown Figure 11 Image [D].

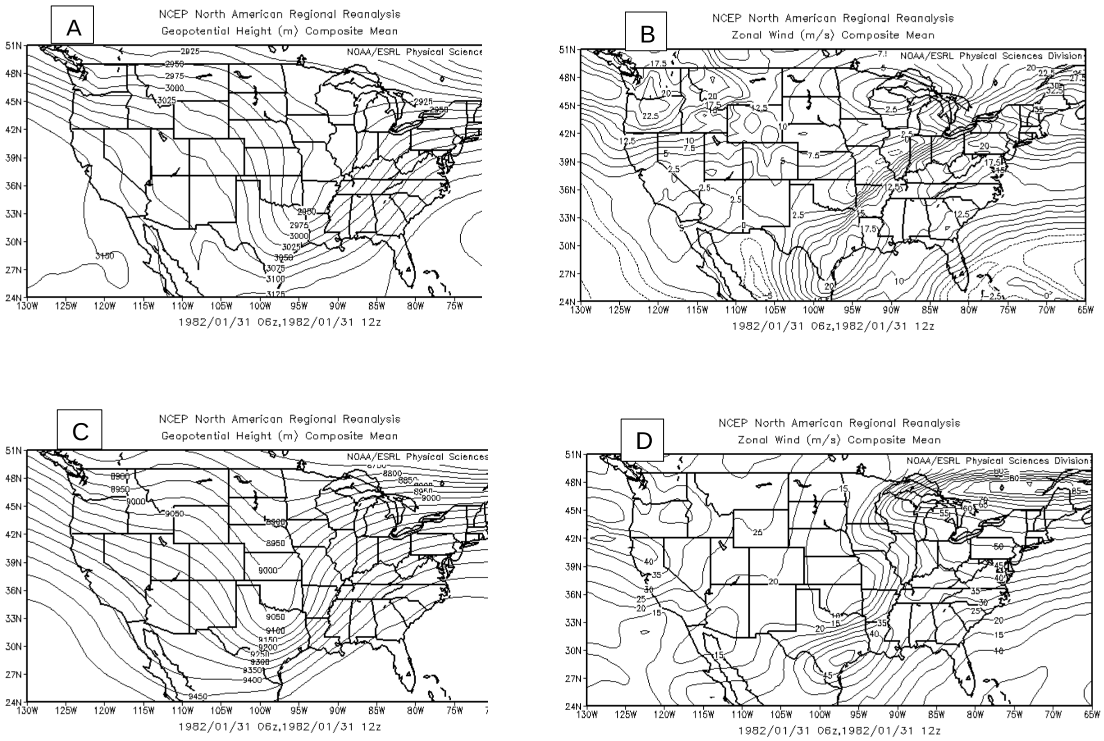


Figure 18. 30-31 January 1982 – Image [A] is event 700hPa Height. Image [B] is event 700hPa Zonal Wind. Image [C] is event 300hPa Height. Image [D] is event 300hPa Zonal Wind. Images [A], [B], [C]. [D], also, indicate a complex interaction of these variables to produce the regional distribution of snowfall shown in Figure 1 Image D.

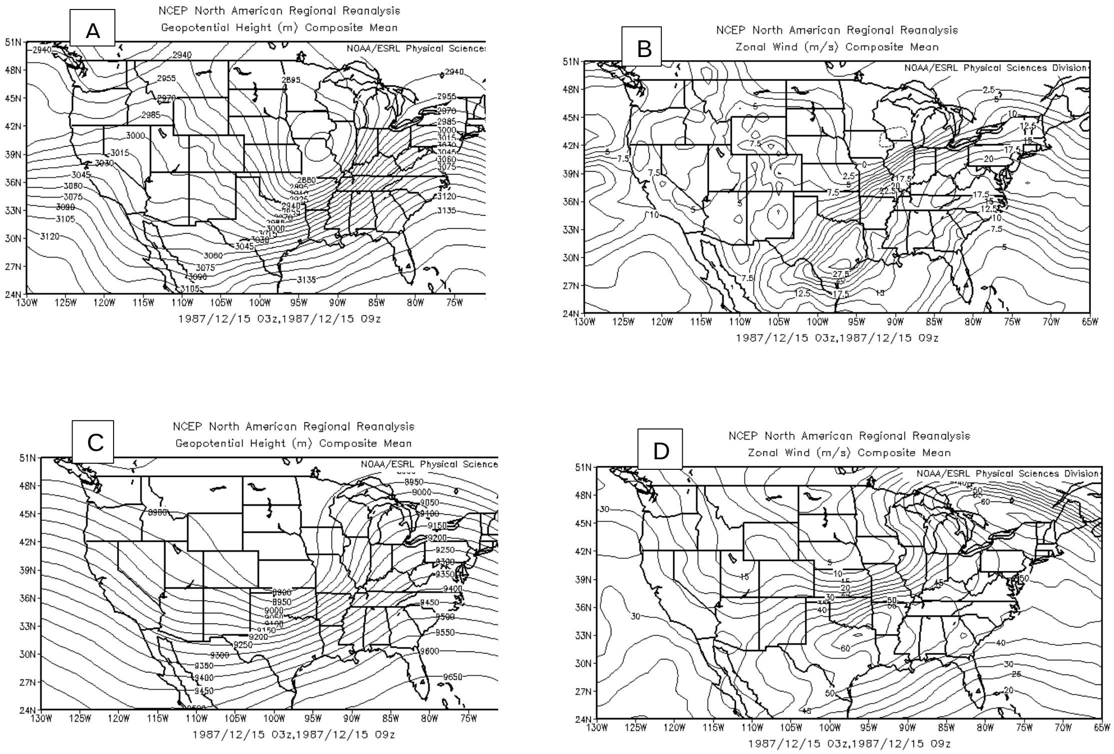


Figure 19. 14-15 December 1987 – Image [A] is event 700hPa Height. Image [B] is event 700hPa Zonal Wind. Image [C] is event 300hPa Height. Image [D] is event 300hPa Zonal Wind. Images [A], [B], [C], [D] indicate a complex interaction of these variables to produce the regional distribution of snowfall shown in Figure 3 Image D.

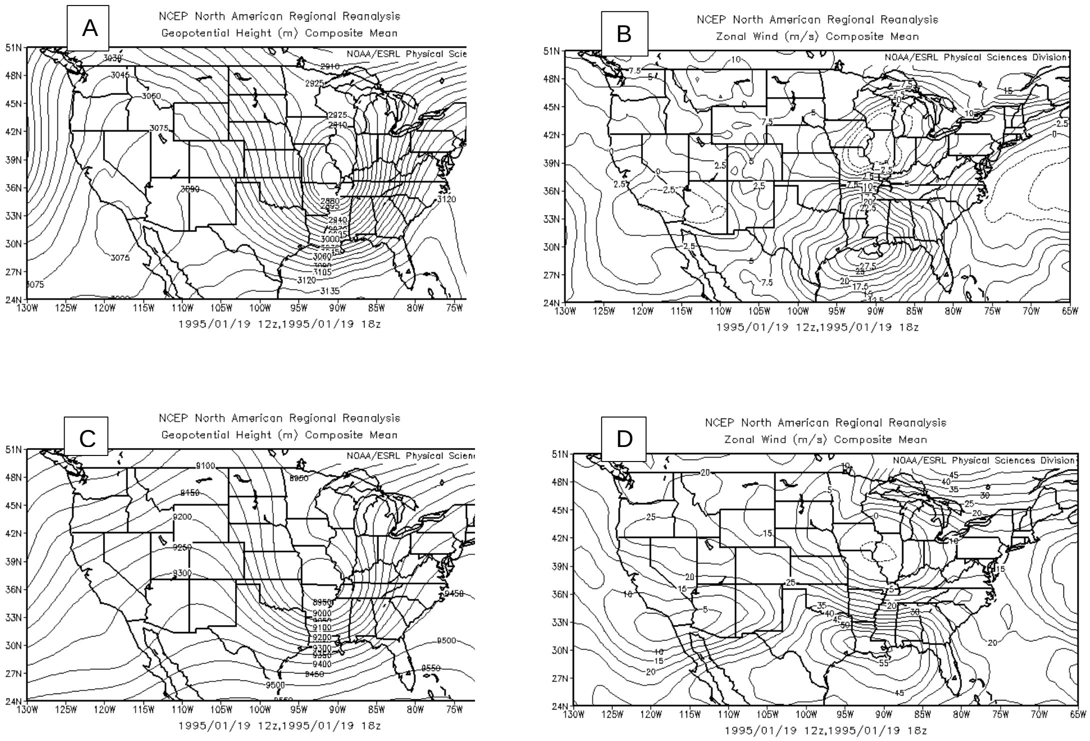


Figure 20. 19 January 1995 – Image [A] is event 700hPa Height. Image [B] is event 700hPa Zonal Wind. Image [C] is event 300hPa Height. Image [D] is event 300hPa zonal wind. Images [A], [B], [C], [D] indicate a complex interaction of these variables to produce the regional distribution of snowfall in Figure 5 Image D.

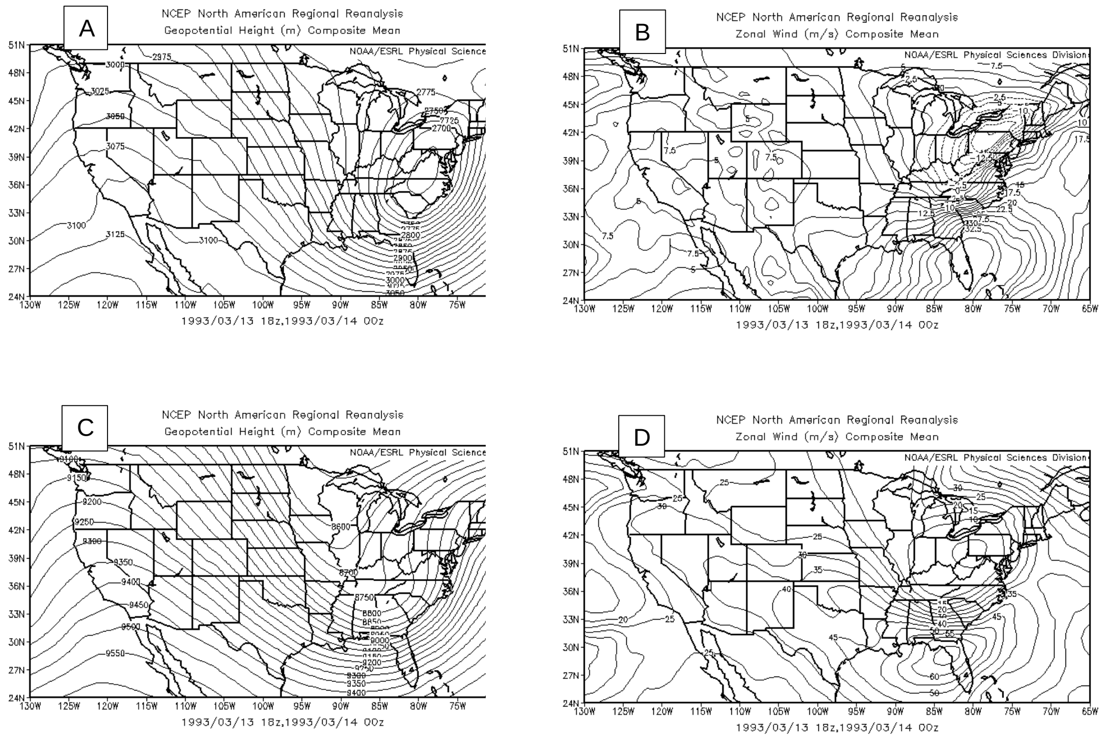


Figure 21. 13-14 March 1993 – Image [A] is event 700hPa Height. Image [B] is event 700hPa Zonal Wind. Image [C] is event 300hPa Height. Image [D] is event 300hPa Zonal Wind. Images [A], [B], [C], [D] indicate a complex of these variables to produce the regional distribution of snowfall shown in Figure 10 Image D.

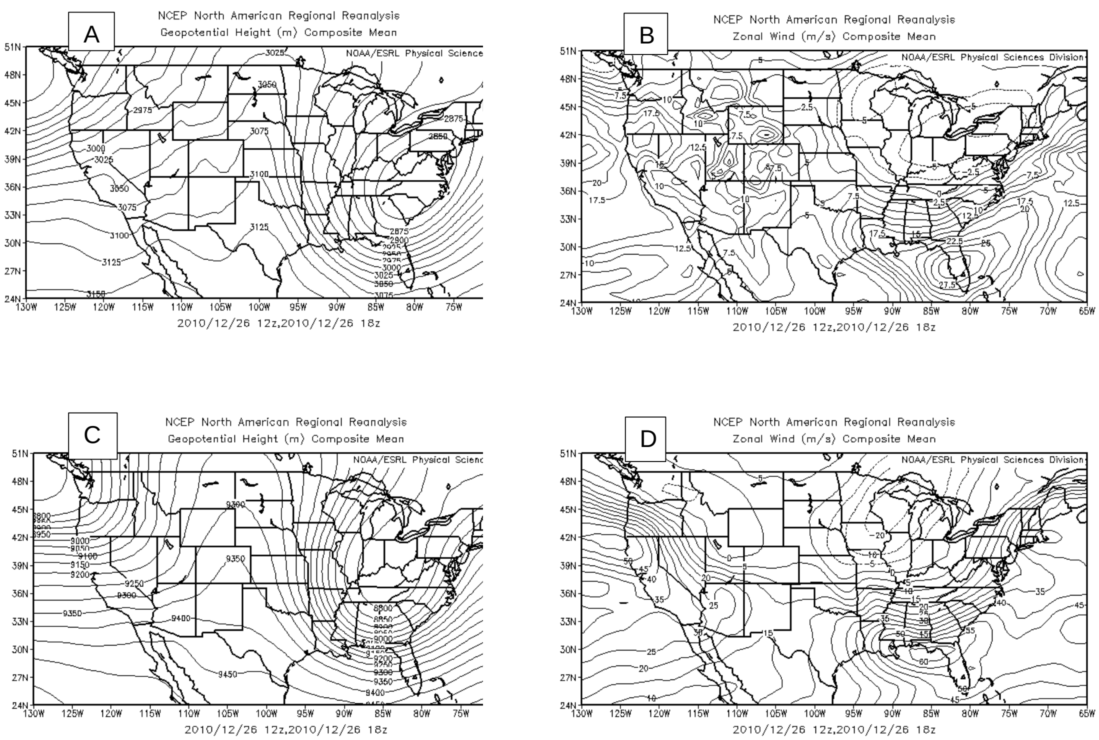
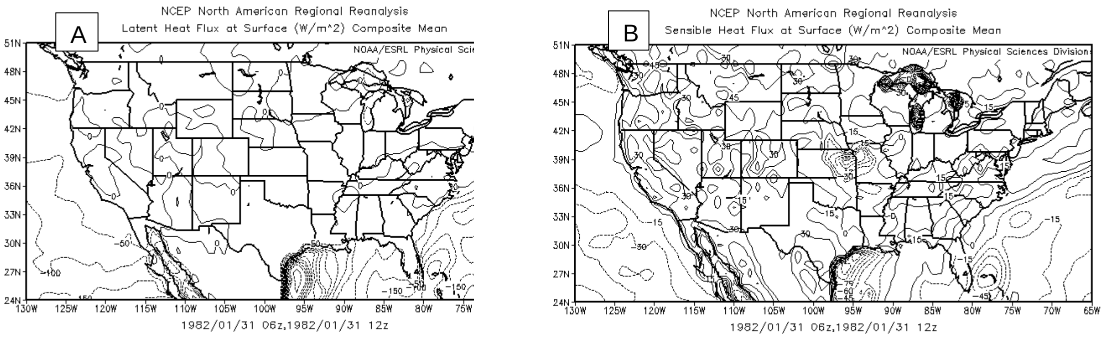


Figure 22. 25-26 December 2010 – Image [A], is event 700hPa Height. Image [B] is event 700hPa Zonal Wind. Image [C] is event 300hPa Height. Image [D] is event 300hPa Zonal Wind. Images [A], [B], [C], [D] indicate a complex interaction of these variables to produce the regional distribution of snowfall shown in Figure 16 Image D.



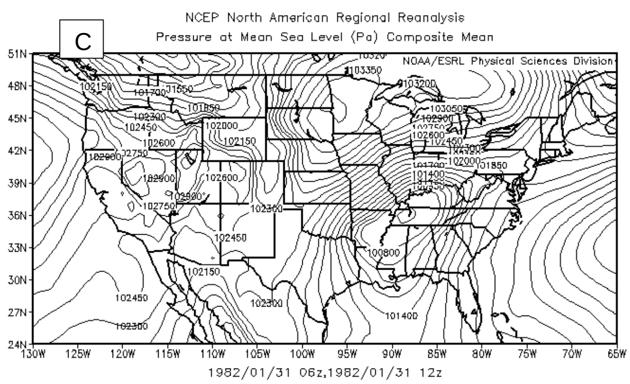


Figure 23. 30-31 January 1982 – Image [A] is selected event Latent Heat Flux at Surface. Image [B] is selected event Sensible Heat Flux at Surface. Image [C] is selected event Pressure at Mean Sea Level.

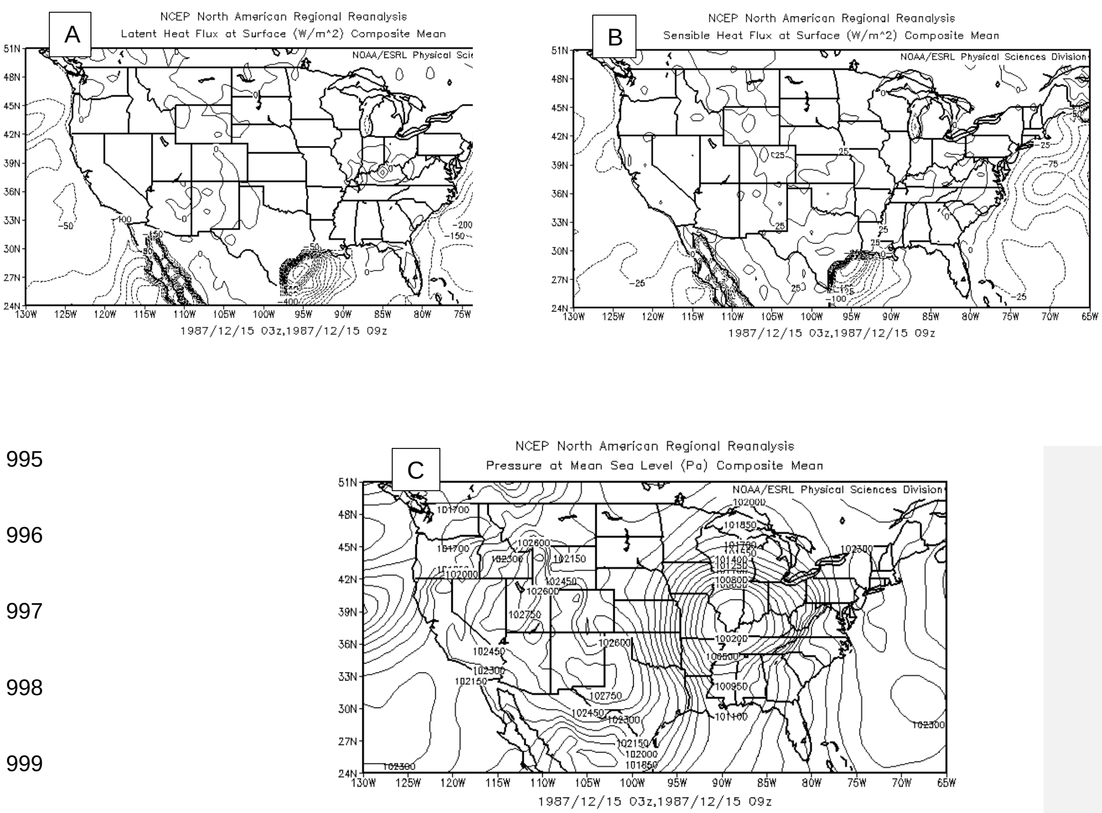


Figure 24. 14-15 December 1987 – Image [A] is selected event Latent Heat Flux at Surface. Image [B] is selected event Sensible Heat Flux at Surface. Image [C] is selected event Pressure at Mean Sea Level.

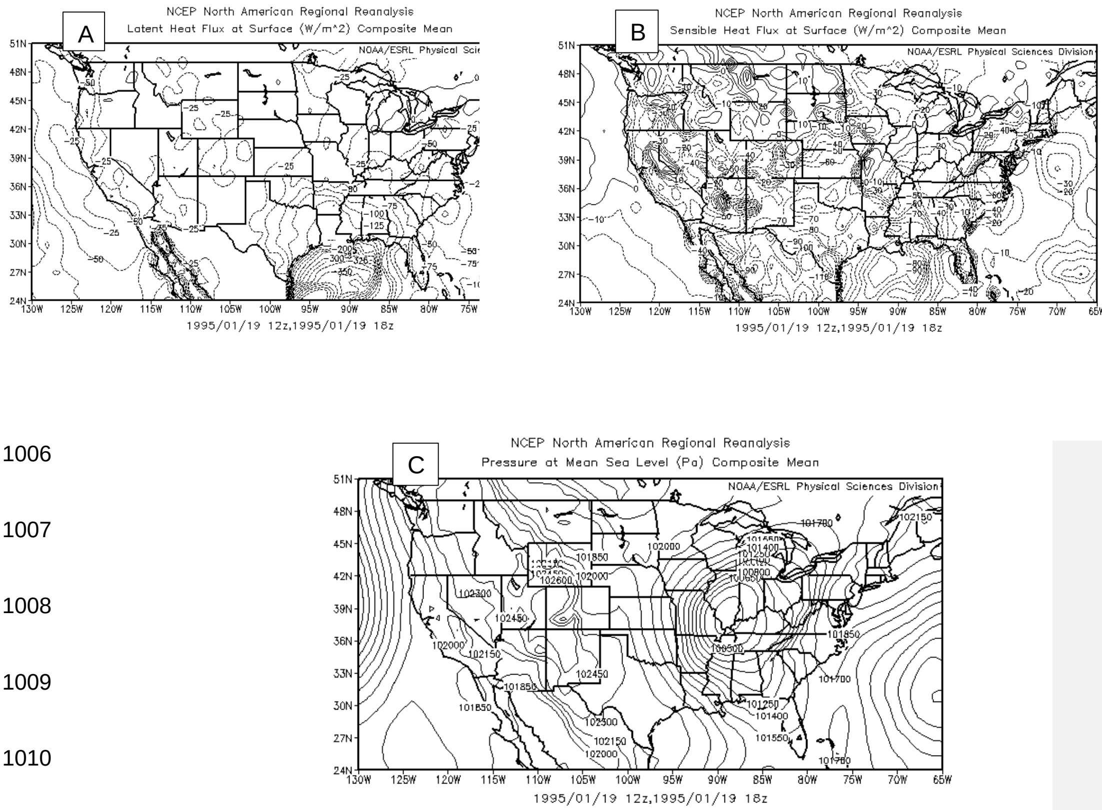


Figure 25. 19 January 1995 – Image [A] is selected event Latent Heat Flux at Surface. Image [B] is selected event Sensible Heat Flux at Surface. Image [C] is selected event Pressure at Mean Sea Level.

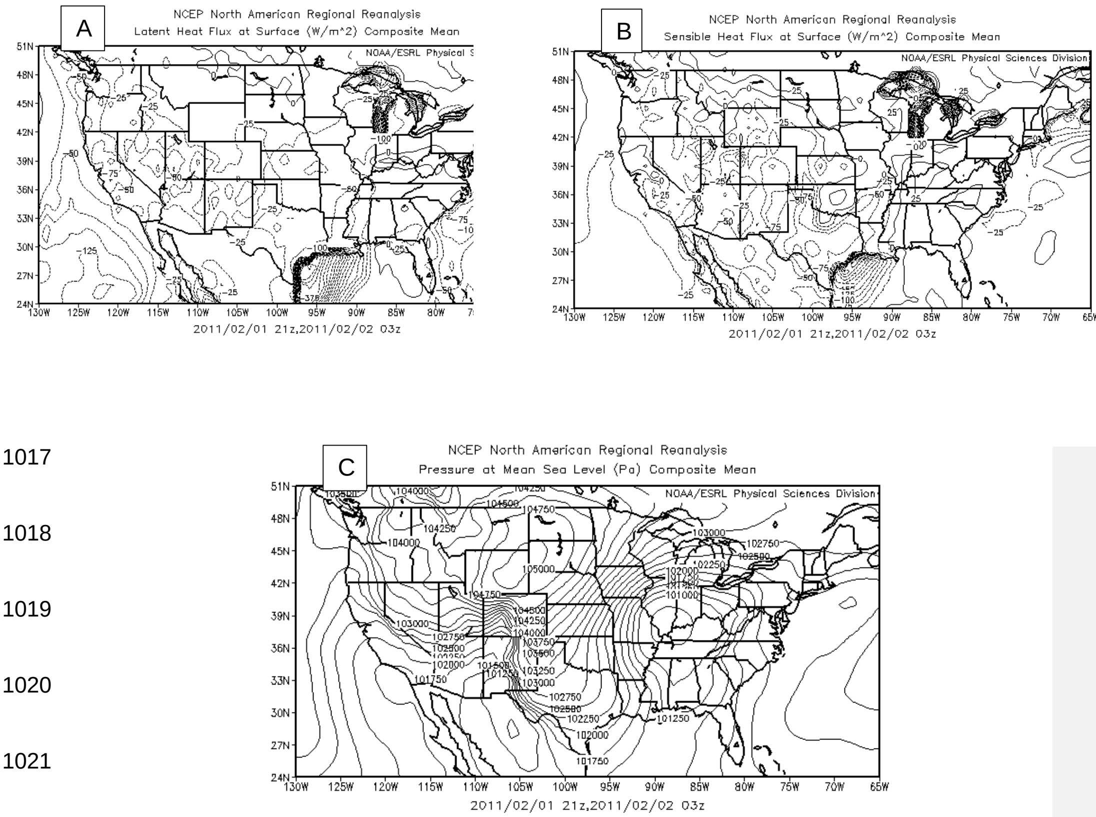


Figure 26. 1-2 February 2011 – Image [A] is selected event Latent Heat Flux at Surface. Image [B] is selected event Sensible Heat Flux at Surface. Image [C] is selected event Pressure at Mean Sea Level.

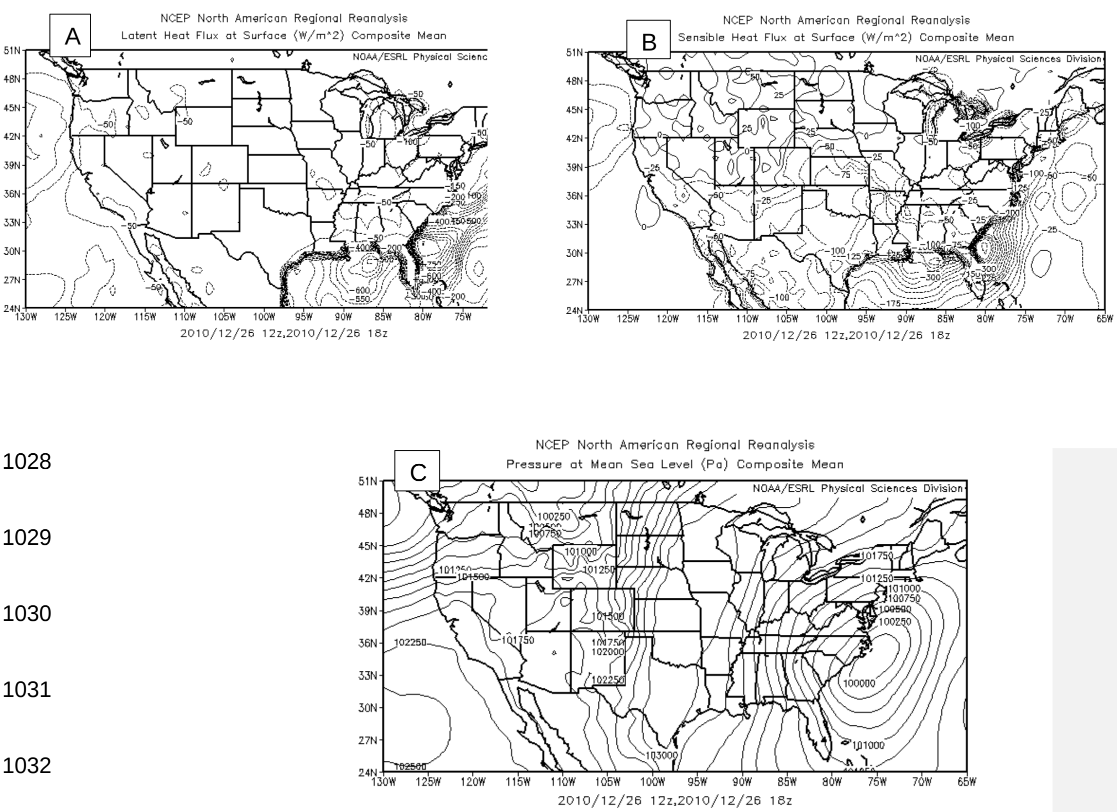


Figure 27. 25-26 December 2010 – Image [A] is selected event Latent Heat Flux at Surface. Image [B] is selected event Sensible Heat Flux at Surface. Image [C] is selected event Pressure at Mean Sea Level.

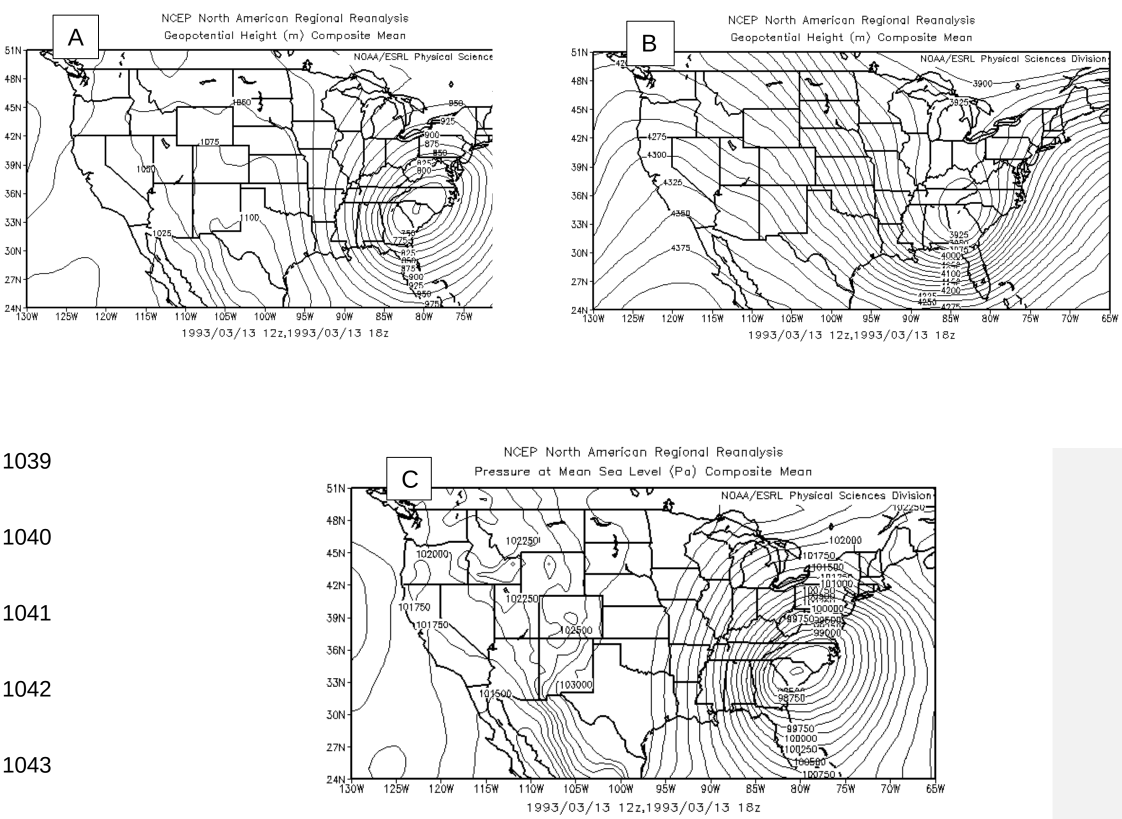


Figure 28. 13-14 March 1993 – Image A is 1200 – 1800 UTC 13 March 1993 900hPa Height. Image B is 1200 – 1800 UTC 13 March 1993 600hPa Height. Image C is 1200 – 1800 UTC 13 March 1993 Pressure at Mean Sea Level.

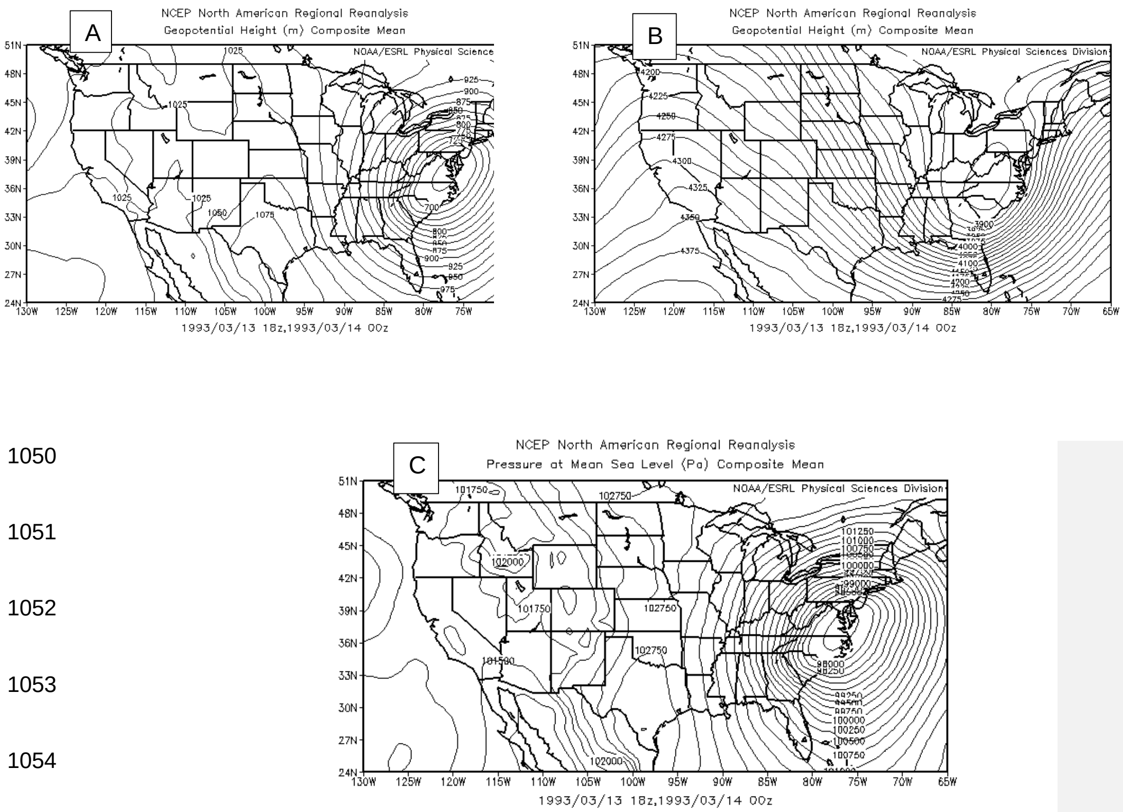
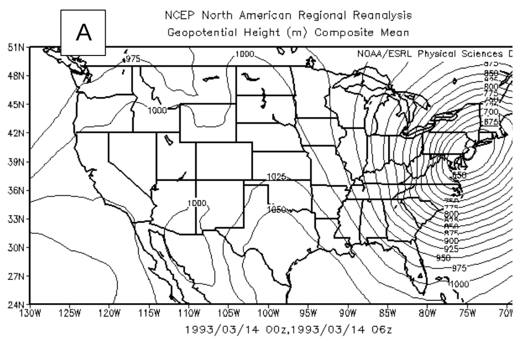
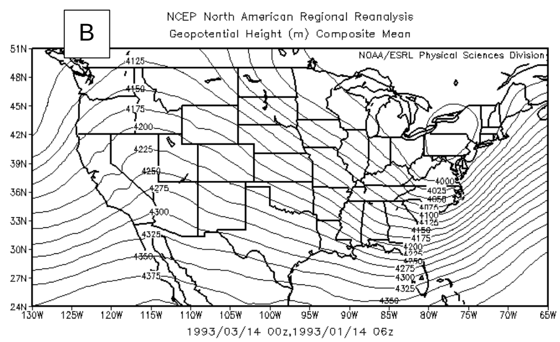


Figure 29. 13-14 March 1993 – Image A is 1800 UTC 13 March – 0000 UTC 14 March 1993 900hPa Height. Image B is 1800 UTC 13 March – 0000 UTC 14 March 1993 600hPa Height. Image C is 1800 UTC 13 March – 0000 UTC 14 March 1993 Pressure at Mean Sea Level.





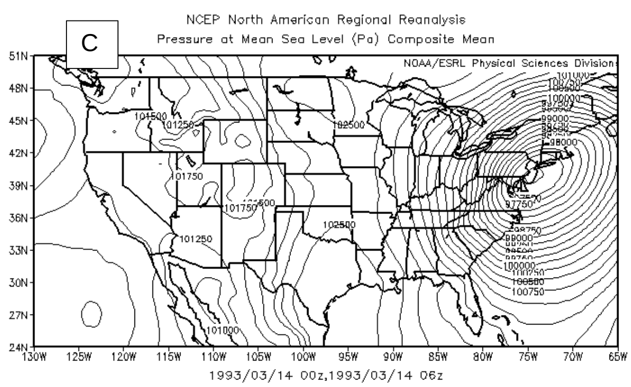


Figure 30. 13-14 March 1993 – Image A is 0000 – 0600 UTC 14 March 1993 900hPa Height. Image B is 0000 – 0600 UTC 14 March 1993 600hPa Height. Image C is 0000 – 0600 UTC 14 March 1993 Pressure at Mean Sea Level.

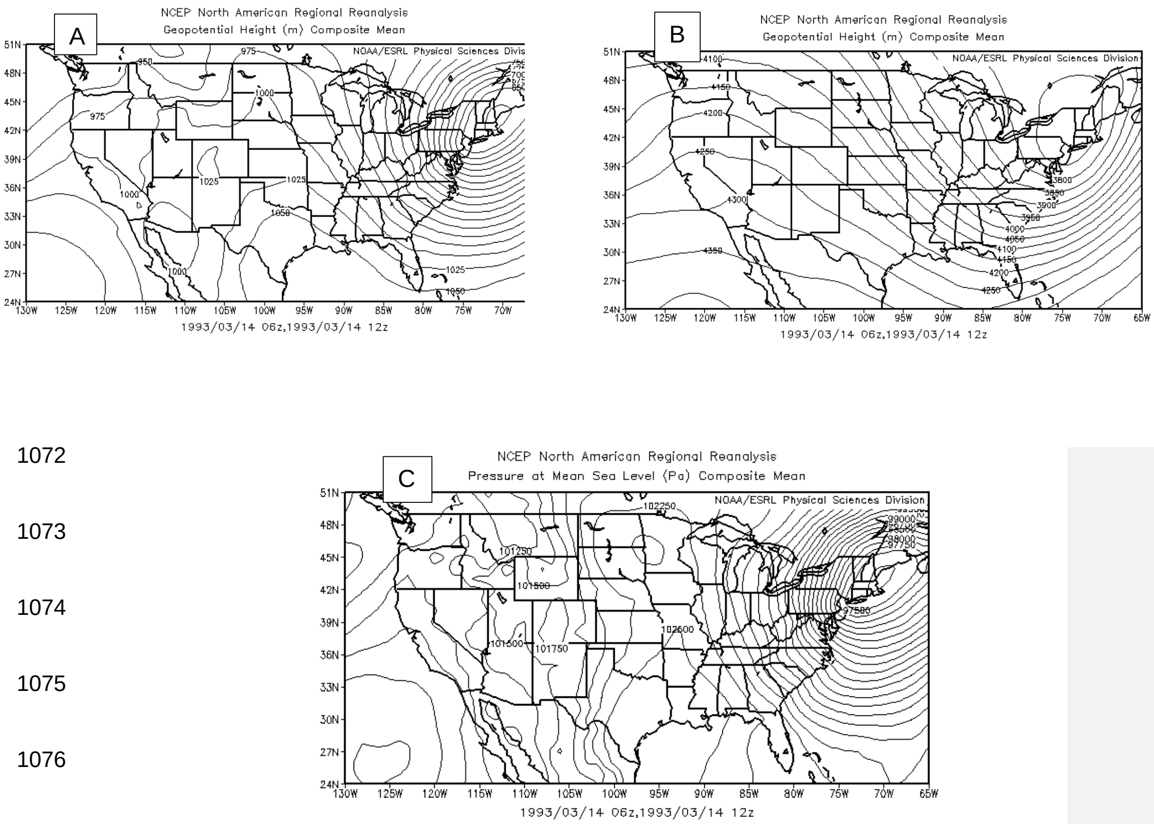


Figure 31. 13-14 March 1993 – Image A is 0600 – 1200 UTC 14 March 1993 900hPa Height. Image B is 0600 - 1200 UTC 14 March 1993 600hPa Height. Image C is 0600 - 1200 UTC Pressure at Mean Sea Level.

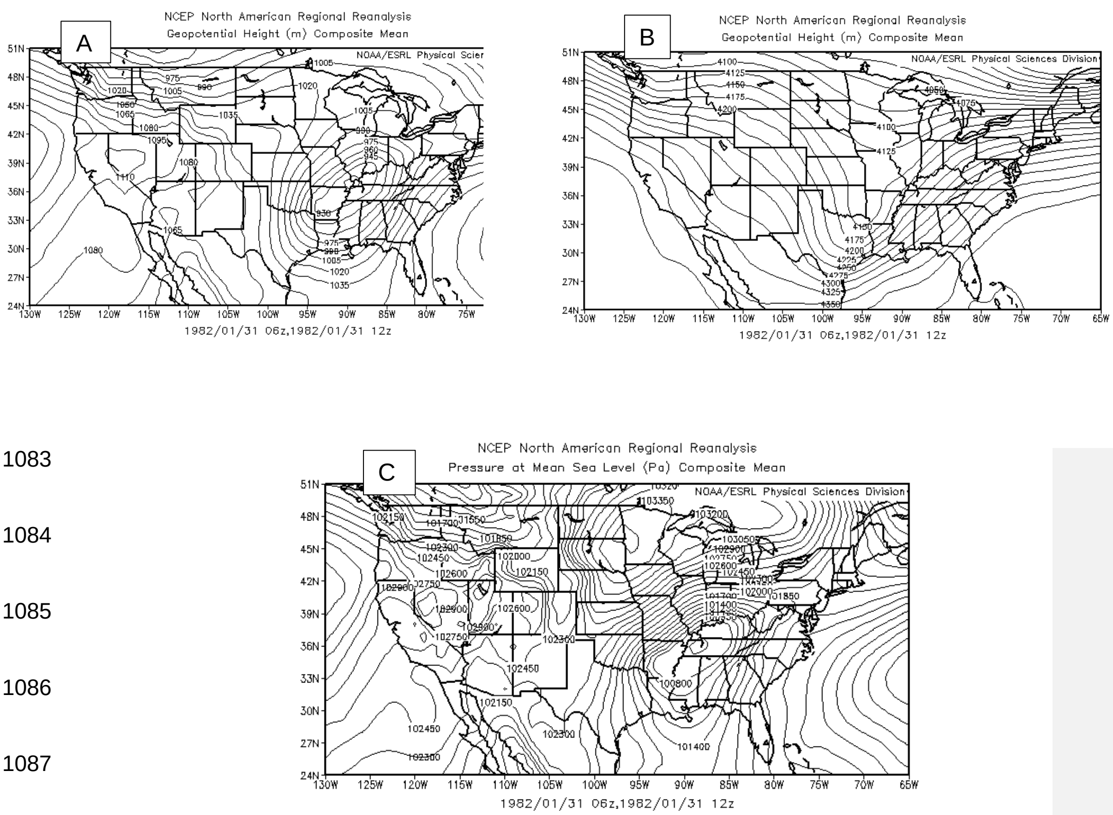


Figure 32. 30-31 January 1982 – Image A is 0600 – 1200 UTC 31 January 1982 900hPa Height. Image B is 0600 – 1200 UTC 31 January 1982 600hPa Height. Image C is 0600 – 1200 UTC 31 January 1982 Pressure at Mean Sea Level.

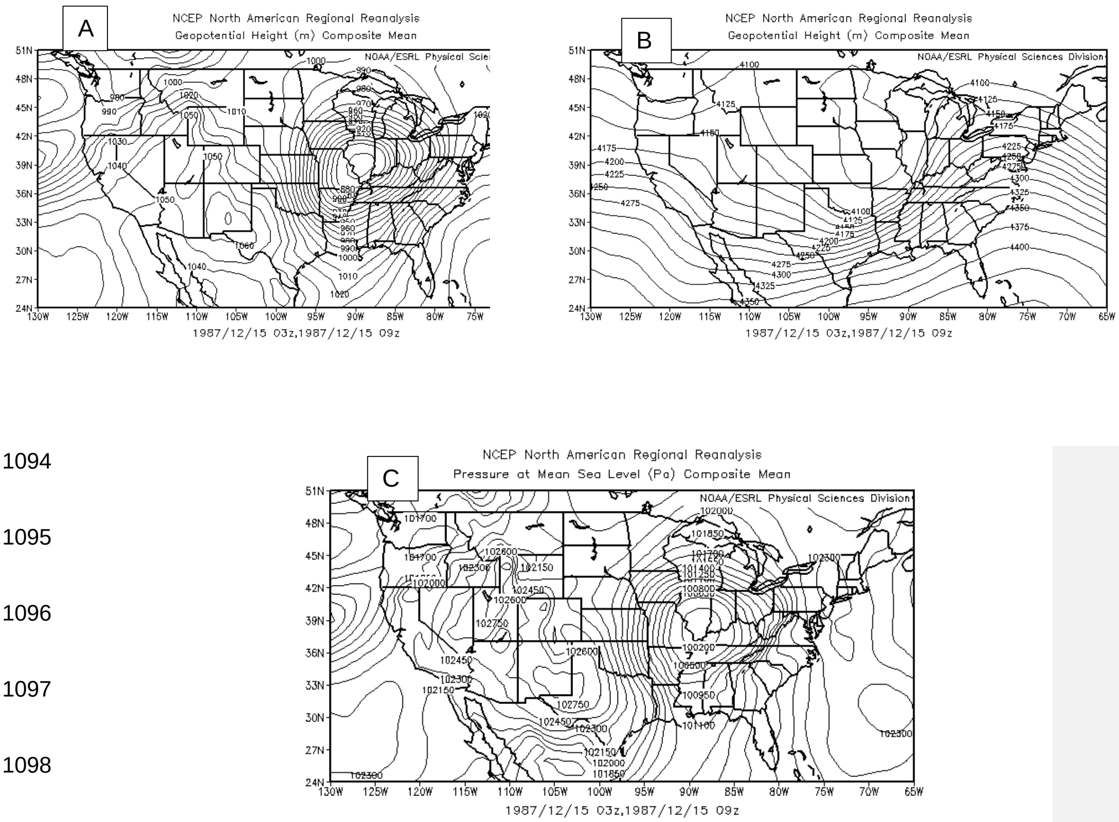


Figure 33. 14-15 December 1987 – Image A is 0300 – 0900 UTC 15 December 1987 900hPa Height. Image B is 0300 – 0900 UTC 15 December 1987 600hpa Height. Image C is 0300 – 0900 UTC 15 December 1987 Pressure at Mean Sea Level.

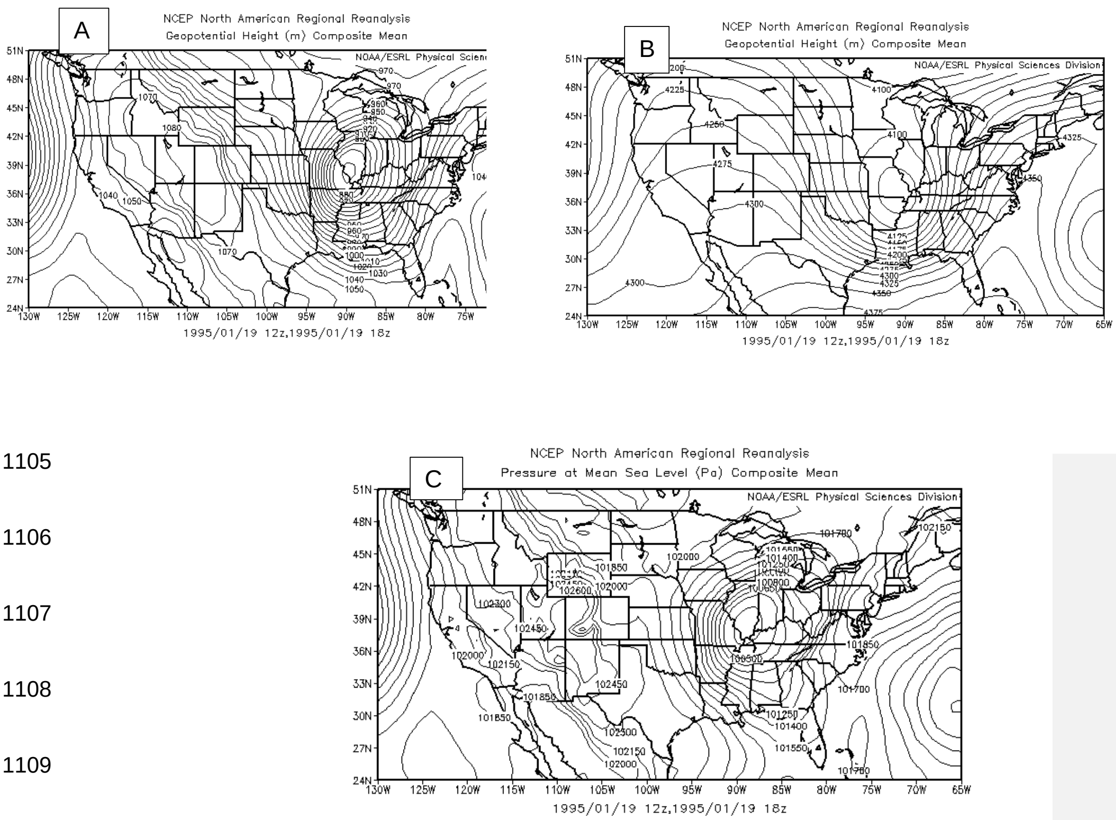


Figure 34. 19 January 1995 – Image A is 1200 – 1800 UTC 19 January 1995 900hPa Height. Image B is 1200 – 1800 UTC 19 January 1995 600hPa Height. Image C is 1200 – 1800 UTC 19 January 1995 Pressure at Mean Sea Level.

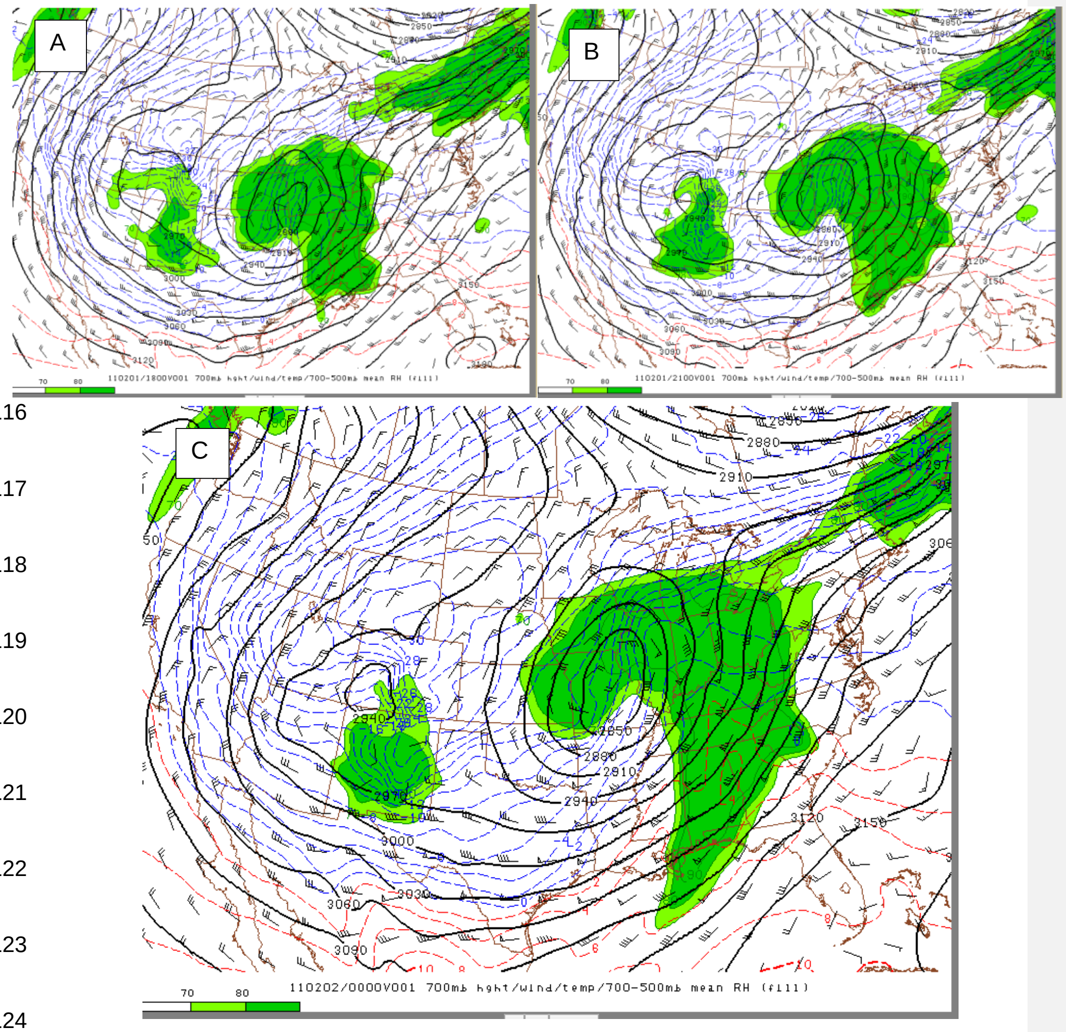


Figure 35. Image A is 1800 UTC 1 February 2011 700hPa Height, Wind, Temperature and 700-500hPa mean RH (fill). Image B is 2100 UTC 1 February 2011 700hPa Height, Wind, Temperature and 700-500hPa mean RH (fill). Image C is 0000 UTC 2 February 2011 700hPa Height, Wind, Temperature and 700 – 500hPa mean RH (fill).

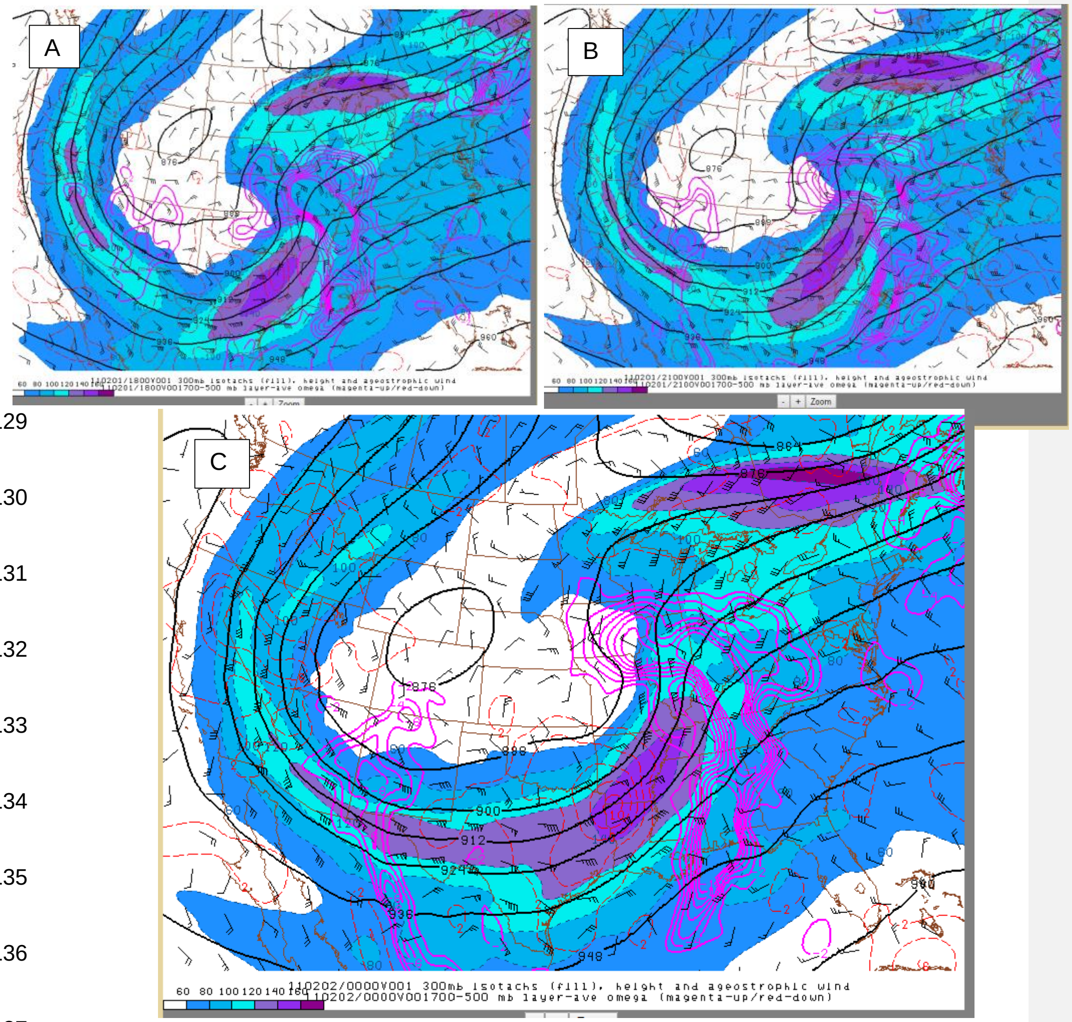


Figure 36. Image A is 1800 UTC 1 February 2011 300hPa Isotachs, Height and Ageostrophic Wind, 700-500hPa layer average Omega (magenta up). Image B is 2100 UTC 1 February 2011 300hPa Isotachs, Height and Ageostrophic Wind, 700-500hPa layer average Omega (magneta up). Image C is 0000 UTC 2 February 2011 300hPa Isotachs, Height and Ageostrophic Wind, 700-500hPa layer average Omega (magenta).

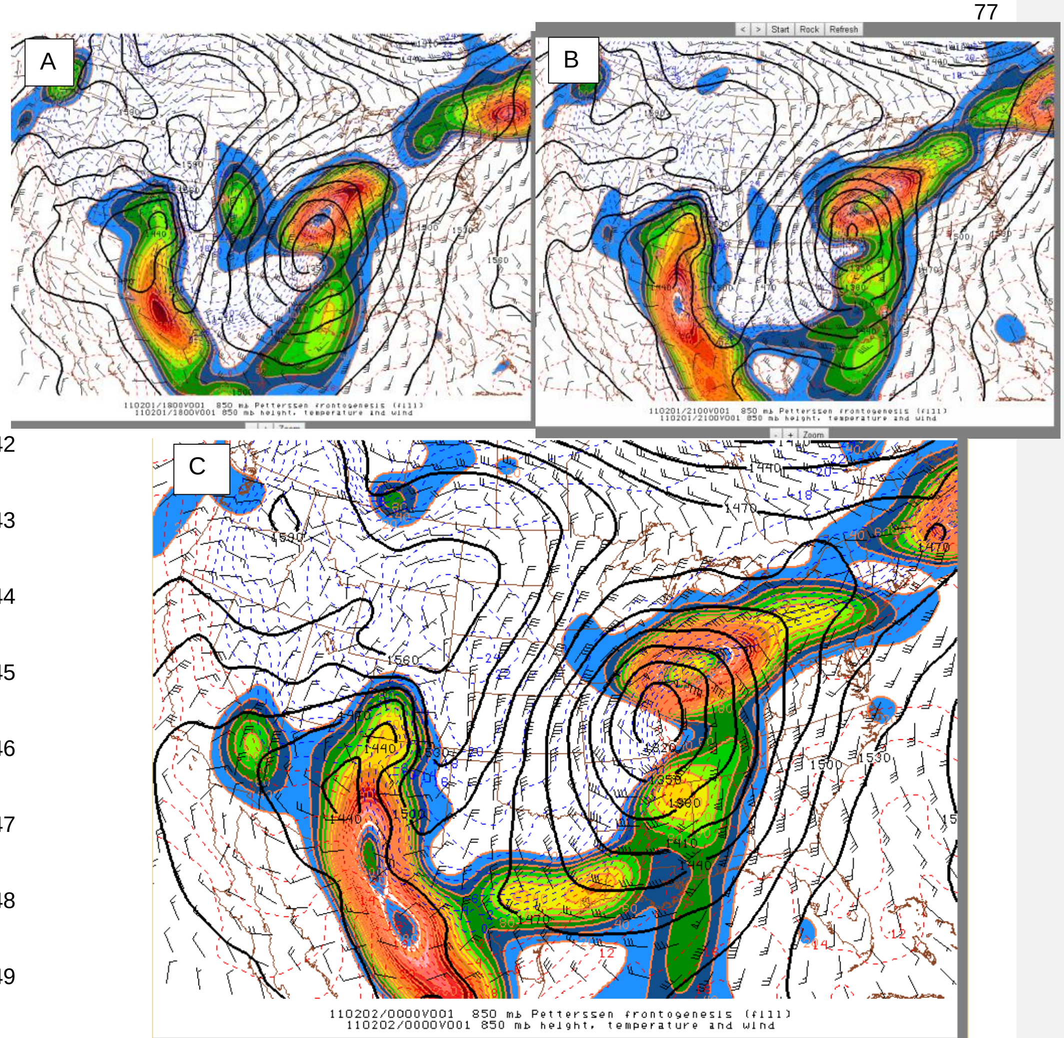


Figure 37. Image A is 1800 UTC 1 February 2011 850hPa Frontogenesis (fill), 850hPa Height, Temperature and Wind. Image B is 2100 UTC 1 February 2011 850hPa Frontogenesis (fill), 850hPa Height, Temperature and Wind. Image C is 0000 UTC 2 February 2011 850hPa Frontogenesis (fill), 850hPa Height, Temperature and Wind.

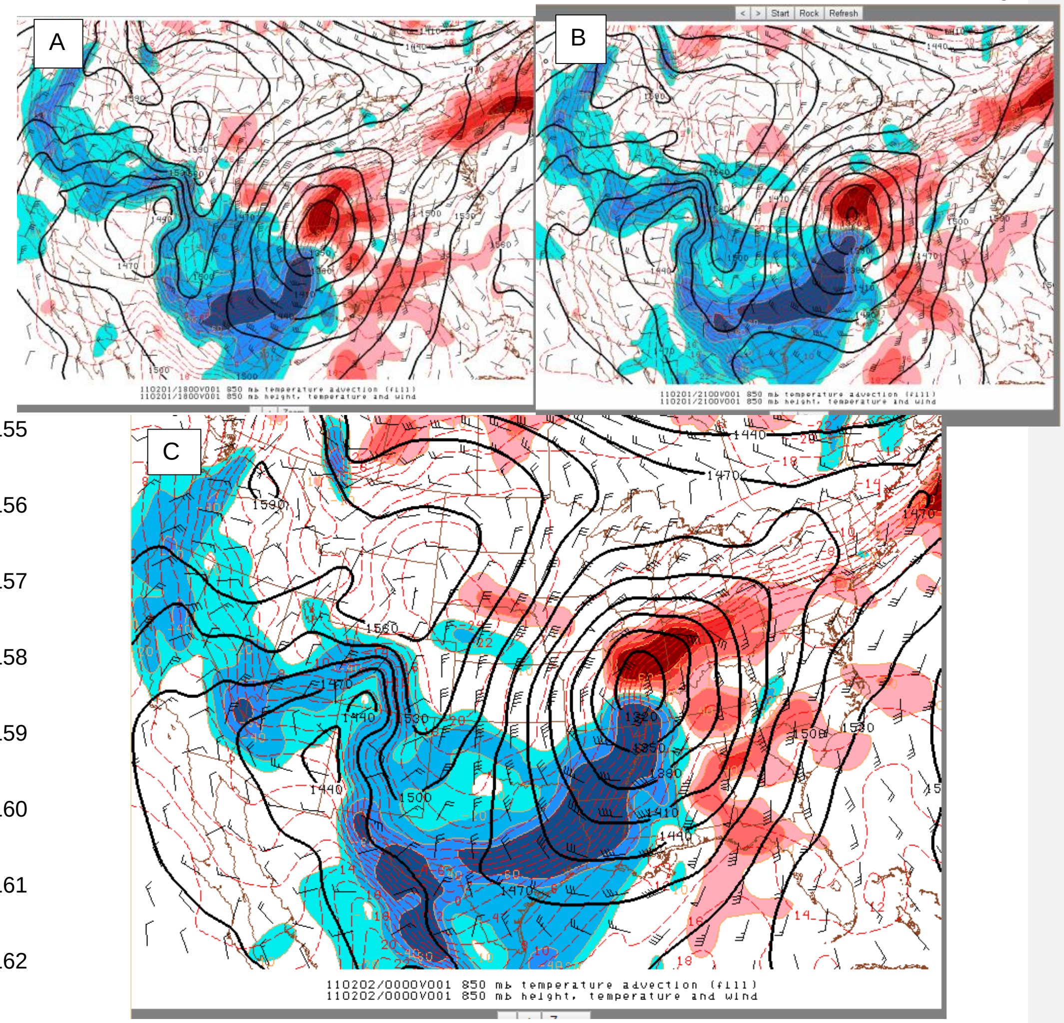


Figure 38. Image A is 1800 UTC 1 February 2011 850hPa Temperature Advection (fill), 850hPa Height, Temperature and Wind. Image B is 2100 UTC 1 February 2011 850hPa Temperature Advection (fill), 850hPa Height, Temperature and Wind. Image C is 0000 UTC 2 February 2011 850hPa Temperature Advection (fill), 850hPa Height, Temperature and Wind.

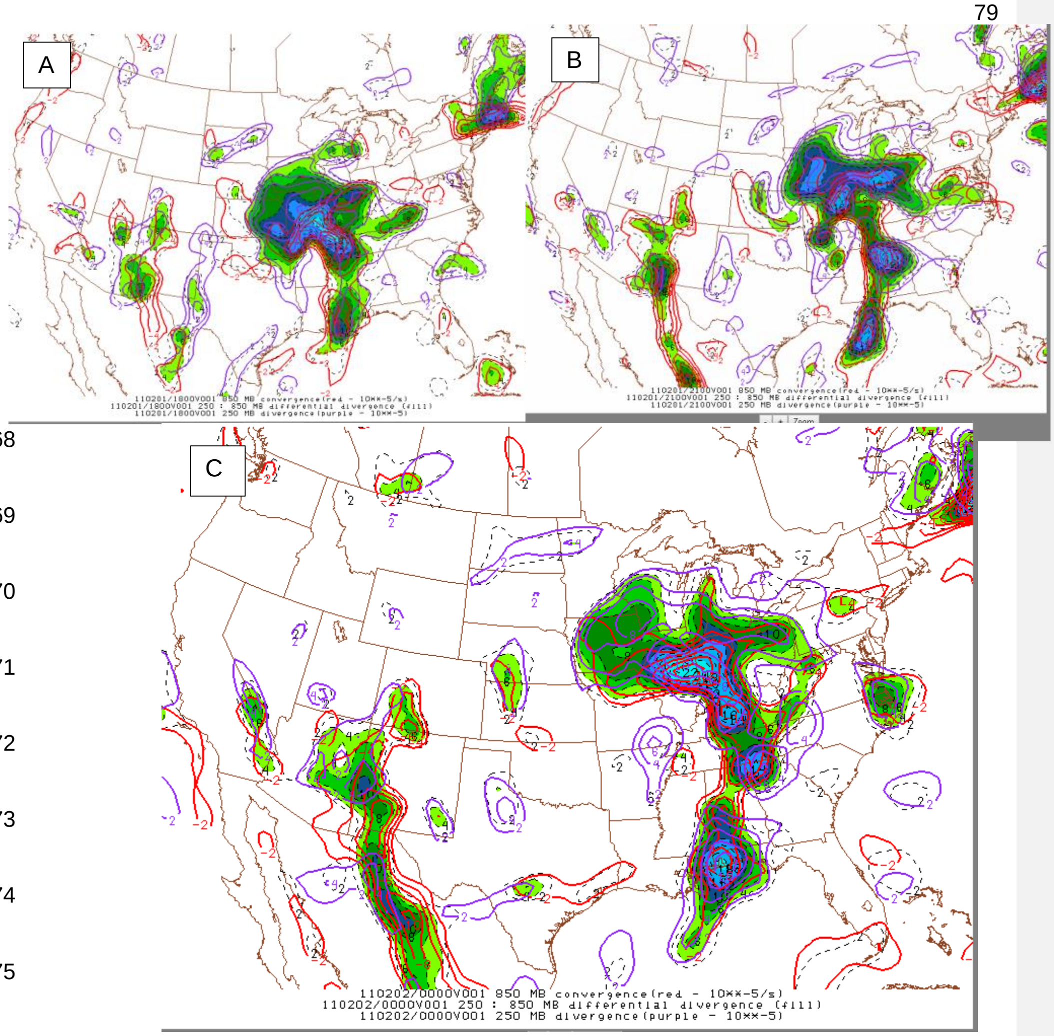


Figure 39. Image A is 1800 UTC 1 February 2011 850hPa Convergence (red), 250-850hPa Differential Divergence (fill) and 250hPa Divergence (purple). Image B is 2100 UTC 1 February 2011 850hPa Convergence (red), 250-850hPa Differential Divergence (fill) and 250hPa Divergence (purple). Image C is 0000 UTC 2 February 2011 850hPa Convergence (red), 250-850hPa Differential Divergence (fill) and 250hPa Divergence.

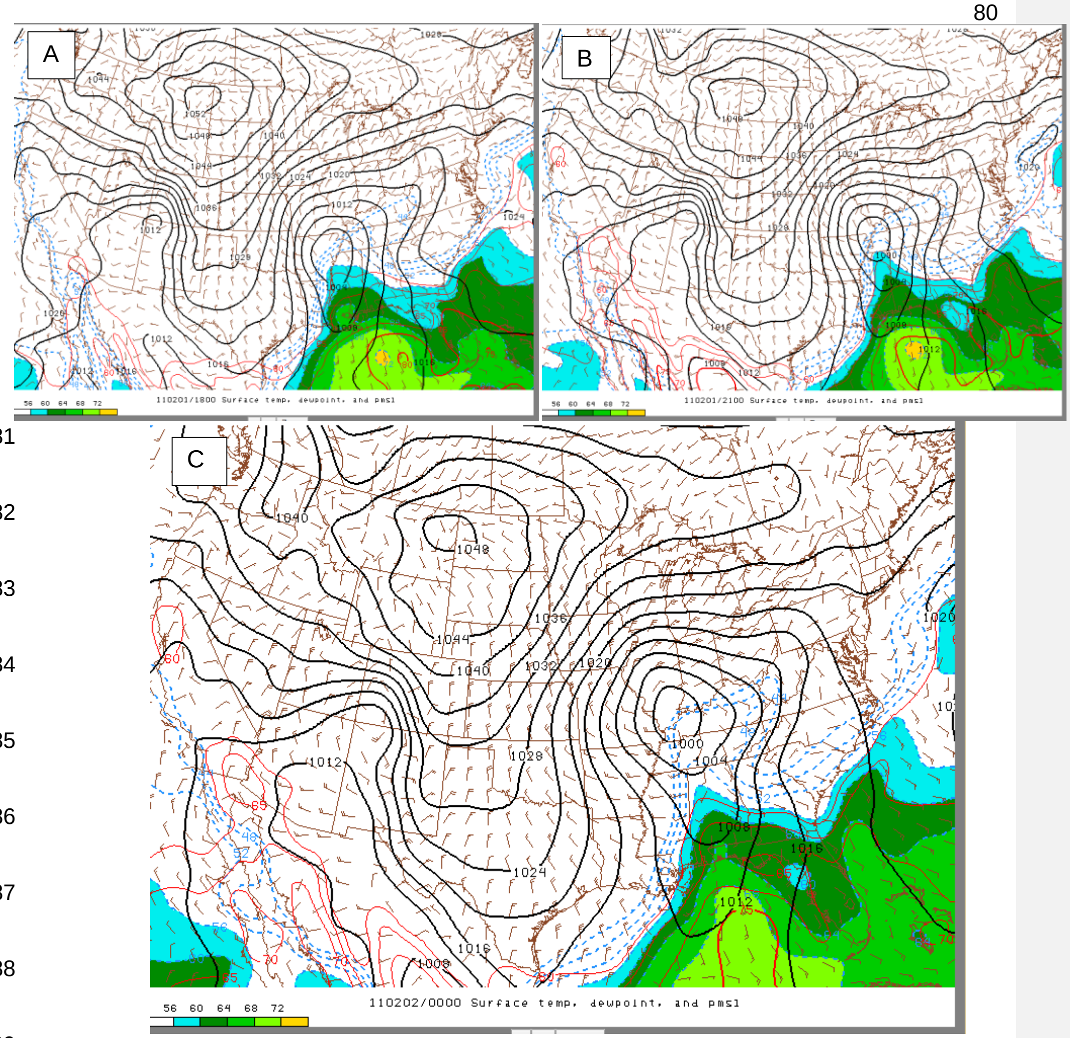


Figure 40. Image A is 1800 UTC 1 February 2011 Surface Temperature, Dewpoint and pmsl. Image B is 2100 UTC 1 February 2011 Surface Temperature, Dewpoint and pmsl. Image C is 0000 UTC 2 February 2011 Surface Temperature, Dewpoint and pmsl.

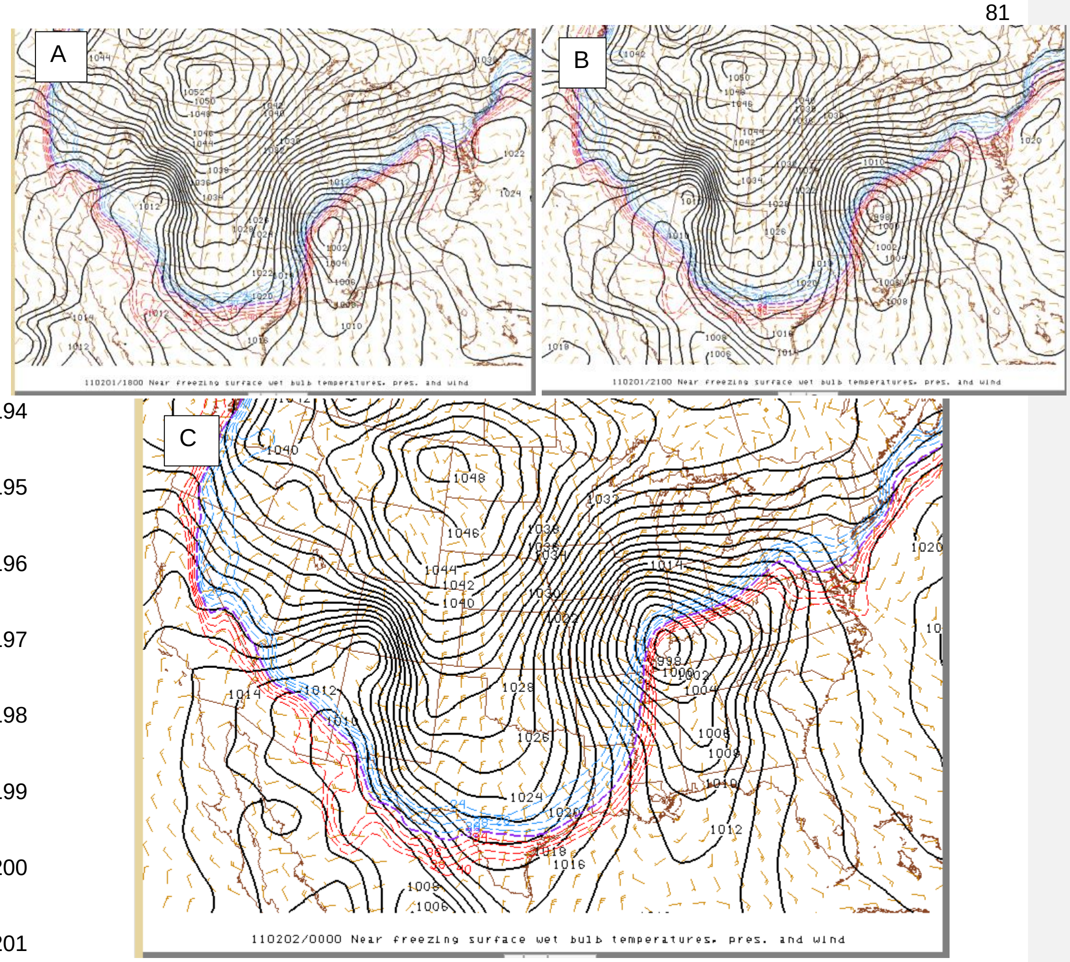


Figure 41. Image A is 1800 UTC 1 February 2011 Near Freezing Surface Wet Bulb Temperatures, Sea Level Pressure and Wind. Image B is 2100 UTC 1 February 2011 Near Freezing Surface Wet Bulb Temperatures, Sea Level Pressure and Wind. Image C is 0000 UTC 2 February 2011 Near Freezing Surface Wet Bulb Temperatures, Sea Level Pressure and Wind.

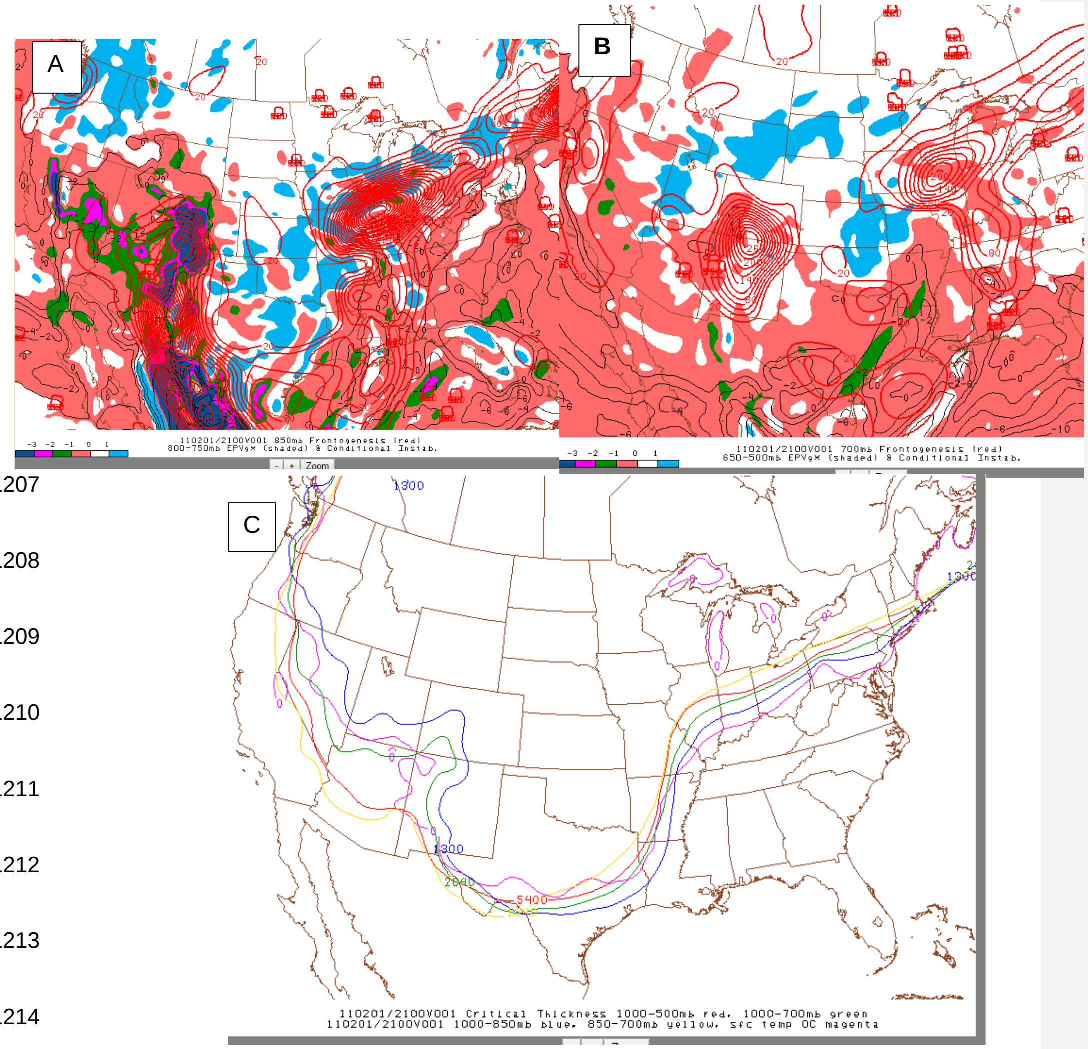


Figure 42. Image A is 2100 UTC 1 February 2011 850hPa Frontogenesis (red isolines), 800-750hPa EPVg (shaded) & Conditional Instability. Image B is 2100 UTC 1 February 2011 700hPa Frontogenesis (red isolines), 650-500hPa EPVg (shaded) & Conditional Instability. Image C is 2100 UTC 1 February 2011 Critical Thickness 1000-500hPa (red), 1000-700hPa (green), 1000-850hPa (blue), 850-700hPa (yellow), Surface Temperature 0C (magenta).

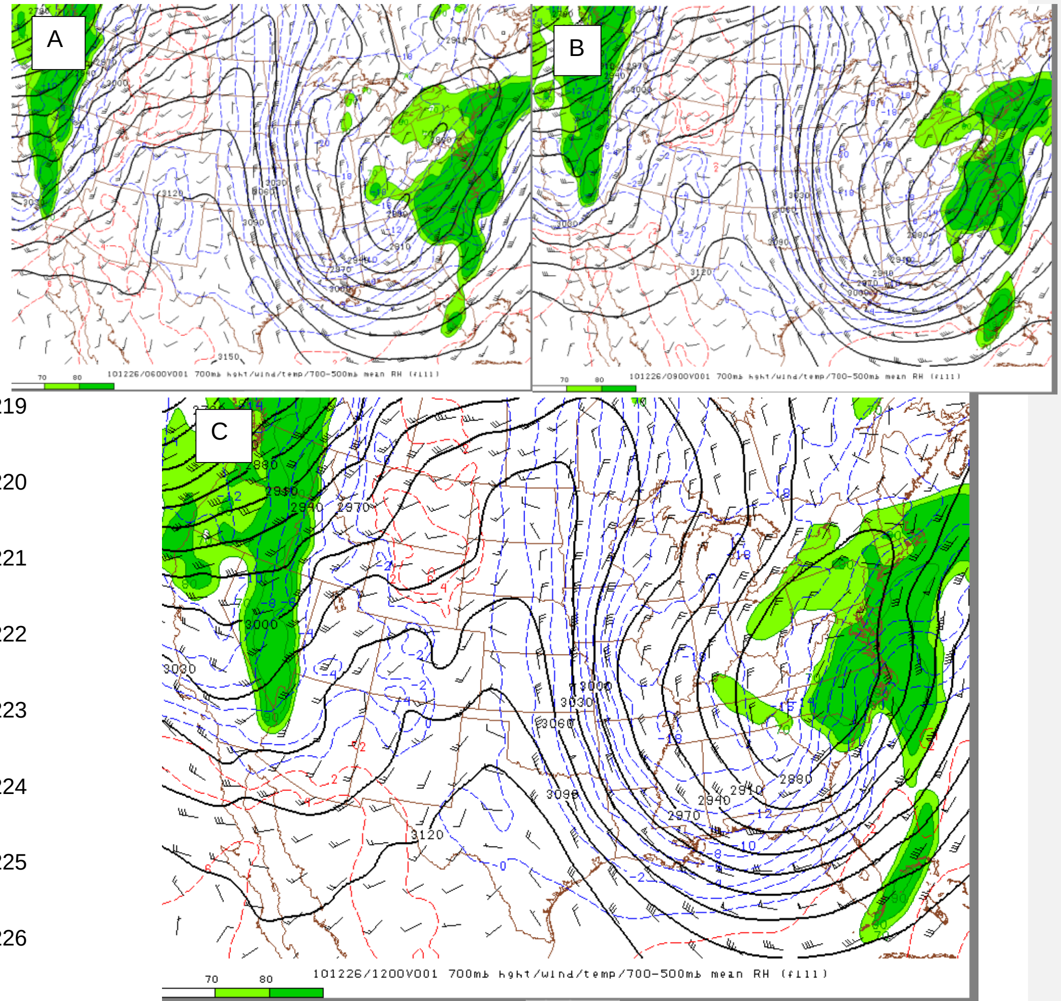


Figure 43. Image A is 0600 UTC 26 December 2010 700hPa height, wind, temperature and 700-500hPa mean RH (fill). Image B is 0900 UTC 26 December 2010 700hPa height, wind, temperature and 700-500hPa height, wind, temperature and 700-500hPa mean RH (fill). Image C is 1200 UTC 26 December 2010 700hPa height, wind, temperature and 700-500hPa mean RH (fill).

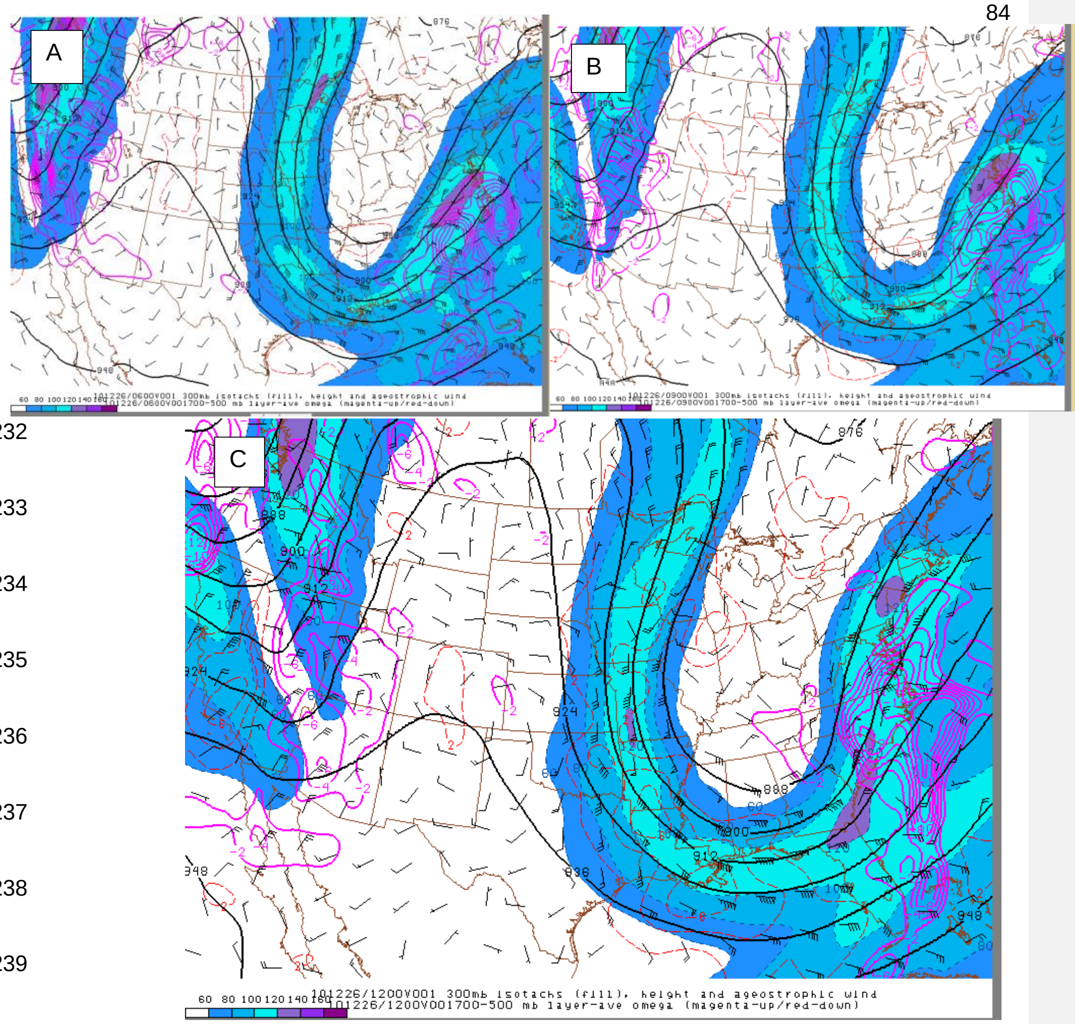


Figure 44. Image A is 0600 UTC 26 December 2010 300hPa isotachs (fill), height, ageostrophic wind and 700-500hPa layer average omega (magenta - up). Image B is 0900 UTC 26 December 2010 300hPa isotachs (fill), height, ageostrophic wind, and 700-500hPa layer average omega (magenta – up). Image C is 26 December 2010 300hPa isotachs (fill), height, ageostrophic wind and 700-500hPa layer average omega (magenta – up).

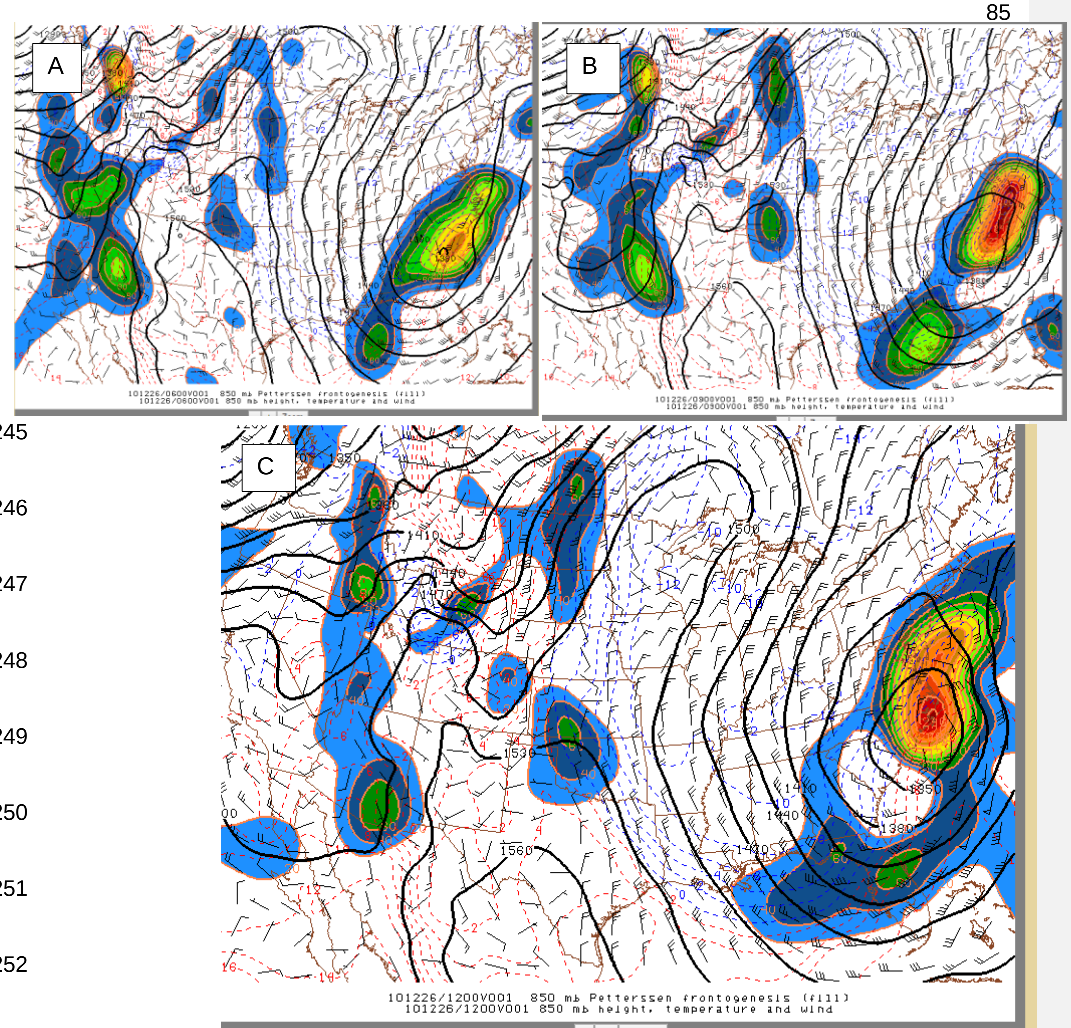


Figure 45. Image A is 0600 UTC 26 December 2010 850hPa frontogenesis (fill), 850hPa height, temperature and wind. Image B is 0900 UTC 26 December 2010 850hPa frontogenesis (fill), 850hPa height, temperature and wind. Image C is 1200 UTC 26 December 2010 850hPa frontogenesis (fill), 850hPa height, temperature and wind.

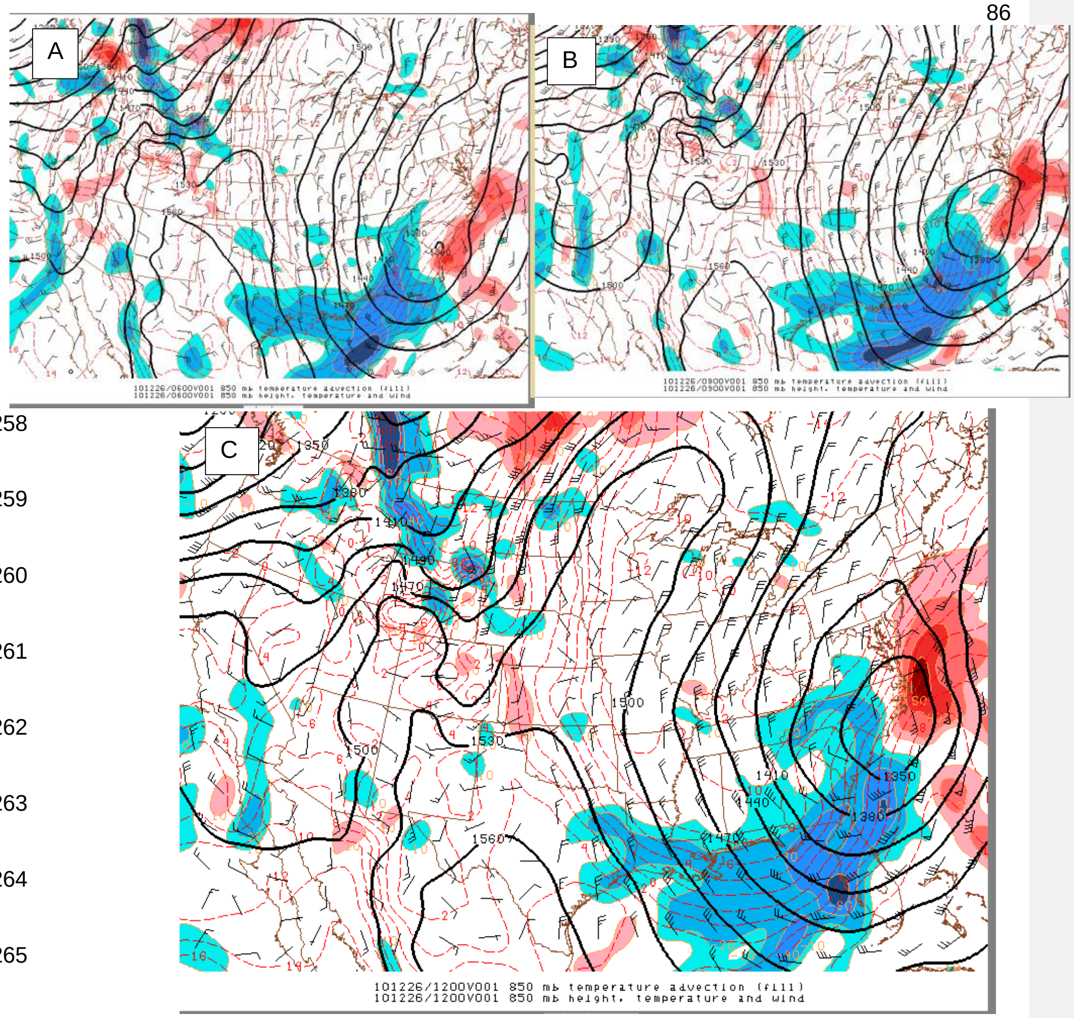


Figure 46. Image A is 0600 UTC 26 December 2010 850hPa temperature advection (fill), 850hPa height, temperature and wind. Image B is 0900 UTC 26 December 2010 temperature advection (fill), 850hPa height, temperature and wind. Image C is 1200 UTC 26 December 2010 850hPa temperature advection (fill), 850hPa height, temperature and wind.

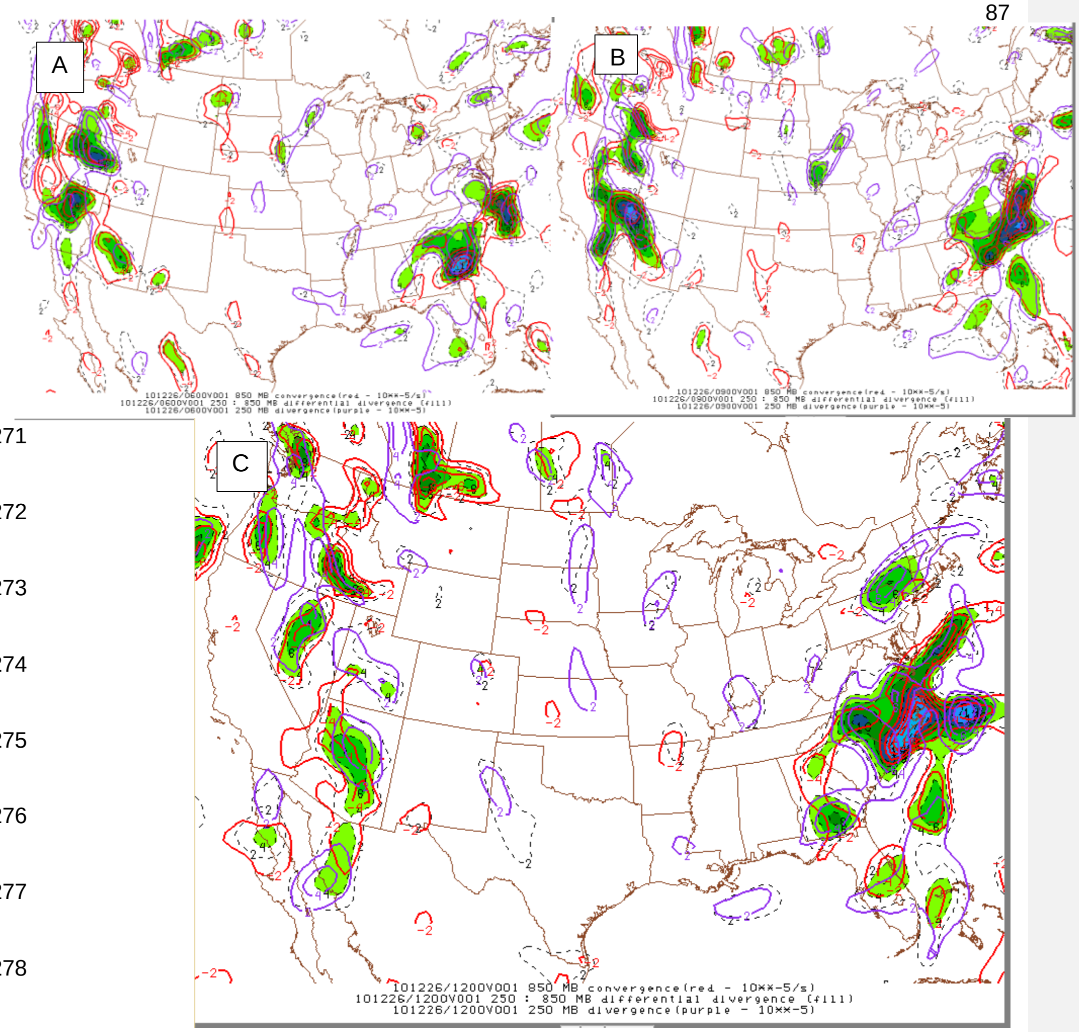


Figure 47. Image A is 0600 UTC 26 December 2010 850hPa convergence (red isolines), 250-850hPa differential divergence (fill), 250hPa divergence (purple isolines). Image B is 0900 UTC 26 December 2010 850hPa convergence (red isolines), 250-850hPa differential divergence (fill), 250hPa divergence (purple isolines). Image C is 1200 UTC 26 December 2010 850hPa convergence (red isolines), 250-850hPa differential divergence (fill), 250hPa divergence (purple isolines).

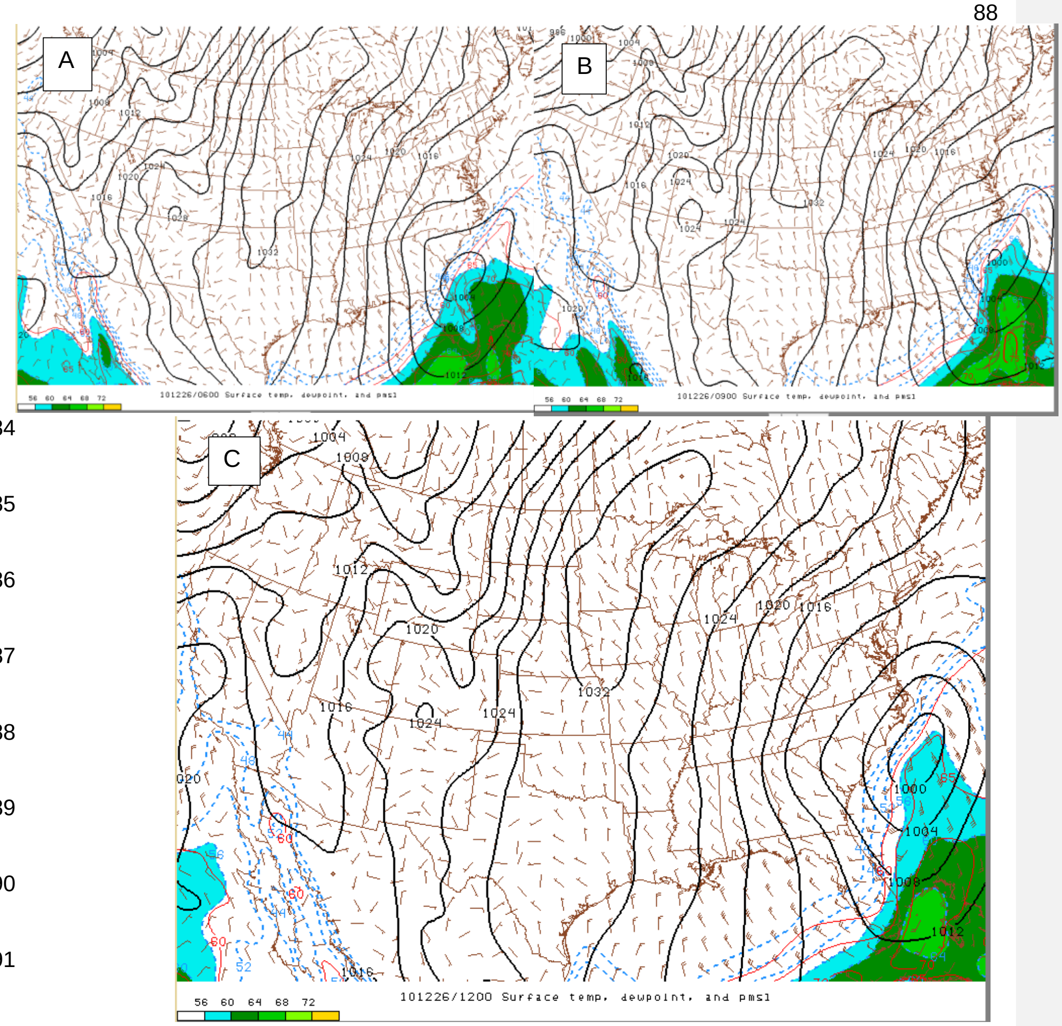


Figure 48. Image A is 0600 UTC 26 December 2010 Surface temperature, dewpoint and pmsl. Image B is 0900 UTC 26 December 2010 Surface temperature, dewpoint and pmsl. Image C is 26 December 2010 Surface temperature, dewpoint and pmsl.

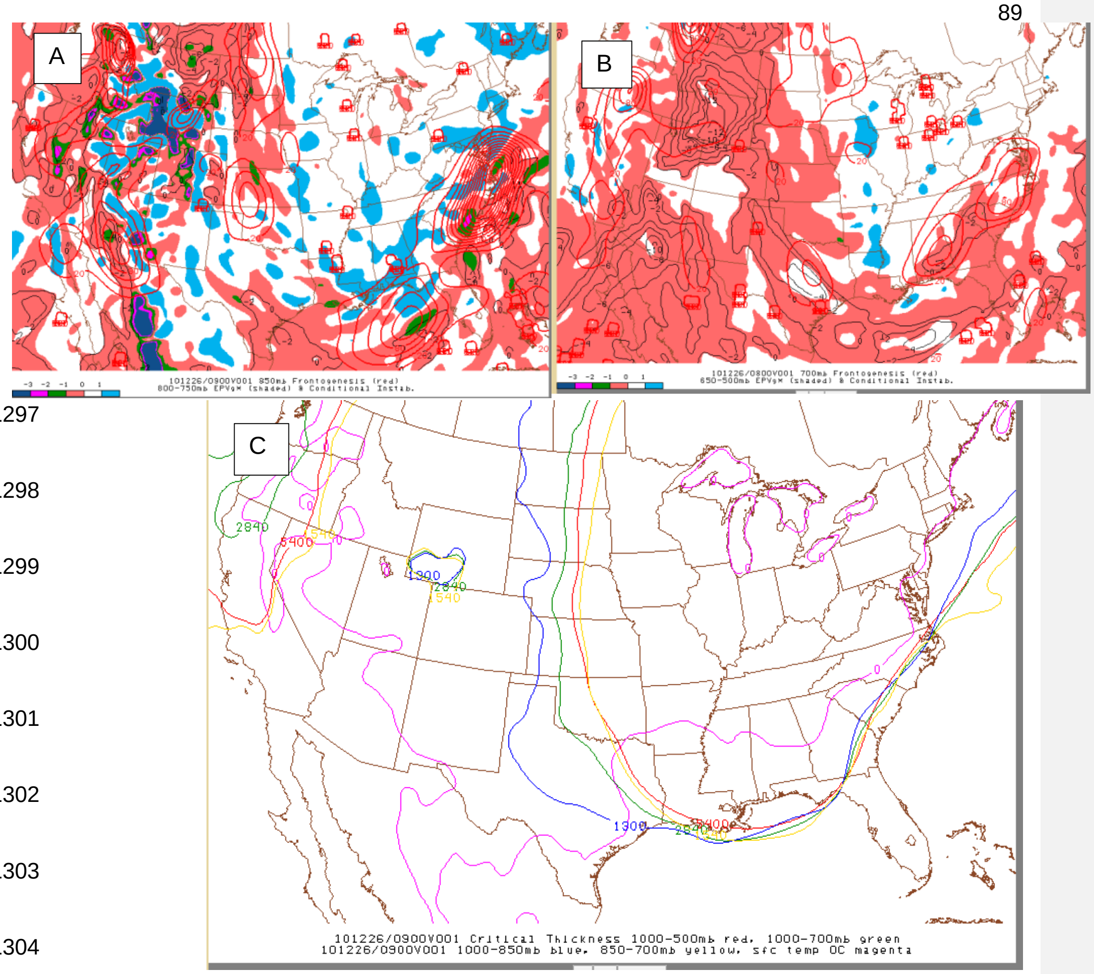


Figure 49. Image A is 0900 UTC 26 December 2010 850hPa Frontogenesis (red isolines), 800-750hPa EPVg (shaded) & conditional instability. Image B is 0800 UTC 700hPa Frontogenesis (red isolines), 650-500hPa EPVg (shaded) & conditional instability. Image C is 0900 UTC 26 December 2010 Critical Thickness 1000-500hPa (red), 1000-700hPa (green), 1000-850hPa (blue), 850-700hPa (yellow), surface temperature 0C (magenta).

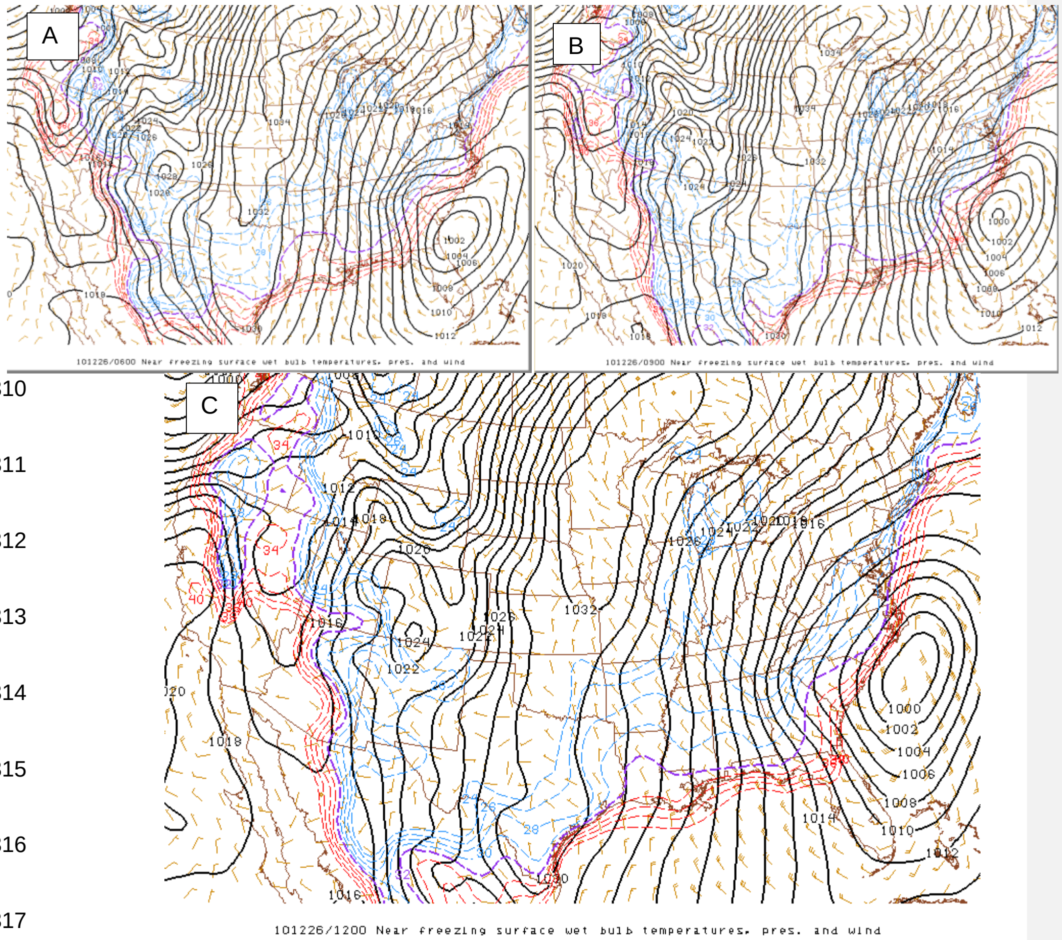


Figure 50. Image A is 0600 UTC 26 December 2010 Near freezing surface wet bulb temperatures, sea level pressure and wind. Image B is 0900 UTC 26 December 2010 Near freezing surface wet bulb temperatures, sea level pressure and wind. Image C is 1200 UTC 26 December 2010 Near freezing surface wet bulb temperatures, sea level pressure and wind.