1. Forecasting Downslope Winds

Instructor Notes: This training module in the AWOC Winter Weather Track is about Forecasting Downslope Winds. Although not exclusive to the winter, downslope winds are generally more frequent and more severe during this season. As a result the societal impact of a winter event of this type is much more significant. This lesson has 50 slides and should take about 45 minutes to complete.

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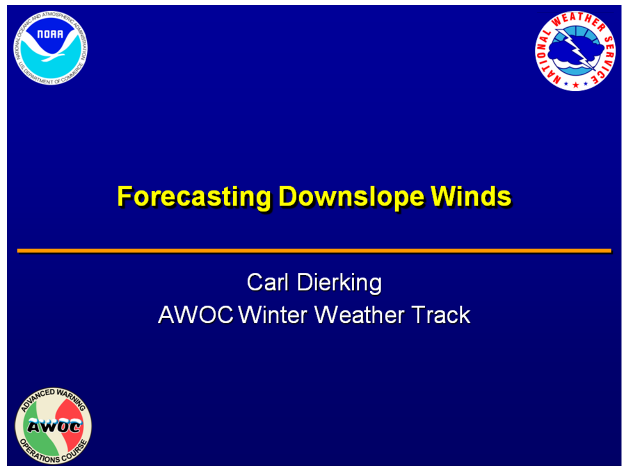

2. Contributors

Instructor Notes: Before getting started, I would like to acknowledge the significant assistance provided by these indiividuals. Special thanks is warrented for their valuable contributions.

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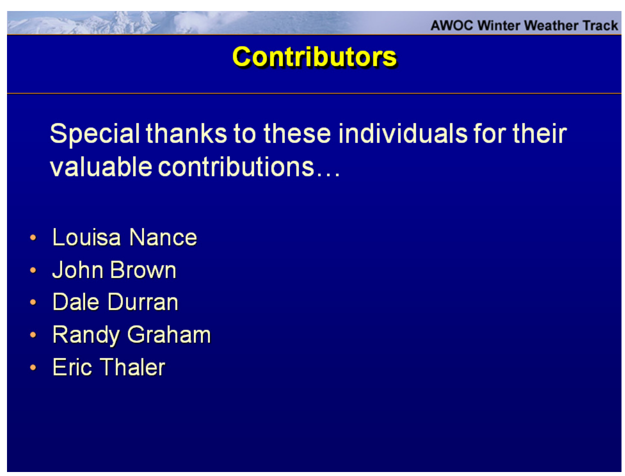

3. Learning Objectives

Instructor Notes: There are four learning objectives for this lesson… First, to provide a basic understanding of linear mountain wave dynamics. Second, to identify atmospheric mean state conditions that can lead to downslope windstorms. Third, to identify ways to predict the evolution and intensity of the event. Fourth, to identify observational resources that can be used to assess the impact of a mountain wave on winds at the surface.

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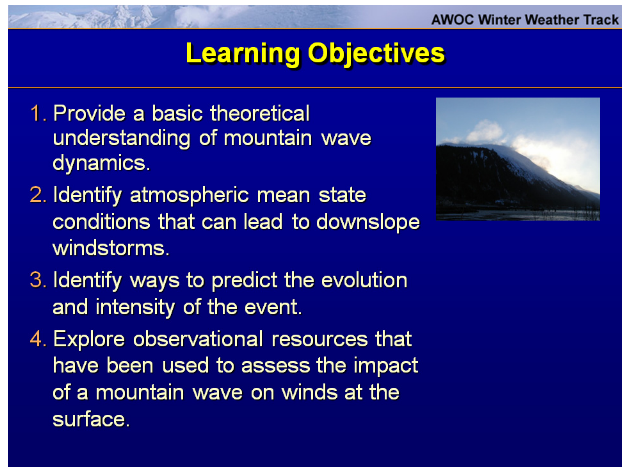

4. Performance Objective

Instructor Notes: These are the performance objective for this module: (1) Demonstrate an ability to identify critical mean state conditions that can lead to the development of a mountain wave. - static stability - cross barrier flow - mean state critical level (2) Evaluate the performance of model guidance in the prediction of mountain wave development and resulting downslope winds. (3) Identify local resources that could be used monitor impacts of the event.

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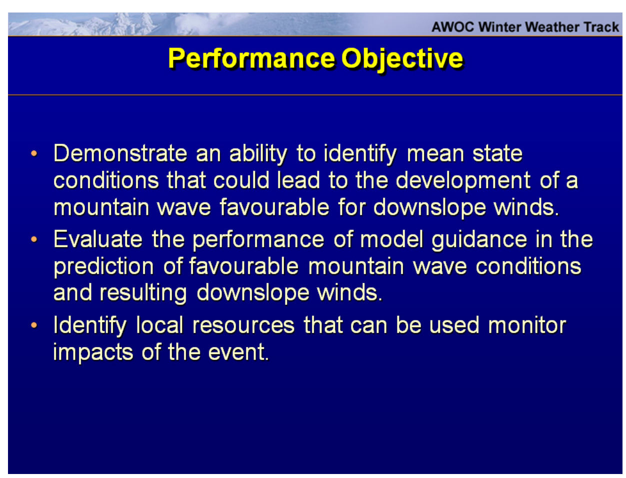

5. Mountain Wave Review

Instructor Notes: Now to review some basic theory. Internal gravity waves develop in a stably stratified atmosphere. From a 2-Dimensional perspective their vertical oscillation frequency is proportional to the Brunt-Vaisala frequency. Mountain waves are a specific type of gravity wave that are initiated when air is forced up a mountain. As the two diagrams show, buoyancy is the restoring force. In a stable atmosphere, air parcels originating at the base of the mountain on the windward end up colder than their environment at the top of the ridge, so they are forced to descend toward equilibrium on the lee side. Momentum can then cause an over-compensation which perpetuates the oscillation for some time downstream. Note that mountain waves generally propagate both downstream and upwards. Only in situations when atmospheric properties impede vertical propagation is the propagation limited to the horizontal. Note in the equation that the Brunt-Vaisala frequency (value of N), increases as the change of potential temperature with height (stability) increases.

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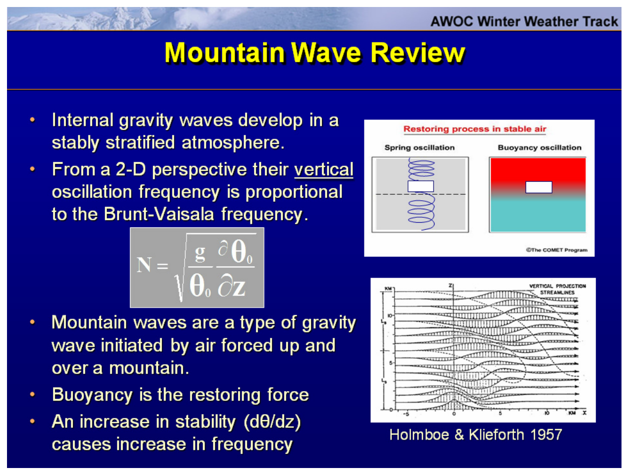

6. Boulder Downslope Windstorm: 11 January 1972 (Klemp & Lilly 1975)

Instructor Notes: The relationship between mountain waves and downslope winds has been studied for a long time. This diagram shows an analysis of one of the more famous downslope windstorms. In 1972 Klemp & Lilly used a research aircraft to conduct an investigation into the structure of the mountain wave aloft during a high wind event in Boulder. The aircraft detected the presence of a very large amplitude mountain wave to the lee of the Continental Divide.

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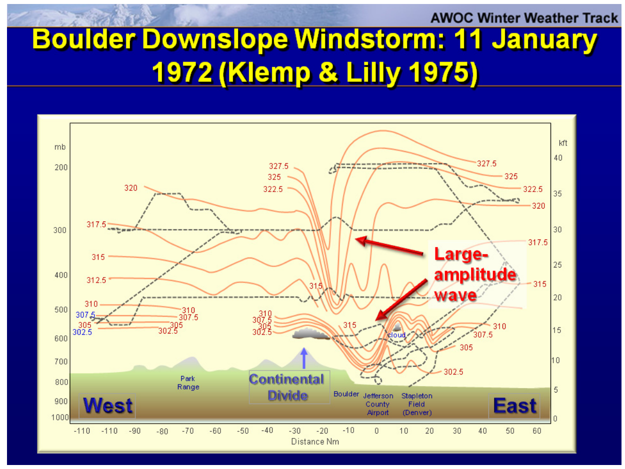

7. King Air Cross-section Study – Jan 16, 2000

Instructor Notes: Another example… In Jan of 2000, as part of an NCAR study, a instrumented King Aircraft flew transects at four levels across Salisbury Ridge and Gastineau Channel during a marginal Taku wind event. The transect levels are shown in the upper left image which is a vertical view looking up the channel to the northwest. The terrain profile for each of the transects is outlined in the corresponding color at the bottom of the chart with Gastineau Channel in the center. The aircraft flew each transect twice except for the lowest altitude, which was deemed to dangerous due to severe downdrafts. A plan view of the aircraft tracks is shown in the upper right. The color contours in the chart on the lower left is an analysis of equivalent potential temperature as measured by the aircraft. The mean terrain profile is shown in black. In this view air flow would be from right to left. You can clearly see the mountain wave in red and orange to the lee of the mountains on the right side of Gastineau Channel (known as Salisbury ridge). The lower right plot shows the vertical velocities measured by the aircraft on each of its transects. Both the Theta plot and vertical velocities show a smaller secondary wave downstream of the first larger wave, followed by increasing variability in the updrafts and downdrafts downstream. The downstream region of high variability is characteristic of a more turbulent “hydraulic jump”.

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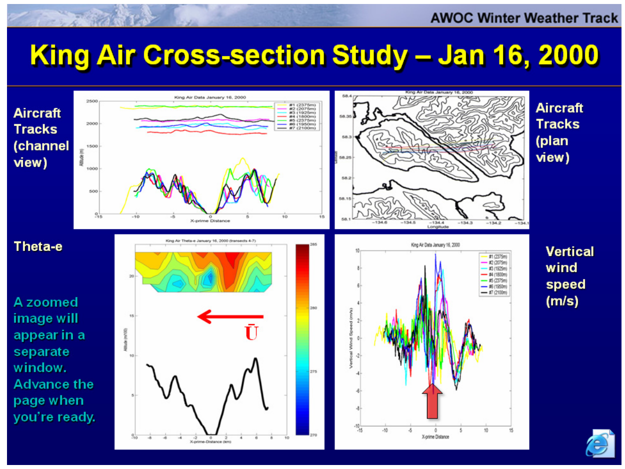

8. Hydraulic Model

Instructor Notes: Because of behavior similarities the Hydraulic Model – used as an analog for downslope winds. Behavior is determined by the Froude Number (Fr) of the flow, which is dependent on the speed and depth of the fluid (ratio of inertial forces to pressure gradient forces). A form of "Fr" more specific to atmospheric conditions is shown on the right where h0 is the mountain height, N is Brunt-Vaisala stability value and U is the cross barrier wind component. Note that some references may use an inverse form of the Froude number. For a very high Fr number, air moves easily over the mountain and wave response is weak. (and) For a very low Fr number, air is completely blocked vertically and must move around terrain. Theoretically the best mountain wave response when Fr is approximately 1 or a little less, but not so low that flow is blocked. One Caution, in terms of the atmosphere and downslope winds, the hydraulic model should be used more qualitatively than quantitatively.

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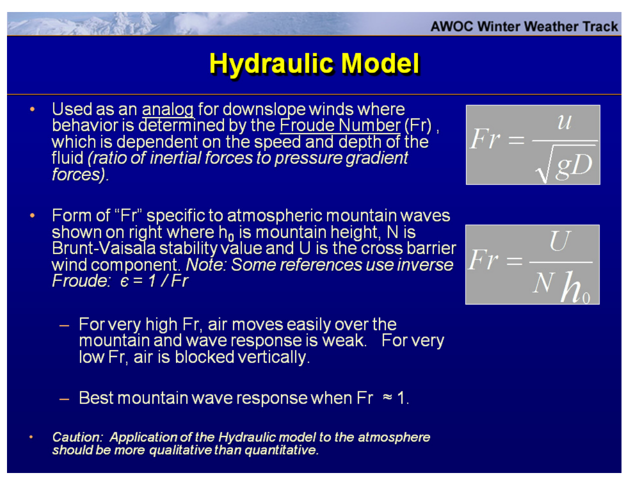

9. Hydraulic Theory

Instructor Notes: In the case of fluids flowing over an obstacle, when Fr > 1 (caused by higher velocities, low stability, or low mtns) the flow is supercritical … the fluid thickens and slows down as it ascends the obstacle converting kinetic energy (KE) to potential energy (PE). Once past the obstacle the fluid reaccelerates as PE is converted back to KE. When Fr < 1 (higher stability, higher mtns, or slower velocities), pressure gradient forcing dominates over acceleration. This is “subcritical flow” As the fluid parcel rises, the fluid thins as it crosses the top of the obstacle resulting in a pressure gradient that accelerates the flow on the windward slope and decelerates the flow on the lee slope. (PE is converted to KE then back to PE once flow is past the obstacle. The pressure changes caused by the disturbance centered over the obstacle is a stationary gravity wave.

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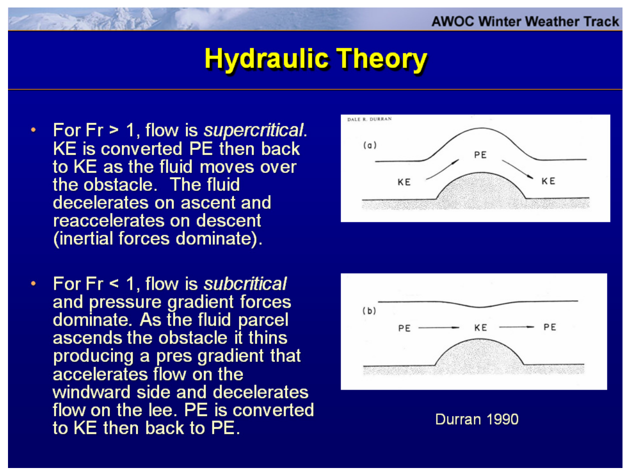

10. Hydraulic Theory

Instructor Notes: In special circumstances a transition from subcritical to supercritical flow occurs as the fluid ascends the obstacle, (initially Froude number Fr < 1 transitions to Fr > 1), PE is converted to KE … and flow continues to accelerate … during the entire time that the fluid traverses the obstacle. The deceleration that would normally occur in the lee-side portion of the gravity wave is disrupted when the flow becomes supercritical. This “unbalanced” state eventually recovers to ambient conditions in a turbulent “hydraulic jump”. An example of a “hydraulic jump” is commonly seen when water in rapids flows over a rock as shown in this photograph. This transition to supercritical flow is achieved when there is an upper boundary that traps energy within the underlying flow (like the interface between water and air in a river). In the atmosphere, conditions that produce this upper boundary include: Capping by a mean-state critical level, which is a layer above the mountain where the mean flow is zero. Wave breaking, where steep mountains force gravity waves to amplify and break.

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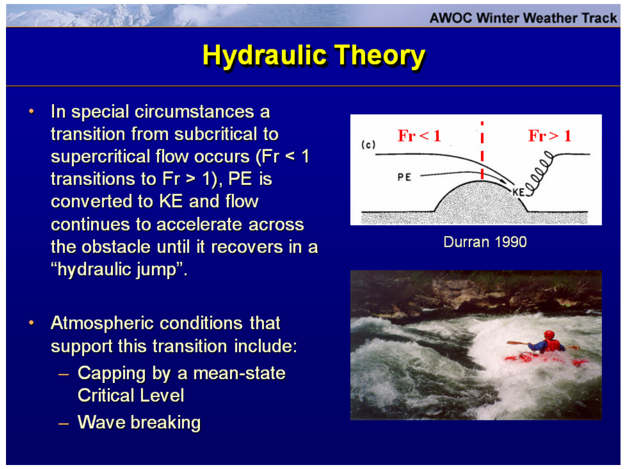

11. Critical Level

Instructor Notes: A Critical Level (CL) is the level at which the phase speed (c) of a wave in a fluid matches the flow speed of that fluid. For a mountain wave, c = 0, so the mean state Critical Level is the level where flow across the barrier is zero. Vertical energy propagation in a stratified fluid is inhibited by the presence of a Critical Level . CL helps to focus wave energy into the lee side gravity wave and promotes the transition from subcritical to supercritical flow.

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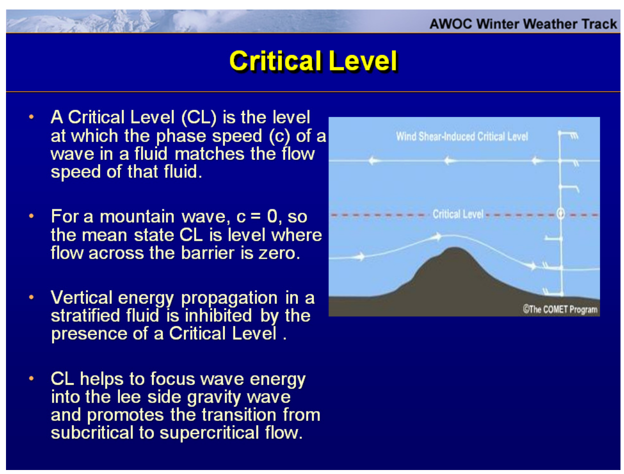

12. Mean State Critical Level

Instructor Notes: Here are a couple of examples of a mean state critical level for an idealized N-S mountain barrier. The Critical Level can be the shear level separating reversed flow aloft (as shown on the left), or it can be the level where flow shifts with height to be parallel to the barrier (as shown on the right). In both cases, the wind component across the barrier decreases with height to zero.

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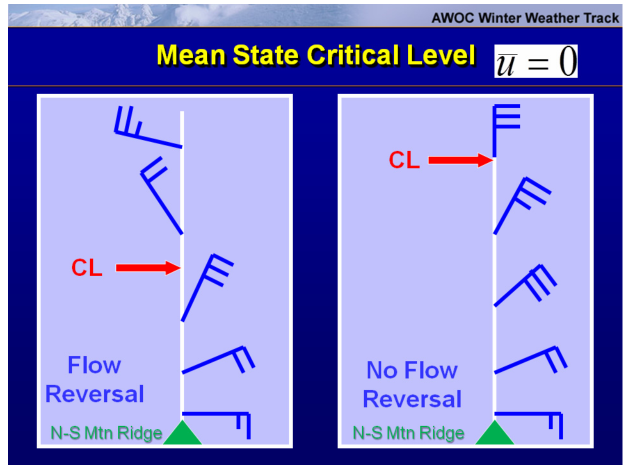

13. Wave-induced Critical Level

Instructor Notes: In certain conditions, strong mountain waves can steepen and eventually break producing a turbulent layer aloft. These breaking waves produce a turbulent region that acts as a "self-induced" Critical Level to enhance the lower level mountain wave response. Reverse shear, cross-barrier flow that does not reverse sign but decreases with height , promotes breaking waves. Steep, high mountains develop breaking waves more easily (Nh/U) and are less dependent on the mean state Critical Level for wave enhancement. Note: Forward shear tends to propagate energy downstream in the form of trapped lee wave.

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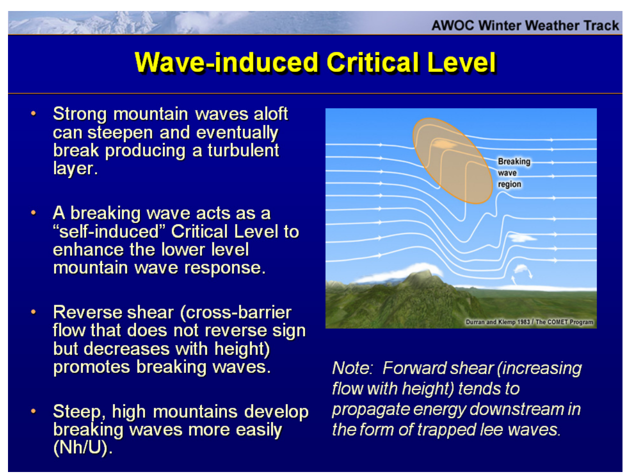

14. Topographic Considerations: Mountain Height

Instructor Notes: The height of a mountain barrier inversely affects the Froude number (U/Nhm), so there is no single Fr in diverse complex terrain. Under the same atmospheric conditions, higher mountains have a lower Fr values. This example by Durran and Klemp shows two model simulations where only difference is mountain-top height. (Nhm/u0 = 0.3 and 0.4) Since real topography is complex, the atmospheric conditions that produce the strongest response are unique to each situation. The underlying conceptual model and general criteria are the same, but historical comparisons are usually necessary at a each location to determine specific thresholds that may be important.

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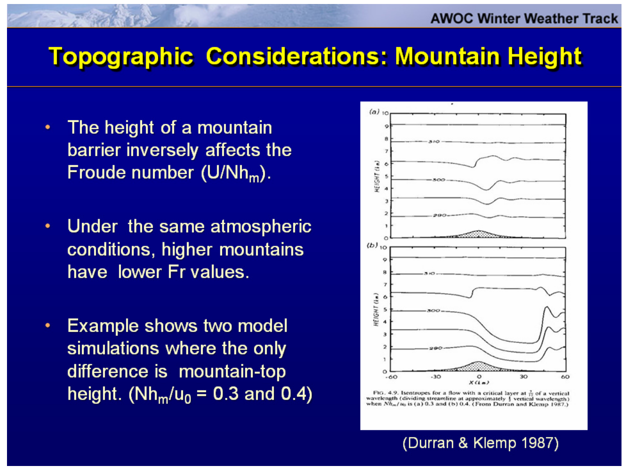

15. Implications for Gap Winds

Instructor Notes: Real topography is never as simple as an idealized long smooth ridge. Besides the irregular shape of a ridge, there are often valleys or passes normal to the ridgeline that provide openings or gaps for the upstream air to flow through. So, how does the existence of a mountain wave affect the flow through those gaps? A modeling study by Duran and Gabersek may provide some insight to this question. Four model simulations were done for flow over an idealized long ridge with a gap cut through the center, but with different Froude values that range from flow moving easily over the barrier to flow completely blocked. The example with the strongest mountain wave response also generated the strongest gap flow with a maximum at the exit region. of "inverse Froude" (Nh/U) parameters. The results of each are shown here. Shaded areas are normalized velocity perturbations, so from a starting uniform velocity field, dark shading shows where the velocities are less than the start and light areas show where velocities are greater. The When Nh/U is equal to .25 the air flows easily over the ridge with little blockage and only minor accelerations on the lee side of the ridge and in the gap.\ The When Nh/U was 5.0 flow was almost entirely blocked by terrain and air was either forced through the gap or horizontally around the ridge. In the vicinity of the gap flow accelerations were strongest within the gap itself. The middle ranges values of Nh/U had the best mountain wave response, especially with Nh/U = 1.4. Strong mountain wave effects are evident, with enhanced flow and wave breaking on the lee side. In addition, there is a produced a jet-like acceleration through the gap that is strongest just beyond the exit region of the gap. Even though flow was enhanced on the lee side of the ridge, the area downstream from the gap exit region was even stronger. With Nh/U = 2.8, there is a little more blockage of flow over terrain and a little more flow around the ridge and through the gap, so the mountain wave effects are not as strong as the 1.4 case. A similar acceleration occurs through the gap, but the velocity perturbation maximum is now just inside the gap at the exit region.

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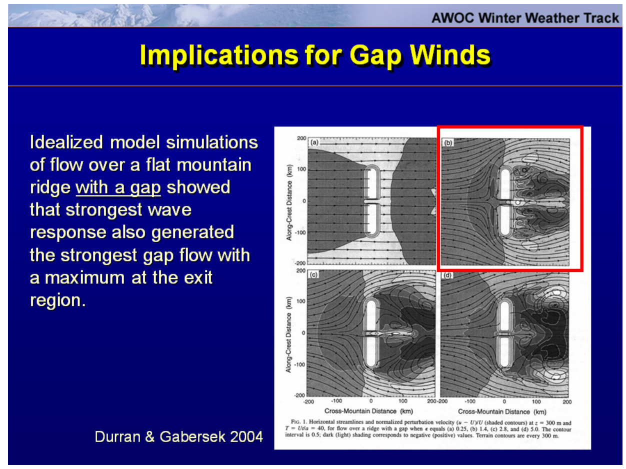

16. Forecasting

Instructor Notes:

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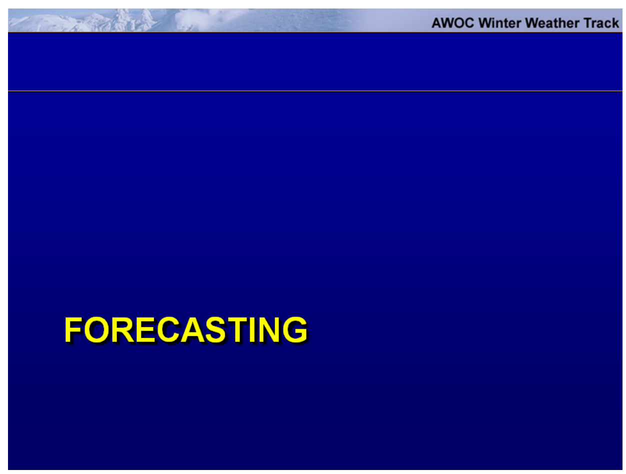

17. Summary of Conditions Favorable for Strong Downslope Winds

Instructor Notes: Parameters that affect the development and intensity of the mountain wave: So to summarize... the list of parameters that affect low level amplification of a mountain wave ... and ultimately... strong downslope winds... Topography (height of the mountain barrier) The strength of cross-barrier flow at crest level Strong low level stability or an inversion (near or slightly above ridgetop) Presence of a Critical Level (either as a mean state or wave-induced) Note that in the absence of a mean state CL - reverse shear aloft conducive to a wave-induced CL The presence of CL promotes the transition from subcritical to supercritical flow.

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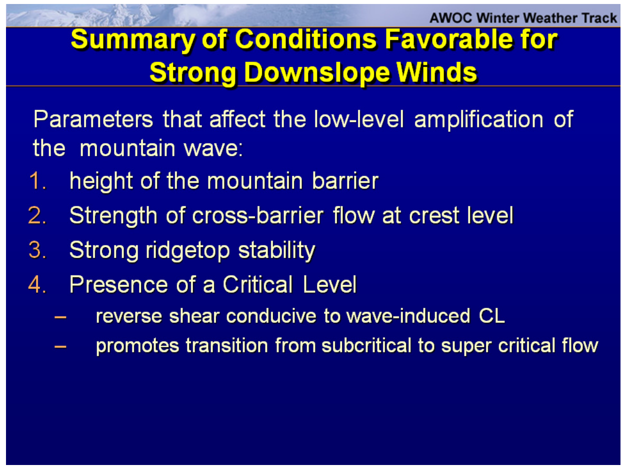

18. Ingredient: Inversion above Ridgetop

Instructor Notes: So how can we objectively evaluate the potential for the mountain wave to develop into a downslope windstorm? There are both synoptic scale and local scale characteristics that should be considered in the analysis. First examine the lower level atmospheric stability for and inversion or highly stable layer above the ridgetop. Look for cold air advection that could lead to a significant cooling in the lower levels. Also look for warm advection in the mid levels or warm overrunning that could increase temperatures above the ridge. Look for regions of large-scale subsidence that could lead to low level increases in stability? Next, compare nearby upstream soundings with model sounding forecasts to see how the models might need to be adjusted. Check sounding forecasts for changes to the height of the inversion and strengthening of low level stability. Consider the larger scale model adjustments that may need to be made to these trends.

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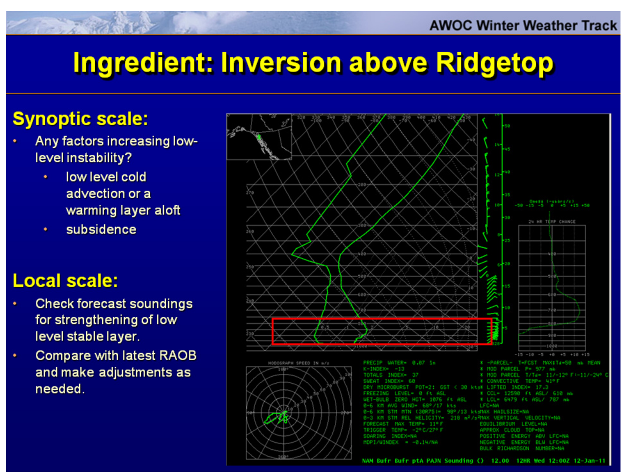

19. Ingredient: Cross-barrier Flow

Instructor Notes: The second ingredient is cross-barrier flow: First evaluate the synoptic scale by checking the MSLP and 850-mb model forecasts for forecast patterns that are conducive to increased low level cross-barrier flow. Then more specifically, try to determine a more quantitative estimate from "course" resolution models such as GFS and ECMWF. Pressure differences across the mountain barrier may be helpful. Care should be taken when using higher resolution models to evaluate CBF, since they may be some enhanced flow near the mountain from an inadequate attempt to resolve the mountain wave. This will be discussed later. With higher resolutions, be sure to check far enough upstream To determine the CBF in D2D, draw a baseline can perpendicular to the mountain range and then load a "Component Along" cross-section. An example is shown above. You'll need to step through the forecast times to determine the magnitude and trend in this wind component. Note that this display will also show the change of winds with height and whether a mean state Critical Level is present. The color curve above was designed to show the level where the wind component was zero in black. This would be the location of the mean state CL

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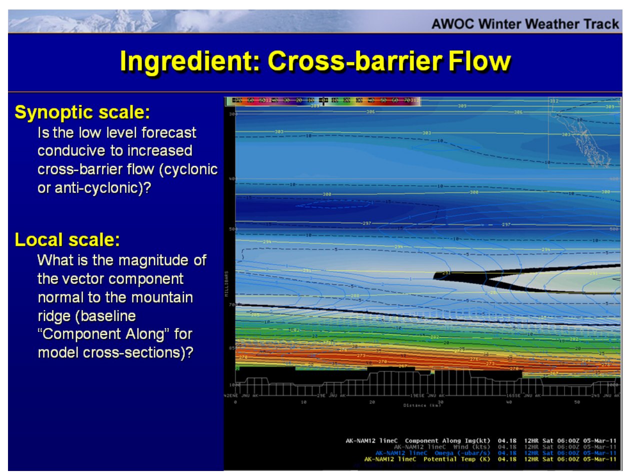

20. Ingredient: Critical Level (Mean state or "self-induced" by reverse shear)

Instructor Notes: The third downslope wind ingredient is more difficult to evaluate. It can be present as a general mean state condition, or it can be "induced" by the presence of reverse shear. Some mountain ranges rarely have the Critical Level occur as a mean state. In these events, a Critical Level is self–induced by wave overturning. Higher mountains, stronger cross-barrier flow, and reverse shear are conducive to wave overturning and self-induced CL's. Things to look for in the synoptic scale are: levels above the mountain-top where the cross-barrier wind component would be weaker than winds at the mountain crest level. This can be produced by a weak flow region such as an elongated trough or "col" developing in the middle levels...wind direction changes from one level to the next, which could indicate a shear level between the reversing wind components... or a gradual wind direction change with height from a direction normal to the ridge to one that is parallel. In the local scale, step through a baseline "Component Along" cross-section plotted perpendicular to the mountain ridgeline. Look for reverse shear or a lever of zero flow across the barrier, which is the Critical Level. This color curve shows the CL in black. When a mean state critical level is present, determine if and when it reaches the optimal elevations (based on previous events)

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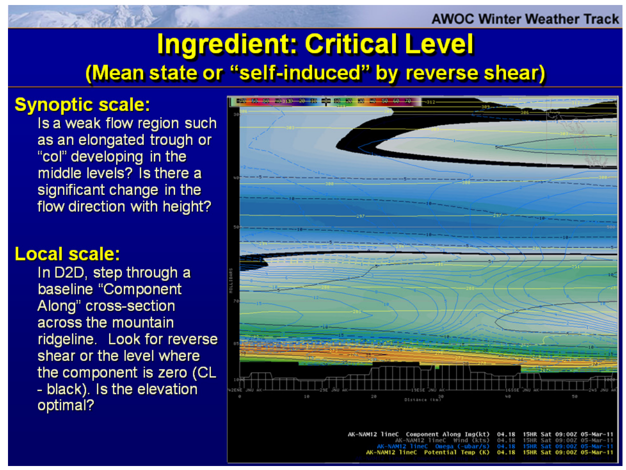

21. Synoptic Analysis for Mean State Criteria

Instructor Notes: Orientation of Presidential Range in N.H. – NNE-SSW. Surface low over New York state produces ESE cross-barrier flow. 500 mb trough over Great Lakes produces SW flow parallel to mountain ridge while delivering warmer air aloft for elevated stable layer. Reverse shear present as cross-barrier component decreases with height to zero.

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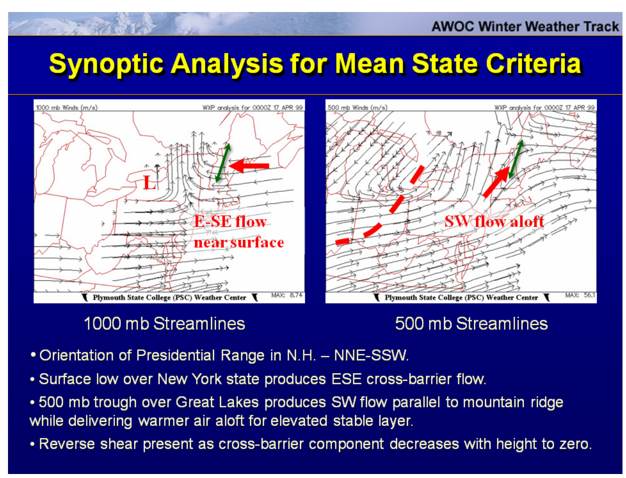

22. Synoptic Variations

Instructor Notes: One thing to keep in mind is that there may be more than one way, synoptically, to achieve favorable mountain wave conditions. Here is an example of conditions leading to two downslope wind events in Juneau that evolved to the criteria in different ways. In the case on the left, cross-barrier flow and low level stability were produced by a building ridge to the west and low level cooling. In the case on the right, a strengthening low to the south caused an increase in the lower level flow while mid level warming produced a stable layer above the mountain top.

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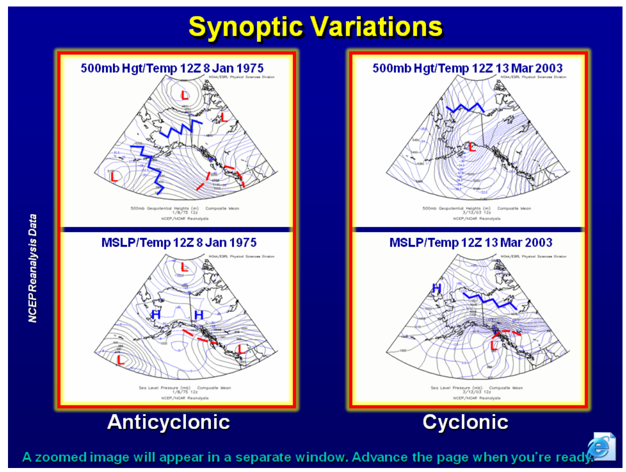

23. Cross-barrier Flow and Critical Level

Instructor Notes: A timeseries of the vertical wind field from BUFR sounding data at a point just upstream of the mountain can show the predicted evolution of the wind field in one image, but a view of wind barbs alone makes it difficult to evaluate changes to mountain wave criteria…especially if the mountain range is not conveniently oriented N-S or E-W, ...or if reverse shear is caused by direction changes. However, a timeseries display of the wind vector component normal to the mountain ridgeline provides an excellent view of model predicted changes to the wind with time in terms of mountain wave criteria. Here is an example of a locally developed application that displays the magnitude of the vector component at any angle, based on input from a BUFKIT BUFR sounding data file. In this example 70 degrees is the selected angle normal to the mountain. In this one view, a forecaster can look for a strengthening of the low level flow and changes in elevation and shear of the mid level critical level. Add an overlay of temperature, or lapse rate, and you can also see changes in the low level stable layer. The approximate top of the stable layer highlighted here with the red line.

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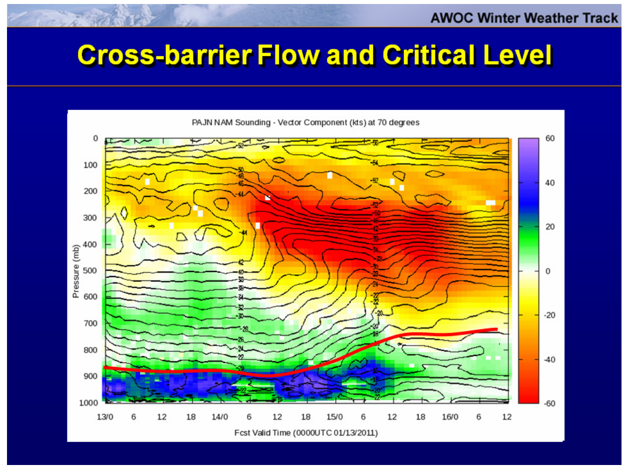

24. High Resolution Models & Mountain Waves

Instructor Notes: High-resolution model data is becoming more and more common in the forecast office as computer resources are becoming more powerful. As the model resolution increases, these models are improving in their ability to resolve mountain wave generated downslope winds, however at the same time, timing and intensity errors vary greatly between one cycle and the next. If sufficient resources are available, high resolution ensembles may help to assess the predictability of a downslope event. Regardless, the high resolution data does not take the place of a thorough synoptic scale criteria analysis.

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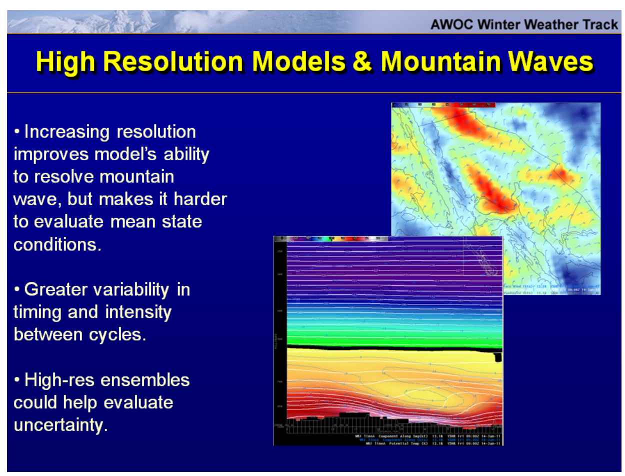

25. Composite Study Example – 49 events

Instructor Notes: So how can you relate the more general theoretical requirements to criteria more specific to a downslope windstorm that may affect your CWA? A simple composite study is probably the easiest way to try to isolate more common thresholds. Here is a composite example of 49 Wind events near Juneau (locally known as Taku Winds). Composites were made from NCEP Reanalysis data at four atmospheric levels.

Note: in this event the orientation of the mountain range is northwest to southeast. Starting with the MSLP composite (shown in black) with surface temperatures overlayed in blue, there is a tightly packed pressure field between high pressure in northwest Canada and low pressure in the Pacific. Strong northeasterly cross-barrier flow in the Juneau area is supported up by the intense pressure gradient across northern SE AK. From the surfact to 850 mb a significant thermal gradient near the coast highlights the barrier effect that the Coast Mountains present to the cold arctic air mass and the relatively warmer maritime air over the northeast Pacific. Intense cold air at the surface supports strong stability in the lower level in the Juneau area. This strong contrast between the two air masses and their close proximity, significantly impacts the structure of the atmosphere above. The opposition of the thermal wind to the geostrophic flow successively weakens the gradient in the height field above the surface that becomes very apparent by 700 mb At 500 mb the gradient decreases to such a degree in the composite, that there is only a weak elongated split trough over southeast Alaska. In terms of the geostrophic wind field over northern southeast Alaska, the strong offshore flow at the surface decreases dramatically in the vertical as the height-field gradients weaken. A 500-mb streamline analysis would locate a “col” region over central southeast Alaska between the interior trough and the low offshore. These composites were used to refine qualitative synoptic scale criteria to more localized requirements important for the development of the downslope windstorm called the “Taku”. That is, (1) strong stability in the lower atmosphere; (2) moderate to strong northeastly low-level cross-barrier flow below 850 mb; and (3) a decreasing cross-barrier component with height that results in a critical level around 500 mb.

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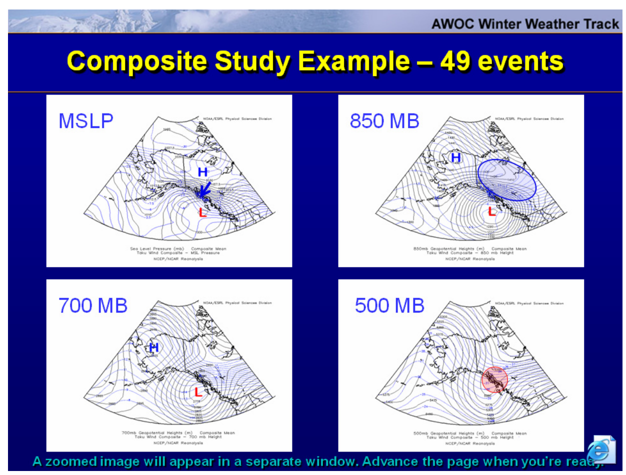

26. Composite Sounding Example – 49 events

Instructor Notes: A sounding composite can help to refine the criteria even more precisely. This is a composite sounding for Juneau from NARR data for the same 49 Taku events. In terms of basic ingredients, Taku winds require: A lower level stable layer between 850-mb and 700-mb. Since this is a mean value, it is likely individual events would have an actual inversion located somewhere in this layer.   At least moderate northeasterly low level winds (crossing a northwest to southeast mountain range) that decrease with height to a critical level at 500 mb.

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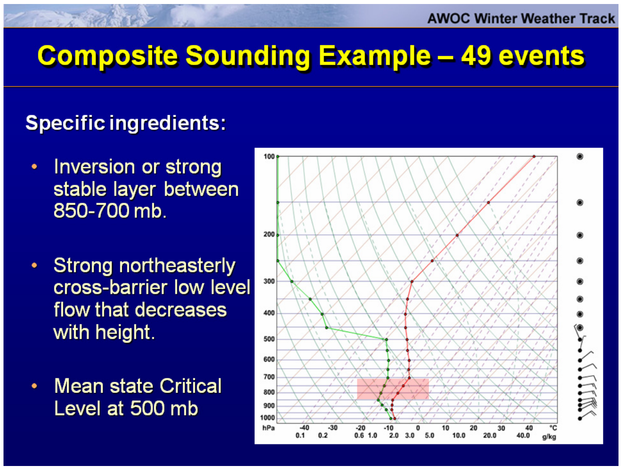

27. WFO Seattle Decision Tree

Instructor Notes: Once more specific criteria have been established, guidance and tools can be developed for addressing tghe local forecast problem. a "Decision Tree" is good way to lead forecasters in step-by-step fashion toward a prediction for downslope winds in specific location This "Decision Tree" example was developed for WFO Seattle by cataloging specific parameter values known to be important during past windstorms in a particular region. Threshold ranges were then identified and related to a windstorm threat. Can be in the form of a simple yes-no flow chart or regression calculations

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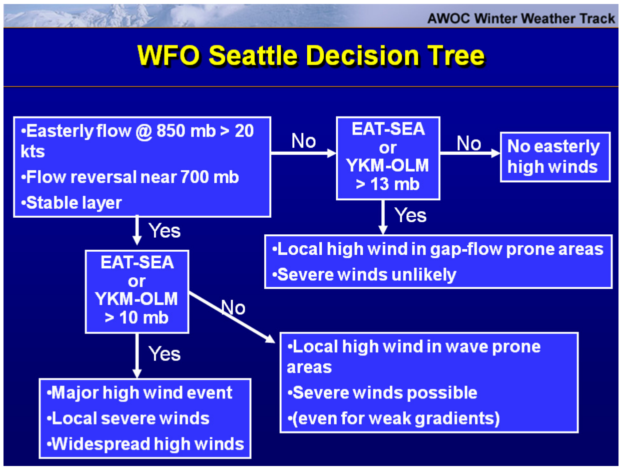

28. WFO Juneau Ingredient Weights

Instructor Notes: Another approach that has worked well for WFO Juneau is to reference past events to help assign points, or weights, to variations of the three main criteria. Marginal events can help to refine marginal ingredient weight values. Then past events can be ranked in terms of the sum of these weights. For locations where a mean state CL is rarely present, the CL weight scale might be strictly defined in terms of vertical shear.

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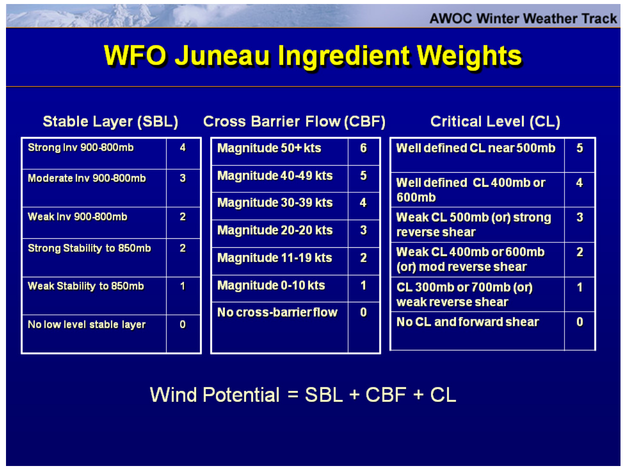
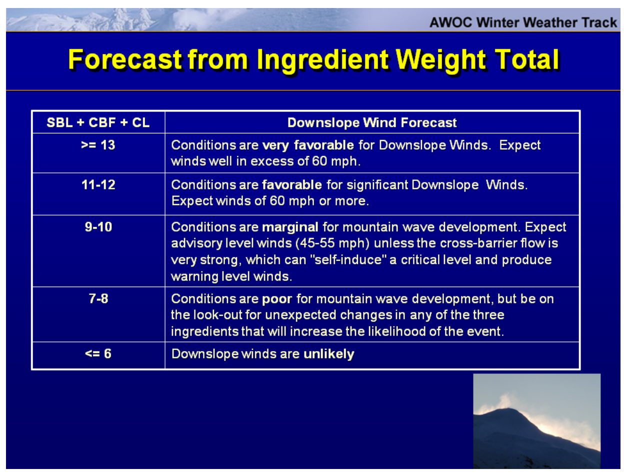


29. Forecast from Ingredient Weight Total

Instructor Notes: After a few iterations, the end result is a table for quantitatively assessing the downslope wind potential based on the sum of the weights of the three ingredients. In this process, forecasters assess the potential from an ingredients-based perspective

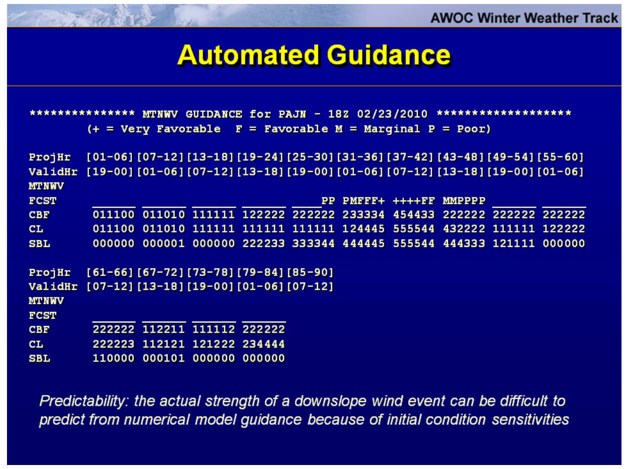
Student Notes:



30. Automated Guidance

Instructor Notes: From the ingredients approach, a script was developed that calculates hourly mountain wave guidance from BUFR sounding data. Guidance from the script not only provides a quick look ahead at potential downslope wind problems, but it shows forecasters what aspect of the ingredients may be missing for the strongest response.

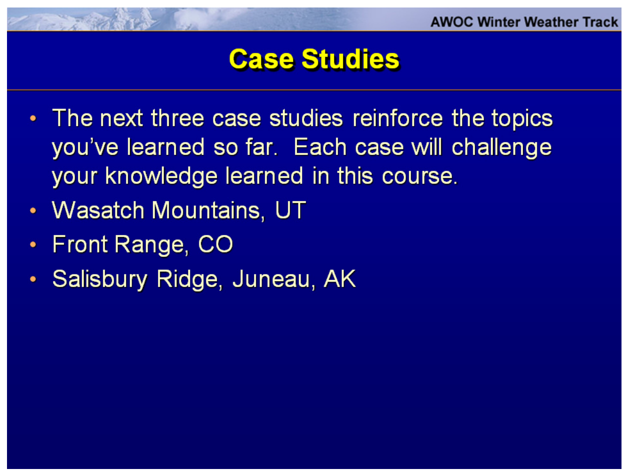
Student Notes:



31. Case Studies

Instructor Notes:

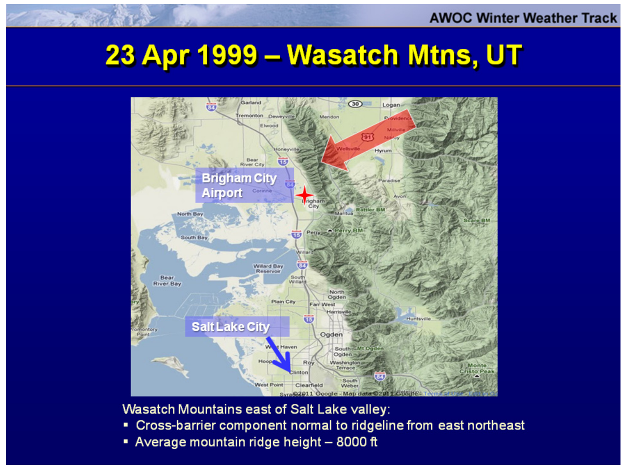
Student Notes:



32. 23 Apr 1999 – Wasatch Mtns, UT

Instructor Notes: The first case study examines an old event that affected portions of the Salt Lake valley from the Wasatch Mountains to the east: Cross-barrier component direction normal to mountain ridgeline from east northeast Average mountain ridge height – 8000 ft

Student Notes:



33. IC8downslope-quiz1

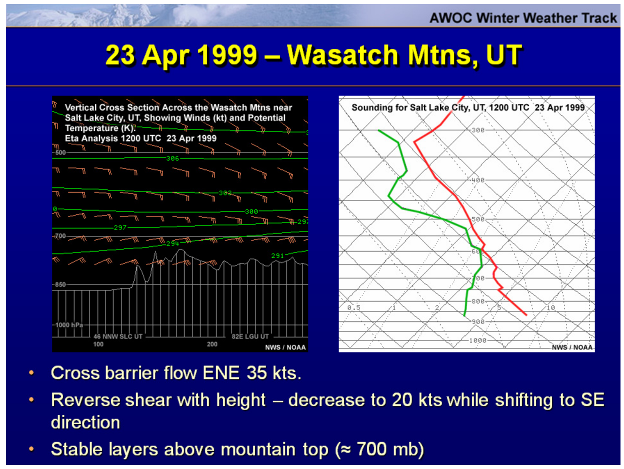
Instructor Notes:

Student Notes:

34. 23 Apr 1999 – Wasatch Mtns, UT

Instructor Notes: Answer #1: Yes, there are multiple stable layers above the mountain range which crests at around 700 mb. Answer #2: Both. The Wasach Mountains oriented NNW-SSE so the 35 kt ENE winds were normal to the ridgeline. From the cross-section you can see that reverse shear is produced by both a speed decrease from 35 to 20 kts, and a direction shift with height from ENE to SE which further reduces the cross-barrier component. However, from this view alone it is difficult to determine if the actual cross-barrier component is near zero, which would be evidence of a mean state critical level.

Student Notes:



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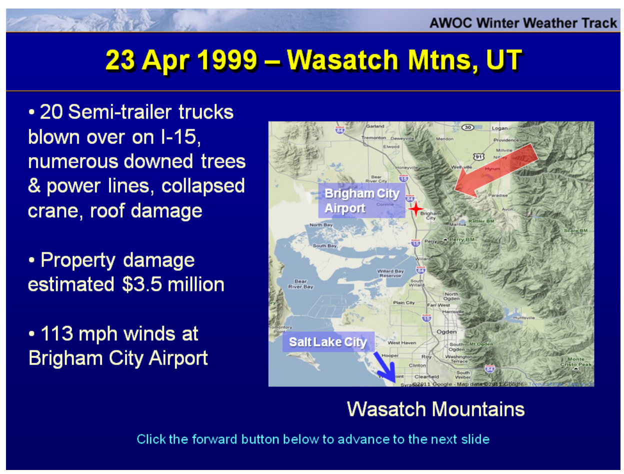
35. 23 Apr 1999 – Wasatch Mtns, UT

Instructor Notes: In 1999, this was the strongest downslope wind event on the Wasatch Front in more and a decade. 20 semi-trailer trucks were blown over on I-15, Construction crane collapsed, numerous power lines were downed, widespread damage to roofs, trees, and small structures. Property damage estimated at $3.5 million. 113 mph winds observed at the Brigham City Airport set a new record for observed winds at low elevation (below 5000 ft) in Utah.

Student Notes:



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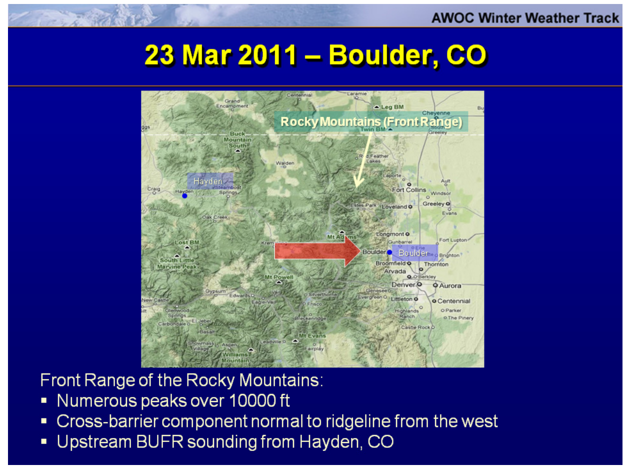
36. 23 Mar 2011 – Boulder, CO

Instructor Notes: The next case study examines an event that occurred on March 23rd, 2011 at Boulder Colorado. To the west of Boulder is the Front Range of the Rocky Mountains: Numerous peaks over 10000 ft. The cross-barrier component normal to this mountain range would be from the west Upstream BUFR sounding from Hayden, CO

Student Notes:



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37. IC8downslope-quiz2

Instructor Notes:

Student Notes:

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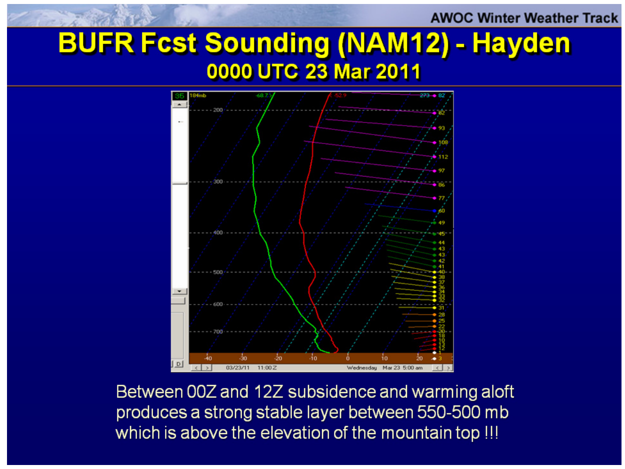
38. BUFR Fcst Sounding (NAM12) - Hayden0000 UTC 23 Mar 2011

Instructor Notes: Answer #3: Between 00Z and 12Z subsidence strengthens and produces a strong stable layer between 550-500 mb which is above the elevation of the mountain top !!!

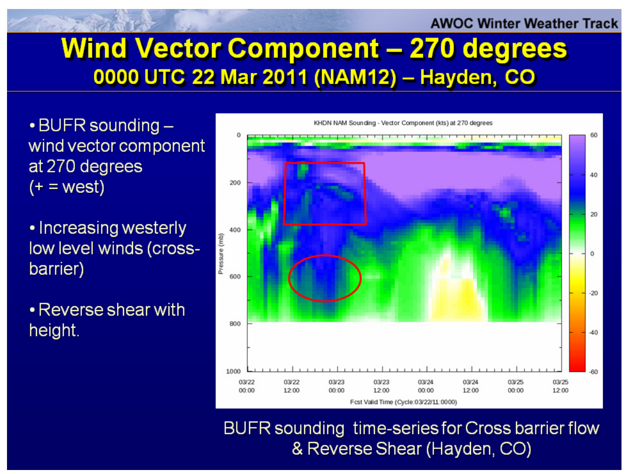
Student Notes:



39. Wind Vector Component – 270 degrees0000 UTC 22 Mar 2011 (NAM12) – Hayden, CO

Instructor Notes: Analyzing the wind vector componenet for the questions #4 & #5, where positive values (green-blue-purple) are from the west... you can see that : There is increasing westerly low level winds (or cross-barrier flow) above 700 mb at 12Z that peaks between 18Z Mar 22 and 06Z Mar 23 (outlined in red) At the same time there are several layers of reverse shear with height above 400 mb (outlined in the red box).

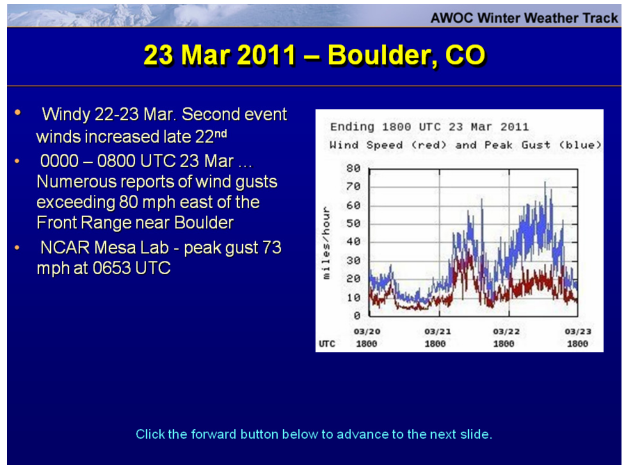
Student Notes:



40. 23 Mar 2011 – Boulder, CO

Instructor Notes: March 22-23 was a windy period in Boulder, but focusing on the second stronger wind event… Winds started to increase around 18Z Mar 22nd but peak winds occurred after 00Z Mar 23rd. 0000 – 0800 UTC 23 … Numerous reports of wind gusts exceeding 80 mph east of the Front Range near Boulder. This wind trace from the NCAR Mesa Lab recorded a peak gust of 73 mph that occurred at 0653 UTC Mar 23rd.

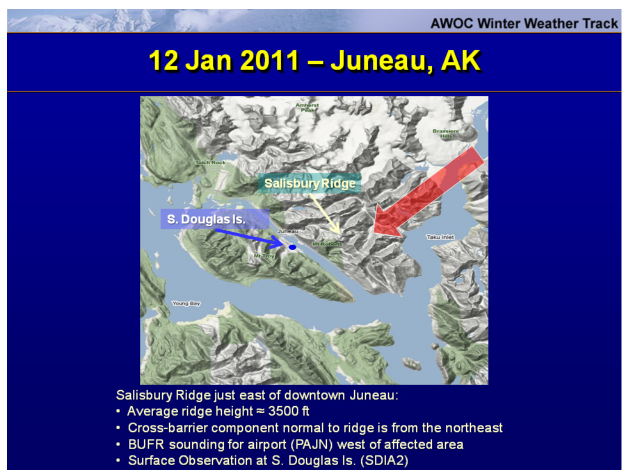
Student Notes:



41. 12 Jan 2011 – Juneau, AK

Instructor Notes: The final case looks at an event that occurred on Jan 12th, 2011 in Juneau. Just east of downtown Juneau is Salisbury Ridge: Average mountain ridge height ≈ 3500 ft Cross-barrier component normal to the ridge would be from the north-east BUFR sounding for airport (PAJN) west of affected area Surface Observation at S. Douglas Is. (SDIA2)

Student Notes:



42. IC8downslope-quiz3

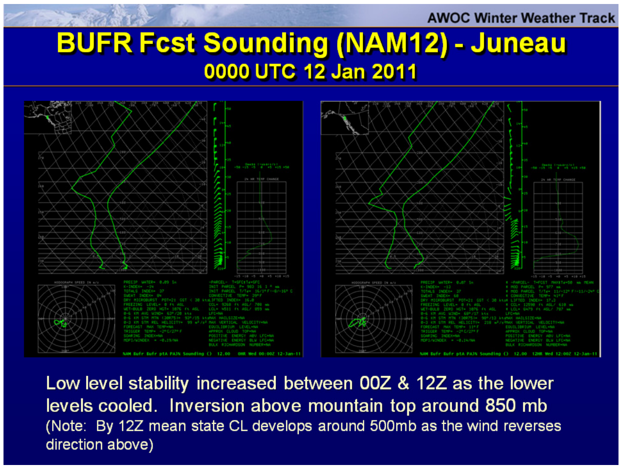
Instructor Notes:

Student Notes:

43. BUFR Fcst Sounding (NAM12) - Juneau0000 UTC 12 Jan 2011

Instructor Notes: Answer #6: Low level stability increased between 00Z & 12Z as the surface and lower levels were cooled by northeasterly outflow from interior Canada. At 12Z an inversion was present above mountain top around 850 mb. (Note: The 12Z sounding also shows the development of a mean state CL around 500mb as the wind reverses direction above)

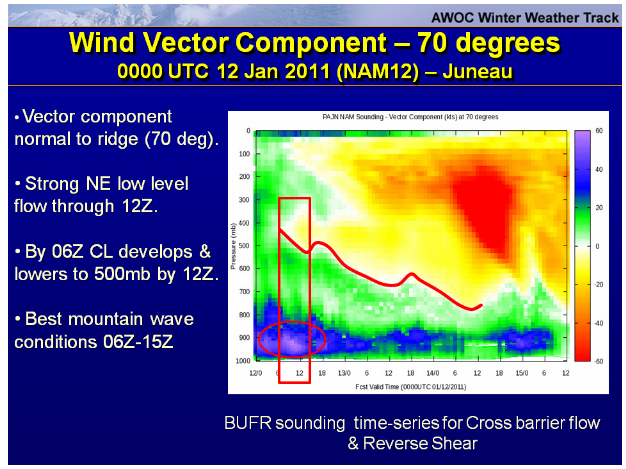
Student Notes:



44. Wind Vector Component – 70 degrees0000 UTC 12 Jan 2011 (NAM12) – Juneau

Instructor Notes: This is yet another example of why a time-series display of the vector component forecast is the best way to diagnose the evolution of cross-barrier flow & reverse shear… Vector component normal to ridge (70 deg) Positive values (green-blue-purple) are wind vector components from the NE (negative for SW) White layer between (zero flow) is the mean state CL Answer #7: NAM shows strong NE low lvl flow continues through 17Z Answer #8: The red line highlights the white layer where flow is near zero. This is the mean state CL which develops around 06Z and lowers to near 500 mb around 12Z Best mountain wave conditions with strong CBF and mean state CL at 500 mb occur around 12Z. This is followed by a weakening of the CBF & lowering CL which would suggest a decrease in the downslope wind. Note: that although conditions before & after are not ideal, there is still some amount of CBF and reverse shear so winds will likely continue quite gusty but not as strong.

Student Notes:



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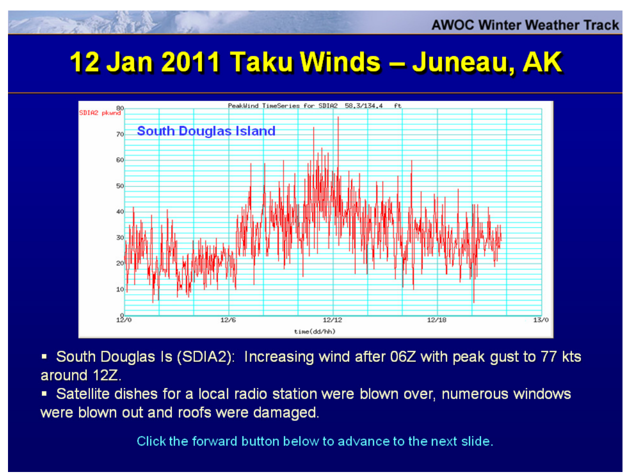
45. 12 Jan 2011 Taku Winds – Juneau, AK

Instructor Notes: This wind trace shows the results of this event recorded by the South Douglas Is. (SDIA2) anemometer: Increasing wind after 06Z with peak gust to 77 kts around 12Z and then slowly diminished after. In this event: Satellite dishes for a local radio station were blown over, numerous windows were blown out and roofs were damaged As you can see in the trace, although the winds slowly decreased after 12Z, they remained quite gusty.

Student Notes:



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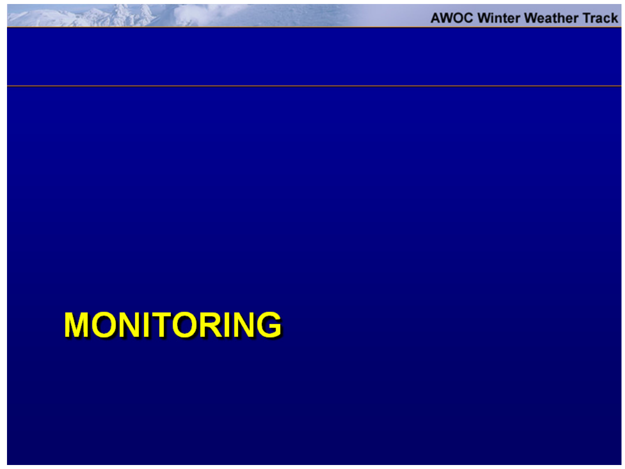
46. MONITORING

Instructor Notes: The next section will show creative examples of monitoring the evolution of downslope winds…

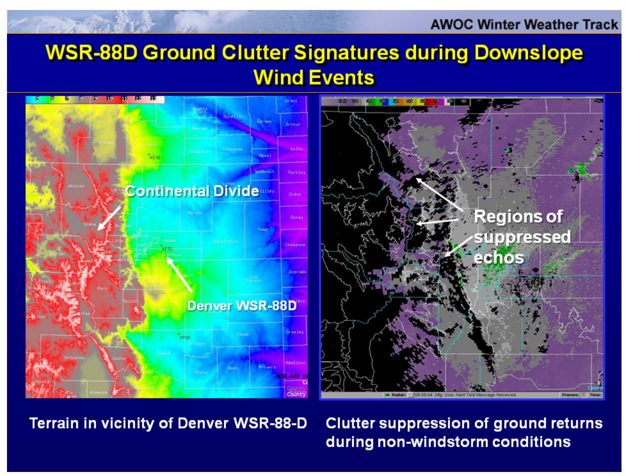
Student Notes:



47. WSR-88D Ground Clutter Signatures during Downslope Wind Events

Instructor Notes: This first example shows the effect of downslope winds on radar ground clutter. These ground clutter signatures during downslope wind events were rirst observed by Denver-Boulder WFO The image on the left shows terrain in the vicinity of the Denver WSR-88-D. the image on the right shows the typical effect of clutter suppression during non-windstorm conditions. Note the regions where echos are suppressed.

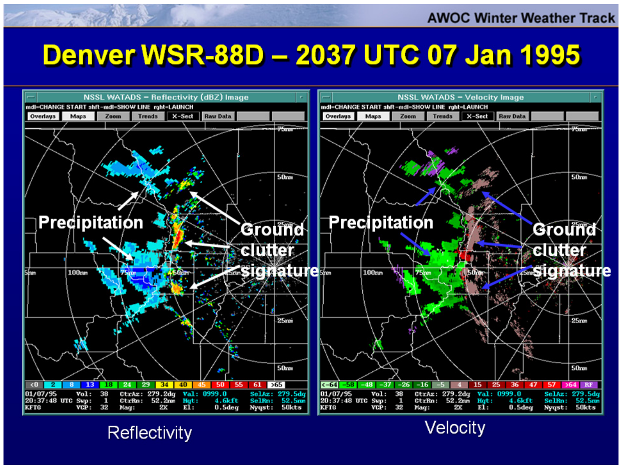
Student Notes:



48. Denver WSR-88D – 2037 UTC 07 Jan 1995

Instructor Notes: High reflectivity signatures during time periods of little, if any, precipitation Near-zero Doppler velocities, low spectral widths, shape & location suggest signatures are ground returns Occurrence appears to be well correlated with strong winds in foothills & presence of large-amplitude mountain wave (possibly caused by wind effects on vegetation)

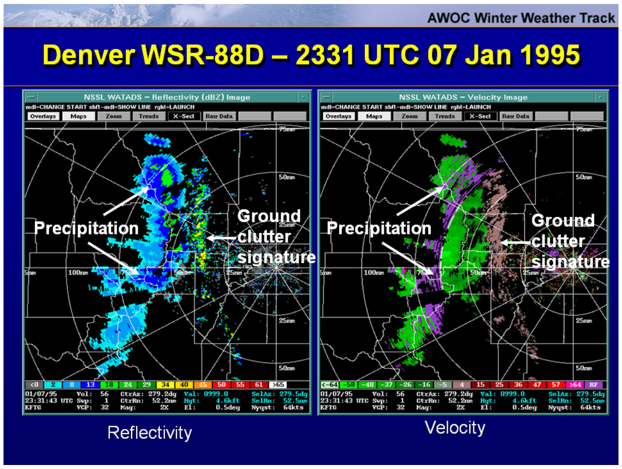
Student Notes:



49. Denver WSR-88D – 2331 UTC 07 Jan 1995

Instructor Notes: Downslope propagation of signature occurs as the strong winds progress down the lee-slope Strong winds tend to be confined to locations along and to the west of the high reflectivity region

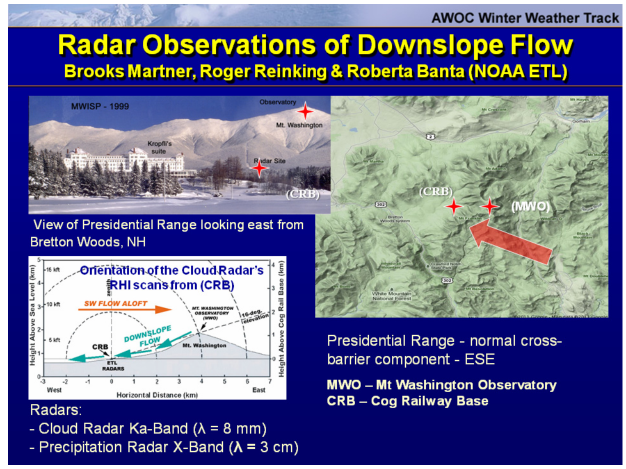
Student Notes:



50. Radar Observations of Downslope FlowBrooks Martner, Roger Reinking & Roberta Banta (NOAA ETL)

Instructor Notes: This radar study of downslope wind flow was conducted on the Presidential mountain range which includes Mt Washington , in N.H. Two types of radars (Cloud radar – Ka-band & Precipitation radar X-band) were located on the western “lee” side of the range near the Cog Railway Base (CRB) in an area affected by easterly low level winds. Note: Radar elevation is approx 800 m above sea level. The image in the lower left shows the orientation of the RHI scan that was used during this study. Although the range is not strictly linear and some 3D effects may complicate the structure... in general the vector component normal to the ridge would be ESE (shown in red)

Student Notes:



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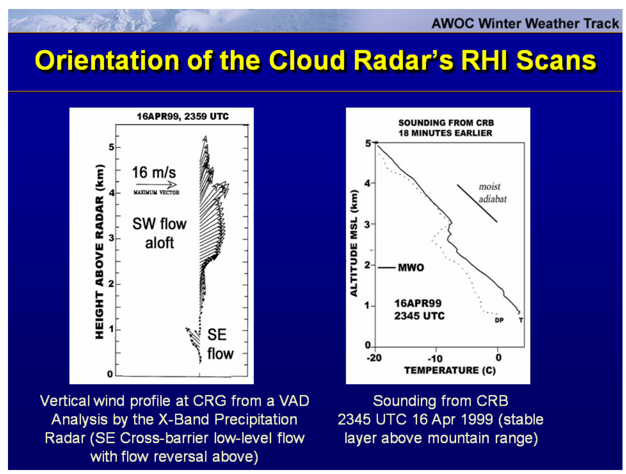
51. Orientation of the Cloud Radar's RHI Scans

Instructor Notes: Around the time of the wind event, the X-band radar VAD wind profile shows SE "cross-barrier" flow that transitions to southwest flow around 2000 ft above the radar. CL around 1200 m above radar. A sounding taken around the same time detected a stable layer at an elevation above the height of Mt Washington.

Student Notes:



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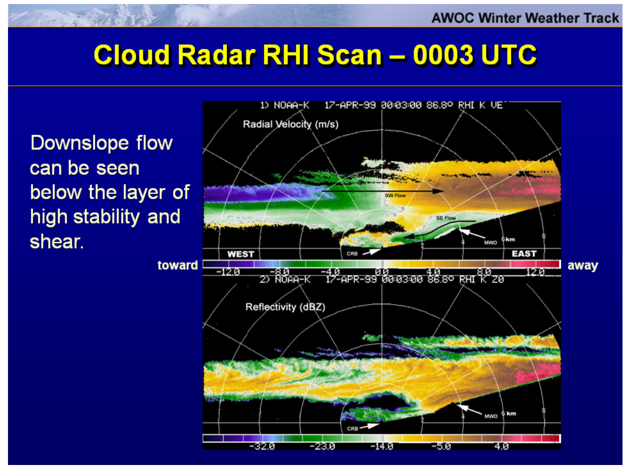
52. Cloud Radar RHI Scan – 0003 UTC

Instructor Notes: Around 00Z the Cloud radar radial velocity image at top shows easterly flow across the top of Mt Washington accelerating as it descends downward the west facing slope. Above the easterly flow there is a shear layer and CL as flow reverses and becomes strong SW.

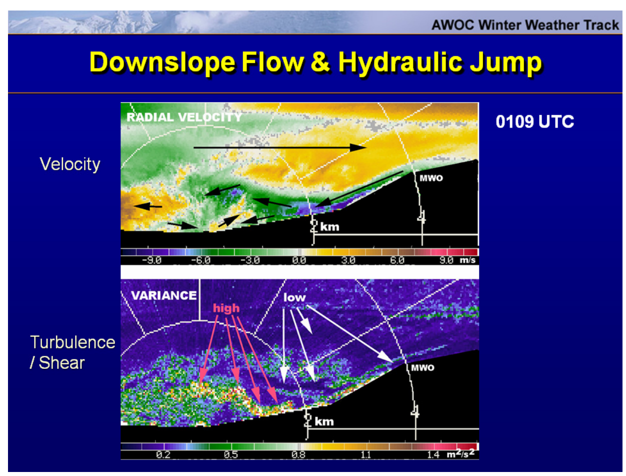
Student Notes:



53. Downslope Flow & Hydraulic Jump

Instructor Notes: An hour later downslope flow intensifies and a lee-side wave is apparent as a region of reverse flow descends and expands above. This reverse flow region is evidence of wave overturning with an “induced” CL in the shear layer between. Note the layer of zero flow near the top of the image which is the level of the mean state CL. Finally in the lower image of “spectrum width” there is a strong turbulence signature near the bottom of the slope indicative of a hydraulic jump.

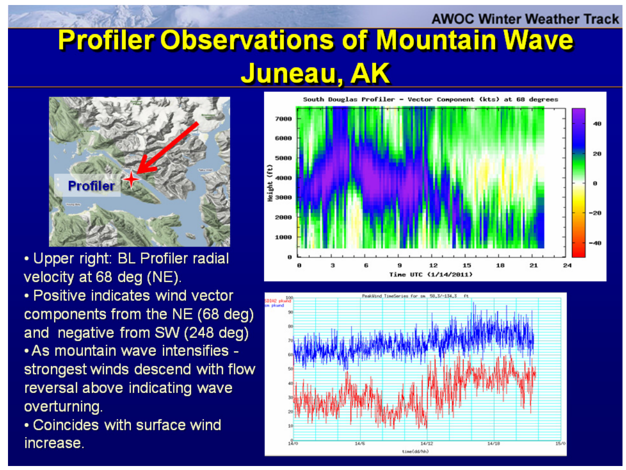
Student Notes:



54. Profiler Observations of Mountain Wave Juneau, AK

Instructor Notes: This example shows how a BL profiler, if strategically located, can provide a wealth of information about the evolution of a mountain wave. The image on the upper right is the radial velocity at 68 degrees from a profiler located to the lee of Salisbury Ridge near downtown Juneau. Time increases to the right. Positive values (green-blue-purple) show the magnitude of the wind vector component from 68 degrees or from the NE (the direction of the arrow). Negative values are for winds from the SW (248 degrees). The image shows that during the later half of the day the mountain wave intensified as the strongest cross-barrier flow descended and a region of reverse flow appeared above. This is the result of turbulent flow downstream of the event. The two wind recordings on the lower right are from an anemometer at the profiler site (red) and near the top of the ridge (blue). Note that the winds at the surface increased coincident with the strengthening of the wave aloft.

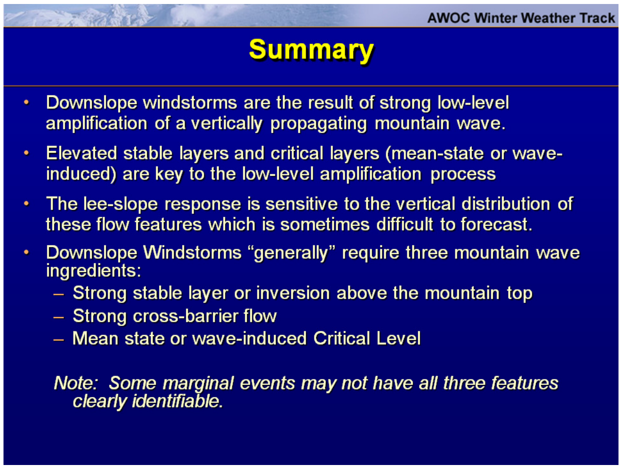
Student Notes:



55. Summary

Instructor Notes: In summary… Downslope windstorms are the result of a strong low-level amplification of a vertically propagating mountain wave. The energy is propagating upward from the mountain in contrast to trapped lee waves where the energy is propagating (or in this case) advecting horizontally. Elevated stable layers and critical layers (mean-state or wave-induced) are key to the low-level amplification process The lee-slope response is sensitive to the vertical distribution of these flow features which is sometimes difficult to forecast. Downslope Windstorms require three mountain wave ingredients: Strong stable layer or inversion above the mountain top Strong cross-barrier flow Mean state or wave-induced Critical Level Model forecasts should first be examined for synoptic scale and local scale "mean state" conditions conducive to mountain wave development. Note that there may be more than one way for synoptic conditions to evolve into a pattern that supports wave development.

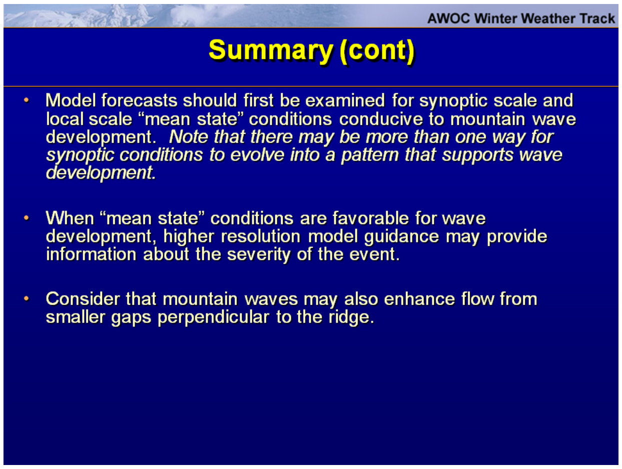
Student Notes:



56. Summary (cont)

Instructor Notes: Summary continued… Model forecasts should first be examined for synoptic scale and local scale "mean state" conditions conducive to mountain wave development. Although high-res models are improving in ability to resolve downslope wind events, an evaluation in the larger scale will add confidence (or doubt) in high-res solution. Note that there may be more than one way for synoptic conditions to evolve into a pattern that supports wave development. When "mean state" conditions are favorable for wave development, higher resolution model guidance may provide information about the severity of the event. Consider that mountain waves may also enhance flow from smaller gaps perpendicular to the ridge.

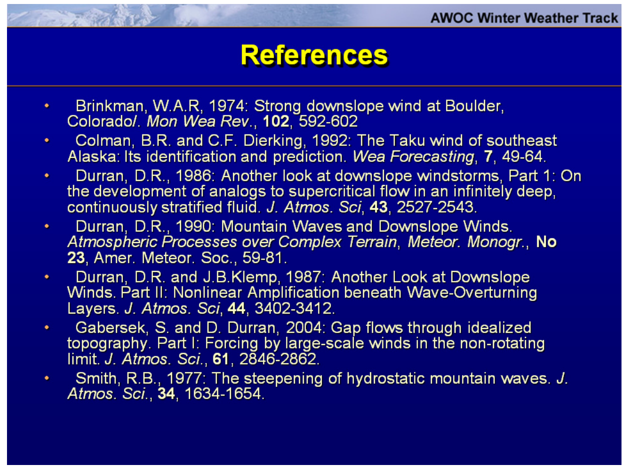
Student Notes:



57. References

Instructor Notes: Here are some references that were used in the preparation of this presentation. If you have any questions about this topic or the contents presented here, please don't hesitate to contact

Student Notes:



58. Have any 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.

Student Notes: