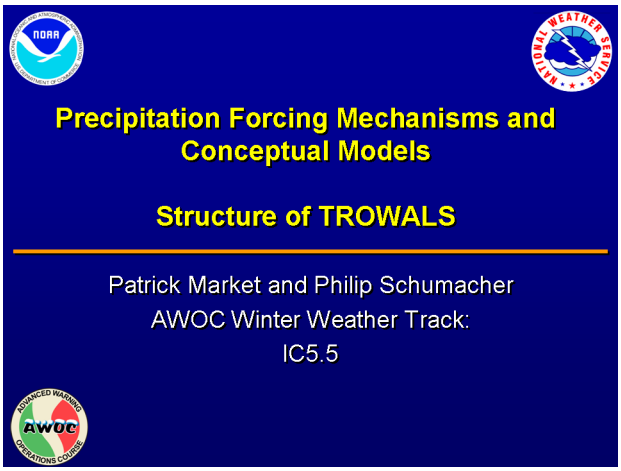
1. IC5.5: Structure of TROWALS

Instructor Notes: Authors: Dr. Patrick S. Market, Department of Soil, Environmental and Atmospheric Sciences, University of Missouri-Columbia; and Philip N. Schumacher, National Weather Service, Sioux Falls, South Dakota. This presentation should last approximately 25 minutes.

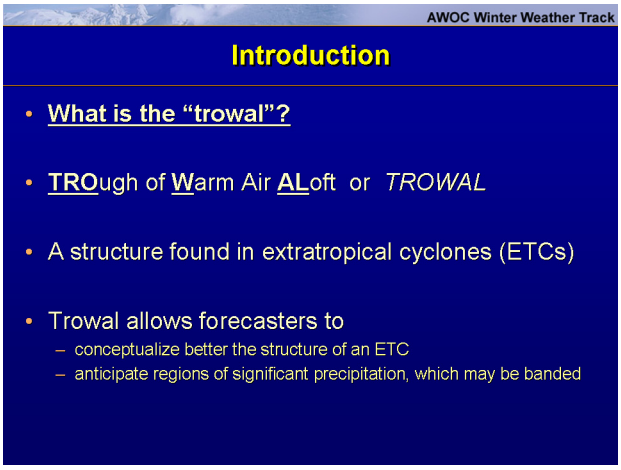
Student Notes:



2. Introduction

Instructor Notes: In this lesson, we will examine the cyclone structure known as the trowal, which is a kind of acronym for “trough of warm air aloft.” The concept of the trowal has been a part of the parlance of operational meteorology for nearly 60 years. Use of the trowal concept is intended to highlight to meteorologists where it is in an extratropical cyclone that precipitation, perhaps banded, may occur over the cold surface air north and west of a cyclone center. When present, an occluded front at the surface is not always the focus of precipitation, low ceilings, and other inclement weather. Also, a trowal-like feature sometimes appears before the surface cyclone may be analyzed as occluded. In either instance, it is often the region of the trowal where significant weather and precipitation occur.

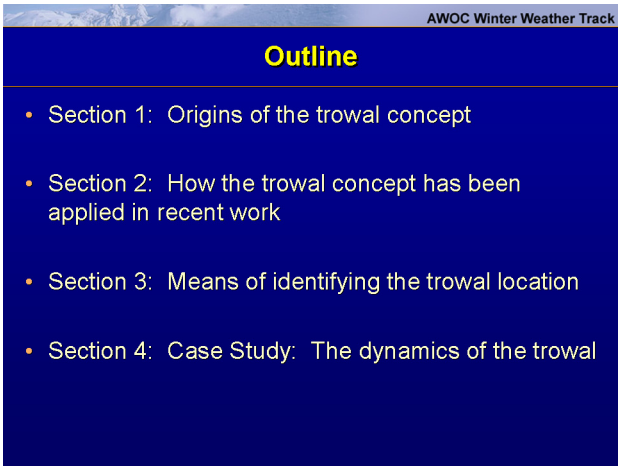
Student Notes:



3. Outline

Instructor Notes: This lesson is broken into four primary components: First, we will examine briefly the origin of the trowal concept in the late 1940s. Next, we will look at Martin's American revival of the phrase in the late 1990s along with the work of some other investigators from about that same time. Third, we will examine different methods for analyzing for and locating the trowal. Finally, we will go about the process of identifying the trowal in an actual case and then looking deeper at the processes that shape and maintain it.

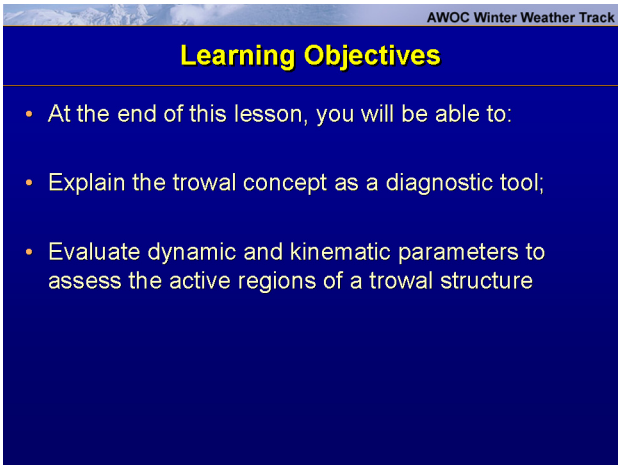
Student Notes:



4. Learning Objectives

Instructor Notes: At the end of this lesson, you will be able to: Explain the trowal concept as a diagnostic tool, evaluate dynamic and kinematic parameters to assess the active regions of a trowal structure, and these learning objectives will be assessed on the final exam (taken on the LMS) for each lesson.

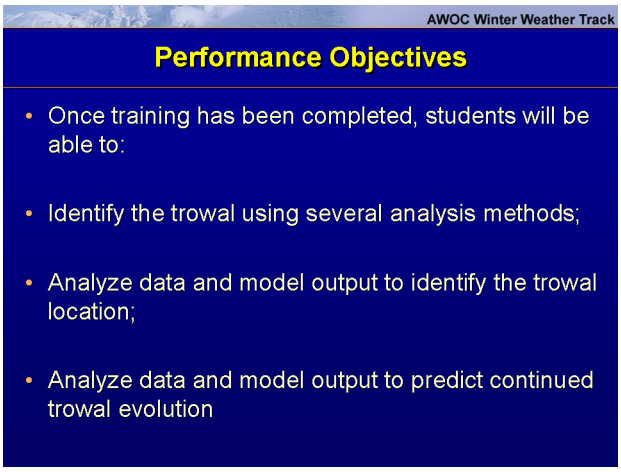
Student Notes:



5. Performance Objectives

Instructor Notes: Once training has been completed, students will be able to: Identify the trowal using several analysis methods, analyze data and model output to identify the trowal location, and analyze data and model output to predict continued trowal evolution. Performance objectives will be evaluated for each student after training is completed, in simulations and on-the-job.

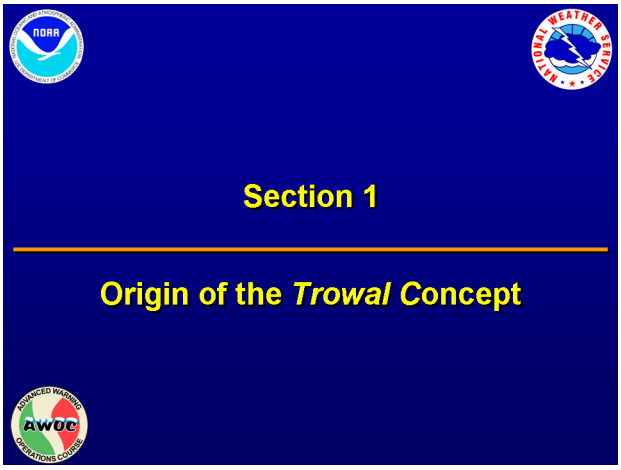
Student Notes:



6. Section 1

Instructor Notes: Now let's start Section 1: Origin of the Trowal Concept.

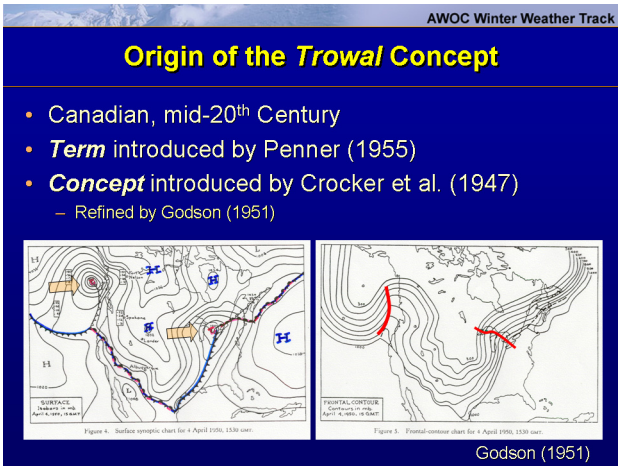
Student Notes:



7. Origin of the Trowal Concept

Instructor Notes: The trowal concept originated in Canada, and the earliest known reference to the feature comes from the paper by Crocker et al. (1947). Throughout each of the referenced studies, the authors were seeking explanations for precipitation and other inclement weather that occurred in the cold air north of a surface cyclone, but away from the analyzed surface occluded front (as often happens). Of the figures shown, the left one is a surface analysis, while the one on the right is a "frontal contour chart." The latter was meant to depict the location of a front at each successive height in the atmosphere. Simply put, each contour represents the location of the frontal zone on each pressure level. In this instance, the analyst identified a baroclinic zone with vertical integrity through a deep layer (1000-300 mb) spanning an area of several thousand kilometers. The West Coast surface occluded front (left) is accompanied by a trowal axis in red (right). This feature marks the farthest poleward extent of the warm sector air at each higher level. Notice a similar, but less pronounced feature with the pre-occlusion surface low over Lake Huron.

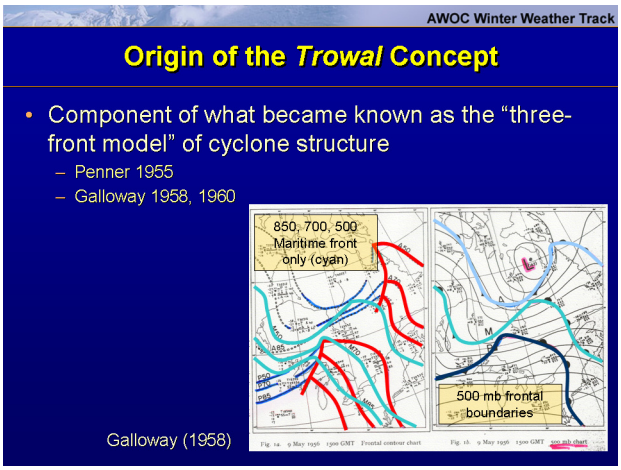
Student Notes:



8. Origin of the Trowal Concept

Instructor Notes: As alluded to previously, finding the trowal was an exercise in first analyzing frontal topography at multiple levels. Sparse data and significant labor in creating such charts likely called the process into question in an age of an improving dynamic understanding of the atmosphere (e.g., the operational emergence of QG theory) and advancing NWP techniques.

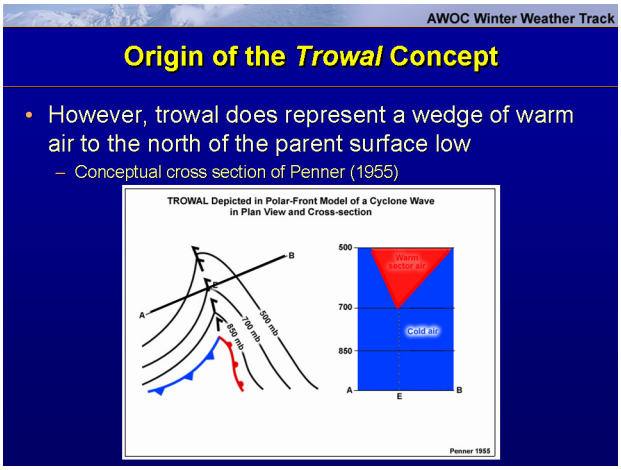
Student Notes:



9. Origin of the Trowal Concept

Instructor Notes: Although the three front approach is cumbersome to use, one artifact remains useful: the trowal. The existence of the warm conveyor belt in an extratropical cyclone ensures the existence of warm air aloft, above much cooler surface air. The sloping axis of that warm sector air is the trowal. The graphic on the screen was captured from a Jim Moore webcast for COMET, based on a presentation by Market (2002).

Student Notes:



10. Interactive Quiz #1

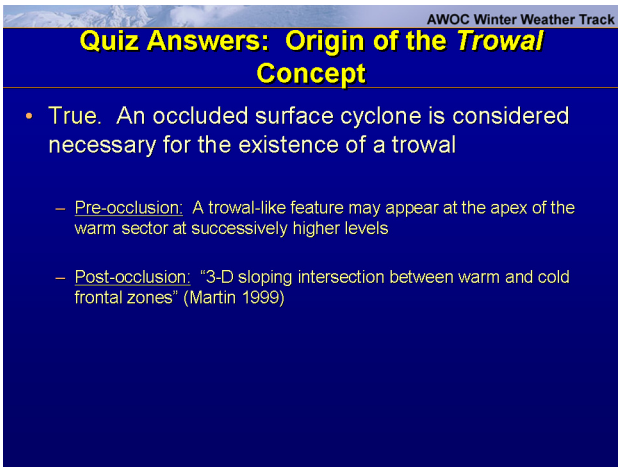
Instructor Notes: Take a few moments to complete the quiz on trowal concepts.

Student Notes:

11. Quiz Answers: Origin of the Trowal Concept

Instructor Notes: This slide explains the correct answer to the first question in interactive quiz #1.

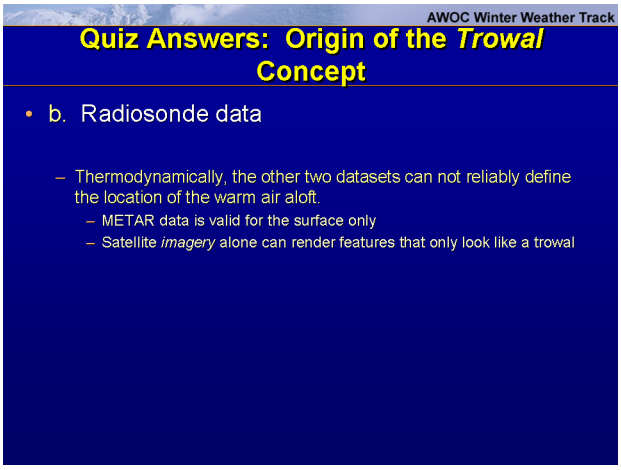
Student Notes:



12. Quiz Answers: Origin of the Trowal Concept

Instructor Notes: This slide explains the answers to the second question in interactive quiz #1.

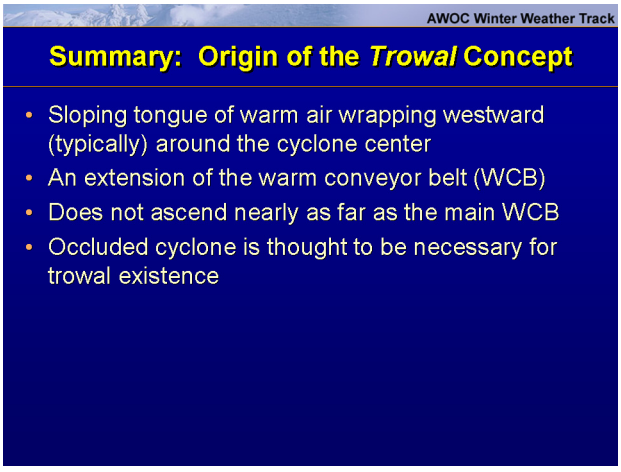
Student Notes:



13. Summary: Origin of the Trowal Concept

Instructor Notes: An excellent VISITView session is available on trowal identification. Although the historical literature suggests that an occluded surface cyclone is necessary for the existence of the trowal (and thus its airstream), recent research has called that view into question.

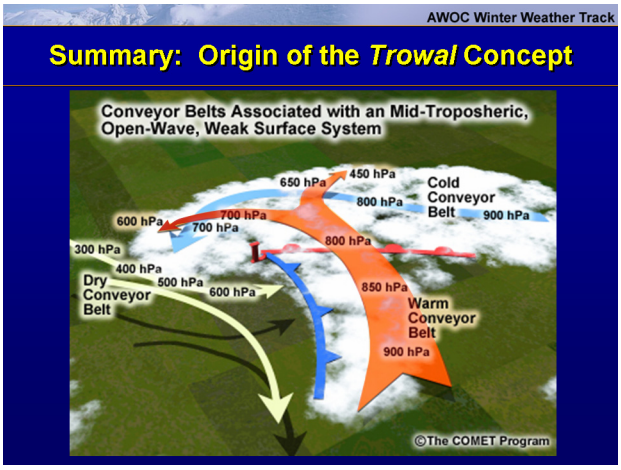
Student Notes:



14. Summary: Origin of the Trowal Concept

Instructor Notes: Here is a screen shot from one of Jim Moore's COMET webcasts showing the bifurcation in the WCB of a surface cyclone that has not yet occluded. Further work by his group (Moore et al., 2005) has shown similar structures in other weak or non-developing cyclones.

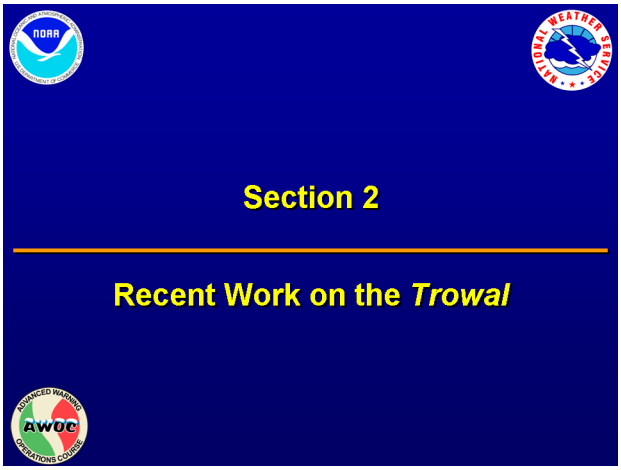
Student Notes:



15. Section 2

Instructor Notes: Now let's look at Section 2: Recent Work on the Trowal.

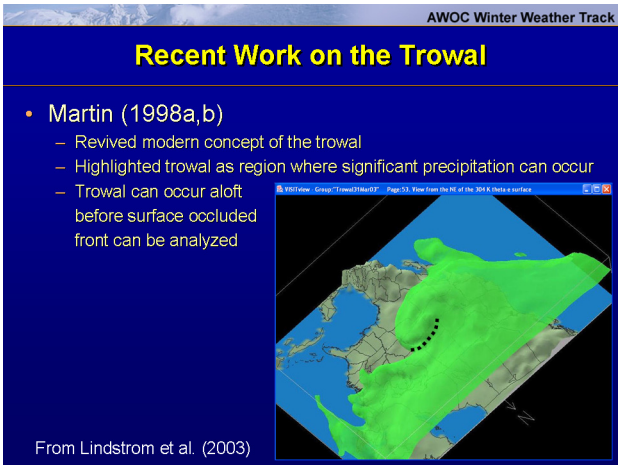
Student Notes:



16. Recent Work on the Trowal

Instructor Notes: Martin's work was the first in recent years to deal directly with the trowal, and its direct influence on banded heavy snowfall. Martin suggested a top-down process for occlusion in this case, wherein the occlusion process occurs aloft before an occluded front can be analyzed at the surface.

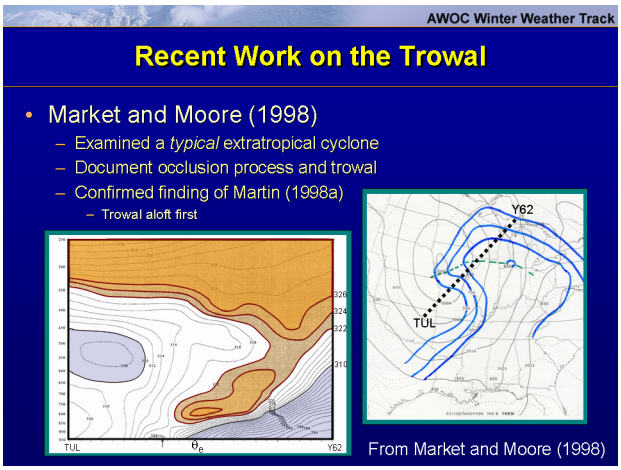
Student Notes:



17. Recent Work on the Trowal

Instructor Notes: The cyclone of Market and Moore generally followed the Norwegian Cyclone Model evolution, with the cyclone occluding first near the surface and thne farther aloft with time (i.e., from the bottom up). The goal was to document the occlusion process in a typical mid-latitude extratropical cyclone. However, a trowal-like feature was present aloft well before a surface occluded front could be analyzed. This feature exhibited cloud and precipitation development.

Student Notes:

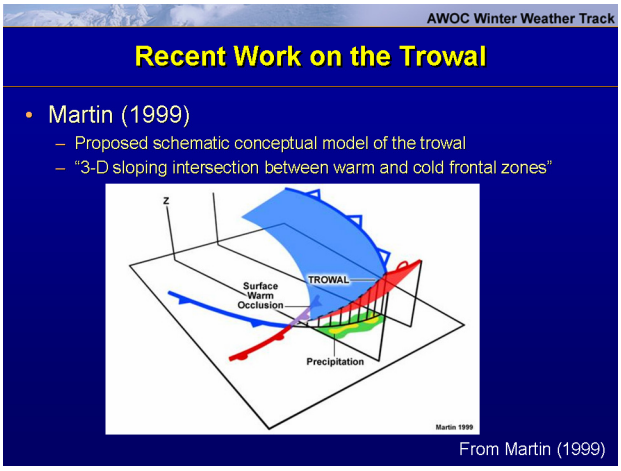


18. Recent Work on the Trowal

Instructor Notes: The seminal work of Martin (1999) detailed for the first time the 3-D structure of the trowal, and its dominant influence over precipitation generation in the region. The model shown here helps forecasters to conceptualize the sloping nature of the trowal, and its strong correlation to the band of precipitation experienced at the surface. Moreover, it highlights the absence of organized precipitation at the surface occluded front as is often the case. Although not unlike the original intent of the Canadian three-front model, Martin's model is a generalized approach which assumes no

elongated frontal boundary with integrity through a deep layer. Instead, this model focuses on the airstream associated with the trowal and its inevitable development within deep extratropical cyclones.

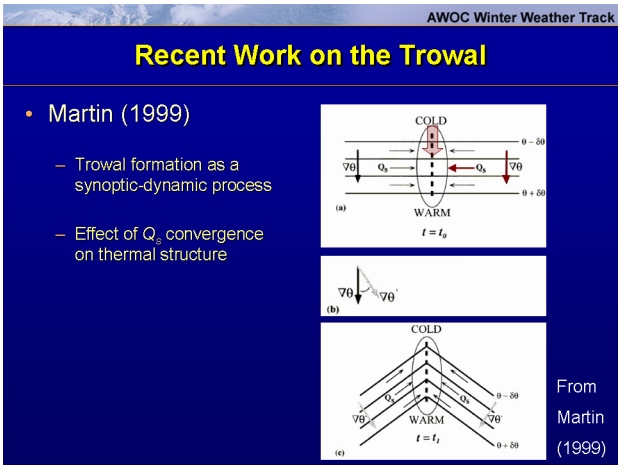
Student Notes:



19. Recent Work on the Trowal

Instructor Notes: Not content to simply conceptualize the trowal structure, Martin sought to explain its evolution. Using the Q-vector and its natural-coordinate, along-stream component, Q_s, Martin set about the task of quantifying the creation of the thermal ridge that is the trowal's signature. We begin with a typical zonal, thermal (potential temperature) gradient with cold air on the poleward side, and the warm air toward the equator (a). The thermal gradient thus points equatorward everywhere on this diagram. Superimposed upon this thermal gradient is a field of Q_s which point toward a common axis in the center of the thermal field. Such an arrangement is common in a young frontal cyclone, where geostrophic motions still dominate the flow. Martin states the following: "The Q vectors located to the left (right) of the Q_s convergence maximum…describe the geostrophic contribution to counterclockwise (clockwise) rotation of the [thermal gradient] vector with time." A known behavior of the Q_s component is its tendency to rotate counterclockwise when cold air exists initially on its left, and a clockwise turn when cold air is on its right. Consequently, the potential temperature gradient vectors rotate toward one another (b). This behavior forces the development of a thermal ridge where the convergence of the Q_s components is maximized (c).

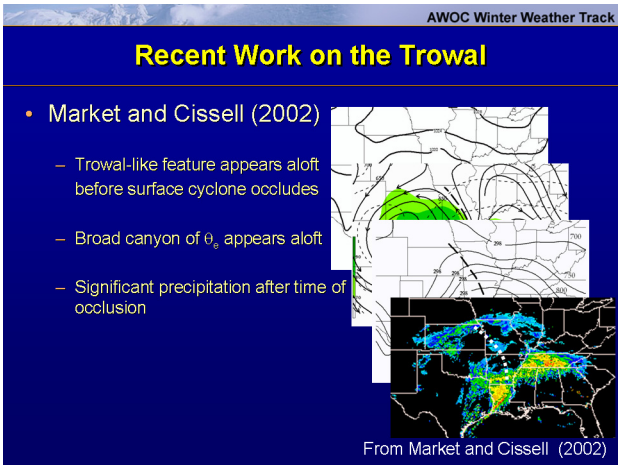
Student Notes:



20. Recent Work on the Trowal

Instructor Notes: Market and Cissell used the trowal concept to help define the axis of greatest precipitation using methods similar to those of Martin. What is of interest in this discussion is the trowal-like feature that emerges before there is evidence of an occluded system at either the surface or in the upper atmosphere. The surface analysis reveals an open wave cyclone with relatively weak centers of circulation near Lake Charles and Shreveport, Louisiana. The analysis of storm-relative winds on the 298K shows a split in the warm conveyor belt (which originates just to the east of the surface lows and follows roughly the Mississippi River), with the westward turning portion originating over Missouri. This airstream also happens to follow the pressure ridge, which in isentropic space, can be shown to be a thermal ridge also. Yet, the equivalent potential temperature gradient fails to show overlapping of surfaces as appeared in Martin's work. Meanwhile the axis of maximum theta-e lies along and just to the west of the pressure ridge depicted in the previous isentropic analysis of 298 K. Nevertheless, significant precipitation fails to appear along this axis at this time. Recall that the original trowal concept was aimed at explaining precipitation bands over cold surface air in a (preferably) occluded system. Although neither of these exist with this system at this time, signatures of what we would call the trowal in occluding cyclones do exist.

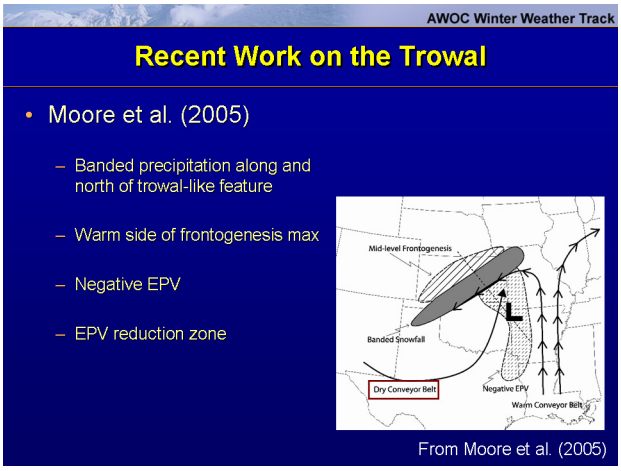
Student Notes:



21. Recent Work on the Trowal

Instructor Notes: Moore and his collaborators examined a weak cyclone that was associated with a band of heavy snowfall over Kansas. Not only was the surface cyclone not analyzed as occluded, but the trough aloft (e.g., 850, 500, 300 mb) was found progressively farther to the west and presenting a positive tilt. A similar cyclone was analyzed by Halcomb and Market (2003). While it is useful to have the trowal and the warm, moist flow that comes along with it, snow totals can be enhanced if the band becomes convective. In that regard, it is ideal for maximum snow totals to produce a layer above the trowal airstream that is potentially colder and/or drier. In this context, Moore et al. (2005) pay particular attention to the presence of the dry conveyor belt which acts to create the comma head of the extratropical cyclone while acting to create instability through Nicosia and Grumm's (1999) concept of EPV reduction.

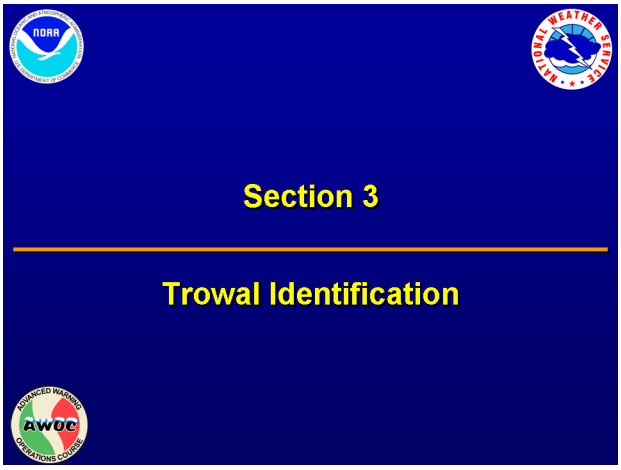
Student Notes:



22. Section 3

Instructor Notes: Now onto Section 3, which is titled Trowal Identification.

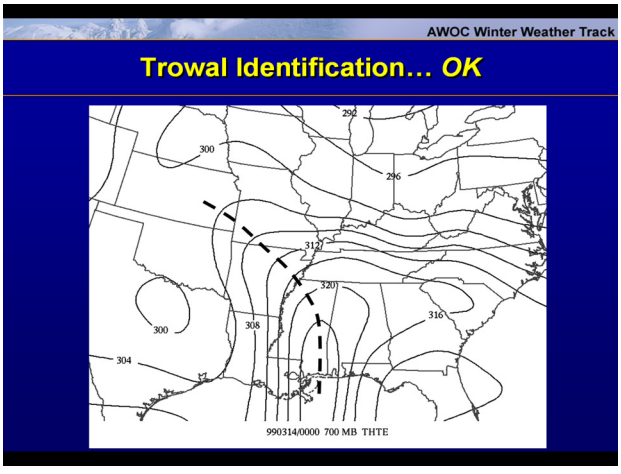
Student Notes:



23. Trowal Identification…OK

Instructor Notes: Equivalent potential temperature on a pressure surface can provide a good first look at the location of the trowal. Plot the equivalent potential temperature on a pressure surface, and assess its pattern. Theta-e is used as it represents parcels with relatively high temperature or humidity or both; more importantly, it is assumed to be largely conserved for both dry and moist processes. 850, 700, and 500 mb are typical levels, with 700 mb being, perhaps, the most common. However, the trowal is a 3-D feature, so confining our analysis to just one level is not the best idea. Moreover, parcels are not bound to pressure surfaces, which also have a much more shallow slope than many equivalent potential temperature surfaces. Even the slope of the dry potential temperature surface is much greater than that of a pressure surface (Moore, 1993).

Student Notes:

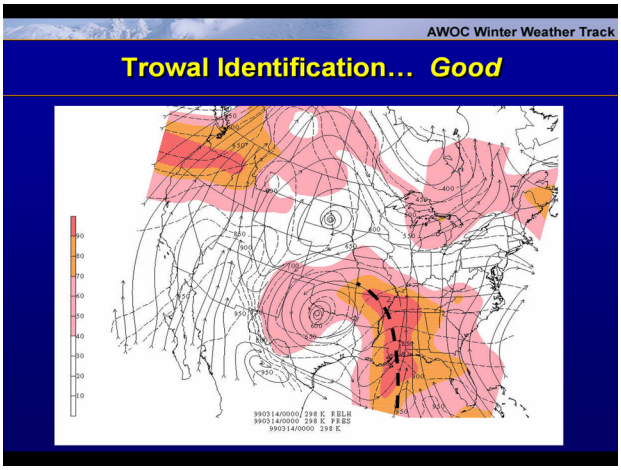


24. Trowal Identification… Good

Instructor Notes: Pressure and storm-relative winds on an isentropic surface. To a first approximation, parcels flow along surfaces of potential temperature. Additionally, surfaces of potential temperature are rarely multi-valued with height; in other words, they

seldom fold over on themselves at higher and higher levels. Thus we have at our disposal surfaces that define, on the synoptic scale, the motion of individual parcels. The following is extra material above what has been mentioned. Through Poisson's equations, we can show that a lower temperature corresponds to a lower pressure on an isentropic surface. Therefore, when we find a pressure ridge, we know that feature is also a thermal ridge with the highest pressures (temperatures) along the axis. Additionally, one may also plot the equivalent potential temperature on a potential temperature surface. The result is often a pattern that is quite similar to that of pressure, but of a parameter that is know to be conserved for moist and dry processes. Given that conveyor belts are system-relative entities, the creation of storm-relative winds is necessary to define any one of the airstreams that comprise an extratropical cyclone. One must first the calculate the storm motion (C), typically the motion of the absolute vorticity maximum over 6 to 12 hours on the surface that is to be examined. This value is then subtracted from the total wind in the observations or the model output as (V-C) in order to get the storm-relative winds. These winds will have their greatest relevance within the radius of the circulation under scrutiny. Moreover, one may think of the resulting streamlines as trajectories, provided the system is translating at a constant pace and in a steady state.

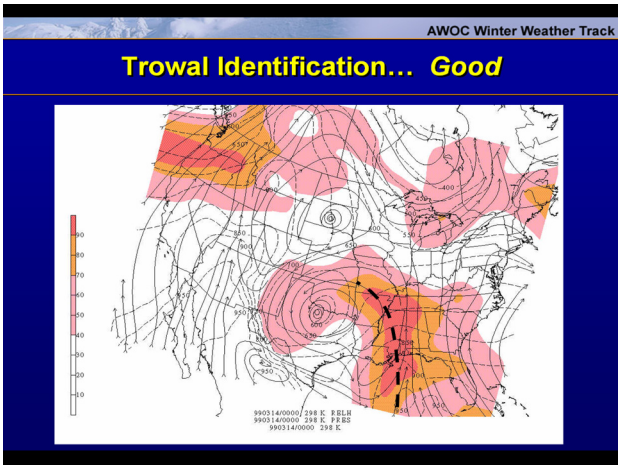
Student Notes:



25. Trowal Identification…Good

Instructor Notes: Pressure and storm-relative winds on an isentropic surface: while valid for synoptic analysis, the traditional isentropic approach begins to break down when applied at too fine a scale. In the instance of the trowal, a region often rich in moisture and ascent, parcels will certainly cease to be purely adiabatic. Consequently, we push the envelope again in order to account for diabatic (primarily latent) heating.

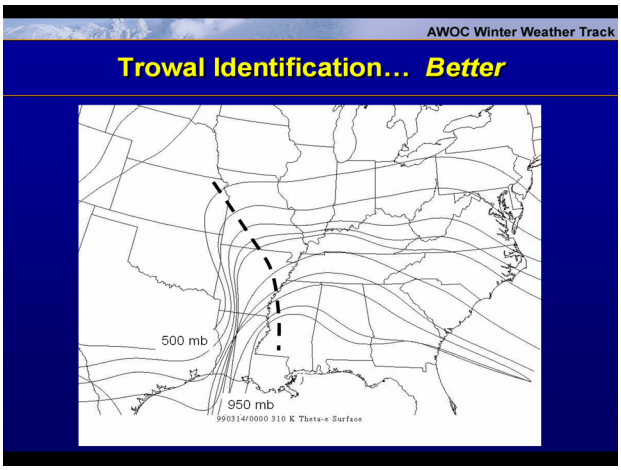
Student Notes:



26. Trowal Identification…Better

Instructor Notes: Topography of the equivalent potential temperature surface: The equivalent potential temperature is assumed to be conserved for unsaturated and pseudo-adiabatic processes. Consequently, their surfaces represent ones on which both dry and moist motions can occur and parcels are still accounted for. Such surfaces are built by plotting only one theta-e contour, say 300 K, at 900, 850, 800, 750, 700 mb, etc. In this instance, the interpretation is the same as it was for the plotting of theta-e on a single pressure surface: that the axis of theta-e ridge represents the axis of the trowal. However, we now use theta-e at multiple levels, and have thus developed a crude theta-e surface.

Student Notes:

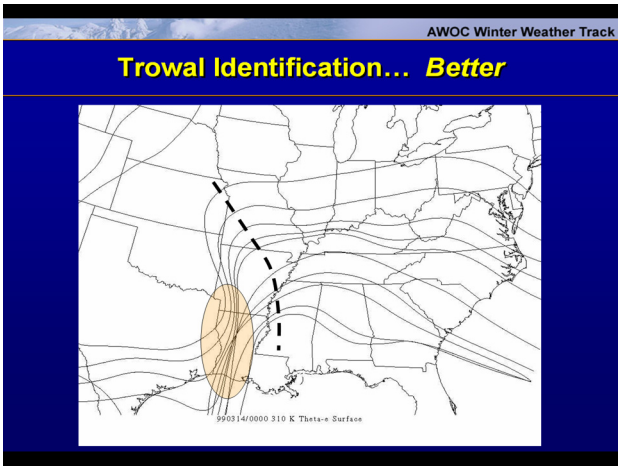


27. Trowal Identification…Better

Instructor Notes: Once you have plotted the different theta-e contours at different levels, you can draw a line connecting the ridge axis between the different contours. This line will indicate the postion of the trowal. It is important to note that in regions where the contours from different pressure levels overlap are areas of potential instability. An exam-

ple of this occurs in the graphic shown over Louisiana where the all the contours are tangled together.

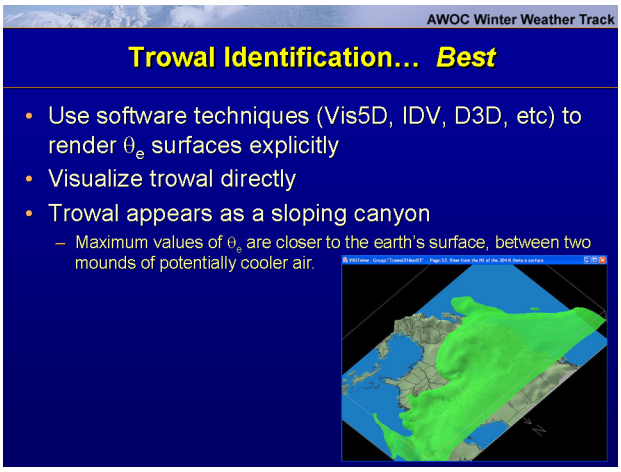
Student Notes:



28. Trowal Identification…Best

Instructor Notes: 3-D visualization of theta-e and trajectories is the best method for identifying the trowal. Expanding on the previous approach leads to the approach of Martin (1999) in visualizing the trowal location. Modern software packages now allow users to interrogate model output to create 3-D surfaces of many kinds. One of these is, of course, the equivalent potential temperature. Additionally, one may also use the model output of u, v, and w wind components to create 3-D trajectories of air parcels through a system as Martin (1999) did with Vis5D. In instances where the computing hardware and software exist to perform this kind of analysis, this may well be the ideal method to examine the trowal and its evolution.

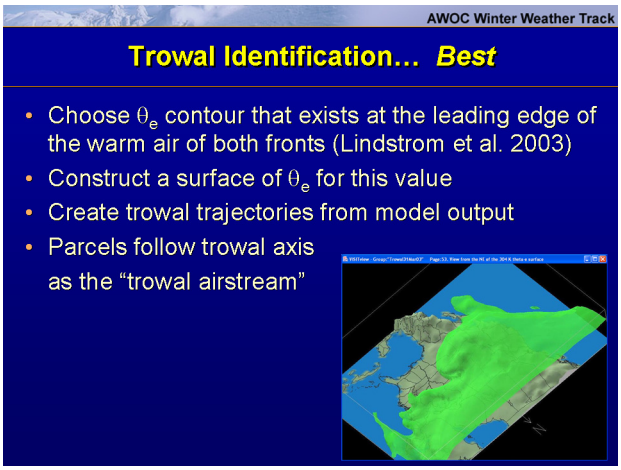
Student Notes:



29. Trowal Identification…Best

Instructor Notes: Further information on this specific approach may be found in the VISITView module on trowal identification.

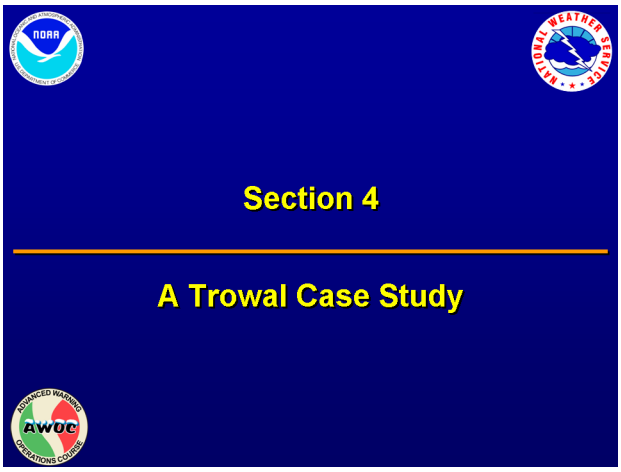
Student Notes:



30. Section 4

Instructor Notes: Now let's move onto Section 4, title A Trowal Cast Study.

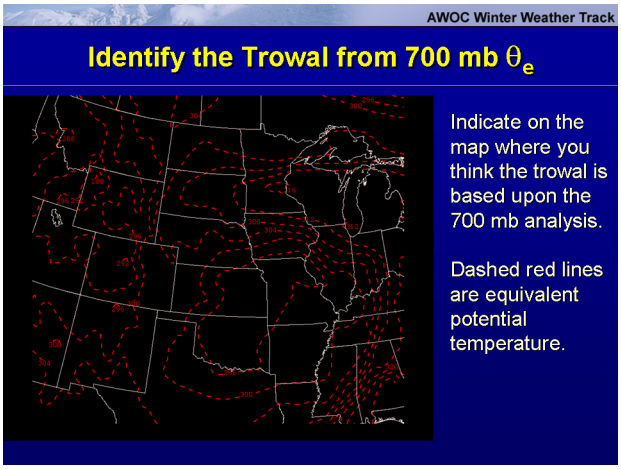
Student Notes:



31. Identify the Trowal from 700 mb θ_e

Instructor Notes: Here is a map of 700 mb theta-E given by the red dashed contours on 03 UTC on the 29th. On the map, indicate where you think the TROWAL would be located. The quiz responder coming in the next slide will allow you to answer this item.

Student Notes:



32. Interactive Quiz #2

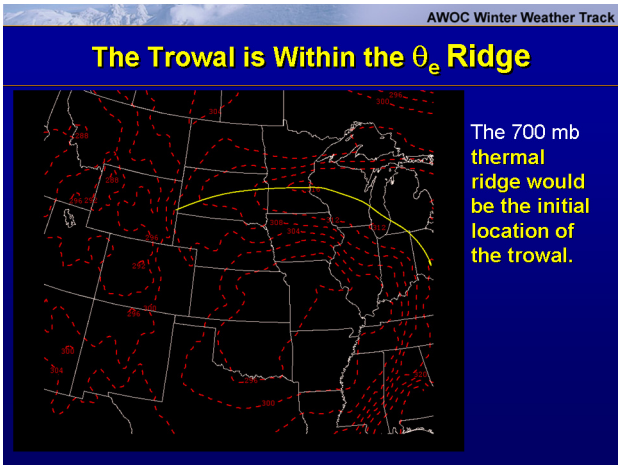
Instructor Notes: Please take a moment to complete this interactive quiz question.

Student Notes:

33. The Trowal is Within the θ_e Ridge

Instructor Notes: As shown earlier, a good first guess for the location of the trowal is the examine equivalent potential temperature on a pressure surface, typically 700 mb although any level from 850 mb to 500 mb would be acceptable. The presence of a thermal ridge indicates that a trowal may be present within the cyclone. In the above diagram the theta-e ridge extends from Wisconsin into western South Dakota.

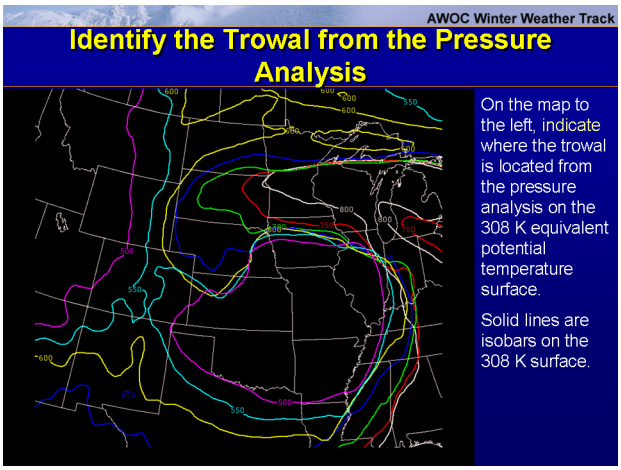
Student Notes:



34. Identify the Trowal from the Pressure Analysis

Instructor Notes: Take a few moments to look at the analysis on the map shown. Use the contours shown to indicate the location of the trowal. Once you have completed this task, please move to the next slide.

Student Notes:



35. Interactive Quiz #3

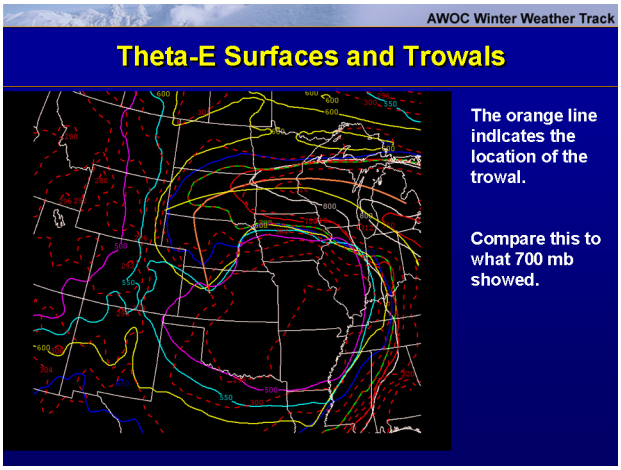
Instructor Notes: Take a moment to complete the interactive quiz on this slide.

Student Notes:

36. Theta-E Surfaces and Trowals

Instructor Notes: Based upon the pressure analysis, the trowal extends from Wisconsin into central South Dakota and then southwest into western Nebraska. The use of isobars on a equivalent potential temperature surface better illustrates the three-dimensional nature of the trowal and provides more insight into where the heaviest snow is likely to be located. When analyzing cyclones in order to determine whether a trowal is present, first use theta-E on a pressure surface as a first guess. If a thermal ridge exists, then examine a theta-E surface. In AWIPS, you can examine the 305, 310 and 315 theta-E surface and plot any variable such as pressure. One can also overlay streamlines and stability to see the flow of moisture and lower stability within the trowal airstream.

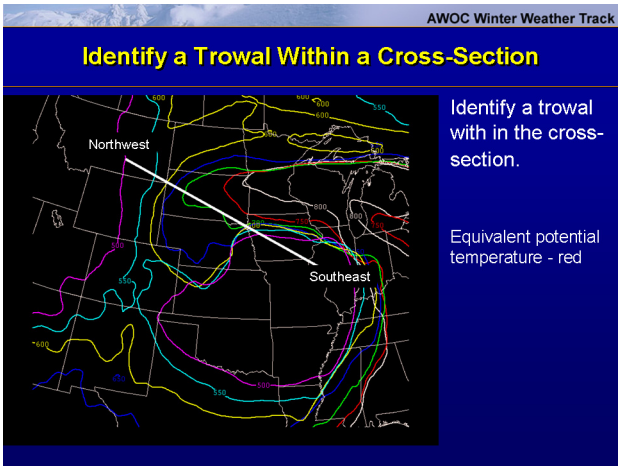
Student Notes:



37. Identify a Trowal Within a Cross-Section

Instructor Notes: We will now use a cross-section (whose endpoint locations are shown on the graphic) to identify the location of a trowal. In the cross-section, the red contours are constant values of equivalent potential temperature.

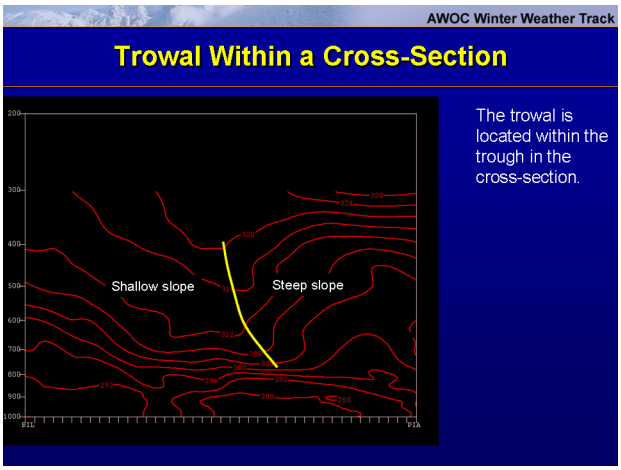
Student Notes:



38. Trowal Within a Cross-Section

Instructor Notes: The trowal is located within the trough in the cross-section. Unlike the case shown earlier, there is not a lot of cold air to the west (or left) of the trowal this makes the trough of warm air appear broader on the west side. On the other hand, much colder air is located to the east of the trowal which makes it easier to identify the eastern edge of the trowal.

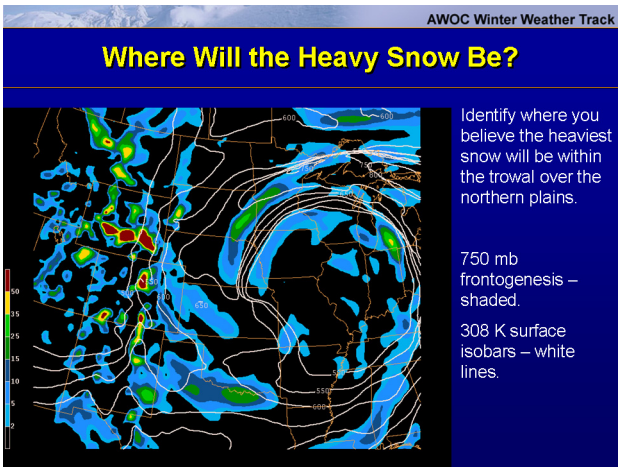
Student Notes:



39. Where Will the Heavy Snow Be?

Instructor Notes: Finally, let's determine where the heavy snow will be over the northern plains. After all, that is why we want to determine the location of the trowal. Use the frontogenesis (shaded contours) and 308 K surface isobars (white contours) to determine where heavy snow will occur.

Student Notes:



40. Interactive Quiz #4

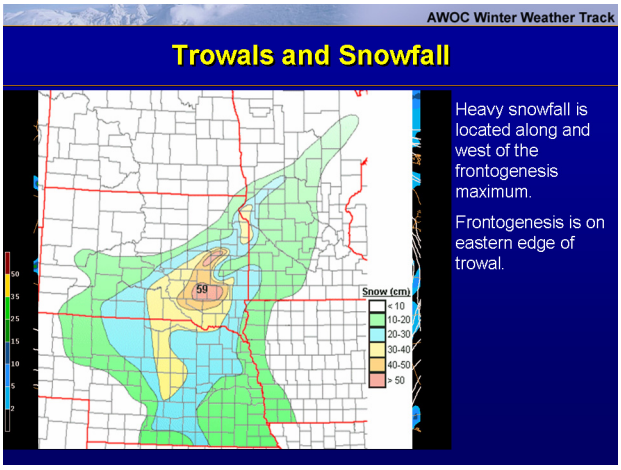
Instructor Notes: Take a moment to complete this interactive quiz on where the location of heavy snow will be.

Student Notes:

41. Trowals and Snowfall

Instructor Notes: Earlier in the talk, it was noted that the heavy snow is on the warm side of the frontogenesis. In most cases in the United States, this will be to the south and east of the maximum frontogenesis and toward the west side of the trowal. However, this case is rather unique. As we noted in the cross-section, the coldest air with the system was to the east of the trowal as one could see the theta-e lines had more vertical slope on the east side of the cross-section. When one looks at the frontogenesis at 750 mb and overlay isobars on the 308 K theta-E surface, the strongest frontogenesis is also along the eastern edge of the trowal. In addition, recall the warm and moist air is located in the trowal axis. This means that the warm side of the frontogenesis maximum is on the north and west side and not to the south and east. When you compare the snowfall map from the event, you can see the heaviest snowfall was coincident with the 750 mb frontogenesis and also closer to the eastern side of the trowal rather than the western side of the trowal.

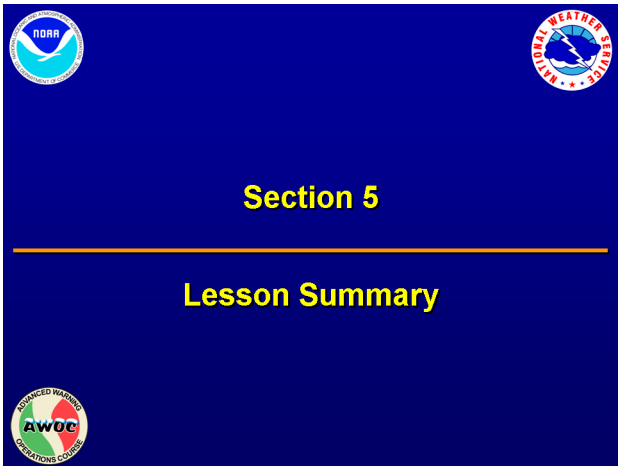
Student Notes:



42. Section 5: Lesson Summary

Instructor Notes: Let's proceed to Section 5: The Lesson Summary.

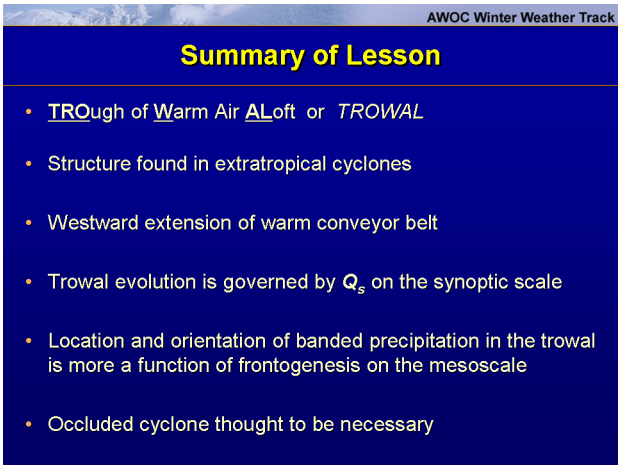
Student Notes:



43. Summary of Lesson

Instructor Notes: This slide provides a brief summary of the material that this lesson covered, including: what a trowal is, what recent research has been conducted on trowals, and what different methods are available to identify the location of a trowal (including which methods are better than others).

Student Notes:



44. Questions???

Instructor Notes: If you have any questions about this lesson, first ask your local AWOC facilitator. If you need additional help, send an E-mail to the address provided. When we answer, we will CC your local facilitator and may consider your question for our FAQ page. We strongly recommend that you take the exam as soon as possible after completing this lesson.

Student Notes: