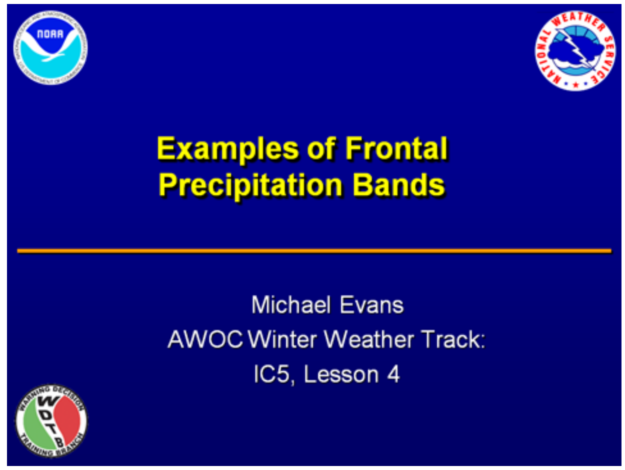
1. Examples of Frontal Precipitation Bands

Instructor Notes:

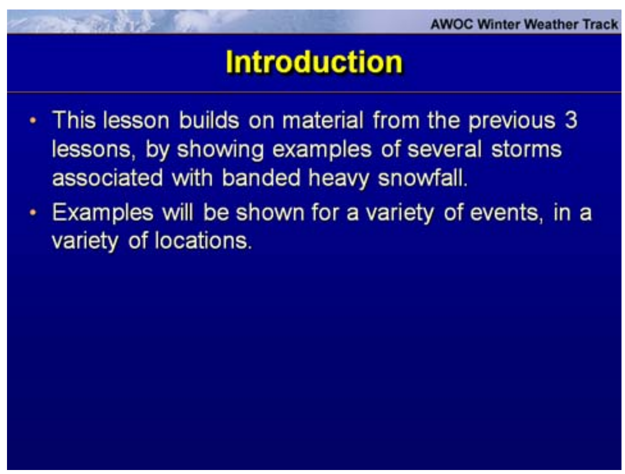
Student Notes:



2. Introduction

Instructor Notes:

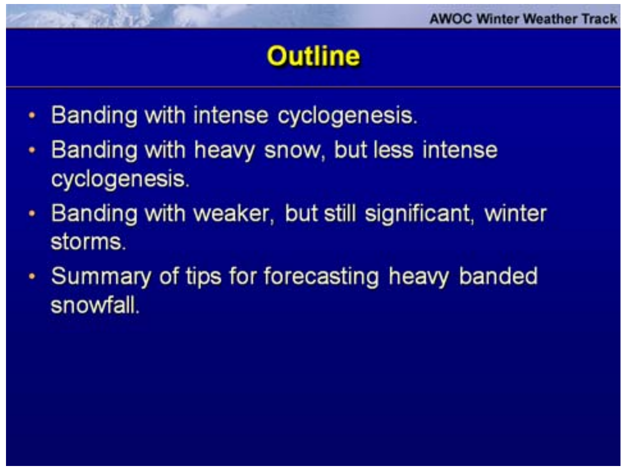
Student Notes:



3. Outline

Instructor Notes: In order to demonstrate how forecasters can use the material from lessons 1 to 3 to forecast banded snowfall in a variety of synoptic and mesoscale situations, several examples will be shown. The first example shows diagnostics and observations associated with intense banding that occurred with a major east coast cyclogenesis event. In the second and third examples, diagnostics and observations will be shown from 2 major snow events that produced intense bands, yet were not associated with a rapidly deepening cyclone. Next, an example will then be shown of less intense, but still significant, banding. The lesson ends with a summary of tips for forecasting banded snowfall.

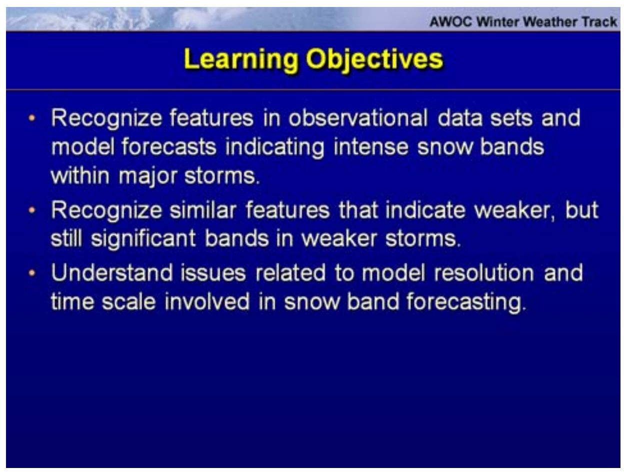
Student Notes:



4. Learning Objectives

Instructor Notes:

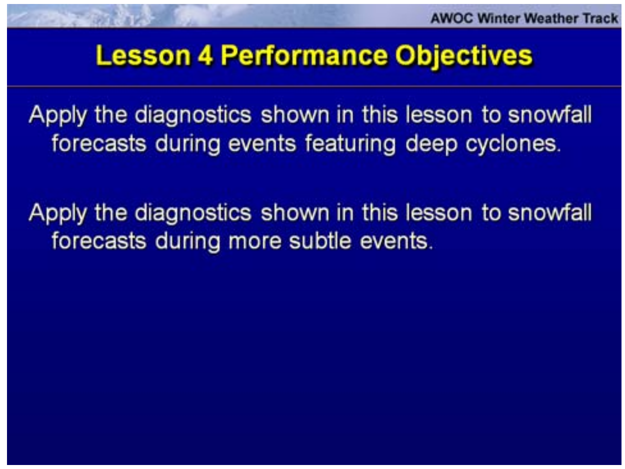
Student Notes:



5. Lesson 4 Performance Objectives

Instructor Notes:

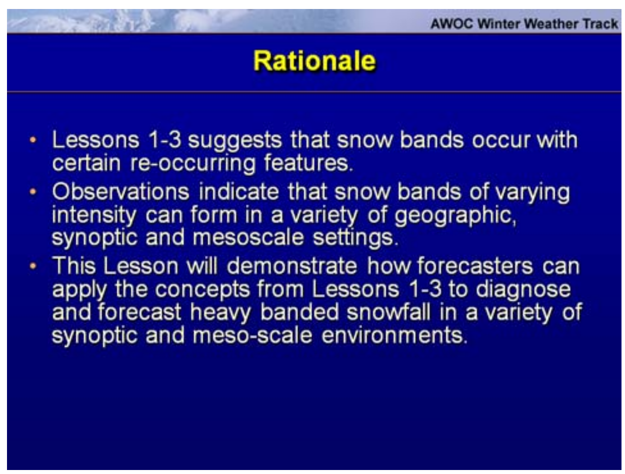
Student Notes:



6. Rationale

Instructor Notes: The theory described in Lessons 1-3 suggests that snow bands occur with certain re-occurring features – namely significant large-scale forcing, frontogenesis and reduced or negative stability to slantwise motion in a near saturated environment. However, observations indicated that snow bands of varying intensity can form in a variety of synoptic and mesoscale settings. This lesson will demonstrate how forecasters can apply the concepts from Lessons 1-3 to diagnose and forecast heavy banded snowfall in a variety of synoptic and meso-scale environments.

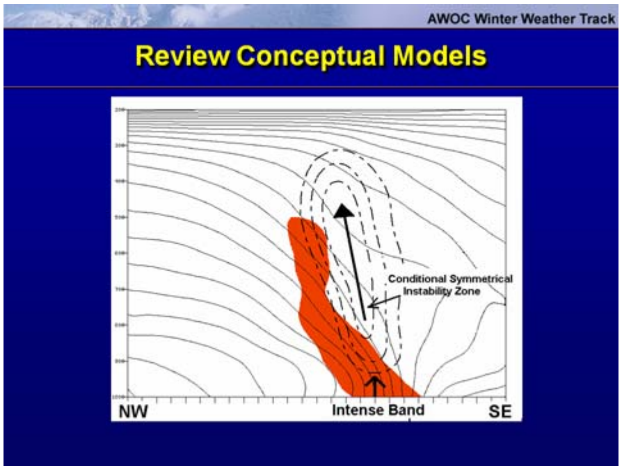
Student Notes:



7. Review Conceptual Models

Instructor Notes: To start, lets briefly review some conceptual models. The images on this slide are based on collaborative research between the NWS and SUNY Albany. The first image on the slide shows a plan view map of a synoptic pattern that typically is associated with heavy snow and banding. Key features are a closed circulation at 500 mb with its associated mid-tropospheric zone of deformation and frontogenesis. The surface low is located just east of the closed circulation, and a dry slot is shown sweeping over the south edge of the cyclone from the southwest. Banding, as indicated by black, dashed lines is shown to the north and northwest of the cyclone, within the mid-level deformation zone. The second image shows a cross-section taken from southeast to northwest across the cyclone shown in the first image. A steeply sloping, southeast to northwest frontal zone is indicated by the red shaded frontogenesis. Upward vertical motion is indicated by the thick, black arrow, on the warm side of the frontogenesis. Equivalent potential temperature is shown by the thin black contours. Note that these contours are packed close together in the frontal zone. Meanwhile, southeast of the frontal zone they are nearly vertical, indicating potential instability to slantwise vertical displacements. Banding would be expected underneath the area where the strongest upward motion is co-located with this potential symmetric instability zone.

Student Notes:



8. Christmas 2002 Storm – Satellite Imagery

Instructor Notes: The first example shown in this lesson is the Christmas day, 2002 storm that brought heavy snow to much of the northeast United States. The satellite imagery on this slide shows how a disorganized cloud pattern at 12 UTC on the 25th evolved into a classic comma-shaped pattern by 00 UTC on the 26th as the surface cyclone deepened rapidly off of the New Jersey coastline.

Student Notes:

9. The Christmas Day 2002 Storm – basic maps

Instructor Notes: This slide shows some forecast data from the NAM model run at 12 UTC on the 25th. The first and second images show a 500 mb closed low forecast to develop over New Jersey. The 3rd and 4th images show the associated surface low forecast to deepen rapidly south of Long Island – down to 982 mb. Subsequent observations indicated that the surface low would actually deepen to below 980 mb by 00 UTC on the 26th.

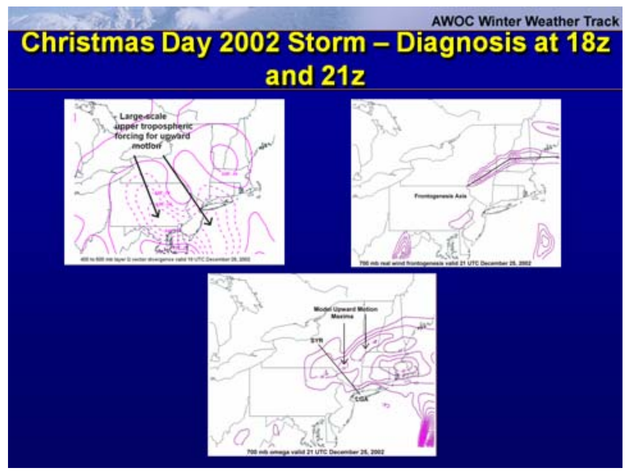
Student Notes:

10. Christmas Day 2002 Storm – Diagnosis at 18z and 21z

Instructor Notes: The relationship between the large-scale forcing, frontal scale forcing and model forecast upward vertical motion for this event is summarized by the NAM forecast data on this slide. The data at the upper left is a 6 hour forecast of 500 to 500 mb layer divergence of Q, displayed on an 80 km grid, and valid at 18 UTC on the 25th. This was the time when intense banding was just starting to develop over eastern and central

New York state. A maximum of convergence is shown extending from Pennsylvania to New Jersey. This indicates where the large-scale forcing associated with the mid to upper-tropospheric wave was being maximized. The slide on the upper right shows a 40 km 21z analysis of 700 mb real-wind frontogenesis extending from New England toward northeast Pennsylvania. This can be considered an indication of the mid-tropospheric frontal scale forcing for upward motion. A 40 km resolution NAM analysis of upward vertical motion, which is a function of all of the forcings, at all scales that the model is able to resolve, is shown at the bottom of the slide. The maximum of upward vertical motion is indicated over western New England and southeast New York, and appears to correlate more closely with the frontogenesis than with the upper-level large-scale forcing. The next slide will show cross-sectional forecast data along the line shown in the figure at the bottom, from Laguardia, NY (LGA) to Syracuse, NY (SYR).

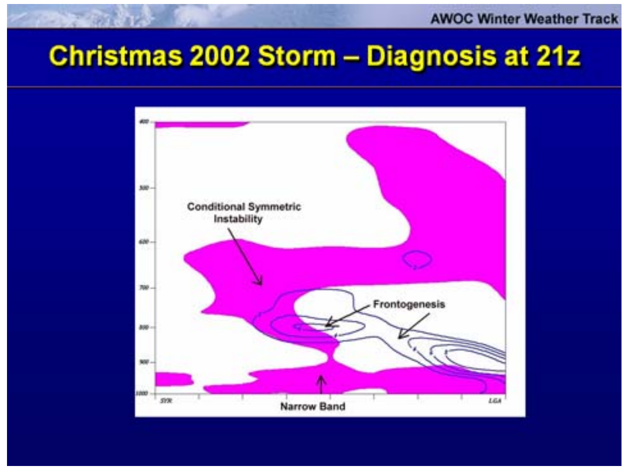
Student Notes:



11. Christmas 2002 Storm – Diagnosis at 21z

Instructor Notes: The relationship between the upward vertical motion and mid-tropospheric real-wind frontogenesis is shown by the first image on this slide. The data is an NAM analysis of frontogenesis and model vertical motion, taken along a cross-section from LGA to SYR and valid at 21 UTC on the 25th. Note that the maximum of upward vertical motion is located above and just to the southeast of the maximum of mid-tropospheric frontogenesis. This data indicates that a strong, thermally direct circulation was forecast to develop in association with the frontogenesis, with upward motion on the warm side of the frontogenesis, and sinking motion on the cold side. Note also that the upward vertical motion shown on this slide is deep, extending upward through 400 mb. This indicates significant coupling between the upward motion associated with the lower to mid-level front, and the upward motion associated with the upper-level support. The next image shows the real-wind frontogenesis, contoured in blue, along the same LGA-SYR cross-section, along with negative EPV shaded purple. The EPV was calculated using the geostrophic wind and saturated equivalent potential temperature. Relative humidity (not shown) throughout this area was forecast to be greater than 80 percent. Note the large area of negative EPV located above the frontogenesis, in the area where the upward motion, shown on in the previous image, was maximized. The data on this slide indicates a favorable condition for conditional symmetric instability, which would be favorable for the development of intense snow bands. The heavy snow band at 21z, marked by the arrow on this image, was located directly beneath the area where the strong upward motion, strong mid-level frontogenesis and negative EPV were all co-located.

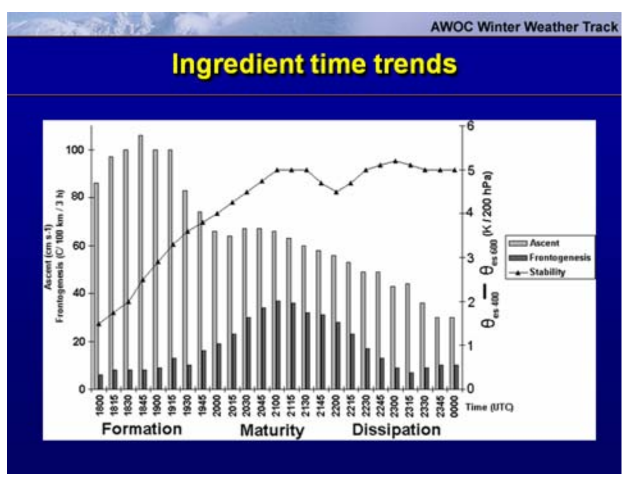
Student Notes:



12. Ingredient time trends

Instructor Notes: Dave Novak, Brian Colle and Sandra Yuter took a closer look at this storm and presented some results in an article published in Weather and Forecasting in 2008. The data shown on this slide is from a 4 km version of the Penn State – NCAR MM5 model, and summarizes some of their findings. Specifically, they found that frontogenesis, lowered stability and resulting enhanced upward vertical motion were all present during the portion of the storm when snowfall rates were most intense. Interestingly, they found that instability and ascent peaked during the early formation stage of the associated intense snow band, with stability over the band gradually rising during the most of the formation stage while ascent gradually decreased. Meanwhile, frontogenesis appeared to peak during the mature stage of the band.

Student Notes:



13. Christmas 2002 Storm – radar images

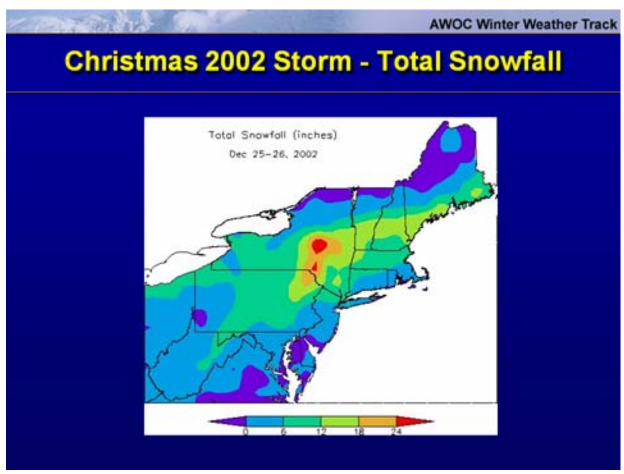
Instructor Notes: The radar loop from the KENX WSR-88D shown on this slide shows that narrow, heavy snow bands did develop within a large area of light to moderate snow over central and eastern New York. Snowfall rates within the heaviest of these bands ranged from 3 to 5 inches per hour.

Student Notes:

14. Christmas 2002 Storm - Total Snowfall

Instructor Notes: This image (courtesy of the Northeast Regional Climate Center) shows that a large area of heavy snow fell across the northeast U.S. on the 25th. The heaviest snow, in excess of 24 inches, fell in association with the narrow, intense bands shown on the previous slide.

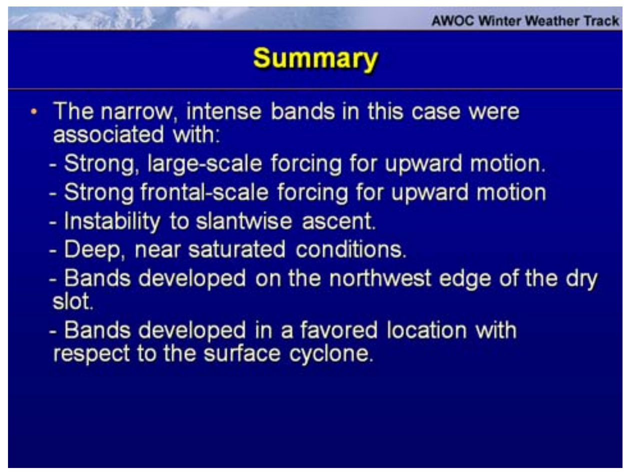
Student Notes:



15. Summary

Instructor Notes: The narrow, intense bands in this case were associated with strong large-scale forcing for upward motion and strong frontal scale forcing for upward motion. Coupling between these two forcing mechanisms resulted in a deep plume of upward vertical motion over central and eastern New York. Instability to slantwise motions was indicated by negative EPV, and deep saturation was associated with the deep plume of upward vertical motion. The favorable co-location between strong forcing for upward motion and mid-level instability occurred at the northwest quadrant of the cyclone, near the northwest edge of the dry slot of the storm.

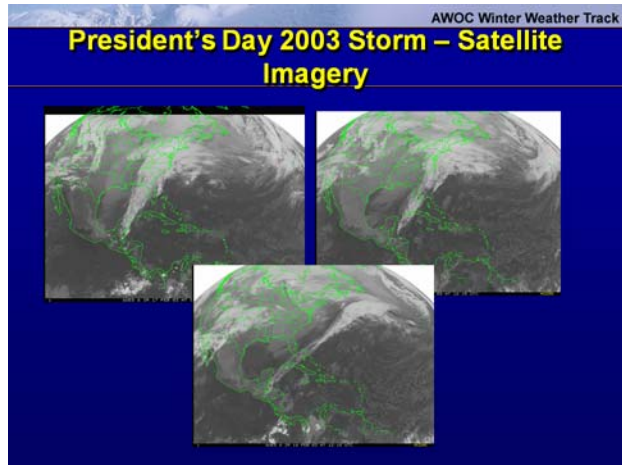
Student Notes:



16. President's Day 2003 Storm – Satellite Imagery

Instructor Notes: Our next example will be the President's Day 2003 snowstorm. The President's Day 2003 storm was another major snowstorm for the northeast and mid-Atlantic states. This series of satellite images shows an elongated north-south cloud band, associated with the warm conveyor belt of the storm, moving east off the east coast. Meanwhile, the head of the developing comma cloud can be seen organizing over the mid-Atlantic and northeastern states.

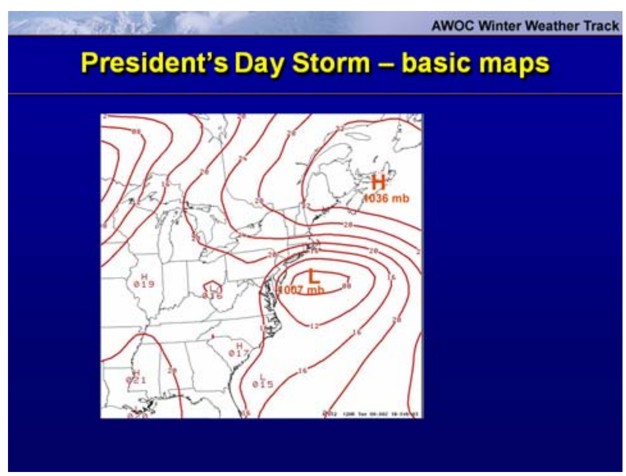
Student Notes:



17. President's Day Storm – basic maps

Instructor Notes: The data on the next few slides are forecasts from the NAM model run at 12 UTC on February 17, 2003. This first two slides show a closed low at 500 mb over the eastern Ohio Valley, while the next two images show a surface low forecast to move slowly northeast along the eastern seaboard. Unlike the Christmas Day storm, neither the 500 mb or the surface low was forecast to deepen much during this period, with the surface low pressure center forecast to deepen from 1009 mb to 1007 mb between 12 UTC on the 17th and 00 UTC on the 18th. A strong high pressure system northeast of New England was resulting in a strong easterly pressure gradient over New England.

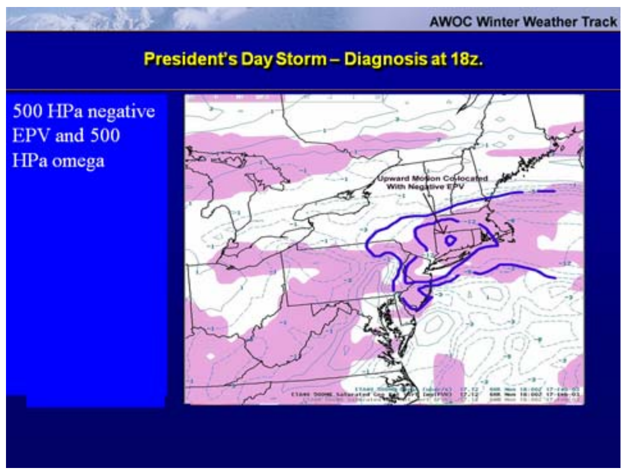
Student Notes:



18. President's Day Storm – Diagnosis at 18z.

Instructor Notes: The images on this slide show the large-scale and frontal-scale forcing for upward vertical motion in this case, valid at 18 UTC on the 17th. The first image shows the 500 to 300 mb Q vector divergence valid at 18 UTC on the 17th and displayed on an 80 km grid. A large, oval-shaped maxima can be seen over the northern mid-Atlantic area, just downstream from the deep upper trough over the Ohio Valley. The next 3 images are shown to illustrate smaller, frontal-scale forcings for this event, and are displayed on a 40 km grid. The second image shows that viewing frontogenesis on a 40 km can be a bit noisy, however an elongated maxima of 600 mb frontogenesis can be seen, extending from New England west toward eastern New York, indicating the potential for strong frontal-scale forcing for upward motion near or just to the south of that area. As was the case with the Christmas storm, the close proximity between the large-scale forcing associated with the upper wave and forcing associated with the lower-tropospheric front indicated the potential for coupling between the two forcings, and a deep plume of upward vertical motion. The third image shows the model forecast upward vertical motion, maximizing just south of the mid-tropospheric frontogenesis, over southern New England westward toward southern New York. Finally, the fourth image shows the co-location between the elongated maximum of 600 mb upward motion (contoured in blue), and an area of negative 500-400 mb EPV (calculated using the geostrophic wind and saturated equivalent potential temperature and shaded purple) over southern New England. The presence of deep saturation over southern New England (not shown), in combination with the factors outlined previously, indicated the potential for intense snow banding over southern New England at 18 UTC on the 17th.

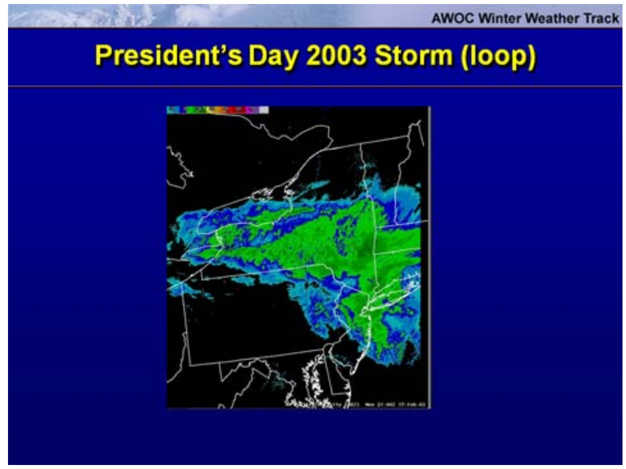
Student Notes:



19. President’s Day 2003 Storm (loop)

Instructor Notes: The data on this slide shows a loop of WSR-88D reflectivity from 16 UTC through 21 UTC on the 17th. We’ll stop the loop at 18z to point out a few key features. There appears to be a broad band of moderate to heavy snow covering the entire area from southern New England to western New York. Note also that there appears to be a more narrow, intense band embedded within the broader band, over southern New England. The precipitation over southern New England at this time was all snow, therefore the strong returns indicated on these images were probably not associated with bright-banding.

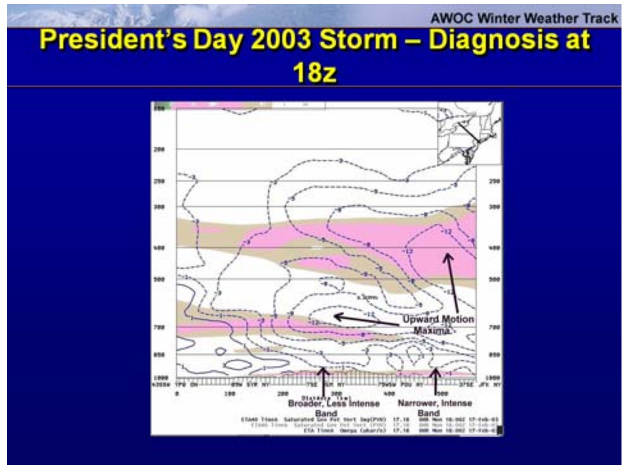
Student Notes:



20. President's Day 2003 Storm – Diagnosis at 18z

Instructor Notes: The data on this slide are shown to try to understand the character of the banding observed in the radar imagery in the last slide. The first image is a NAM 40 km analysis of real-wind frontogenesis, taken along a southeast-northwest cross-section from south of Long Island to near Lake Ontario. Two maxima can be seen, one representing the mid-level front over south central New York, and one representing the low-level front near New York City. The next image shows the upward vertical motion maxima associated with the frontogenesis. Note the deep plume of upward vertical motion, indicating coupling between the upper-tropospheric forcing and forcing associated with the lower-tropospheric front. The final image shows the upward vertical motion overlayed with negative EPV (shaded pink) and weakly positive EPV (shaded light brown). The key point here is that the area where the narrow, intense banding was observed was characterized by co-location of a deep layer of negative EPV and a large area of strong upward motion, while the area where the band was broad and only moderately intense was characterized by a smaller area of strong, upward motion and only a narrow layer of negative EPV. In this case, one could conclude that reduced stability narrowed and intensified the frontal circulation through-out the area from New England to New York state, leading to an enhanced upward branch of the circulation across the area from southern New England to southern New York. The result was a broad band of moderate to heavy snow located across that entire area. Slant-wise instability may have been released in the area of co-location between deep negative EPV and deep, strong upward vertical motion, over southern New England, which led to a further narrowing and intensification of the band in that area.

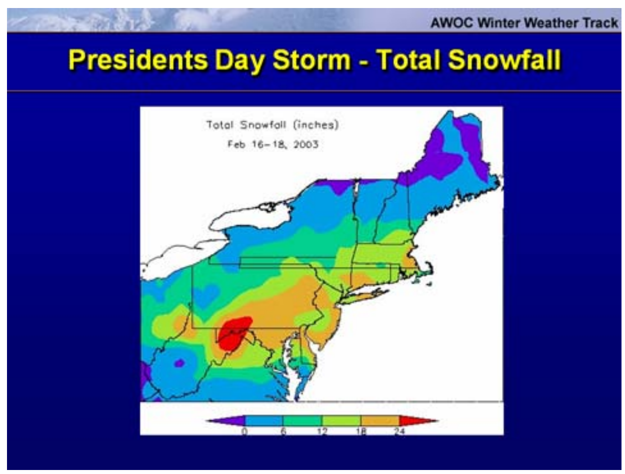
Student Notes:



21. Presidents Day Storm - Total Snowfall

Instructor Notes: This image of total snowfall (courtesy of Northeast Climate Data Center), shows that snowfall totals of 18 to 24 inches were observed within the intense bands over southern New England. Meanwhile, totals of around 12 inches were common farther to the west, underneath the broader, less intense band.

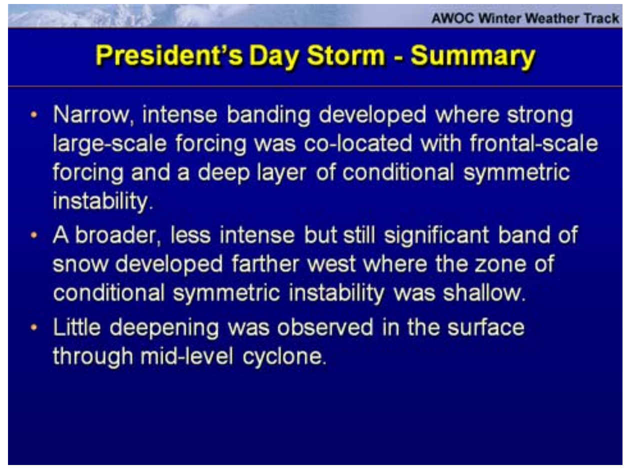
Student Notes:



22. President's Day Storm - Summary

Instructor Notes:

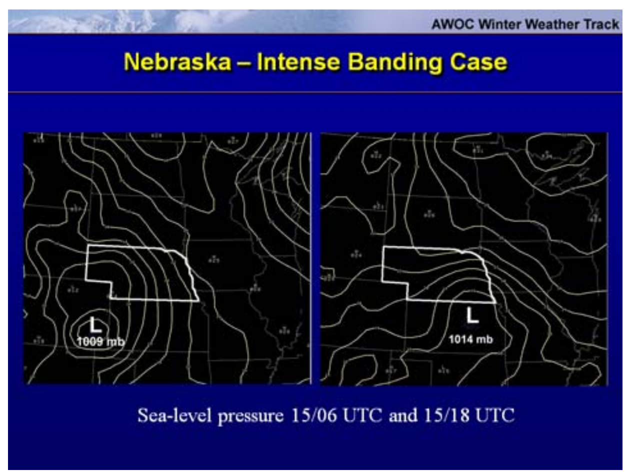
Student Notes:



23. Nebraska – Intense Banding Case

Instructor Notes: The next example in this lesson shows data from another event that produced significant bands of heavy snow, despite a lack of strong surface cyclogenesis. The sea-level pressure maps shown on this slide are from March 15, 2004. Low pressure developed to the lee of the central Rockies by 06 UTC on the 15th, then moved northeast to south central Nebraska by 18 UTC. No deepening was occurring during this time.

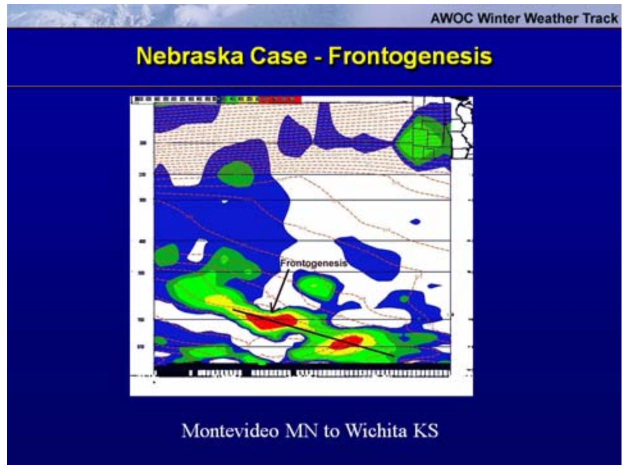
Student Notes:



24. Nebraska Case - Frontogenesis

Instructor Notes: This cross section shows the sloping front associated with this system, located from Kansas at low levels north to eastern South Dakota at mid-levels. A maxima of mid-level frontogenesis is indicated at around 700 mb across eastern Nebraska.

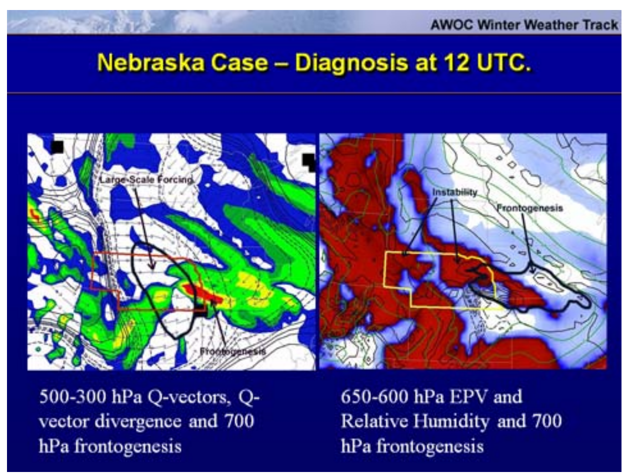
Student Notes:



25. Nebraska Case – Diagnosis at 12 UTC.

Instructor Notes: The data on this slide shows how the large-scale and frontal-scale forcing were co-located with instability in this event. The image on the left shows large-scale forcing associated with the upper wave, as shown by the black-contoured 500-300 mb Q vector divergence, centered over Nebraska at 12 UTC. Meanwhile, the mid-level frontal-scale forcing, as indicated by the yellow to red-shaded 700 mb frontogensis, was located along an east-west axis from Iowa to Nebraska. The image on the right shows the instability, as indicated by red-shaded negative 650-600 mb EPV, co-located with the black-contoured frontogenesis maxima over Iowa and Nebraska.

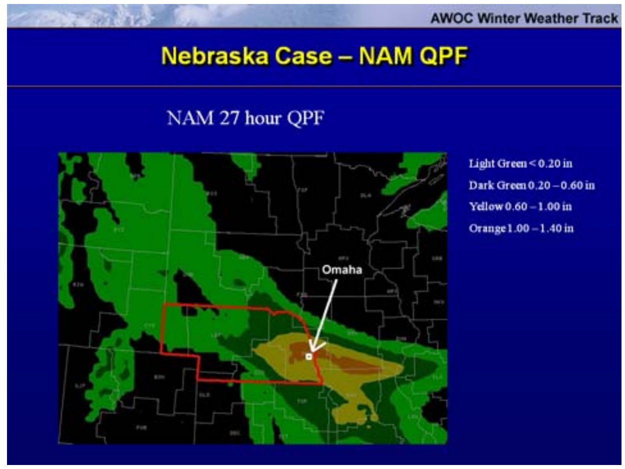
Student Notes:



26. Nebraska Case – NAM QPF

Instructor Notes: The NAM 27-hour QPF was indicating a narrow band of heavy precipitation stretching from southern Iowa to eastern Nebraska for this event. This forecast implied a heavy snow event centered over Omaha.

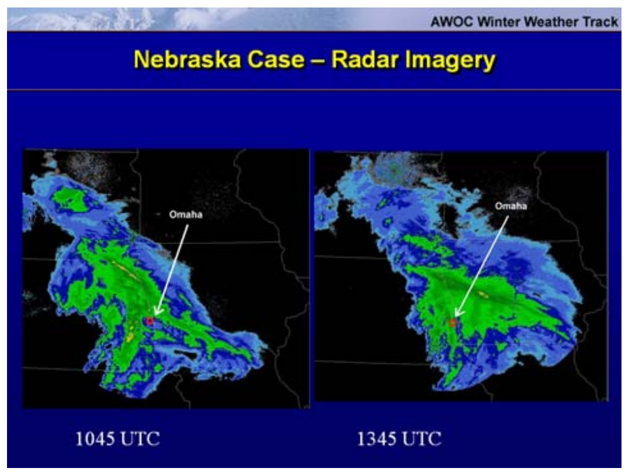
Student Notes:



27. Nebraska Case – Radar Imagery

Instructor Notes: Radar data around the time of the diagnostics shown in the previous slides show that bands of heavy snow did develop over eastern Nebraska and western Iowa.

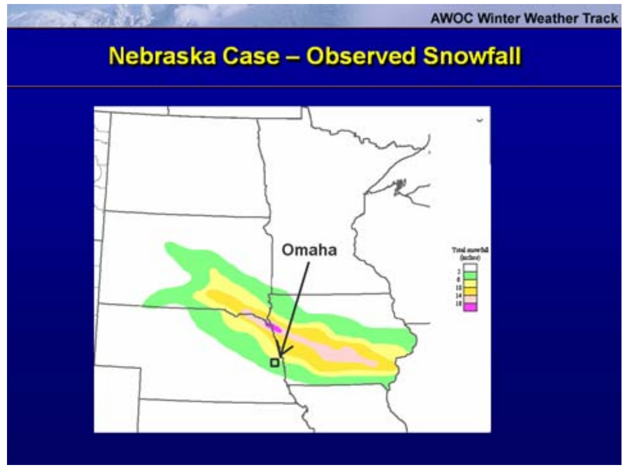
Student Notes:



28. Nebraska Case – Observed Snowfall

Instructor Notes: This slide shows that the observed heavy snowfall with this case did fall in roughly the same location as was indicated by the NAM. However, the devil was in the details. Note that the heavy snow actually fell just to the north of Omaha, into extreme southeast South Dakota and eastward to western Iowa. So, one could conclude from this case that while the NAM model was giving the forecaster important clues on the potential for a band of heavy snow, forecasters would still need to closely monitor observational clues in order to pinpoint the actual location of the heavy snow.

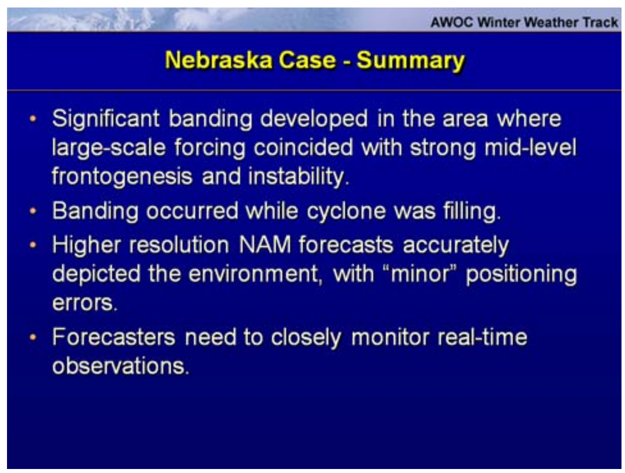
Student Notes:



29. Nebraska Case - Summary

Instructor Notes:

Student Notes:



30. Choices

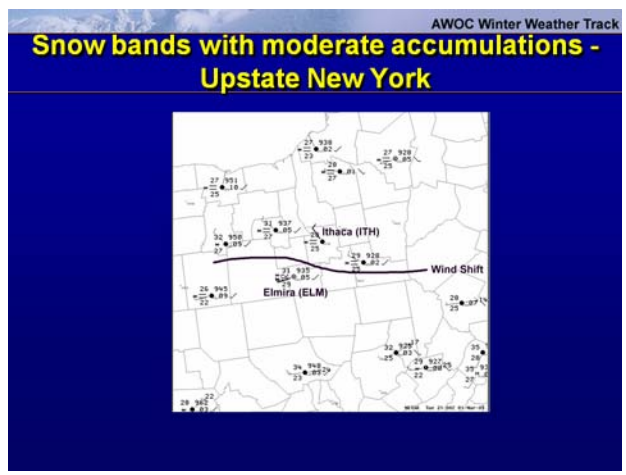
Instructor Notes:

Student Notes:

31. Snow bands with moderate accumulations - Upstate New York

Instructor Notes: For our next case – March 1st – 2nd, 2005 - we return to upstate New York. The first image shows a 6 hour NAM forecast of 500 mb heights and sea-level pressure forecast valid at 00 UTC on the 2nd. This data shows that upstate New York was in an area of north to northwest cyclonic flow on the backside of a major cyclone located over New England. The next image shows that the strongest upper-level large-scale forcing for upward motion, as indicated by the 500 to 300 mb Q vector convergence, was located over the Canadian Maritimes, with weaker upper-level forcing indicated over upstate New York. This type of large-scale setup is typically associated with a large area of light snow or snow showers across upstate New York, and may be associated with significant lake effect snow under certain conditions. The next image shows a surface plot over New York and Pennsylvania at 00 UTC on March 2nd. An east-west surface trough is indicated over southern New York, embedded within the northwest flow Strong convergence is evident along the surface trough between Elmira (ELM) and Ithaca (ITH). Moderate to heavy snow was developing along and ahead of the trough at this time.

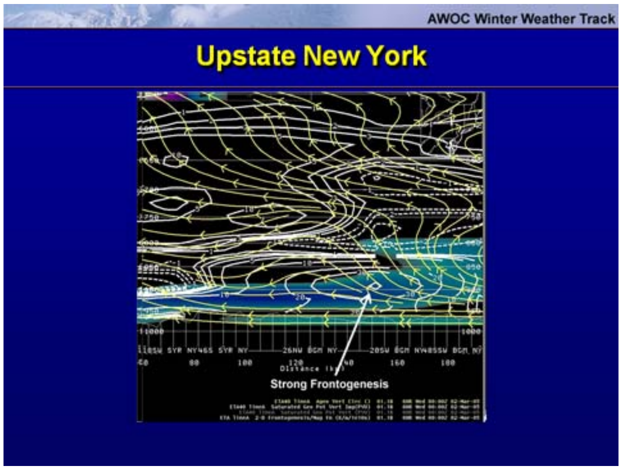
Student Notes:



32. Upstate New York

Instructor Notes: The series of images on this slide shows the NAM forecast development of low-level frontogenesis associated with this surface trough as it moved south across upstate New York. At 18 UTC, the frontogenesis was not significant. By 21 UTC, a strengthening area of frontogenesis is indicated below 850 mb. An area of negative geostrophic EPV is also indicated below 850 mb. The bottom image shows a strong maxima of frontogenesis, confined to the area below 850 mb, and co-located with an area of negative EPV. Ageostrophic vertical circulation vectors are included to illustrated the shallow nature of the circulation (confined mainly below 700 mb). High relative humidity values, not shown on these figures, were also confined to a shallow, surface-based layer.

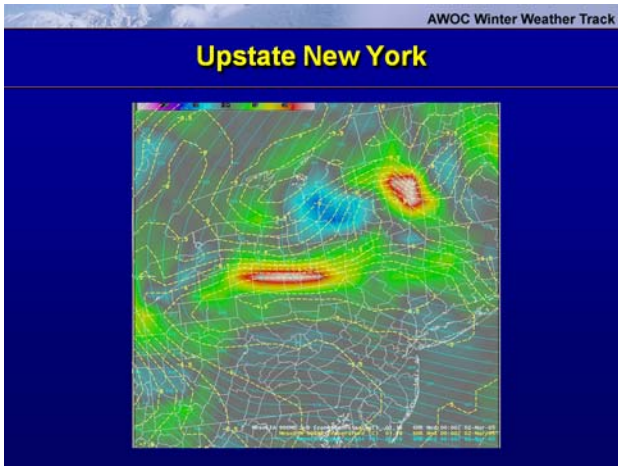
Student Notes:



33. Upstate New York

Instructor Notes: This slide shows a plan view of 900 mb frontogensis and temperature valid at 00 UTC on March 2nd. The frontal-scale forcing is clearly evident. Note the strong 900 mb temperature gradient, depicted by the yellow contours, associated with the frontogenesis. The frontogenesis was completely confined to the layer below 850 mb. This case illustrates the importance of not restricting your search for frontogenesis to the usual middle tropospheric levels.

Student Notes:



34. Upstate New York (loop)

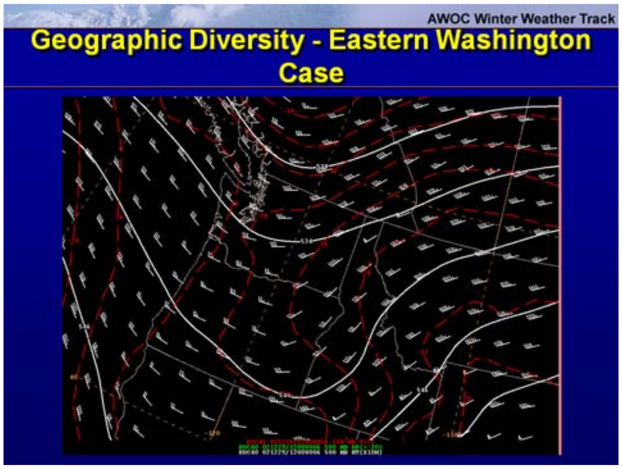
Instructor Notes: This loop shows the development of the associated snow band. The band produced snowfall rates of 1 to 2 inches per hour over the southern tier of New York and northern Pennsylvania. The area defined by the white contour picked up a quick 5 inches of snow in about 5 hours during the evening on March 1st.

Student Notes:

35. Geographic Diversity - Eastern Washington Case

Instructor Notes: While the majority of published case studies of these banding-type events are from the northeast or mid-west, these types of events can occur in other places. For the sake of some geographic diversity, we next take a quick look at a case that occurred over eastern Washington state. This first slide shows a 500 mb trough moving east across the area. Note that there is no mid-level closed circulation associated with this system, just an open wave.

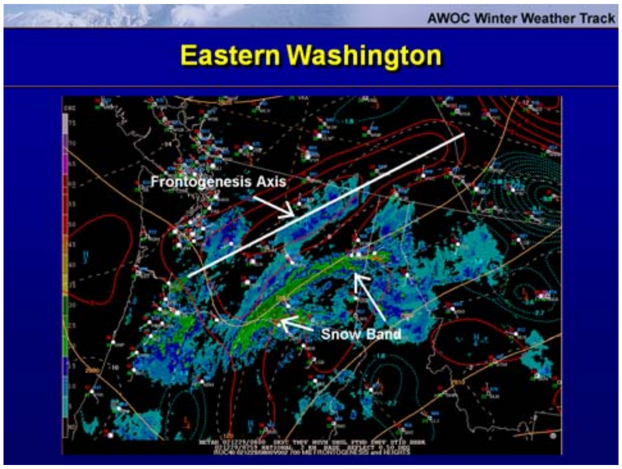
Student Notes:



36. Eastern Washington

Instructor Notes: This next slide shows that a significant band of snow, with snowfall rates of an inch per hour, developed over eastern Washington with this system. The red contoured field is 700 mb frontogenesis. So, as was the case with our other events, the banding developed on the southeast side of the mid-level frontogenesis.

Student Notes:



37. Eastern Washington

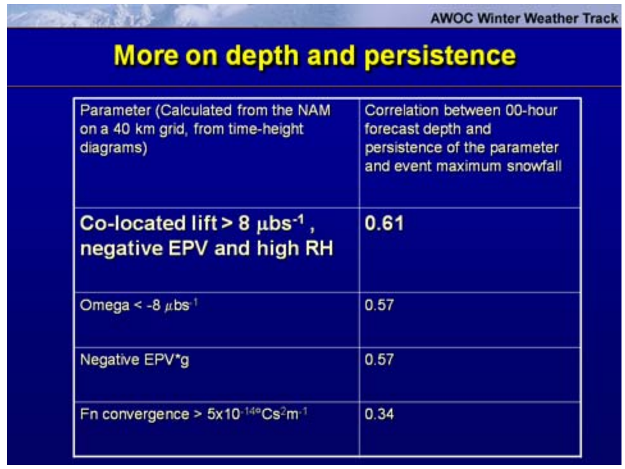
Instructor Notes: This slide shows a RUC model forecast sounding at Spokane Washington, valid at the time when banding was occurring across the area. Note the deep layer of saturation and near moist adiabatic lapse rates indicated on the sounding. To briefly summarize this case then: Once again banding developed in an area where large-scale and frontal-scale forcing became co-located with saturation and reduced stability.

Student Notes:

38. More on depth and persistence

Instructor Notes:

Student Notes:

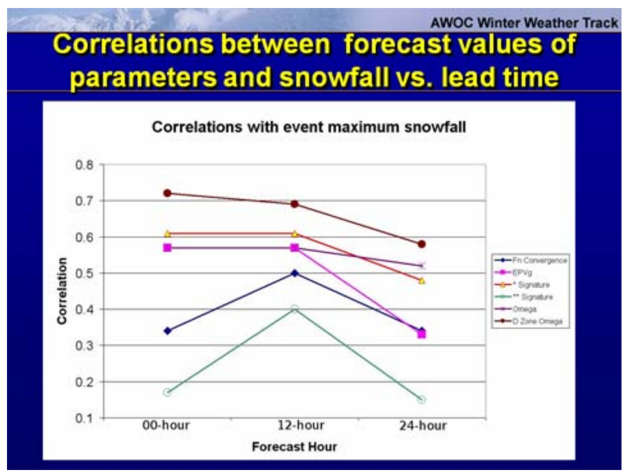


Parameter (Calculated from the NAM on a 40 km grid, from time-height diagrams)	Correlation between 00-hour forecast depth and persistence of the parameter and event maximum snowfall
Co-located lift > 8 μbs^{-1}, negative EPV and high RH	0.61
Omega < -8 μbs^{-1}	0.57
Negative EPV*g	0.57
Fn convergence > 5x10^{-14o}Cs^{2}m^{-1}	0.34

39. Correlations between forecast values of parameters and snowfall vs. lead time

Instructor Notes:

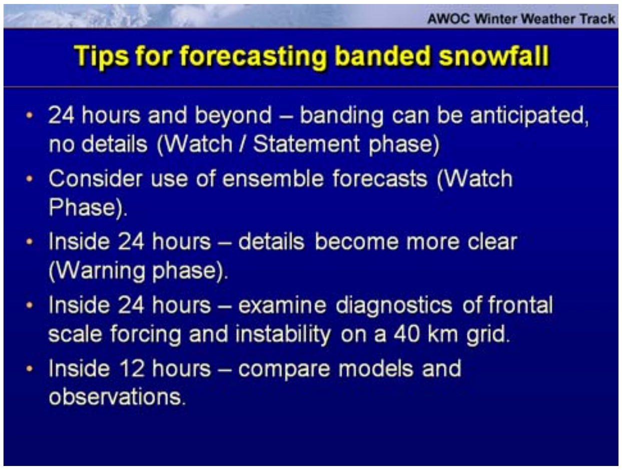
Student Notes:



40. Tips for forecasting banded snowfall

Instructor Notes: So, now let's summarize how we can apply all of this material in a real-time forecasting environment. When you are looking at a potential event that is expected to occur at 24 hours or beyond, you need to be looking primarily at fields that the models do best with at those time scales. That means mostly forecasts of large-scale flow patterns. For example, the potential for major banding events can become apparent at times beyond 24 hours when the models are forecasting that your area of interest will be in the northwest quadrant of a deepening surface cyclone, with diffluent mid-tropospheric flow and associated mid-tropospheric deformation. However, 24 hours or more is still too early to have much confidence in the details of the placement of the band. This is the time when statements or watches could be issued for large portions of your area. At these extended time periods, forecasters should also consider the use of short range ensemble forecasts. For example, spaghetti and probability charts can be used to help forecasters gauge the uncertainty of the flow evolution, and find areas where favorable conditions for banding are most likely. Inside 24 hours, the details of the potential banding scenario become more certain. By this time, the forecaster should have a situational awareness that banding is likely somewhere in the area – now is the time to try to pinpoint the location and intensity of the bands and to issue warnings. Examination of model forecasts of frontal-scale forcing and instability becomes critical during this period, as the models begin to hone in on the location and intensity of these signatures. Examining these types of diagnostics on a 40 km grid is recommended – a larger grid spacing may "wash-out" some critical signatures, while a smaller grid can sometimes be too noisy. Inside 12 hours, as well as during the event, integration of the model forecasts with observations becomes the main challenge. During this time, model forecasts can be adjusted based on how well the diagnostics and model QPF forecasts are matching the observations.

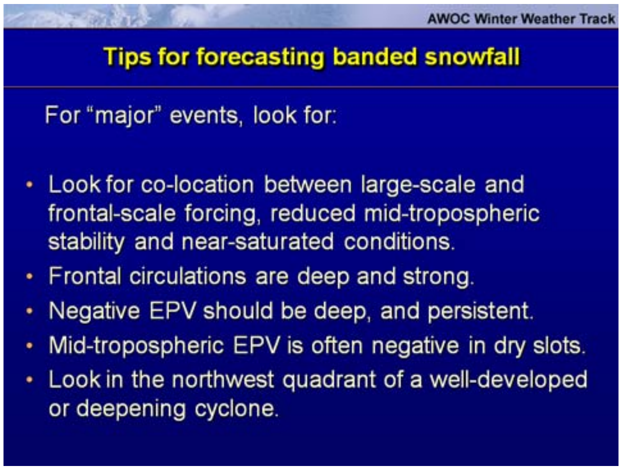
Student Notes:



41. Tips for forecasting banded snowfall

Instructor Notes: The information on this slide summarizes some of the characteristics of model forecast diagnostics that you are likely to see prior to and during a "major event", or an event that features intense bands with snowfall rates in excess of an inch per hour, and snowfall totals of greater than 6 inches. For these events, look for co-location between strong mid to upper tropospheric large-scale forcing and lower to mid-tropospheric frontogenesis, reduced or negative stability to slantwise displacements, as indicated by EPV, and near saturated conditions. The frontal circulations, or plumes of upward vertical motion, associated with these major events tend to be deep and intense. Likewise, the forecast areas of negative EPV are also usually deep and persistent. For example, some local research here at BGM and SUNY Albany indicates that 40 km grid-forecasts of negative EPV for major events are usually at least 50 mb deep and usually persist for at least 3 hours. Keep in mind that EPV is often negative in dry slots, where moisture decreases with height. Obviously, the dry slot is not a favored location for heavy, banded precipitation. The most common location for heavy snow bands will be at the northwest edge of the dry slot, in the northwest quadrant of the surface to mid-level cyclone.

Student Notes:



42. Tips for forecasting banded snow

Instructor Notes: For "moderate" events, or events that feature snow bands with accumulation rates of an inch per hour or less, and total snow accumulations of less than half a foot, the large-scale forcing may not necessarily be as strong as with "major" events, and may not be as well co-located with the lower-to mid-tropospheric frontal-scale forcing. As a result, the frontal circulations associated with these systems may not as deep as in "major" events. Likewise, research at SUNY Albany and BGM indicates that, while negative EPV is commonly forecast with these types of systems, it is usually not as deep or persistent as in stronger systems. These types of events can still be quite disruptive, especially if they are not forecast with adequate lead times.

Student Notes:

43. Choices

Instructor Notes:

Student Notes:

---

44. References

Instructor Notes:

Student Notes: