1. IC5.6: Cool-Season Orographic Precipitation Processes and Prediction

Instructor Notes: Welcome to IC 5, Lesson 6: Cool-Season Orographic Precipitation Processes and Prediction. This lesson was developed by Michael Meyers, James Steenburgh, and Doug Wesley and should take approximately 45-50 minutes to complete.

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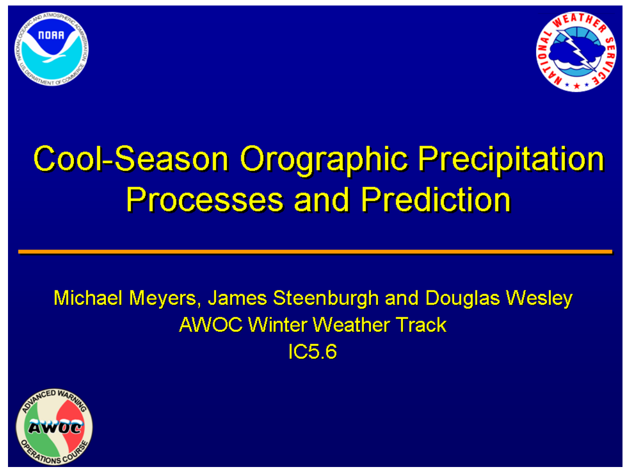

2. Lesson Objectives

Instructor Notes: After completing this lesson you will be able to: identify the primary orographic precipitation mechanisms, understand the relationship between the barrier width and the location of the precipitation maximum over a barrier, become familiar with the climatological variations of different mountain ranges in the western US, identify the general storm stage transitions for western US snowstorms, and explain the practical limitations to model accuracy over complex terrain.

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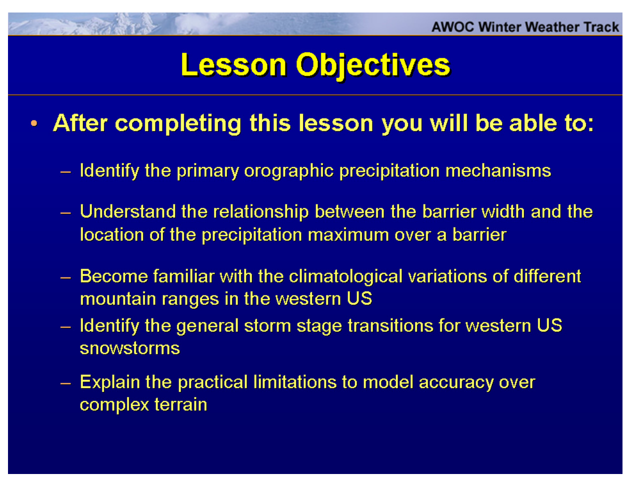

3. Performance objectives

Instructor Notes: By the end of this lesson, you should be able to: describe the major precipitation mechanisms in complex terrain; improve your knowledge of orographic precipitation processes and their geographical, climatological, and storm-to-storm variability for several North American Mountain ranges; and enhance your orographic precipitation forecasting skills based upon climatology, observations and numerical modeling associated with complex terrain.

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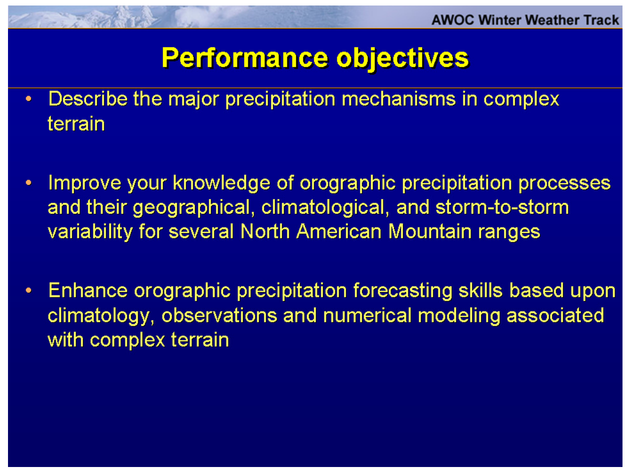

4. Outline

Instructor Notes: We are going to examine the main mechanisms in enhancing precipitation over complex terrain. Next the climatology of orographic precipitation processes in different regimes will be discussed. Finally, forecasting tools and techniques for orographic precipitation will be examined.

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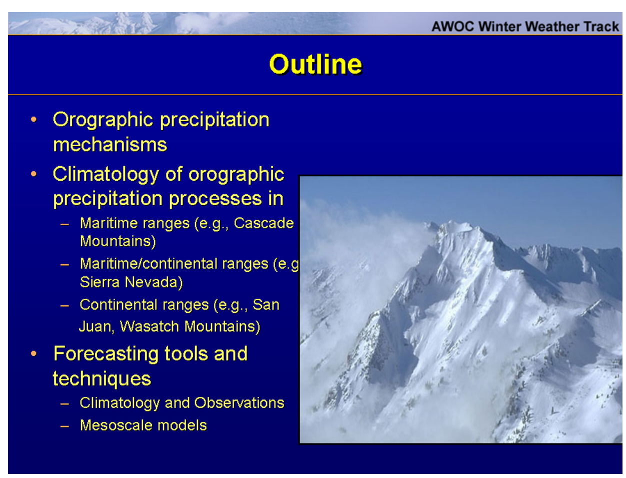

5. Part I: Orographic Precipitation Mechanisms

Instructor Notes: Here is a picture of a snow plow operator clearing an avalanche in the San Juan mountains of Colorado.

Student Notes:

6. Orographic Precipitation

Instructor Notes: Forcing of orographic precipitation occurs on the large scale (wind, moisture, stability, lift, the mesoscale-dynamics of orographic air flow) and on the fine scale (local topographic forcing and microphysics).

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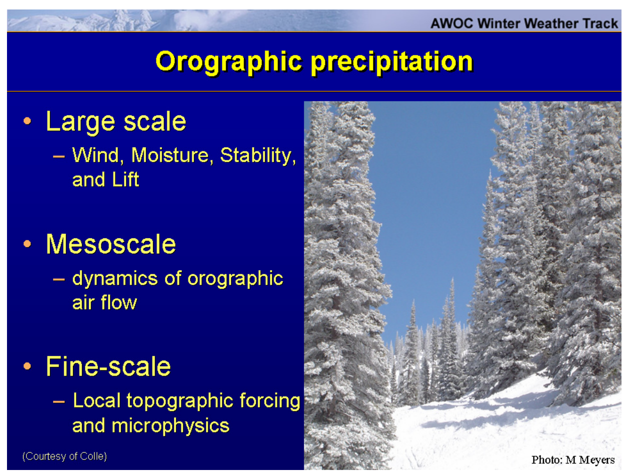

7. Primary Orographic Precipitation Mechanisms

Instructor Notes: The primary orographic precipitation mechanisms which we will discuss are: stable upslope processes, the seeder-feeder, sub-cloud evaporation contrasts, precipitation transport on leeward side of barrier, upslope release of potential instability, terrain-driven convergence, cold air damming/barrier jet mechanisms, and precipitation transport on the leeward side of the barrier. We usually find several of these processes occurring at one time. One topic which we will not discuss is terrain induced-thunderstorms initiation which can occur during all seasons.

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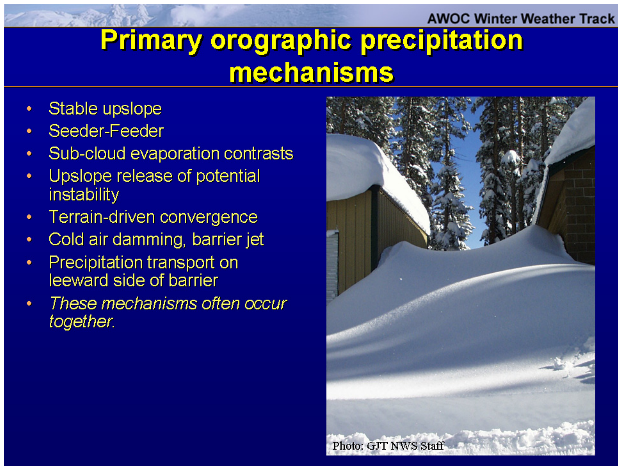

8. Stable Upslope

Instructor Notes: This process is a simple example of orographic precipitation. Here stable ascent is forced by flow over mountain. The parcel will adiabatically cool as it is forced over a mountain range. If the air is sufficiently moist through a deep enough layer, clouds and subsequently, precipitation occurs. Stable upslope flow is an inefficient process for orographic precipitation. In cases, where the layer of upslope ascent is shallow, or not sufficiently moist, non-precipitation clouds may develop.

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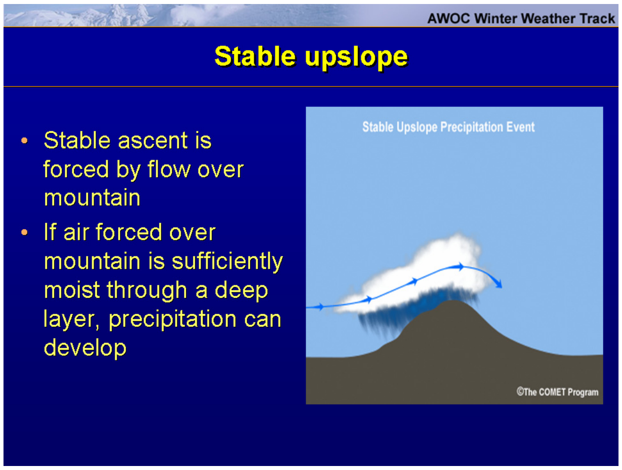

9. Stable Upslope

Instructor Notes: In very shallow upslope events, cold cloud processes may be absent, resulting in freezing drizzle (e.g. Front Range, Appalachians). Results from WISP field project over the Front Range of Colorado (Rasmussen et al. 1995) showed the necessary ingredients for freezing drizzle: supercooled liquid water, low droplet concentrations (a few 10s per cc), spectral broadening of the cloud droplet distribution (including larger cloud droplets), and, finally, an absence of ice.

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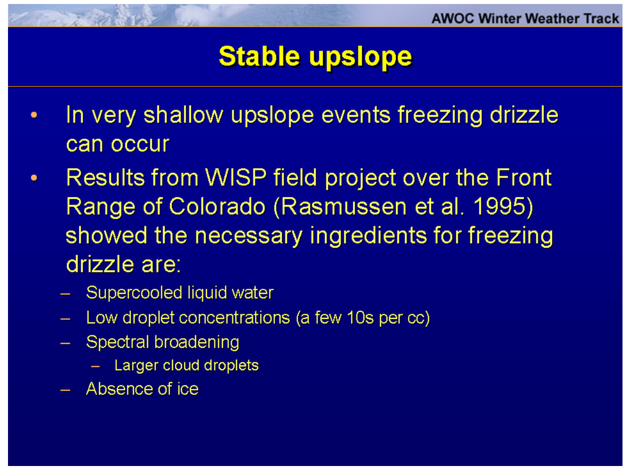

10. Barrier Width Implications

Instructor Notes: With wide barriers (but not so wide Coriolis effects become important), waves are hydrostatic (due to the large horizontal size) and propagate vertically. Wave crests are confined to the area over the terrain and trough/ridge lines slope upstream with height. This mountain wave can be an important source of upward motion in the cloud.

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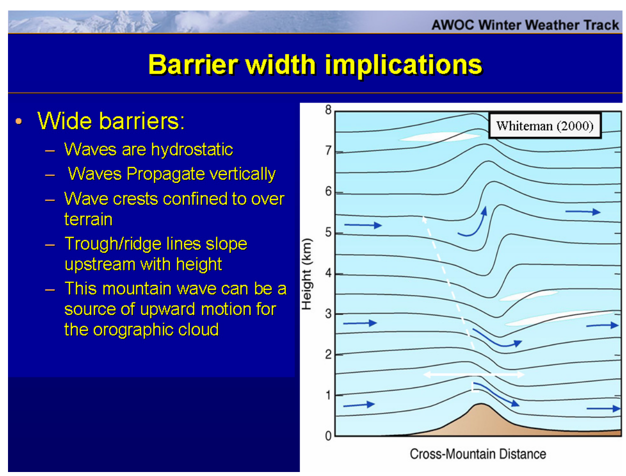

11. Barrier Width Implications

Instructor Notes: Wide barriers: Precipitation maximum is on the windward slope, due in part, to the upward motion resulting from the upstream-tilted mountain wave. A wide barrier allows hydrometeors more time to grow and precipitate over the windward side of the barrier. The effects of blocking and barrier jets can also shift the precipitation maximum over the windward side of the slopes. Narrower barriers: The precipitation maximum is usually near or along the barrier crest. For narrow barriers, the upstream bias for vertical velocity due to the upstream-tilted mountain wave is approximately offset by downstream bias of fallout location over the crest and to the lee due to the shorter residence time for hydrometeor growth aloft.

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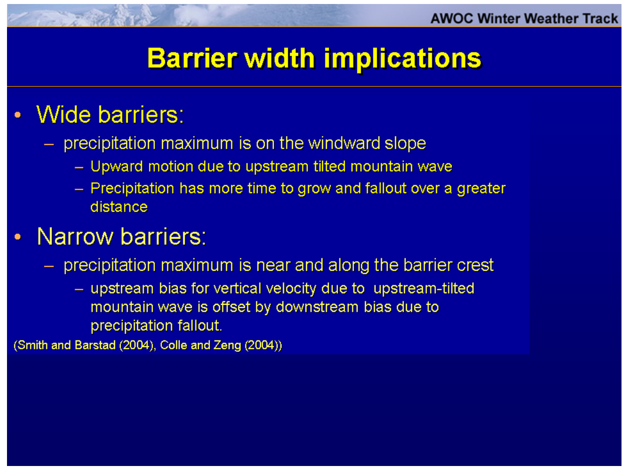

12. Seeder-Feeder

Instructor Notes: In the Seeder-Feeder process, stable ascent occurs producing an orographic cloud, which is then fed by hydrometeors generated by precipitation falling from a higher seeder cloud aloft. This feeder cloud might not precipitate without the precipitation generated in the seeder cloud. A seeder cloud can be frontal, or orographically generated/enhanced. Precipitation in the feeder cloud is enhanced primarily by depositional growth through the Bergeron-Findeisen process, and collision-coalescence in warm rain processes or aggregation in cold cloud process, and by accretion/riming. A feeder cloud may be located to the lee of the mountains (e.g. Front Range). In these situations, higher precipitation rates are found over the mountains than over the lower elevations since this mechanism is not occurring over the lower elevations.

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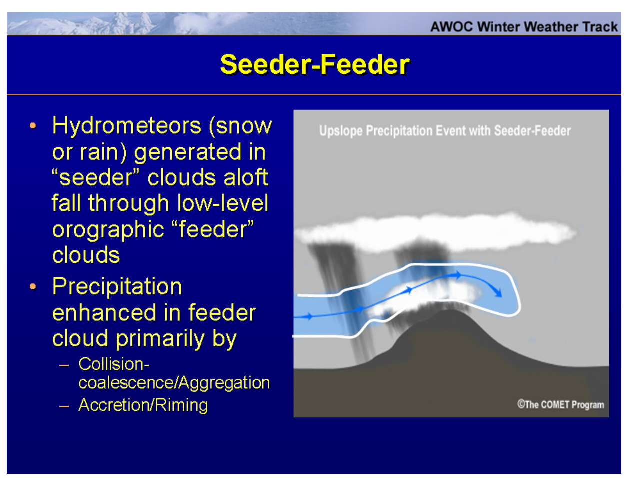

13. Seeder-Feeder

Instructor Notes: The seeder and feeder cloud may not be mutually exclusive and may be more complex than originally thought. A deep frontal cloud (seeder) is often enhanced by vertically propagating gravity wave. Purely orographic cloud (e.g., post-frontal) can often seed itself (Colle and Zeng, 2004). Roe (2005) argues “there is not a clear distinction between upslope ascent and seeder-feeder, and the differences are perhaps somewhat semantic.”

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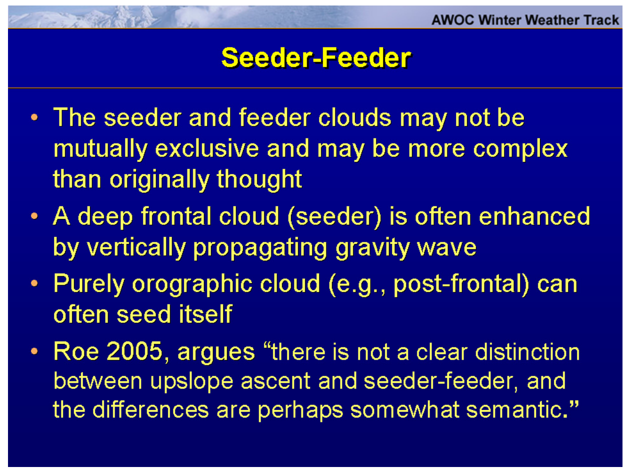

14. Seeder-Feeder

Instructor Notes: Here is an example from the Improve-2 field project over the Oregon Cascades in 2001. In pre-frontal situations, a weak low-level easterly flow often develops off of the Washington Cascades. In these situations, the deep frontal cloud is the main cloud for precipitation. In this 2001 case over the Oregon Cascades, strong cross-barrier westerly flow occurred, which generated an orographic cloud. This high LWC cloud combined with frontal cloud created an optimal structure for a seeder feeder mechanism, where heavily rimed crystals were observed reaching the ground.

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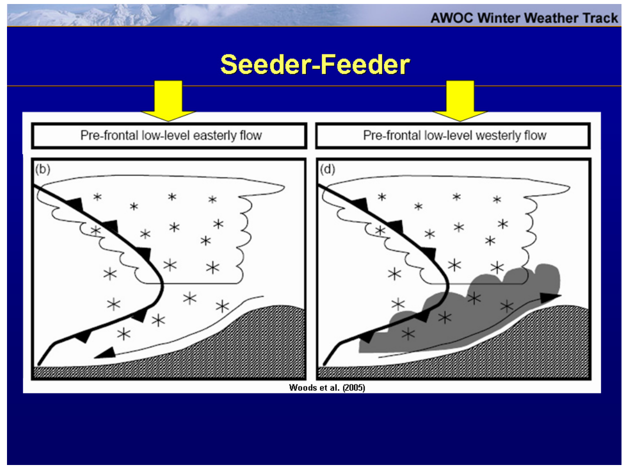

15. Seeder-Feeder

Instructor Notes: The conceptual model (from Houze and Medina, 2005) uses data obtained over the Oregon Cascade Mountains during IMPROVE-2 during 2001 and over the Alps during MAP in 1999. Vertically pointing S-band Doppler radar data suggest that turbulence contributed to the orographic enhancement of the precipitation associated with fronts passing over the mountain barriers. Cells of strong upward air motion (>2 m s^{-1}) occurred in a sheared layer just above the melting layer as the frontal cloud was over the barrier. The flow at the higher levels is strong and is able to cross over the barrier. The low-level layer flow is stable, and it becomes retarded or blocked as it approaches the terrain. The cells develop at this interface between the two flow regimes, likely due to some form of turbulence. The existence of turbulent cells results in the rapid growth and fallout of condensate over the lower windward slopes of the mountains, due to increased accretion growth, riming, and aggregation. Without the turbulent cells, the condensate would more likely be advected farther up and perhaps even over the mountain range, which would shift the precipitation distribution over the mountain. This conceptual model shows that even a stable flow has the capacity to generate cells that will enhance the precipitation processes over the windward slopes of a barrier. Nearly any baroclinic system passing over a mountain range has the capacity to produce cellular overturning over the windward slope regardless of its stability characteristics.

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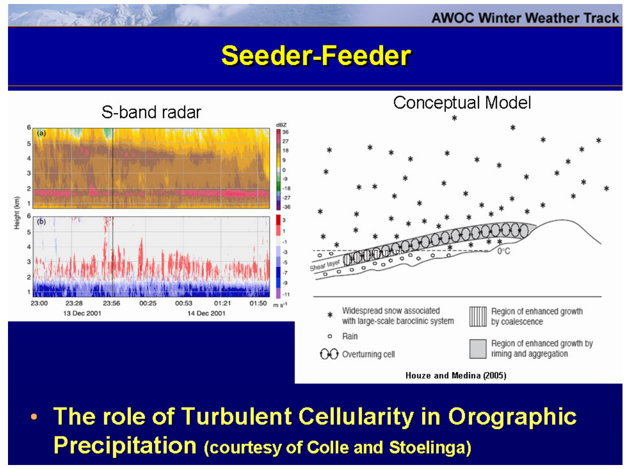

16. Sub-Cloud Sublimation/Evaporation Contrasts

Instructor Notes: Another important mechanism is evaporation/sublimation differences over the mountains and over the lower elevations. This process is very important in the Great Basin region in the western US. In this situation, the deficit between the mountain and valley precipitation is due to the valleys reducing the precipitation. This occurs when you have a dry continental airmass at low levels, and the precipitation will evaporate and sublimate before it reaches the ground. However, over the mountain locations, the precipitation is able to reach the ground since there is less hydrometeor loss due to evaporation/sublimation. In another environment, the airmass that is lifted over the mountains doesn't produce a cloud, but has a higher RH than the airmass over the lower elevations. Similarly, the precipitation rates will be higher over the mountains than the lowlands since the sub-cloud evaporation contrast will be greater over the valleys. This process is very common over the Intermountain West.

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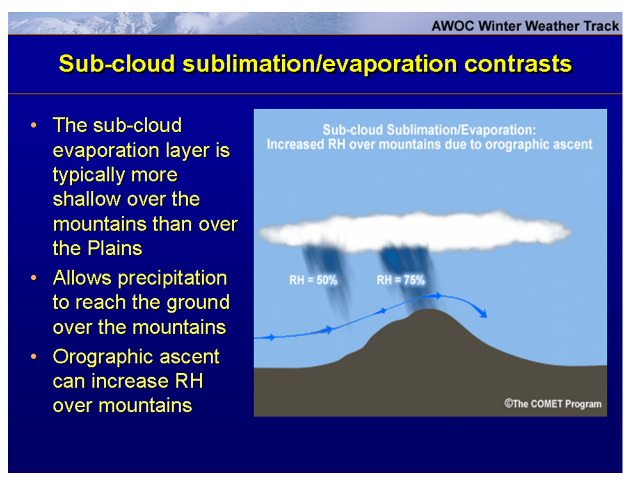

17. Upslope Release of Potential Instability

Instructor Notes: Mechanisms that produce the greatest precipitation rates in orographic storms is the upslope release of potential instability. In these cases, the upstream profile is potentially unstable, q_e is decreasing with height. Convection may not be strong but will enhance precipitation rates. Orographic uplift causes the development and release of convection usually over the windward slopes and crest of the mountains. Convection may be deep or shallow - both can result in substantial precipitation enhancement. From a forecaster's perspective, deep instability is more obvious; shallow convection is more problematic in forecasting when it occurs. Enhanced precipitation rates evident in the form of heavily rimed crystals in shallow convection to graupel in deeper convection.

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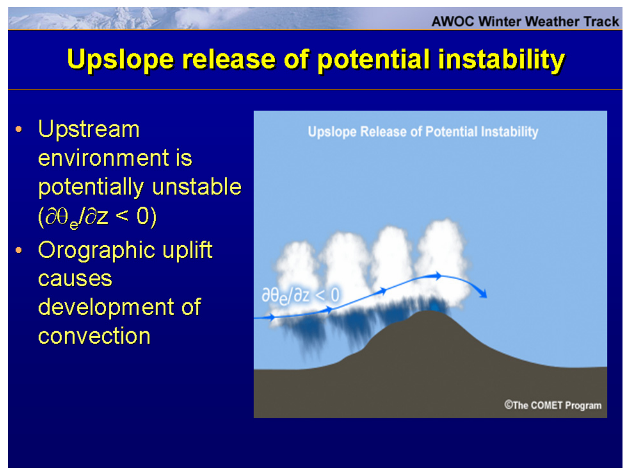

18. Upslope Release of Potential Instability

Instructor Notes: There are preferred synoptic environments in which potential instability will occur. One of the favored areas occurs ahead of a cold front. Here, surges of low q_e aloft ahead of high q_e air ahead of the front. This mechanism is most effective over smaller hills. In big mountains like the Cascades, the mountain induces its own flow pattern, easterly flow at crest level creates subsidence, which dampens out potential instability.

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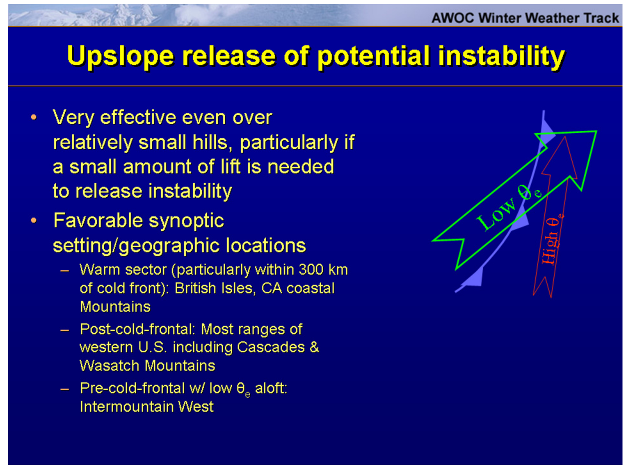

19. Terrain-Driven Convergence (TDC)

Instructor Notes: Terrain-driven convergence (TDC) occurs in many shapes and sizes, depending on the geography of the area. The basic idea is that in low Froude number flow, which is relatively stable flow, the air moves around the barrier. Convergence can occur to the lee of the mountains such as in the Puget Sound, on the windward side of barriers (such as the coastal ranges of North America, Wasatch Mountains, San Juan Mountains, and the Front Range). Many different types of terrain driven convergence can occur which is dependent on the orientation of the topography. The bottom line is that there is a dramatic impact on precipitation due to terrain-driven convergence.

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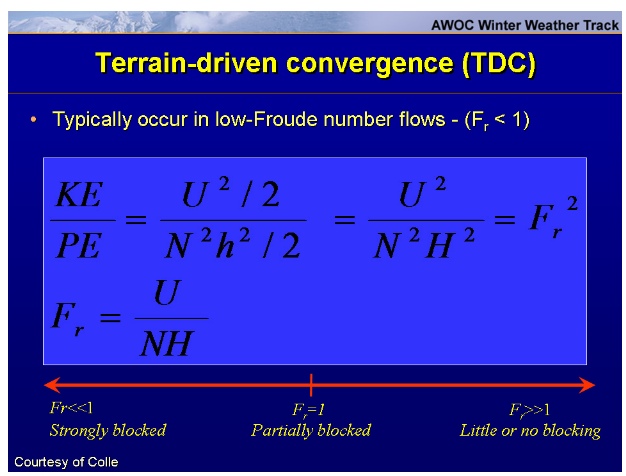

20. Terrain-Driven Convergence (TDC)

Instructor Notes: Examples of convergence windward of the initial slope of a quasi-linear mountain range or ridge are the coastal ranges of North America, Wasatch Mountains, San Juan Mountains, and the Front Range. An example of lee-side convergence is the Puget Sound convergence zone. An example of convergence windward of isolated obstacles is the Hawaiian cloud bands. Example of other terrain-driven convergence zones are the Snake River convergence zone and the Denver convergence zone.

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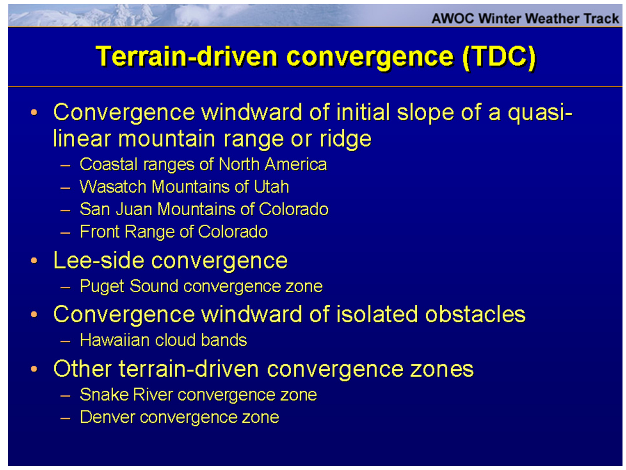

21. Cold Air Damming (CAD)/Barrier Jet

Instructor Notes: As shown in this conceptual model from Bell and Bosart (1988), the approaching upslope flow responds to both the actual terrain and the modified air mass, which creates an effective barrier. This effective barrier influences the approaching flow higher and wider than actual topography and it frequently displaces snowfall maximum well upwind of the steepest slope. The existence and degree of cold air damming (CAD) can also be a dominant factor in precipitation type (e.g. freezing/frozen precipitation in Appalachians and freezing drizzle in Front Range). When trying to diagnose precipitation rates in a blocked flow regime, be sure to use the flow upstream or above the blocked flow, otherwise you would probably underestimate precipitation estimates. (Neiman et al., 2002, used the upslope flow at 1km in the CalJet experiments in the Sierras.)

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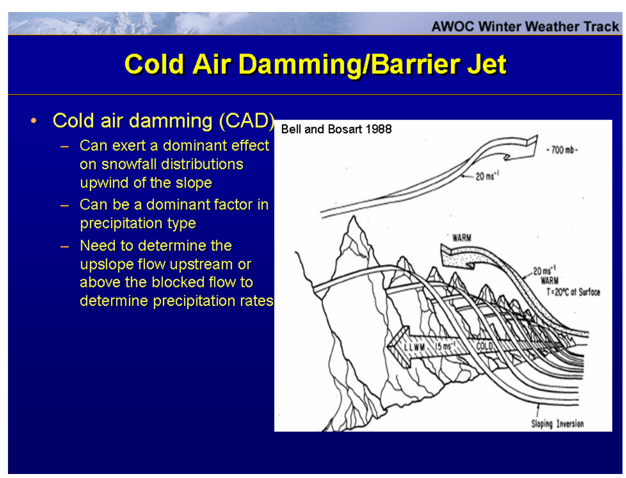

22. Cold Air Damming/Barrier Jet

Instructor Notes: As stable, low-level flow approaches a barrier, it becomes blocked and decelerates. The apparent resultant wind, the barrier jet, develops parallel to the barrier. Barrier jets always blow to the left as they approach a barrier. For instance, a west wind impinging on a N-S barrier will generate a southerly barrier jets. The barrier jets is often associated with CAD. The barrier jet can intensify the degree of blocking-induced overrunning. Barrier jets can impact precipitation type, and modify the spatial precipitation distribution, as is often seen in the Sierras. In such a case, the barrier jet shifts the precipitation distribution to the north. The barrier jet can also be quite strong as indicated by the southerly barrier jet seen in the Sierras as detailed by Parish. The core of the barrier jet reached 25 ms^{-1}. The next example shown is for the Front Range snowstorm 18 March 2003, where an easterly gradient wind is observed well east of the barrier over the Plains with stable flow near the surface. As the flow approaches the barrier, a northeast barrier jet is evident as the topography gradient increases near the foothills of the Rockies.

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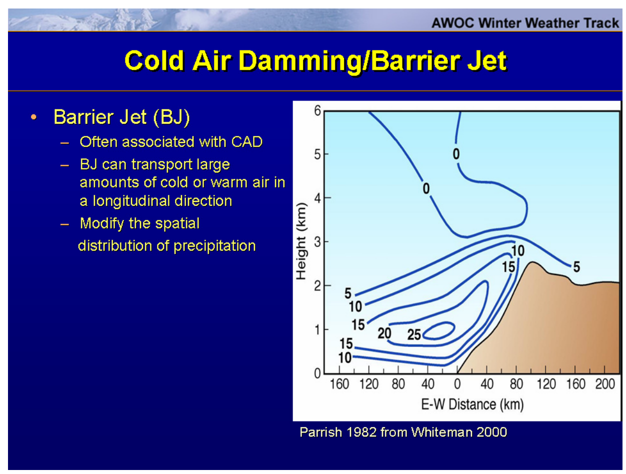

23. Precipitation Transport on Leeward Side of Barrier

Instructor Notes: Typically precipitation amounts rapidly decrease on the leeward side of the mountain crest. In strong downslope situations, precipitation can be transported several miles and produce light accumulations (mainly due to transport of precipitation from the windward side of the crest). However, sometimes there will be significant precipitation transport on the leeward side of the barrier. In the March 16-20 2003 snowstorm over the Front Range of Colorado, precipitation was carried west of the Continental Divide producing ~80” of storm total snowfall at the top of Winter Park Ski area in CO. A stable cloud on the lee side may extend the precipitation much farther downwind of the crest and, typically, there is strong wind shear between the stable cloud and the orographic cloud aloft.

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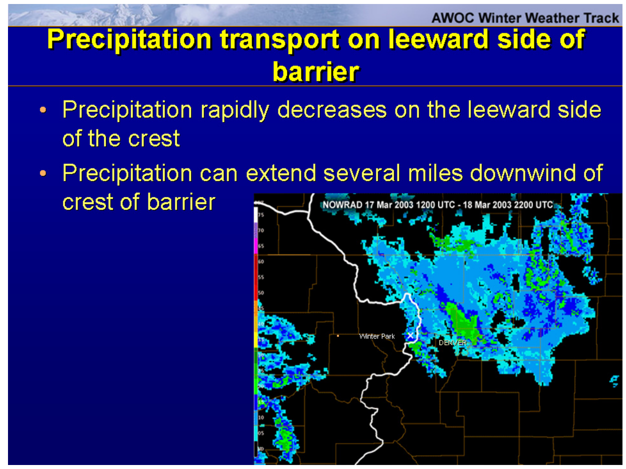

24. Interactive Quiz #1

Instructor Notes: Take a few moments to complete this interactive quiz.

Student Notes:

25. Precipitation Efficiency

Instructor Notes: Studies by Smith (1979), and more recently by Smith and Barstad (2004) using a model based on linear mountain wave theory, conclude the following: in general, precipitation efficiency, which is the ratio of the precipitation/total condensate produced by the cloud, increases with more moist inflow, a higher barrier, and a wider barrier.

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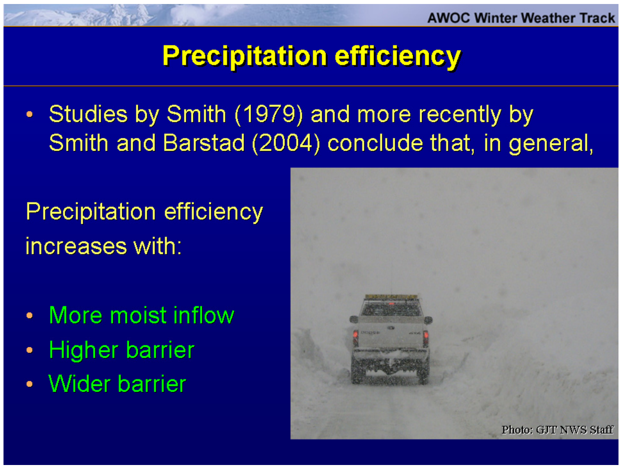

26. Summary

Instructor Notes: Several mechanisms contribute to orographic precipitation: stable upslope flow, the seeder-feeder mechanism, sub-cloud evaporation contrasts, precipitation transport on leeward side of barrier, upslope release of potential instability, terrain-driven convergence, and cold air damming/barrier jet. These mechanisms are not mutually exclusive and may occur in concert.

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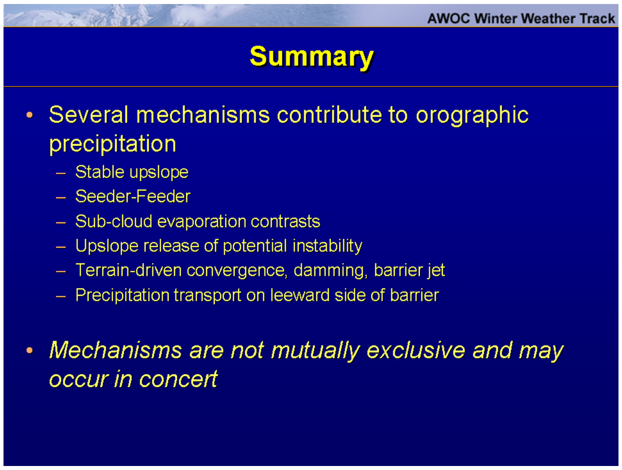

27. Part 2: Climatology of Western U.S. Orographic Storms

Instructor Notes: A winter weather traffic mishap in the Salt Lake City, Utah area. Next we will look at storms for several mountain ranges of the western US.

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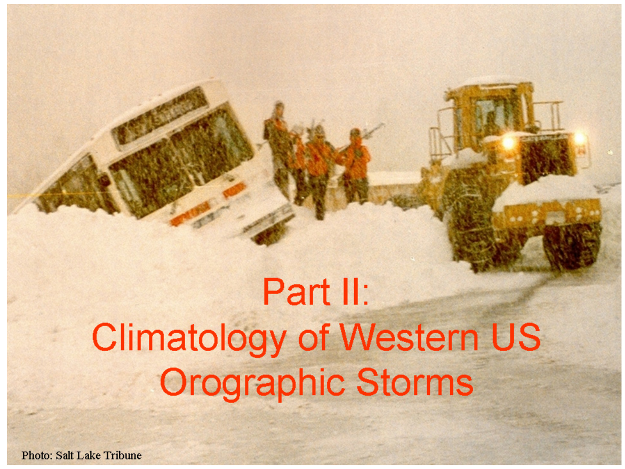

28. Cascade Mountains

Instructor Notes: First we will talk about the Cascade range, which has weather similar to the Coast Range of southwestern British Columbia. The Cascades are a quasi-maritime range due to the influx of pollution from Seattle and Vancouver, which tends to make it more continental, at times. The Cascades are approximately 100 km wide. This mountain width affects the orographic storm evolution, which has been detailed by the work of Colle and Zeng (2004). The Cascades separate the Columbia Basin from the Puget Sound lowlands and the Willamette Valley. Some notable passes/gaps include the Columbia River Gorge (MSL), Stampede/Snoqualmie Passes (~1000 m), and Stevens Pass (~1200 m). Some volcanoes in this range include Mt. Rainier, Mt. Adams, Mt. Baker, Mt. St. Helens, and Mt. Bachelor.

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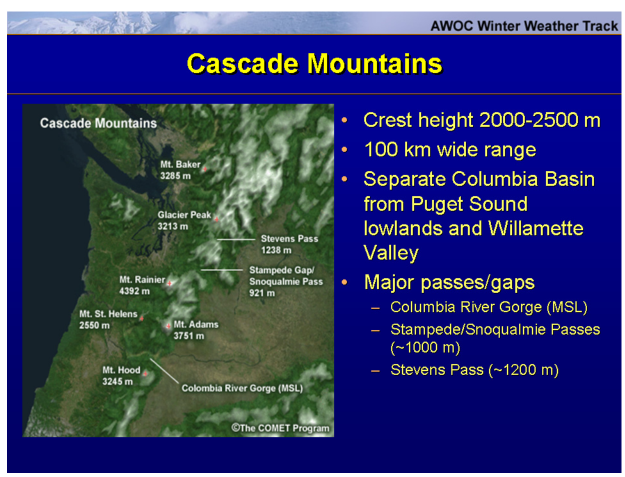

29. Annual Precipitation: Cascade Mountains

Instructor Notes: The precipitation climatology of the Cascades is shown here (the Oregon Climate Service provided the annual precipitation). The heaviest precipitation falls on the windward side of the crest. This feature is typical of broad mountain ranges like the Cascades, Sierra Nevada Range, and Coast Range of British Columbia. Narrow ranges, like the Wasatch range in Utah, however, exhibit a precipitation maximum near the crest. Wide barriers allow hydrometeors to grow and fallout over the windward slope, while narrow ranges typically have more precipitation falling out over the crest, and spilling over into the lee of the barrier. Washington snow highlights include: 1. Mt. Baker Ski Area (4,300'), 647" annually, 1,224" 1998/99 (world record) and 2. Paradise Ranger Station (5,420'), 633" annually, 1,222.5" 1971/72. Areas observing heavy precipitation in Oregon include: Mt. Hood and Mt. Bachelor/Sisters east of Bend.

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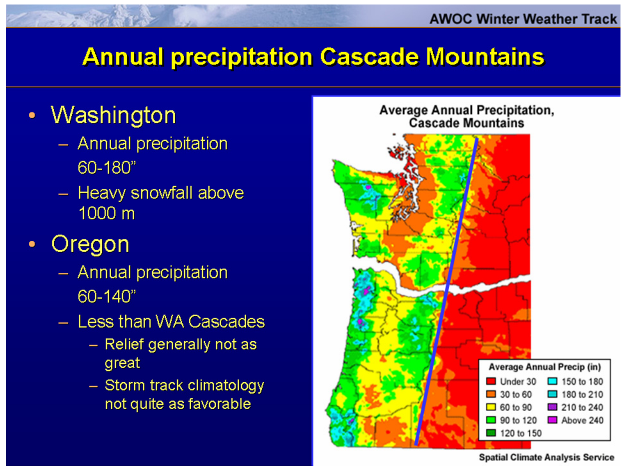

30. Sierra Nevada Mountains

Instructor Notes: Next we will talk about the Sierra Nevada range. It has similar width as the Cascade range (100 km wide), and is oriented slightly NW to SE. The Sierras feature a gradual windward slope 2-3% from near sea level to the crest (the exception being the coastal range, which are relatively small coastal mountains which extend up to ~500 m MSL). The Sierras also feature some dramatic leeward slope in some areas. Mt. Whitney is one example. There are numerous peaks over 3500 m that also have strong leeward slopes.

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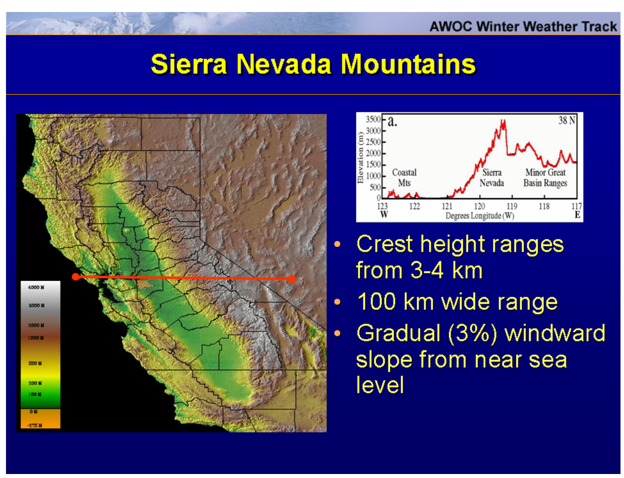

31. Sierra Nevada: Annual Precipitation

Instructor Notes: Like the Cascades, the Sierras feature a precipitation peak on the windward side of the barrier rather than at the barrier crest. Typically the precipitation peak is 10-20 km upstream of the barrier crest. Barrier jets that form can be as strong as 25 ms^{-1} and tend to force precipitation to the northern sections. U.S. snowfall records for this region include: a. seasonal snow depth 454”, Tamarack, Mar 1911; b. monthly snowfall 390”, Tamarack, Jan. 1911; c. snowfall from single storm 189”, Mt. Shasta Ski Bowl, 13-19 Feb. 1959; and d. 24-hour snowfall (2nd greatest) 67”, Echo Summit 4-5 Jan. 89. Sierra Nevada records include: the seasonal snowfall 884”, Tamarack, 1906-07.

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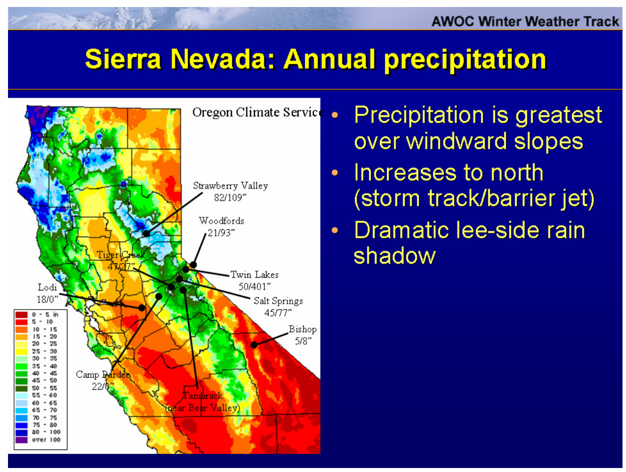

32. Coastal Orographic Precipitation in the Cascades and Sierras

Instructor Notes: Here are two examples in the literature of heavy precipitation producers for the coastal regions of the Sierras and the Cascades. Atmospheric rivers were examined over the coasts of California and Oregon during the CALJET (1998) and PACJET (2001) field projects. Most of the subtropical vapor flux in atmospheric rivers is below 2.5 km, which usually leads to flooding along the coast and in the coastal mountains. Colle and Mass (200) also details the warm moist subtropical southwesterly flow which impacts the coastal regions from California to Washington which often leads to coastal and inland flooding in these locations. The pattern is often dubbed the “Pineapple Express” since the flow often originates near Hawaii.

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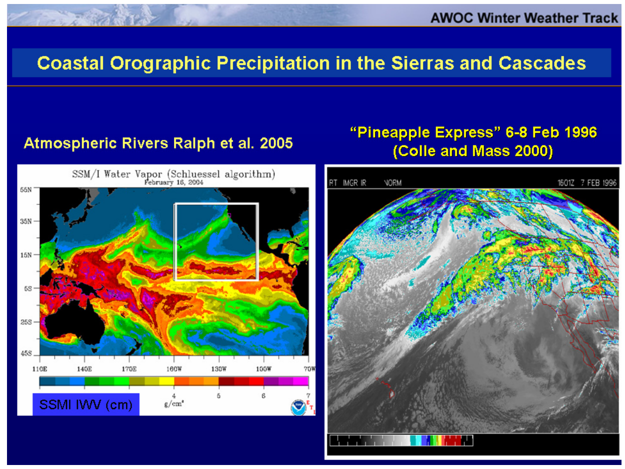

33. Cascades and Sierra Nevada Snowstorms

Instructor Notes: This generalization of Cascade and Sierra Nevada snowstorms, does not apply to all storms. However, these storms tend to evolve from prefrontal to transitional to post-frontal conditions. Many of the fronts are associated with deep well-occluded storms in the later stages. The prefrontal regime is usually when the storms are the deepest. However, precipitation rates are steady, but not the greatest. Ice particles, with LWC, dominate over water droplets and, therefore, limit riming. The transitional stage occurs as the occluded front moves through the region. The air becomes increasingly unstable. The upper level cloud shield moves east, reducing the cloud depth (i.e., ice particles become less common). LWC increases to relatively high values, with lowering cloud tops and convection, and riming increases. The precipitation tends to be more showery and heavy, with heavy showers on the western slopes and clearing on the eastern slopes. During the post-frontal regime, unstable conditions will continue and increase. LWC is moderate, with strong updrafts and heavy riming. This riming is very important for the total snow water content of the storm. Precipitation is showery and occasionally heavy.

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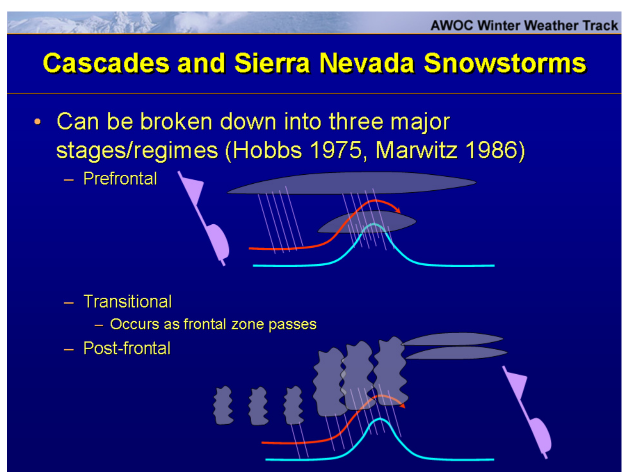
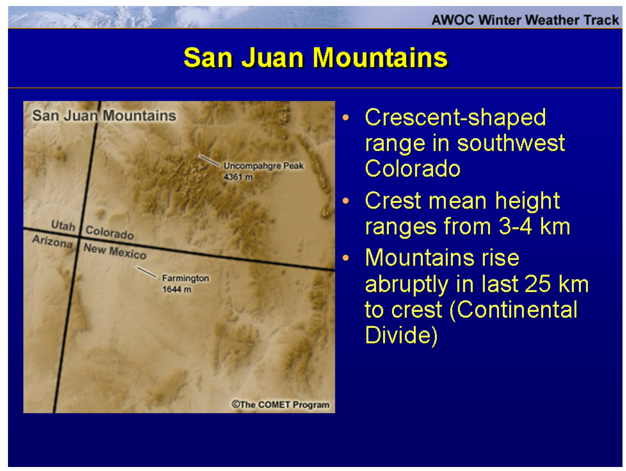


34. San Juan Mountains

Instructor Notes: Next we will look at the San Juan mountains of western Colorado in the interior United States. The San Juans are a crescent-shaped range in southwest Colorado, where crest mean height ranges from 3-4 km. These mountains rise abruptly in last 25 km to the crest (Continental Divide). The Cascades are narrower than the coastal mountains of the west, but not as narrow as the Great Basin ranges of Utah.

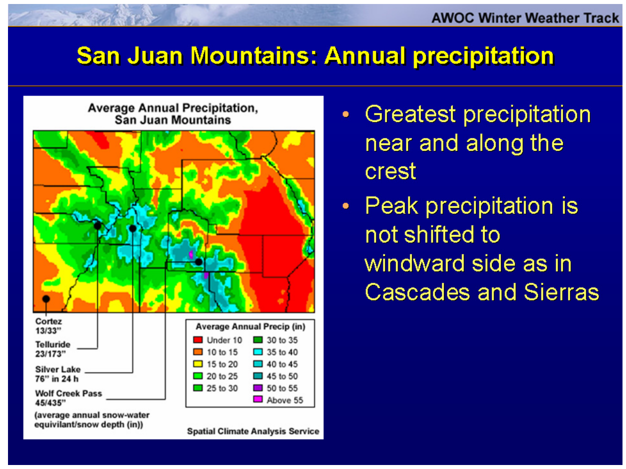
Student Notes:



35. San Juan Mountains: Annual Precipitation

Instructor Notes: The greatest precipitation in the San Juans is near and along the crest. Peak precipitation is not shifted to the windward side as in Cascades and Sierras. The contrast between windward and leeward precipitation is not as great as in the Sierras and Cascades. One reason for this feature is that during the storm evolution, the favored upslope flow will shift from typically the south-facing slopes as the storm approaches to the north-facing slopes as the storm moves east of the area. Since it is an interior mountain site, the San Juans have lower annual winter precipitation than Cascades and the Sierras.

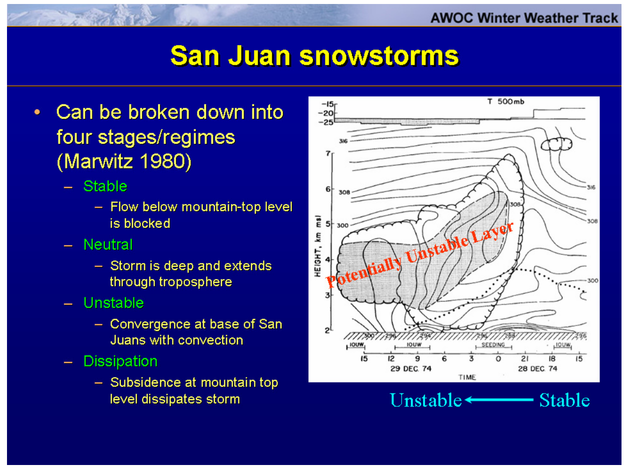
Student Notes:



36. San Juan Snowstorms

Instructor Notes: The storm stages for the San Juan storms are similar to those over the Cascade and Sierra Nevada mountains. In the stable regime, there is usually no potential instability. The flow below mountain level is blocked, which reduces the effective height of the barrier. In this environment, orographic ascent is only observed halfway up the barrier to the crest reducing the depth of the orographic ascent. Windward convergence zones are also observed which spatially affect the precipitation distribution. Since there is little liquid water, snow is usually light in the stable regime (where diffusional growth dominates). Precipitation is more focused on the southern facing slopes of the San Juans during this stable regime since the flow is typically from the south/southwest. As it transitions into the neutral stage, many of the storms are associated with closed lows. As a result, the storms have a good baroclinic zone in the midlevels but usually lack a good surface cold front. As the low q_e air aloft moves across the area, neutral or unstable conditions aloft develop. In association with orographic lift, this potential instability can be released. There is also a deepening of the storm during the neutral stage. The strongest snowfall usually occurs over the southern facing slopes of the San Juans with lesser amounts across the north facing slopes due to "snow shadow effect". Riming increases as liquid water increases. As it finally transitions to the unstable stage, a convergence zone sets up at the base of the mountain. Enhanced precipitation shift to the north facing slopes of the San Juans as flow becomes more northwest as the system moves east of the area. Significant accumulation can occur on these north-facing slopes as the upslope flow shifts to a more northerly direction. Heavily rimed crystals, or graupel, are observed in the unstable stage. This process is similar to the Cascades and Sierra Nevada ranges when a stable regime transitions to unstable regime.

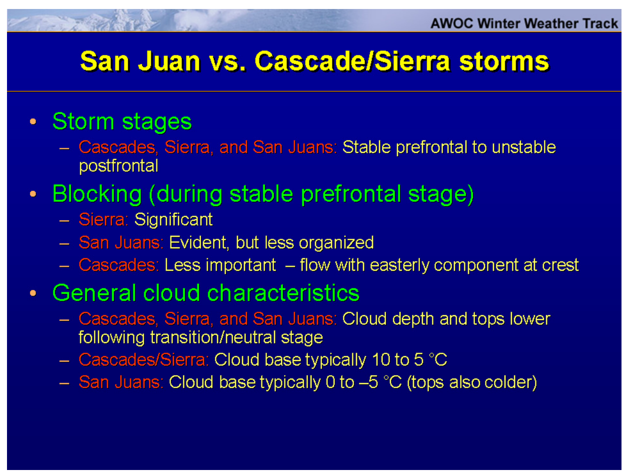
Student Notes:



37. San Juan vs. Cascade/Sierra Storms

Instructor Notes: The same general storm stage transitions occur in inland range as they do in a maritime range. Blocking is significant in the Sierras, (i.e., barrier jet), but is less organized in the San Juans (and is even less important in the Cascades). Cloud depth and tops lower in the transition/neutral stages which leads to less ability to nucleate the ice. The Cascade and Sierras are typically warmer than the San Juans.

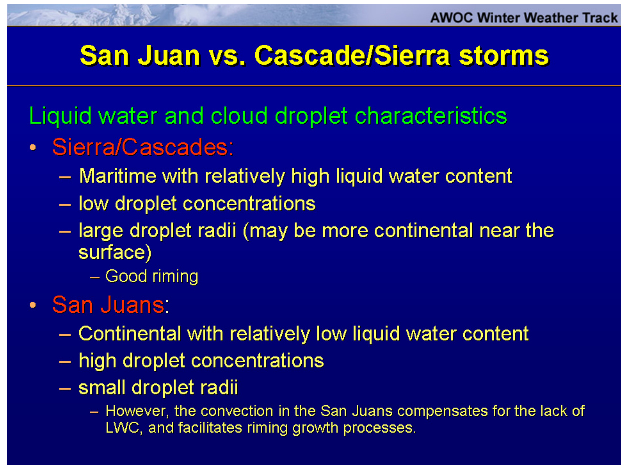
Student Notes:



38. San Juan vs. Cascade/Sierra Storms

Instructor Notes: More maritime cloud spectra in the Sierras and the Cascades, which leads to better riming. However, the convection in the San Juans compensates for the lack of LWC, and facilitates riming growth processes.

Student Notes:



39. San Juan vs. Cascade/Sierra Storms

Instructor Notes: Depositional growth is more important in the prefrontal/stable stages in each mountain range. However, accretional growth and riming is still important in the Sierras. Accretional growth and riming become more dominant in the transitional/neutral and post frontal/unstable stages.

Student Notes:

40. Wasatch Mountains

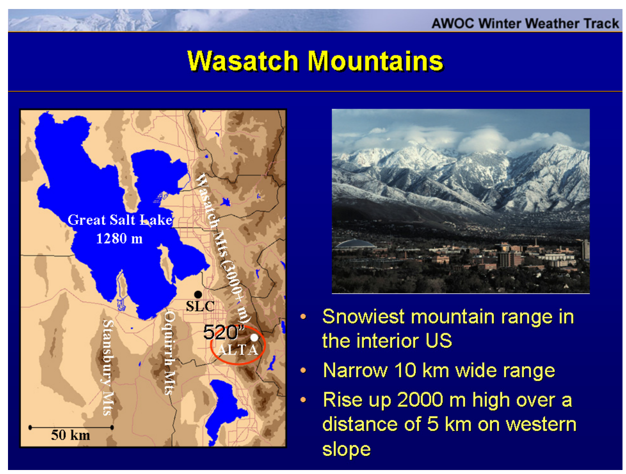
Instructor Notes: Next, we will examine the Wasatch Mountains, with Dr. James Steenburgh (from the University of Utah) leading the training.

Student Notes:

41. Wasatch Mountains

Instructor Notes: The Wasatch are the snowiest mountain range in the interior U.S. The Wasatch is a narrow (10 km wide) range. It rises up 2000 m high over a distance of 5 km on its western slope. The Great Basin has numerous mountain peaks, with broad lowlands in between the peaks. For the Wasatch, the precipitation maximum is over the crest.

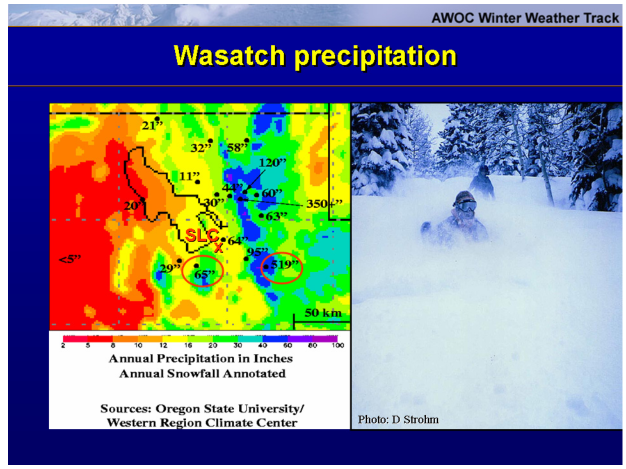
Student Notes:



42. Wasatch Precipitation

Instructor Notes: The precipitation maximum is over the crest. Salt Lake City has an annual precipitation of 15” and the mountains to the southwest have an annual precipitation of 65”. This variation occurs over a distance of 15 km or less.

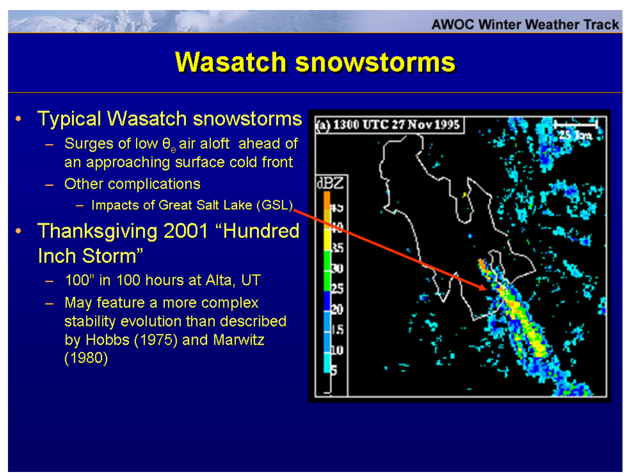
Student Notes:



43. Wasatch Snowstorms

Instructor Notes: Over the Great Basin, we get surges of low θ_e air aloft ahead of an approaching surface cold front. These cold fronts can be associated with intense convection. Immediately behind the cold front stable air will occur, then it will transition back to an unstable air mass. The Great Salt Lake also complicates the forecasts and can impact snowfall. Next will talk about a 100” storm at Alta, UT. This storm features a more complex stability evolution than described by Hobbs (1975) and Marwitz (1980).

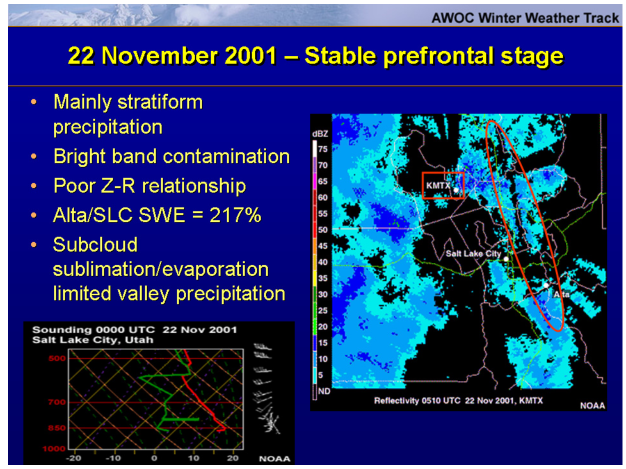
Student Notes:



44. 22 November 2001 – Stable Prefrontal Stage

Instructor Notes: In the stable storm stage, we observe mainly stratiform precipitation. Also, we see bright band contamination; as a result, Z-R relationships are poor. In this stage of the storm, there is double the precipitation in Alta as compared to SLC. From the sounding profile, dry conditions in the lower atmosphere lead to subcloud sublimation/ evaporation processes which limited the valley precipitation.

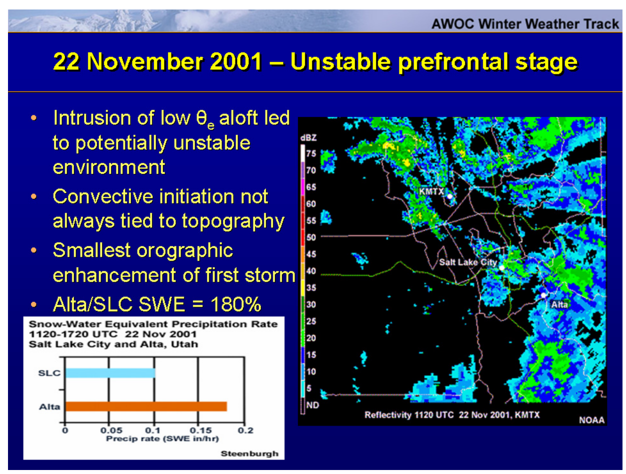
Student Notes:



45. 22 November 2001 – Unstable Prefrontal Stage

Instructor Notes: Intrusion of low θ_e aloft led to a potentially unstable environment (and lightning). Convective initiation is not always tied to topography. There was the smallest orographic enhancement of the first storm. This process all occurred ahead of the surface cold front.

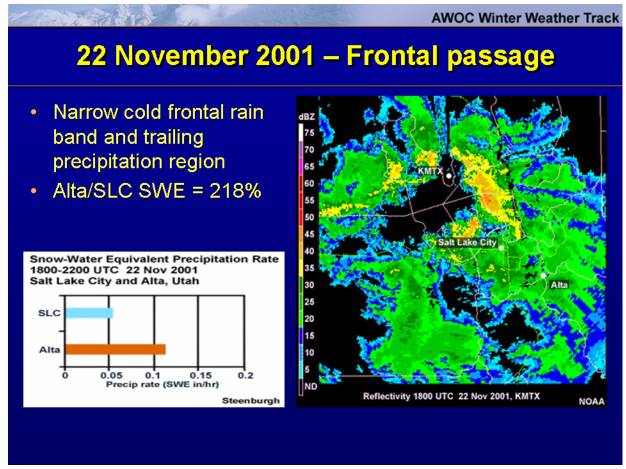
Student Notes:



46. 22 November 2001 – Frontal Passage

Instructor Notes: Here you see evidence of the narrow, cold frontal rain band and trailing precipitation region, which is more stratiform. There was a more stable period after the frontal passage.

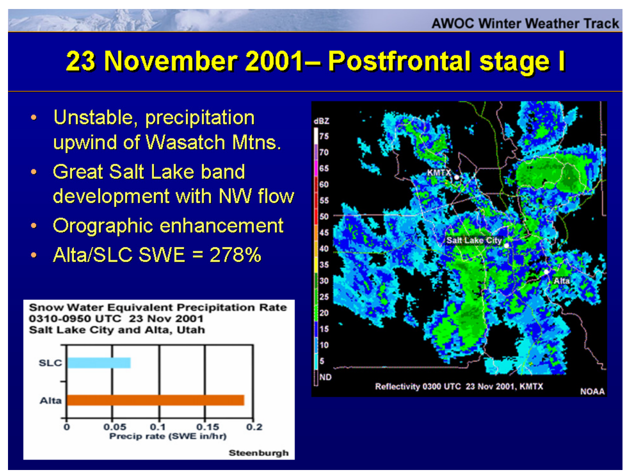
Student Notes:



47. 23 November 2001– Postfrontal Stage 1

Instructor Notes: The atmosphere became more unstable and more post-frontal instability showers developed. Higher reflectivities were seen in the NW flow downwind of the lake. An increase in orographic enhancement was also observed over the Wasatch Mountains.

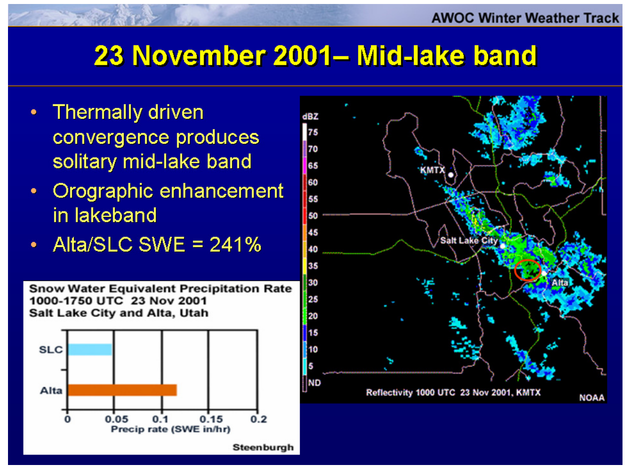
Student Notes:



48. 23 November 2001 – Mid-Lake Band

Instructor Notes: Here the thermally driven convergence produces a solitary midlake band. Orographic enhancement also occurred in the lake band. Typically, during the biggest events in the lowlands, you can get 20” of snow. 33% of the SWE was produced by the lake effect band and orographic enhancement.

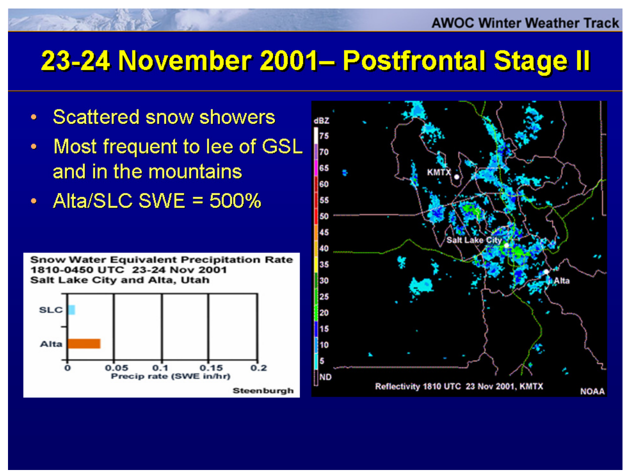
Student Notes:



49. 23-24 November 2001– Postfrontal Stage 2

Instructor Notes: Towards the end of the event, the precipitation is mainly over the mountains. Precipitation had become more showery in nature.

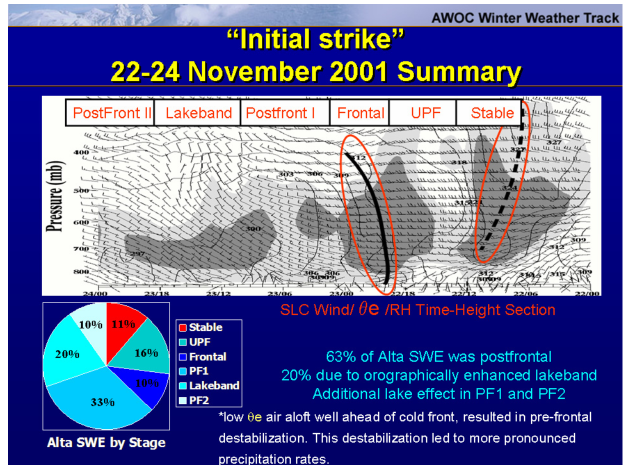
Student Notes:



50. "Initial Strike" 22-24 November 2001 Summary

Instructor Notes: Here is a time-height cross-section for the Alta area during this storm that was created from the RUC analyses. Here you can see the surge of low q_e air aloft well ahead of the surface cold front, resulting in pre-frontal destabilization. This destabilization led to more pronounced precipitation rates.

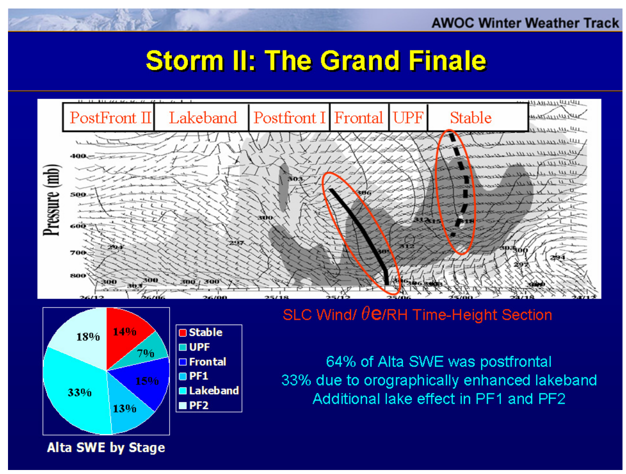
Student Notes:



51. Storm 2: The Grand Finale

Instructor Notes: The next storm, which produced 50" of snow, showed a very similar structure to the first storm.

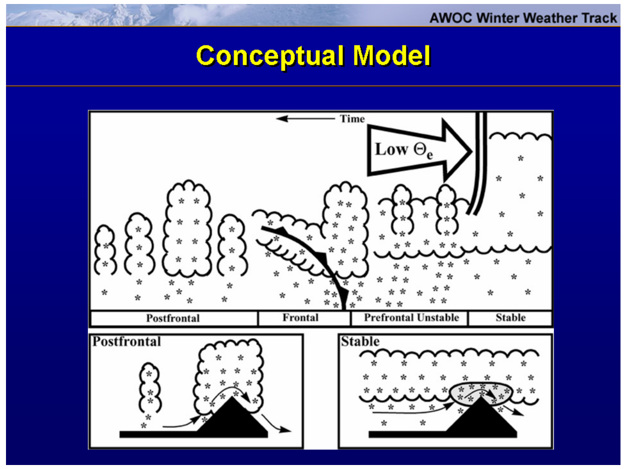
Student Notes:



52. Conceptual Model

Instructor Notes: Based on several cases, this conceptual model applies to some storms which may occur over the interior U.S. Usually, you will see a surge of low q_e air aloft ahead the cold front which leads to destabilization ahead of the front. Using wind profiler data, the troughs tend to be rearward sloping upstream of the Sierras. As they move downstream the upper-level forcing moves ahead of the surface trough position. This may be caused by the upstream topography, plus they are usually old occluded storms that made landfall over the Sierras, where the upper-level cold air may be progressing ahead of the surface cold front.

Student Notes:



53. Interactive Quiz #2

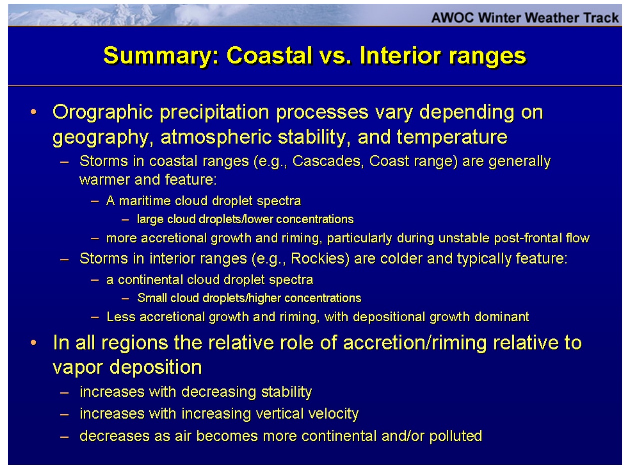
Instructor Notes: Take a moment to complete this quiz.

Student Notes:

54. Summary: Coastal vs. Interior Ranges

Instructor Notes: Orographic precipitation processes vary depending on geography, atmospheric stability, and temperature. Storms in coastal ranges (e.g., Cascades, Coast range) are generally warmer and feature: a maritime cloud droplet spectra, large cloud droplets/lower concentrations, and more accretional growth and riming, particularly during unstable post-frontal flow. Storms in interior ranges (e.g., Rockies) are colder and typically feature: a continental cloud droplet spectra, small cloud droplets/higher concentrations, and less accretional growth and riming, with depositional growth dominant. In all regions, the relative role of accretion/riming relative to vapor deposition increases with decreasing stability, increases with increasing vertical velocity, and decreases as air becomes more continental and/or polluted.

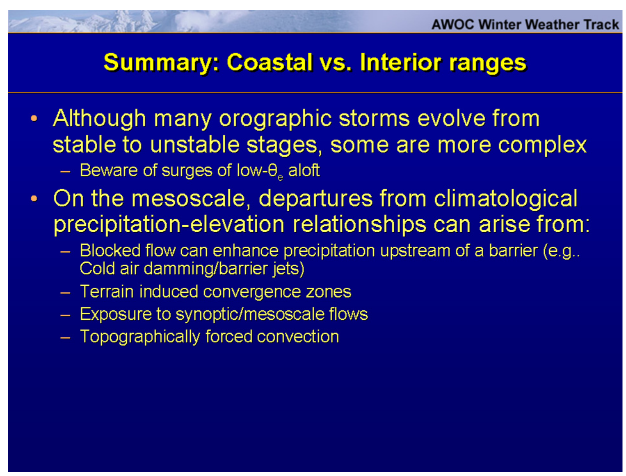
Student Notes:



55. Summary: Coastal vs. Interior Ranges

Instructor Notes: Although many orographic storms evolve from stable to unstable stages, some are more complex. Beware of surges of low-θ_e aloft! On the mesoscale, departures from climatological precipitation-elevation relationships can arise from: blocked flow enhancing precipitation upstream of a barrier (e.g., Cold air damming/barrier jets), terrain inducing convergence zones, exposure to synoptic/mesoscale flows, and topographically forced convection.

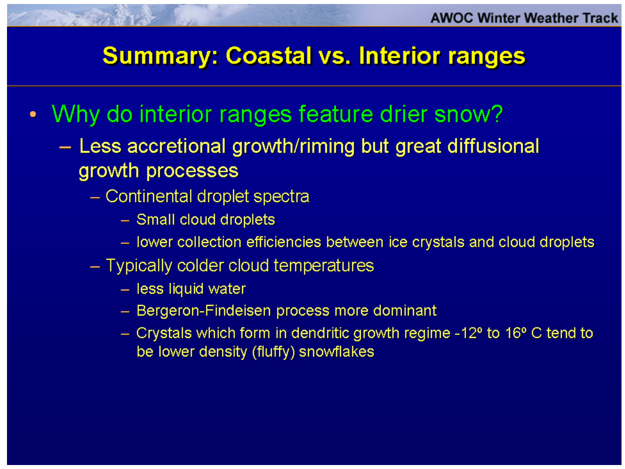
Student Notes:



56. Summary: Coastal vs. Interior ranges

Instructor Notes: Interior ranges usually have less accretional growth/riming, but great diffusional growth processes, continental droplet spectra, small cloud droplets, and lower collection efficiencies between ice crystals and cloud droplets. They also typically feature colder cloud temperatures with less liquid water. The Bergeron-Findeisen process is more dominant under these conditions and crystals that form in dendritic growth regime (-12º to 16º C) tend to be lower density (i.e., fluffy) snowflakes.

Student Notes:



57. Part 3: Forecasting Tools and Methods

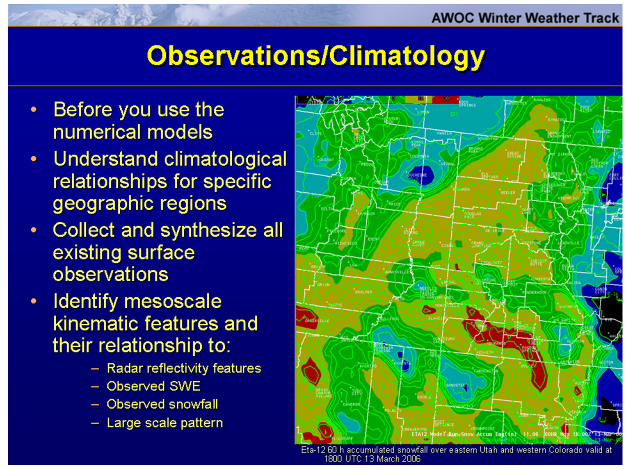
Instructor Notes: The next section of this lesson details forecasting tools and methods for orographic precipitation.

Student Notes:

58. Observations/Climatology

Instructor Notes: Before you use the numerical models, understand that the models produce results that are realistic based upon the specific parameters and physics coded into the model. The problem is that those results may not necessarily be skillful from a forecasting standpoint. It is critical to understand climatological relationships for specific geographic regions. Collect and synthesize all existing surface observations (including both precipitating and non-precipitating features) and radar data to understand physical processes and validate them.

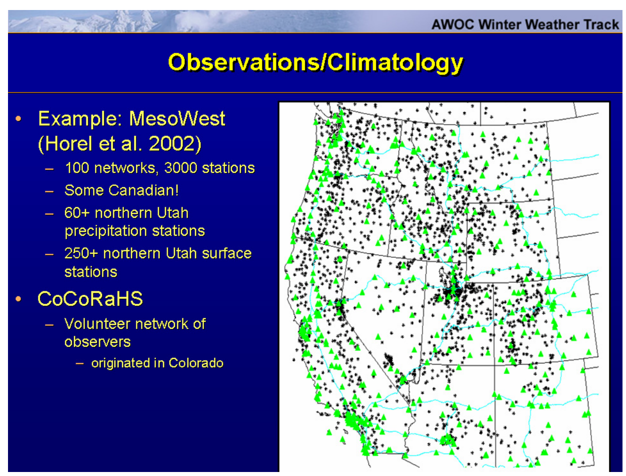
Student Notes:



59. Observations/Climatology

Instructor Notes: Here's an example of an observation system in the west. MesoWest (Horel et al. 2002) utilizes 100 networks with 3000 stations, including some Canadian observations. MesoWest also utilizes 60+ northern Utah precipitation stations and 250+ northern Utah surface stations. The CoCoRaHS Volunteer network of observers, which originated in Colorado, is another example of an important observation system.

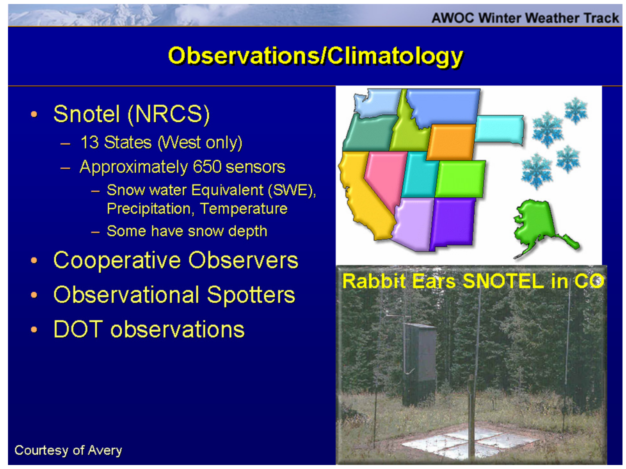
Student Notes:



60. Observations/Climatology

Instructor Notes: Another example of these observations systems is the Snotel network. There are approximately 650 Snotel, or snowpack telemetry, sites from the National Resources Conservation Service across 13 states in the western U.S. Each site generates SWE, precipitation, and temperature, with some reporting snow depth. Other sources of information are the NWS Cooperative Observers, observational spotters, and other data such as the DOT observations.

Student Notes:



61. Observations/Climatology

Instructor Notes: Great errors in the snow density measurements can occur during wind events. For instance, undercatch of the precipitation can occur during high winds. Judson and Doesken (2000) noted differences between actual precipitation and catch from an unshielded gauge may exceed 50% for wind speeds of 3 ms^{-1}. This undercatch results in an over assessment of snow-liquid water ratio. In addition to undercatch, settling of snow due to wind and metamorphism can also occur. Lastly, other errors caused by mixed precipitation events or potential melting between observations can also impact observation quality.

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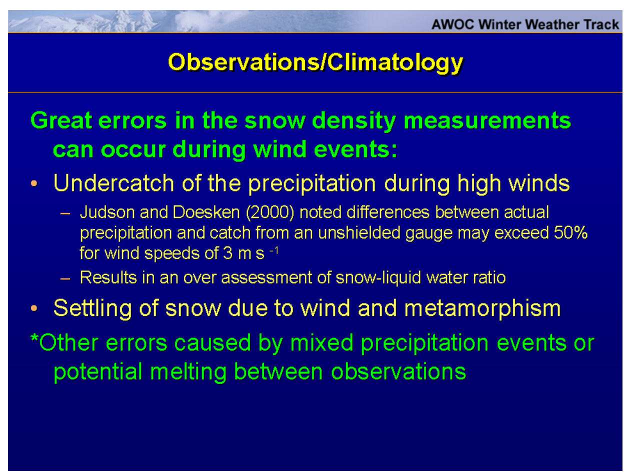
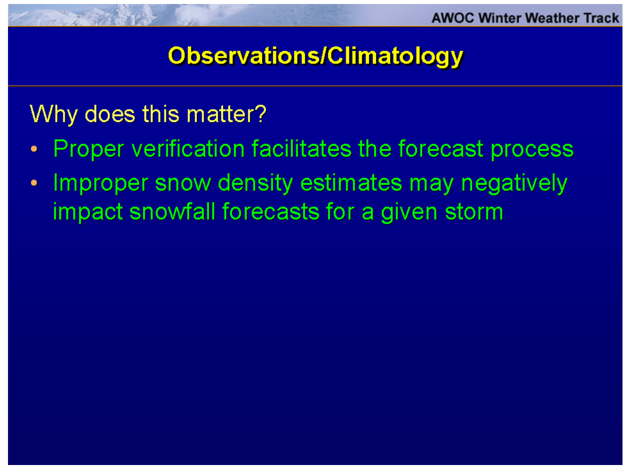


62. Observations/Climatology

Instructor Notes: Why does this matter? Proper verification of snow density facilitates the forecast process for current and future storms. Improper snow density estimates may also negatively impact snowfall forecasts for a given storm.

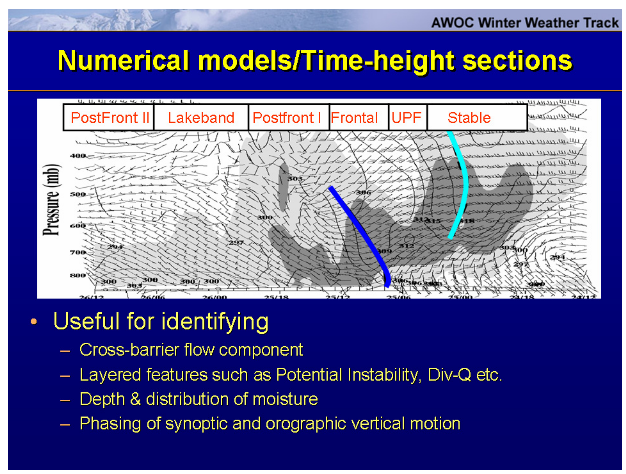
Student Notes:



63. Numerical Models/Time-Height Sections

Instructor Notes: Time-height sections are useful for identifying the cross-barrier flow component, layered features such as Potential Instability, Q-vector divergence, moisture depth and distribution, and phasing of synoptic and orographic vertical motion.

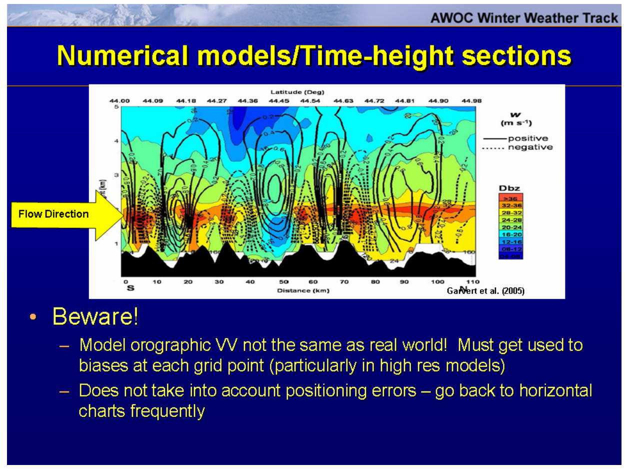
Student Notes:



64. Numerical models/Time-height sections

Instructor Notes: Beware of model produced vertical velocity over significant topography since it may be unrealistic. This diagram shows observed vertical velocities and reflectivity during the IMPROVE 2 field project. Vertical velocity and local precipitation enhancements are being generated by the mountain waves over the terrain. The model depiction for this structure may be quite different. It is important to understand the grid biases. If the topography is not represented well, the location of primary forcing may be altered spatially. Go back to horizontal charts frequently!

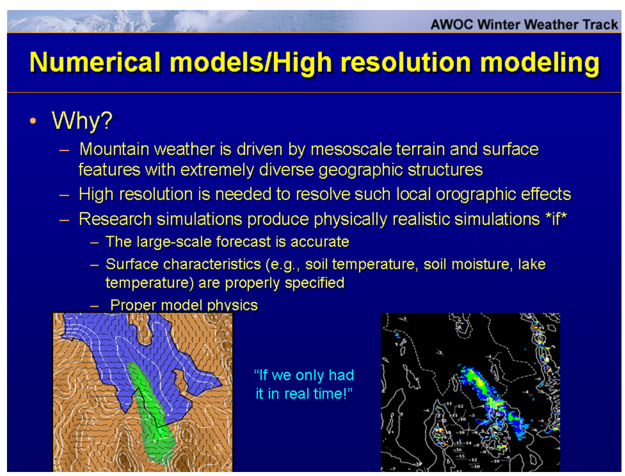
Student Notes:



65. Numerical Models/High Resolution Modeling

Instructor Notes: Mountain weather is driven by mesoscale terrain and surface features with extremely diverse geographic structures. High resolution is needed to resolve such local orographic effects. Research simulations produce physically realistic simulations if: the large-scale forecast is accurate. However, this accuracy is not a given. Surface characteristics (e.g., soil temperature, soil moisture, and lake temperature) need to be properly specified, which can be another big if. The validity of the forecasts are also tied to the sophistication of the model physics. Fixed surface forcing of topography should enhance predictability, but there are a few caveats.

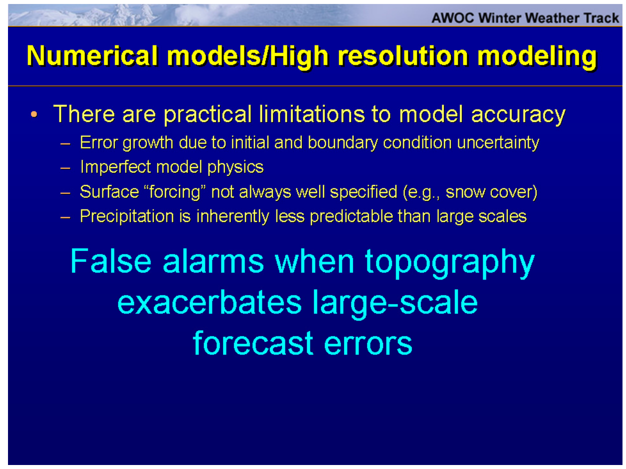
Student Notes:



66. Numerical Models/High Resolution Modeling

Instructor Notes: There are practical limitations to model accuracy, such as: error growth (large scale, mesoscale etc.) due to initial and boundary condition uncertainty, imperfect model physics, and surface "forcing" not always being well specified (e.g., snow cover). Precipitation is inherently less predictable than large scales.

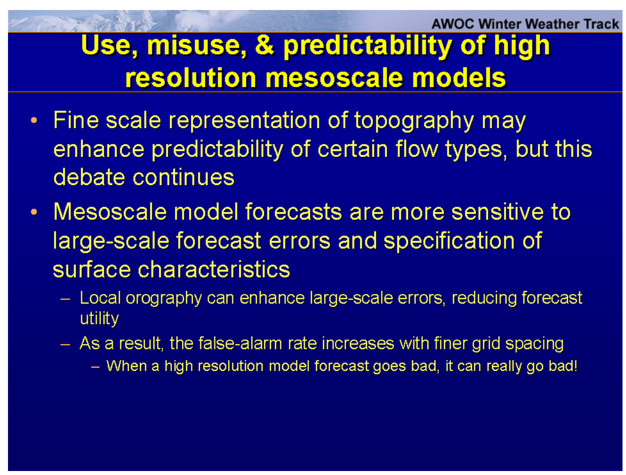
Student Notes:



67. Use, Misuse, & Predictability of High Resolution Mesoscale Models

Instructor Notes: Fine-scale representation of topography may enhance predictability of certain flow types, but this debate continues. Mesoscale model forecasts are more sensitive to large-scale forecast errors and specification of surface characteristics. Local orography can enhance large-scale errors, reducing forecast utility. As a result, the false-alarm rate increases with finer grid spacing; in other words, when a model forecast goes bad, it can really go bad!

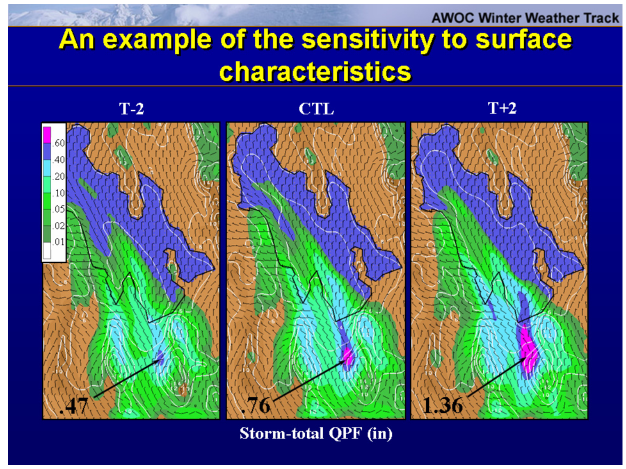
Student Notes:



68. An Example of the Sensitivity to Surface Characteristics

Instructor Notes: Here is an example of the model sensitivity to the Great Salt Lake water temperature, which can vary greatly. Just by changing the lake temperature 2 degrees cooler or warmer, the overall QPF model output changed dramatically. It is amazing how a surface condition can have such a profound effect on QPF.

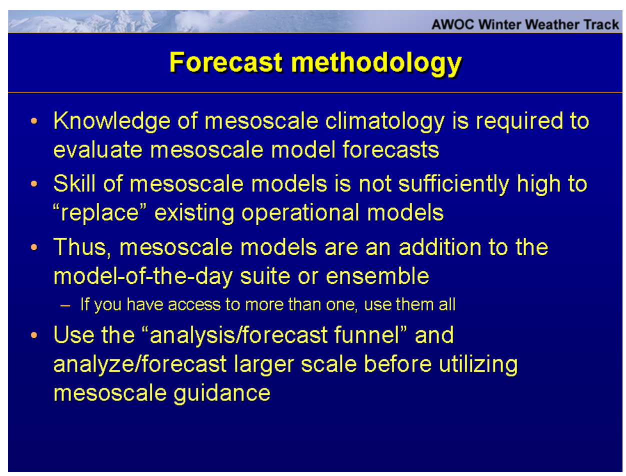
Student Notes:



69. Forecast Methodology

Instructor Notes: Knowledge of mesoscale climatology is required to evaluate mesoscale model forecasts. Skill of mesoscale models is not sufficiently high to "replace" existing operational models. Use them in addition to other operational models to qualitatively create an ensemble of the forecast. Thus, mesoscale models are an addition to the model-of-the-day suite or ensemble. If you have access to more than one, use them all. Use the "analysis/forecast funnel" and analyze/forecast larger scale before utilizing mesoscale guidance.

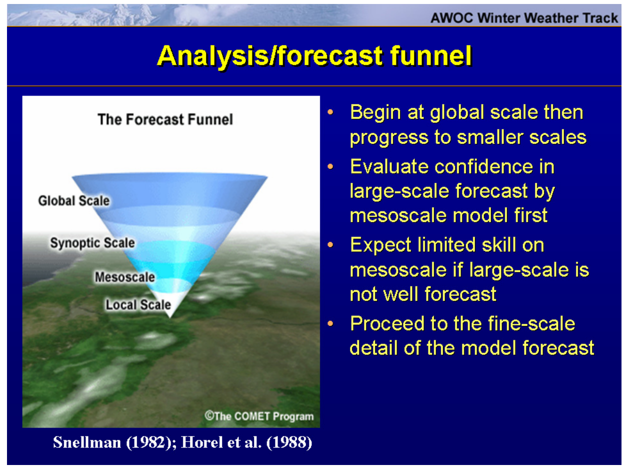
Student Notes:



70. Analysis/Forecast Funnel

Instructor Notes: Begin at global scale then progress to progressively smaller scales. Evaluate confidence in large-scale forecast by mesoscale model first. Expect limited skill on mesoscale if large-scale is not well forecast. Proceed to the fine-scale detail of the model forecast.

Student Notes:



71. Interactive Quiz #3

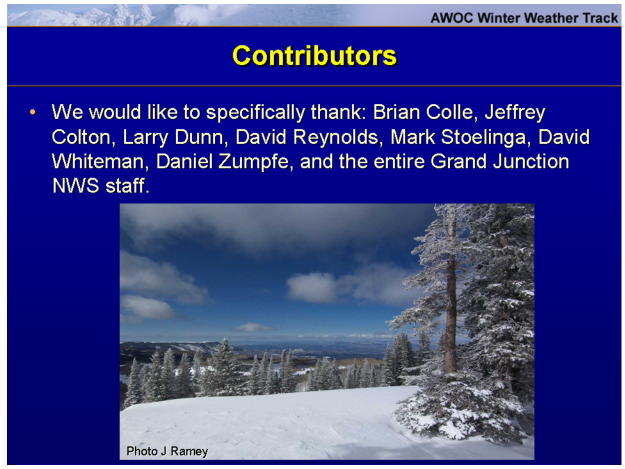
Instructor Notes: Take a few moments to complete this quiz.

Student Notes:

72. Contributors

Instructor Notes: This slide mentions all of the people who helped contribute to this lesson.

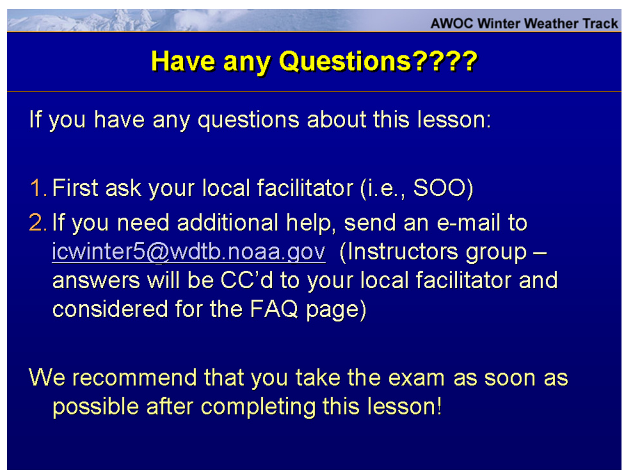
Student Notes:



73. 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. We strongly recommend that you take the exam as soon as possible after completing this lesson.

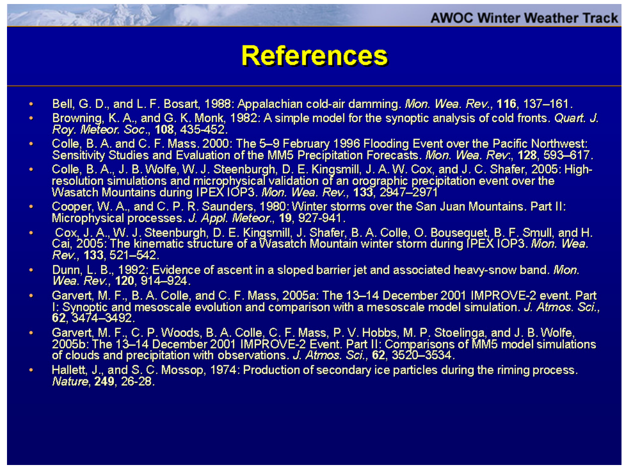
Student Notes:



74. References

Instructor Notes: This slide is the first of six slides that contain a list of all the references in this presentation.

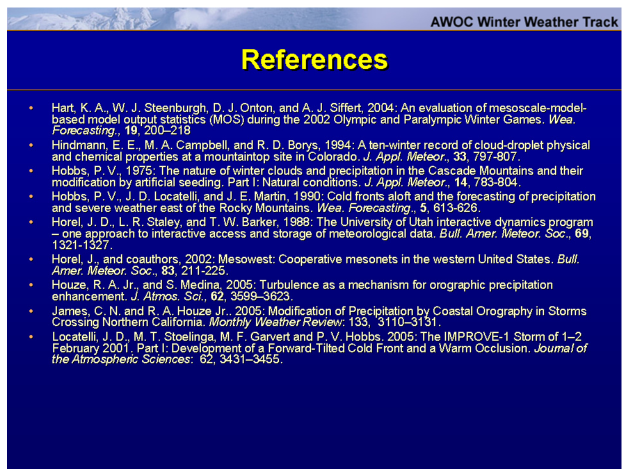
Student Notes:



75. References

Instructor Notes: This slide is the second of six slides that contain a list of all the references in this presentation.

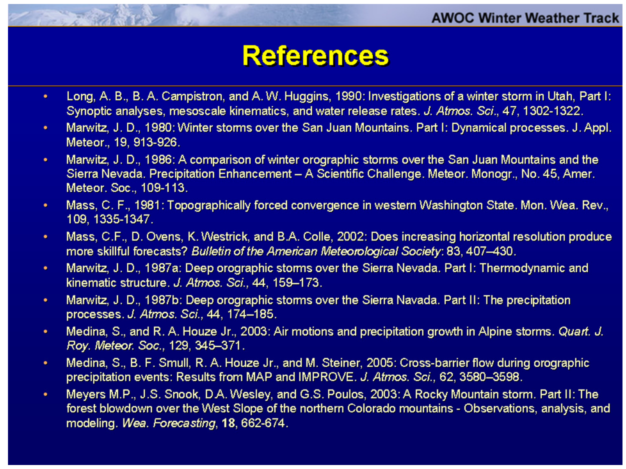
Student Notes:



76. References

Instructor Notes: This slide is the third of six slides that contain a list of all the references in this presentation.

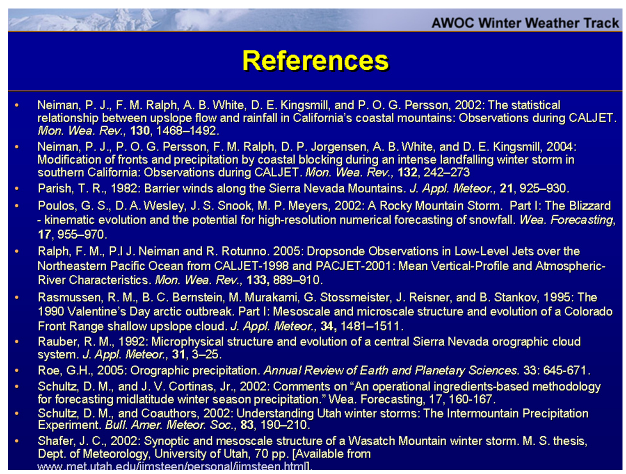
Student Notes:



77. References

Instructor Notes: This slide is the fourth of six slides that contain a list of all the references in this presentation.

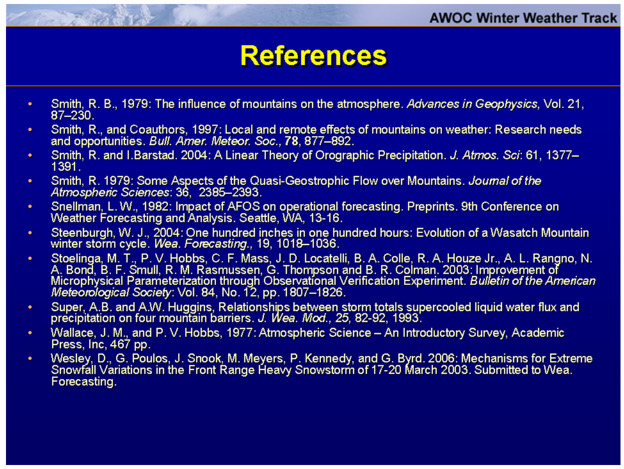
Student Notes:



78. References

Instructor Notes: This slide is the fifth of six slides that contain a list of all the references in this presentation.

Student Notes:



79. References

Instructor Notes: This slide is the sixth of six slides that contain a list of all the references in this presentation.

Student Notes: