

## Talking points for “Satellite Interpretation of Orographic clouds / effects”

1. Title page
2. Objectives
3. Topics
4. Gap wind event over New Mexico. Strong winds affect Albuquerque and introduce moist airmass which may impact convective forecast the next day.
5. Topography of New Mexico. In easterly flow, winds may be funneled through Tijeras gap east of Albuquerque and produce locally strong winds in the city.
6. Surface observations (METARs) from 00:00 – 12:00 UTC (3 hour increments) 12 June 1999. At 00:00 UTC we observe a warm and dry air mass and southwest flow over most of central New Mexico (including Albuquerque). As time goes on, the easterly flow advects westward. Eventually, the easterly flow makes it to Albuquerque where the dewpoint goes from the 20's to the low 50's. The gap wind effects are very localized, at the Albuquerque airport winds gusted up to 30 mph, while on the west side of town at Double Eagle airport winds were southeast at 10 mph.
7. Fog Product 02:46 – 10:30 UTC 12 June 1999. This loop shows the origin of the easterly flow which helped produce the gap winds in Albuquerque. Deep convection on the plains of eastern New Mexico produced strong outflow that moved westward. Since this loop is at night, we can utilize the fog product to identify the outflow boundaries readily. The fog product is good at distinguishing low-level outflow boundaries at night. The outflow pushes westward towards Albuquerque, as it reaches the Tijeras gap the gap wind event begins. The fog product can be used in this way (at night) to determine when the conditions favorable for gap winds will begin.
8. Albuquerque soundings taken at 00:00 and 12:00 UTC 12 June 1999 (2 frames). Shows the transition from a warm/dry airmass in southwesterly flow to a moist airmass in easterly flow. Sometimes the easterly flow is of insufficient depth to break through the Tijeras gap and get into Albuquerque. In this case, we can see the easterly winds are sufficiently deep (up to about 750 mb). The elevation at the entrance to the Tijeras canyon is 7600 feet so the depth of the easterly airmass is a factor. Gap winds can introduce a moist airmass into regions that are typically dry, having significant consequences on the convective potential for later in the day. Typically, a convergence zone will setup to the west (near the Continental Divide for this case) that can be the initiation point for later convection.
9. Orographic convective initiation mechanisms (from Banta 1990). **When analyzing the effects of orography on convection over the mountains, keep in mind that the large scale dictates if thunderstorms will form or not, and the small scale dictates where and when convection will occur.** Mountain flows play a role in convective initiation, but should be kept in mind together with other physical and dynamic processes. The important mountain flows that play a role in convective initiation are:
  - a. Orographic lifting – forced ascent due to upslope flow. Air can be lifted to the LFC when the LFC is near or below ridgetop.

b. Thermal forcing – elevated heating produces lower pressure over the mountain, leading to flow towards the mountain and thus convergence and updrafts near the peaks.

c. Obstacle effects – convergence due to flow interacting with the terrain.

The flow at ridge top level determines which mechanism plays a larger role

10. Light flow at ridgetop level - Thermal forcing dominates. Thermal forcing is more (less) pronounced when the soil moisture is low (high) and there is less (more) vegetation cover. Solar angle is also key, meaning that convection begins on the east facing slopes, and later in the day develops on the west facing slopes.
11. 500 mb HT (green) overlaid with 700 mb winds (salmon), 00hr forecast valid 18:00 UTC 23 June 2005. The region of interest here is New Mexico, which is under the influence of a strong ridge. The near ridge top level flow (700 mb winds) is light, especially across southwest New Mexico. (Remember to show New Mexico Topographic map that was shown earlier before proceeding to the next slide).
12. GOES visible imagery from 16:15 – 23:16 UTC 23 June 2005. Thermal forcing dominates where the convection initiates. Convection begins on the east facing slopes, and later on the west facing slopes (due to the change in solar angle). The one advantage to this setup is that the level of predictability of the convection is relatively high due to the terrain induced local circulations that routinely provide updrafts. The level of predictability depends on ridgetop winds, cloudiness, and soil moisture.
13. Strong flow at ridgetop level - As the ridge top flow gets stronger, the effects of solar angle become less important on cumulus initiation and cumulus clouds tend to form downwind of the peak unless the LCL is below mountain top (in which case clouds will tend to form upwind of the peak). **Strong ridge top winds interfere with the thermally forced wind systems that lead to convective initiation. Thermally forced upslope flow becomes shorter and more disorganized.** Thermal forcing effects are limited while obstacle and dynamically driven (i.e. gravity waves, convergent flow) effects tend to dominate.
14. SPC Mesoscale Discussion issued 12 August 2005. Note that much of Wyoming is highlighted for severe potential with MUCAPE values in the 1000-1500 J/kg range and a cold front coming in from the north.
15. The 12:00 UTC 12 August 2005 sounding from Riverton, WY looks favorable for severe weather. The ridge top level winds are in the moderate to strong category depending on what mountain range is being considered.
16. Wyoming topographic map. Note the various ranges, the Bighorn mountain range in north central WY, the Wind River range in west-central WY and the Absaroka range to the north of them. Also note the lower elevation areas (basins) in between the ranges.
17. GOES-11 Visible loop from 17:30 UTC 12 August – 01:00 UTC 13 August, 2005. Jet cirrus in strong southwest flow aloft moves over WY early in the loop. Unstable low-level cloud streets across northeast WY, extending southeast into Nebraska. Most unstable region based on METARs appears to be correlated to this region of low-level cloud streets. **Strong flow at ridge top level over the mountains ventilate the surface as it tries to heat up, this mixes away heat from the surface. This prevents the buildup of a strong slope-atmosphere temperature difference that would drive thermal circulations.** Stronger flow at ridgetop level, discourages

but does NOT prevent convective initiation over mountains. Under the right conditions (i.e., high low-level moisture and thus buoyancy) cumulus clouds may grow deep. This case has significant low-level moisture and CAPE in place over the region outlined earlier. Early storms initiate off the higher mountain ranges, note the lack of thunderstorm development over the lower basin areas throughout the day (i.e., the region between the Bighorns and the Absaroka ranges). Notice over much of the higher ranges, we see cumulus but only a few areas see thunderstorms develop and persist. **Where the thunderstorms do initiate, obstacle effects such as blocking, flow deflection and gravity-wave effects play a role.** Looping fast and rocking shows how significant the role of terrain is in thunderstorm development. The storms that moved into the most unstable region were severe with reports of tornadoes and hail up to 1.75" in diameter.

18. Lee wave clouds
19. Visible loop from 15:30 – 18:30 UTC 5 November 2006. Lee-wave clouds downwind of the Teton and Absaroka ranges in northwest Wyoming.
20. Visible loop from 22 June 2003. In this situation, we have what appear to be lee-wave clouds, however we see that this is over eastern Nebraska where the terrain is flat. These are stable wave clouds, not lee-wave clouds, they appear very similar in the satellite imagery but form under different mechanisms. The terrain is key for the development of lee-wave clouds.
21. Visible loop from 17:45 – 23:00 UTC 21 October 2006. A cold front has gone through the Texas panhandle and eastern New Mexico. Behind the front we can observe lee-wave clouds downwind of the Sangre De Cristo Range and the Pederal hills (to the south). The southern portion of wave clouds are a combination of lee-wave and stable wave clouds (note the cold front position in the METARs). Sometimes both types of wave clouds may exist simultaneously in the same general region. The relatively long wavelength wave clouds in eastern New Mexico would be a region to be concerned about turbulence for aviators.
22. Toggle between water vapor and visible image. Waves that present turbulence problems for aviators may not be associated with any clouds. Toggle between the visible and water vapor imagery and note the waves that appear easily in the water vapor image do not show up in the visible image due to clear skies. Use of water vapor imagery under clear skies to detect waves is necessary when assessing turbulence potential.
23. Orographic cirrus – easy to spot in the satellite imagery since they are 1) stationary and 2) form along a mountain range and advect only in the downwind direction of the range. The terrain is key to the development of the downwind cirrus in that wave produced by the mountain range is transmitted to upper levels as shown in the diagram. Orographic cirrus can have a major impact on temperature forecasts. Note, clouds at location B may or may not be present.
24. Topographic map for the region of interest. Note the Cascades in Washington, the mountain ranges in western MT and western WY.
25. GOES-11 Visible loop from 15:30 – 23:30 UTC 5 November 2006. Orographic cirrus exists throughout the loop across central Washington. Orographic cirrus develops rapidly later in the loop across western Montana and Wyoming. The cirrus

is often thick enough to block out insolation, potentially resulting in much colder temperatures than a model forecast.

26. A tool for forecasting orographic cirrus is synthetic imagery from model output. Synthetic imagery is model output that is processed through a separate model to produce what satellite imagery would display for a particular band. The limitations are the usual model limitations that you're familiar with (i.e., insufficient horizontal resolution, microphysics packages that attempt to parameterize complicated processes etc.) The advantage to synthetic imagery is that it is an efficient visual comparison with GOES imagery, therefore simulated orographic cirrus will appear very similar to that observed in GOES imagery – as regions of colder brightness temperatures that develop along and downwind of mountain ranges. There is an entire VISIT training session devoted to this topic, see the student guide listed under the training sessions link on the VISIT web-pages for more information.
27. Example of synthetic IR imagery from the 4-km NSSL WRF-ARW on the left, and 4-km NAM-Nest on the right. Both models forecast orographic cirrus downwind of the Front Range of Colorado, however there are some differences between the two models. The areal extent of the colder cloud tops in the NSSL WRF is less than that in the NAM-Nest, this is due to differences in microphysics packages that you can learn more about in the VISIT training session mentioned on the previous slide. There are also differences in the model forecast, note the NSSL WRF dissipates the orographic cirrus along the Front Range during the late morning hours, while the NAM-Nest retains the cloud cover for most of the day. Which model came closer to reality? We'll check the corresponding GOES imagery on the next slide.
28. The GOES IR imagery for the same time period we just looked at from the synthetic imagery shows that orographic cirrus did develop along the Front Range of Colorado and persisted through the morning hours, helping to prevent insolation and thus keep temperatures cooler. By the afternoon hours, most of the orographic cirrus has dissipated in a similar way that was forecast by the NSSL WRF. In practice, the various model outputs can be compared with the GOES imagery throughout the day to assess confidence in particular model solutions. The main idea to take away is how easy it is to spot orographic cirrus in the synthetic imagery and readily compare it to GOES imagery.
29. Inferring turbulence from satellite imagery – here, we are considering thin cirrus moving nearly perpendicular to a mountain range. Downwind of the range, we either see thick cirrus immediately along the range or a clear zone along the range followed by thicker cirrus further downwind.
30. GOES-11 visible loop from 16:00 – 22:30 UTC 27 October 2006. The area of interest is the Cascade range in Washington. We observe a region of thin cirrus moving eastward near Seattle over the Cascades, then we see a Foehn gap east of the range followed by thick cirrus that develop further downstream. The Foehn gap is a good indicator of turbulence. We also observe orographic cirrus and lee-wave clouds in Montana.
31. The wall cloud has a number of different terms, also known as the barrage or stau cloud. It is characterized by thick low to mid-level clouds on the windward side of the mountains and a cloud free region on the downwind side of the mountains. Precipitation may be prolonged on the windward side of the mountains since it is tied

to the terrain. In sub-freezing conditions, icing can be a problem for aviation due to large amounts of supercooled water within the cloud.

32. GOES-11 Visible loop from 15:00 – 23:00 UTC 14 November 2006. The area of interest is the Front Range of Colorado. West-northwest flow is prevalent over the region, which on the upwind side of the Front Range causes thick low to mid-level clouds and precipitation, this is the wall cloud. On the downwind side of the Front Range we see a clear region associated with downslope subsidence. The clear region is not a “Foehn gap” because these clouds are thick low to mid-level clouds, not thin cirrus on the upstream and thicker cirrus on the downstream side.

### **Orographics Effects Session (continued)...**

**Slide 35** – Intro to destructive winds plus other significant terrain forcing.

**Slide 36** – 10.7 um IR image of April 8-10, 1999 windstorm(s). Point out or have them find signature for strong downslope winds. Also point out or have them find cold front Apr. 8 and mini “dry line” April 9, plus other upper level features.

April 8 – 10 1999 Front Range Windstorm: (Synopsis)

#### **APRIL WINDS UPGRADED TO MOST COSTLY COLORADO WINDSTORM**

The Rocky Mountain Insurance Information Association (RMIIA) estimated that strong winds caused about \$7.2 million in insured damage along Colorado's Front Range on April 8. But the winds kept blowing for two more days, raising the total estimated insured damage to \$20 million for April 8, 9 and 10.

#### **Strongest winds occurred each day between:**

**April 8 – between 13Z and 19Z.**

**April 9 – between 21Z and 03Z on the 10th**

**April 10 – between 12Z and 19Z**

"We now have a tie for the most costly windstorm to hit Colorado," reports RMIIA Executive Director, Carole Walker. "Both the April 1999 windstorm along the Front Range and the January 1982 windstorm in Boulder County each caused an estimated \$20 million in insured damage to homes, personal property and autos." The \$20 million estimate breaks down into \$16.6 million in damage to homes and personal property and \$3.4 million in damage to autos. Insurers expect to handle more than 10,500 claims.

**Slide 37** – METARs Winds for April 8 00Z through April 10 00Z.

**Slide 38** – Sounding for Grand Junction (upstream) for April 8 at 12Z. Show signatures/what to look for in sounding.

**Slide 39** – Colorado Terrain. Point out significant features.

**Slides 40 through 44** – Talk about Forecasting Downslope windstorms (39, 40, 41) – and then move to schematic diagrams – 42, 43.

**Slide 45** – 10.7 um image of October 25, 1997 event over northwest CO. Highlight area between A-basin and Steamboat (Zirkel Mountains). Show strong gradient region of cloud top temperatures during the event. Show wave clouds embedded in strongest flow and at the time of greatest measured velocities. Show bright “explosive” areas where clouds dissipate very quickly due to extreme downward motion and drying over areas in question. Explain (may go back to Colorado Terrain map – 35 ) mountain orientation with the wind and why these two areas were hit hard. Also explain that LL (sfc) inversions in most of the valleys kept svr winds up on higher slopes. Explain significance of old growth forest just happening to be in the right place at the right time...and the fact that there were hunters who were affected by this event ...otherwise may have been undiscovered till much later in the year (or next year). Located in a very remote region of CO. As time allows, talk about greater synoptic set-up and the other weather going on due to this system and the forcing of the terrain (front range heavy snows).

**Slide 46** – METAR winds of the region. Very coarse observations...do not catch the “wind event” at all. Very significant snows in the front range corridor highlight the weather on that day...not the destructive winds.

**Slide 47** – Denver Sounding (“upstream” with respect to the winds) from October 25, 1997 at 12Z. Again, explain signatures in the sounding.

More details of the event follow if needed.

## **THE 25 OCTOBER 1997 ROUTT NATIONAL FOREST BLOWDOWN**

The Routt National Forest blowdown of 25 October 1997 is one of the only recorded mountain wave events occurring west of the Continental Divide in the Colorado Rockies. This event produced wind gusts in excess of  $50 \text{ ms}^{-1}$ , which downed up to 20,000 acres (est) of old growth forest in the Park Range. The toppled trees covered a swath several miles wide and 20 miles long.

Analyses of 25 October 1997 at 0000 indicated a deep, cut-off low in northeast New Mexico which produced lower and middle tropospheric easterly flow of  $15\text{-}20 \text{ ms}^{-1}$  across northern Colorado. Contours of the forecast height fields at 850 hPa and 700 hPa showed the tightest gradient to be across northern Colorado. Wind profiler data from Platteville, Colorado (PTL) confirmed this synoptic scale flow. The PTL profiler also

showed the presence of a mean-state critical level around 2 km AGL. Sfc obs during this event indicated a cross-barrier SLP difference of only 6.3 hPa between CYS and CAG. There was also a very cold lower tropospheric air enhanced mountain wave formation during the 1997 blowdown. Mountain top temperatures of -20°C were recorded in the 1997 event. The extremely cold lower tropospheric air present may have been a significant factor in the magnitude of that event. Post analysis (model) showed a cross-section of wind and taken approximately perpendicular to the Park Range blowing at  $40\text{ms}^{-1}$  at times descending the west side of the barrier along with tight isentrope packing just above ridge top. The mountain wave structure was evident in the isentrope pattern. Post model analysis also showed a wave induced critical level was observed in the middle troposphere, characterized by a wind minimum

The destruction of thousands of acres of old growth forest during the blowdown event discussed here is but one of several catastrophic results of the October 1997 Rocky Mountain Winter Storm. Deep snowdrifts and zero visibility left transportation and commerce paralyzed, including the closure of the Denver International Airport. Subfreezing temperatures combined with the huge snowdrifts caused thousands of livestock deaths.

This storm was significant in many ways...the cold...the snow...and the wind. The storm's two most powerful attributes were the blizzard conditions and heavy snowfall along the Front Range of the Rockies, with extreme winds exceeding 100 mph at some locations west of the mountains.

Observations showed total snowfall amounts exceeding 100 cm (39 inches) in many Colorado mountain locations east of the Continental Divide. Snow accumulation variability of as much as 25 inches was recorded within small spatial areas (a 5-mile region, for instance), especially between the mountains and the plains.

On the west side of the Divide, snowfall amounts were light, but high winds caused numerous serious weather related problems. Meteorological records confirmed that wind gusts at 3800 m (12,500 ft) exceeded  $45\text{ m s}^{-1}$  (100 mph) for 5 hours at the Arapahoe Basin ski area just west of the Continental Divide, and a peak gust of  $51\text{ m s}^{-1}$  (114 mph) from the east. Very cold mountain top temperatures around -20°C created extreme wind chill temperatures as low as -50°C (-60°F). Wind gusts were “possibly” higher in the Park Range of Routt National Forest...specifically the Zirkel Wilderness areas, northeast of Steamboat Springs, where a region of severe wind destroyed up to 20,000 acres of old growth forest. According to the U.S. National Forest Service, this was the largest known forest blowdown ever recorded in the Rocky Mountain region. The fallen trees were stacked 30 ft high in some locations, requiring nearly two days for emergency operations to rescue some trapped hunters from the wilderness. There were also the associated environmental and economic concerns regarding fire hazard, beetle infestation, spruce/fir ecosystem, timber salvage, and restoration of recreational areas.

The barrier height in the vicinity of the Mount Zirkel range is relatively low by Rocky Mountain standards, with an average height of about 1000 m, which is roughly half that

of the Colorado Front Range. The lower barrier height also allows forest growth which is nonexistent over the higher terrain of the Front Range. The fact that old growth forest exists in the areas northeast of Steamboat Springs is testimony to the rare nature of this event.

The indication of very strong downslope winds over a relatively low barrier suggests the importance of the observations that indicated the rather “unusual” concurrence of two primary features: One, a strong synoptically driven “deep” easterly flow, and two, very cold low-tropospheric air contributing to a stability profile that favors the enhancement of mountain wave development by nonlinear effects (in other words, waves). This cyclonic systems was deep and usually in these cases are not (generally speaking) accompanied with such an extremely cold boundary layer this time of year. Very cold boundary layers are more typically observed with shallow anticyclonic events that normally generate weaker easterly flow over the mountain barrier.

**Bottom line:** The likely explanation for this rare event is that the combination of a deep, very cold boundary layer and a strong cyclonic easterly flow over a relatively low mountain barrier created the perfect conditions to generate a severe downslope wind storm that destroyed many acres of old growth forest.

**\*\*slope windstorm**—(Also called downslope windstorm.) Occurs when strong synoptic-scale winds blow over a mountain ridge top, where the winds are trapped below a strong temperature inversion located at an altitude just above the ridge top. The resulting fall winds on the lee side of the ridge are trapped close to the surface and can destroy buildings and blow down trees.

**Slide 48** – Washington/Oregon Terrain map.

**Slide 49** - May 14, 2003 Visible image (loop) with 250mb isotachs. Show/ask about some of the cloud features talked about in similar cases (Dan’s)...also show first hints during the day of the PSCZ.

**Slide 50** – Terrain Driven Convergence Types slide pointing out different kinds of CZs...leading to the following cases.

**Slide 51** - Visible loop for May 16, 2003 showing third day of PSCZ...with sfc obs toggled..

**Slide 52** – Schematic/Map of PSCZ.

**Slide 53** – Streamline analysis May 16, 2003 00Z showing PSCZ.

Additional Information for the PSCZ follows if needed (to “detail” the event):

**Puget Sound Convergence Zone**



Surface-level convergence in rugged terrain can produce updraft regions, which may generate clouds, convective showers or enhance ongoing precipitation fields. This first example is called the **Puget Sound Convergence Zone**. Along the coast, west of Seattle, westerly winds off the Pacific Ocean have a relatively difficult time crossing the Olympic Mountains. One of the easiest paths for the air to follow inland is through the Strait of Juan de Fuca, into the Georgian Basin and then south through the channels of Puget Sound. Air flow further south, however, will often traverse the lower coastal range, and move through the Chehalis Gap (see map) to the fjords, finally pushing north into Puget Sound.

Look for regions of surface convergence because they favor the formation of convective precipitation (enhanced) and possibly severe storms. They are “boundaries after all! Also, convergence of winds (the zone) lying coincident with a frontal boundary can even initiate the development of a extratropical cyclone...especially if an upper-level divergence zone is also present.

Synopsis of May 14 through 16: A weak Pacific cold front made landfall on the Washington coast during the morning hours of 14 May 2003 and moved through the interior lowlands and across the Cascades by the early afternoon. A cold upper-level trough was off the Pacific Northwest coast moving slowly east. A weak PSCZ formed over the north Puget Sound several hours after frontal passage, as surface high pressure built into western Washington from the southwest and the low-level flow veered to westerly.

The activity of the PSCZ reached its climax during the afternoon and evening hours of 16 May, as mesoscale diurnal forcing combined with the synoptic-scale dynamics. The 500-mb temperature had fallen to around -33C over western Washington as the trough was approaching the coast...with a freezing level (indicated in the soundings) of around 3500 ft msl. Model forecast lifted indexes were around -2 C over the Seattle area, with CAPE values falling between 300 and 500 Jkg<sup>-1</sup>. Pretty good for this area in May. WV imagery showed a shortwave moving through the east side of the trough while a 140 knot jet moving onto the Oregon coast placed western Washington in the vicinity of its left exit region (upward vertical motion).

The PSCZ that formed aided in focusing convection along a band that extended east-southeast from the east entrance of the Strait of Juan de Fuca and into the Cascades. Radar data showed maximum echoes at times around 60 dBZ and lightning being detected...showing thunderstorms. Spotter reports confirmed that some of the storms had up to quarter-inch hail, and one spotter reported that hail had accumulated on the ground to a depth of half-inch. Not big by central plains standards, but significant for the nwrn CONUS. 00Z Soundings by May 17 showing snow levels falling to 2500 ft...and there scattered areas of very heavy convective (thunder) snow.

As the upper-level trof axis finally moved through the region later on the 17<sup>th</sup>, the PSCZ ended. However, the generally slow progression of the upper trough (which took about 3

days to move through western Washington after the initial surface front started), caused an “unusually long-lived PSCZ.”

Interestingly, even with the overall strong synoptic conditions, there was a clear diurnal cycle and the PSCZ followed this pattern, with the convergence zone gaining strength during the day, peaking in the late afternoon, and then weakening in the evening. This was obviously due in part to instability driven by insolation, but the diurnal sea breeze circulation also played a significant role.

**Slide 54** – Visible image loop for October 4, 2004 in Colorado. Explain what is going on. What kind of CZ (how) formed. (LL SERLY flow...drainage winds off of front range mountain...sometimes reinforced by upr lvl wrly flow (downslope). Can also lead at times to formation of mesoscale cyclogenesis (Denver cyclone)...but, they ARE NOT the same thing. Tell consequences (below). Bring up accelerated flow around Palmer Ridge...turning of the flow into the mountains, etc.

#### **Colorado – October 4, 2004 – the DVCZ**

There were 11 tornadoes reported (all F0 to F1) and four reports of hail between 0.75 and 1.00 inch. The DVCZ stretched roughly from around DIA in Adams County into south central Weld County. (Show streamlines).

**Slide 55** – Streamline analysis for Colorado October 4, 2004 (22Z).

**Slide 56** – Visible image loop for July 31, 2006 in Arizona. Explain what is going on. What kind of CZ (how) formed. (SERLY drainage flow into the low lands E/NE of Mogollan Rim (go to **map slide 64**). Explain consequences (below). With drainage winds down the LCV and WRLY to SWRLY synoptic winds (follow the LL Cu).

#### **Arizona – July 31, 2006 – the MRCZ**

There was a funnel cloud, hail (1.00 inch) and flash flooding conditions all reported near Snowflake/Taylor AZ within an hour of each other late that afternoon. (Show streamlines)

**Slide 57** – 15Z Streamline analysis of region for Arizona July 31, 2006.

**Slide 58** – Intro map/diagram to the ID SRPCZ.

**Slide 59** - Visible image loop November 26, 2005. Show areas talked about in slide 57. . Explain what is going on. What kind of CZ (how) formed. (Synoptic Northwest flow through the mountains (behind cold front) with (also) WRLY synoptically driven winds “up” the Snake River valley...colliding in SERN ID over the SRP. Drainage winds off the NRN mountains can also produce an effect similar to this one. Explain consequences (below).

## **Southeast Idaho**

A cold front passed through the Snake River Plain (SRP) early on the morning of 26 November 2005 bringing a sharp drop in temperatures. Surface winds picked up significantly behind the cold front, with southwesterly gusts up to 40 mph (up river). Common in this region with the passage of a strong cold front over eastern Idaho, northwest winds flowing out of the mountain valleys north of the SRP began to converge with the southwesterly winds in the upper SRP. Snow first appeared over the central Idaho mountains N of Idaho Falls. Then, as the convergence zone began to push slowly to the south, snow spread into the SRP, eventually reaching Pocatello area. The relatively slow movement to the south by the CZ in this case helped enhance snow fall (over model predictions) – with some snowfall totals exceeding 12 inches in the southern portion of Pocatello (four inches on the north end)...well above the 2 to 4 the models were predicting.

In addition to the synoptic and mesoscale conditions leading to the convergence zone, there were also indications that there was even more enhanced flow and thus convergence by the channeling of the northwest winds flowing out of these valleys...creating convergence “hotspots” along the slow(er) moving SPCZ.

Model generally underestimated this event, with the NAM/ETA12 provide the best hints with the 26/0600Z run indicating relatively strong low level forcing associated with low level wind convergence (represented to a point in the 700mb omega fields). However, associated much higher increases in precipitation amounts did not accompany this (model forecast) forcing.

**Slide 60** - ID 20Z Streamline analysis from November 26, 2005.

**Slide 61** - Visible image loop from April 28, 2003. Show areas talked about in slide 57. . Explain what is going on. What kind of CZ (how) formed. (S/SWRLY warm dry flow, channeled at times through ERN ID mountains...converging with cool moist NRLY flow out of mountains on the north side of the SRP - behind exiting shortwave and precipitation). Explain consequences (Tornado(es)/hail...boundary...channeled flow enhancement of inflow at storm scale, etc.).

**Slide 62** - ID Streamline analysis for 20Z April 28, 2003.

**Slide 63** – Mesonet data from 21Z, April 28, 2003...showing sfc flow and convergence region.

**Slide 64** – Quiz Intro Section is time allows.

## **Questions:**

**Slide 65** – Topographic map for the region of interest

**Slide 66** - Visible loop from 15:00 – 23:00 UTC 27 November 2006. Along that clear line in southwest Colorado, we go from wall cloud (SW of the clear line) to Foehn gap to orographic cirrus. Orographic wave clouds in southeast Wyoming with a large wavelength, suggesting the potential for severe turbulence. Contrast the lack of cloud cover in the higher terrain of the Palmer divide with the lack of cloud cover over the lower terrain of the San Luis valley.

**Slide 67** - Visible Loop from October 20, 2006. What is going on here? Highlight “Wall Cloud...gap...or are they? Point out synoptic conditions and cold front making way down front range causing the “gap”...not the wind in this case. Why does the front bulge to the south? What else do you see?

**Slide 68** - Visible loop for 4 November 2006 case. Highlight why the orographic cirrus goes away quickly. Note the effects of individual peaks in the Cascade Range or Oregon and Washington.

**Slide 69** – 300 mb analyses to go along with the previous slide (4 November 2006 visible loop).

**Additional info for session next page:**

## **CLOUDS**

**Wall Clouds (Chinook or Foehn):** Form when winds and moisture increase on the windward side of the of the mountain range. Can be associated with strong winds on both sides of the range. Severe/dangerous turbulence inside the cloud.

**Chinook Arch clouds:** Form in the lee of long barriers near the beginning of Chinook downslope windstorms. These more indicative of strong wind damage than just wall clouds alone. They may also (often) disappear after the windstorm gets going in earnest. There is a “layer” of clear air separating cloud from the mountains “under the arch.”

**Rotor clouds:** Strato or alto cumulus that form downwind of mountain barrier...tucked inside the crest of a large amplitude atmospheric wave. Indicative of strong winds and turbulence and form parallel to the barrier with bases near mountain top level. Extreme hazard to aviation.

**Lenticular clouds:** Shaped like lenses...nearly stationary...also form in the crest of atmospheric waves. Can form at nearly any height in the atmosphere. Form as moisture condenses as air rises into the crest of the wave...with evaporation and drying occurring as air descends from the crest...giving it its distinct shape. When seen, they indicate moisture within a moderately stable to highly stable layers. They are also associated with strong winds at or near there level.

**Billow clouds:** Form when there is strong vertical windshear...and it occurs across a sharp temp change in a “cloudy” atmosphere. Cloud waves often appear to “break” when viewed from the side...these are referred to as Kelvin-Helmholtz waves or instabilities. Obvious sign of strong shear and turbulence (CAT often present around these formations).

### **General: Orographic Flow -**

As stable air flows over a barrier, gravity waves are often generated over or in the lee of the barrier. As the stable air is lifted over the mountains, it cools and becomes denser than the air around it...and therefore, due to gravity’s influence, sinks on the lee side trying to get back to its equilibrium level. However, it will overshoot...rise again...overshoot...descend...etc. until damping out downstream.

If developed over the mountains, then they are called “mountain waves”...which usually propagate vertically and can be found throughout the troposphere even into the strat. Stacked lenticulars are often indicators of this. Lee waves are obviously formed in the lee of the barrier. They are most often trapped waves with heavily stratified flow above the lee wave level.

If sufficient moisture...then clouds will form in the crests of the waves. Lenticulars are a definite indicator of orographic waves. Chinook arches are associated with longer wavelength waves...and stronger flow. Even without clouds...it can usually be assumed that whenever a stable air mass approaches a significant barrier, there will be a strong cross barrier wind.

### **The wind profile:**

1. If the winds are relatively weak and nearly constant with height, shallow waves will form downwind. 2. When winds become stronger and show some increase with height, the air will then overturn on the lee side of the barrier, forming standing eddies with axis parallel to ridgeline. 3. When winds are much stronger and increase greatly with height, much deeper waves form and propagate even further downwind of the mountains.

**Generally:** Short wave lengths of lee clouds indicate relatively light winds and strong static stability. Long(er) wavelengths indicate strong(er) winds and weak static stability (ie. Stability decreases).

**Under the most severe conditions** (flow and topography), large scale instability can cause mountain or orographic waves (lee) to transition to **hydraulic flow** ...with a hydraulic jump.

**High wind events:** Generally – High pressure upwind...low pressure in the lee (lee trof, eg) PG is locally intensified by descending air in the lee (sometimes).

Also, arrival of mid/upper sw trof will further enhance the pg. Also, look for elevated inversions near mountain top level.

### More Definitions:

**slope windstorm**—(Also called downslope windstorm.) Occurs when strong synoptic-scale winds blow over a mountain ridge top, where the winds are trapped below a strong temperature inversion located at an altitude just above the ridge top. The resulting fall winds on the lee side of the ridge are trapped close to the surface and can destroy buildings and blow down trees.

**lee-wave separation**—The production of small wavelength mountain waves near a mountaintop under conditions of very strong static stability. When the air is very stable and wind speeds are slow, the natural wavelength of air is often much shorter than the width of the mountain, as indicated by a very small Froude number. For this situation, the buoyant restoring force in the air is so strong that the air resists vertical displacement to get over the mountaintop, and instead most of the air flows around the sides of the mountain. The shallow layer of air near the mountaintop that is able to be displaced upward over the mountain will continue in vertical oscillation as it blows downstream, or separates, from the mountain. *Compare* lenticular cloud, downslope windstorm.

**lenticularis**—(Or lenticular cloud.) A cloud species the elements of which have the form of more or less isolated, generally smooth lenses or almonds; the outlines are sharp and sometimes show irisation.

These clouds appear most often in formations of orographic origin, the result of lee waves, in which cases they remain nearly stationary with respect to the terrain (standing cloud), but they also occur in regions without marked orography. This species is found mainly in the genera cirrocumulus, altocumulus, and (rarely) stratocumulus. Altocumulus lenticularis differs from cirrocumulus lenticularis in that, when smooth and without elements, it has shadowed parts while the latter is very white throughout. When undulated or subdivided, the altocumulus species differs from stratocumulus lenticularis in that its elements subtend an angle of less than  $5^\circ$  when viewed at an angle of more than  $30^\circ$  above the horizon.

**downslope windstorm**—A very strong, usually gusty, and occasionally violent wind that blows down the lee slope of a mountain range, often reaching its peak strength near the foot of the mountains and weakening rapidly farther away from the mountains.

Gust speeds in such winds may exceed  $50 \text{ m s}^{-1}$  and occasionally strong vortices capable of doing F1 to F2 damage (*see* Fujita scale) may occur in association with these winds. Such windstorms are most likely to the lee of elongated quasi-two-dimensional mountain ranges and can be distinguished from gap winds, which are confined to within or downstream of notable gaps or breaks in a mountain barrier and are generally weaker and

less gusty. Downslope windstorms of great severity require an upstream mountain range having a crest at least roughly 1 km in height above terrain to its lee, and with a steep leeside slope. Meteorological conditions favoring downslope windstorms are strong synoptic-scale flow across the mountain barrier at the level of its crest, with the cross-range component of the flow either decreasing with height or not increasing too rapidly with height above the crest. Also favorable is high static stability at the level of the mountain crest in the flow approaching the mountain range, decreasing with height above. A mean-state critical level in the middle troposphere, where the flow component across the mountain drops to zero and reverses sign, is often very favorable for downslope windstorms. Downslope windstorms can be considered a gravity wave phenomenon in the sense that vertically propagating gravity waves launched by the passage of stable air over high-amplitude terrain become very steep or break, creating an internal region above the mountain that is characterized by turbulence and a lapse rate approaching the dry adiabatic. Such a region restricts the vertical propagation of energy, allowing the flow near the surface of the mountain to accelerate downslope. Downslope windstorms can also be considered hydraulic jump phenomena in which flow becomes supercritical above and to the lee of a mountain barrier. Downslope windstorms are often known by local names in areas where they occur throughout the world (e.g., the bora along the northeastern shore of the Adriatic Sea and the Taku wind along the Gastineau Channel in southeast Alaska).

**pressure jump**—Dynamically the same as the hydraulic jump, but in meteorological contexts the equations are applied to a temperature inversion or to a system of two inversions. The phenomenon of a pressure jump is thus a steady-state propagation of a sudden finite change of inversion height, in analogy to the shock wave in a compressible fluid. The prefrontal squall line has been interpreted as a pressure jump, with the cold front providing the initial pistonlike impetus.

**chinook**—The name given to the foehn in western North America, especially on the plains to the lee or eastern side of the Rocky Mountains in the United States and Canada. On the eastern slopes of the Rocky Mountains the chinook generally blows from the west or southwest, although the direction may be modified by topography. Often the chinook begins to blow at the surface as an arctic front retreats to the east, producing dramatic temperature rises. Jumps of 10°–20°C can occur in 15 minutes, and at Havre, Montana, a jump from –12° to +5°C in 3 minutes was recorded. Occasionally the arctic front is nearly stationary and oscillates back and forth over an observing station, causing the temperature to fluctuate wildly as the station comes alternately under the influence of warm and cold air. As in the case of any foehn, chinook winds are often strong and gusty. They can be accompanied by mountain waves, and they can occur in the form of damaging downslope windstorms. The air in the chinook originates in midtroposphere above the ridgetops, and its warmth and dryness result from subsidence. When moisture is present, a variety of mountain-wave clouds and lee-wave clouds can form, such as the chinook arch of the Canadian Rocky Mountains west of Calgary, Alberta. The chinook brings relief from the cold of winter, but its most important effect is to melt or sublimate snow: A foot of snow may disappear in a few hours. As with the foehn, researchers have attempted to classify chinooks as downslope winds with warming and boras as those

accompanied by cooling. Again, these schemes have produced limited success because of the many ambiguous or erroneously classified cases.

**Froude number**—1. The nondimensional ratio of the inertial force to the force of gravity for a given fluid flow; the reciprocal of the Reech number.

It may be given as

$$Fr = V^2/Lg,$$

where  $V$  is a characteristic velocity,  $L$  a characteristic length, and  $g$  the acceleration of gravity; or as the square root of this number. 2. For atmospheric flows over hills or other obstacles, a more useful form of the Froude number is

$$Fr = \frac{V}{N_{BV} L_w},$$

where  $N_{BV}$  is the Brunt–Väisälä frequency of the ambient upstream environment,  $V$  is the wind speed component across the mountain, and  $L_w$  is the width of the mountain.  $Fr$  can be interpreted as the ratio of natural wavelength of the air to wavelength of the mountain. Sometimes  $\pi$  will appear in the numerator, and other times the ratio will be squared.

When  $Fr = 1$ , the natural wavelength of the air is in resonance with the size of the mountain and creates the most intense mountain waves, which can sometimes contain lenticular clouds and rotors of reverse flow at the surface. For  $Fr < 1$ , some of the low-altitude upstream air is blocked by the hill, short-wavelength waves separate from the top of the hill, and the remaining air at lower altitudes flows laterally around the hill. For  $Fr > 1$ , very long wavelengths form downwind of the hill, and can include a cavity of reverse flow just to the lee of the hill near the surface. Another form of the Froude number, using  $(z_i - z_{hill})$  in place of  $L_w$ , is useful for diagnosing downslope windstorms and hydraulic jump, where  $z_i$  is the depth of the mixed layer above the base of the mountain, and  $z_{hill}$  is the height of the mountain.

**resonance waves over hills**—Mountain waves with very large amplitudes produced when the natural wavelength of the air matches the width of the hill. The Froude number is near 1 in this type of flow.

**mountain-gap wind**—A local wind blowing through a gap between mountains, a gap wind. This term was introduced by R. S. Scorer (1952) for the surface winds blowing through the Strait of Gibraltar. When air stratification is stable, as it usually is in summer, the air tends to flow through the gap from high to low pressure, emerging as a “jet” with large standing eddies in the lee of the gap. The excess of pressure on the upwind side is attributed to a pool of cold air held up by the mountains. Similar winds occur at other gaps in mountain ranges, such as the tehuantepecer and the jochwinde, and in long channels, such as the Strait of Juan de Fuca between the Olympic Mountains of Washington and Vancouver Island, British Columbia.

**lee wave**—1. Any wave disturbance that is caused by, and is therefore stationary with respect to, some barrier in the fluid flow.

Whether the wave is a gravity wave, inertia wave, barotropic wave, etc., will depend on the structure of the fluid and the dimensions of the barrier. Most research has been



devoted to the gravity lee wave (mountain wave) in the atmosphere, of wavelength of order

$$2\pi V[T/g(\gamma_d - \gamma)]^{1/2},$$

where  $V$  is the current speed,  $T$  the Kelvin temperature,  $g$  the acceleration of gravity, and  $\gamma_d$  and  $\gamma$  the dry-adiabatic and environmental lapse rates, respectively. This is the wave that is evident in lenticular or Moazagotl cloud systems and is strikingly exemplified in the Bishop wave. Dynamically, the lee wave is the sum of the free waves of the system and those wave components forced by the particular shape of the barrier. The disturbance is, in general, negligible at any distance upstream of the barrier, a result that follows from the dynamics when the system is started from rest, but a point that requires special attention when the steady-state assumption is made. The term lee wave is also applied loosely to nonwave disturbances in the lee of obstacles, such as the rotor cloud. 2. A mountain wave occurring to the lee of a mountain or mountain barrier.

These waves can become visible in the form of lenticular or trapped lee-wave clouds.

**mountain wave**—An atmospheric gravity wave, formed when stable air flow passes over a mountain or mountain barrier. Mountain waves are often standing or nearly so, at least to the extent that upstream environmental conditions (and diurnal forcing) are stationary. Two divisions of mountain wave are recognized, vertically propagating and trapped lee waves. Vertically propagating mountain waves over a barrier may have horizontal wavelengths of many tens of kilometers or more, usually extend upward into the lower stratosphere, and in pure form, tilt upwind with height. They can accompany foehn, chinook, or bora wind conditions. They have the capability to concentrate momentum on the lee slopes, sometimes in structures resembling a hydraulic jump, leading to occasionally violent downslope windstorms. When sufficient moisture is present in the upstream flow, vertically propagating mountain waves produce interesting cloud forms, including altocumulus standing lenticular (ACSL) and other foehn clouds. Intense waves can present a significant hazard to aviation by producing severe or even extreme clear air turbulence. Trapped lee waves generally have horizontal wavelengths of 5–35 km. They occur within or beneath a layer of high static stability and moderate wind speeds at low levels of the troposphere (the lowest 1–5 km) lying beneath a layer of low stability and strong winds in the middle and upper troposphere. These conditions are often diagnosed using a vertical profile of the Scorer parameter, a sharp decrease in midtroposphere indicating conditions favorable to trapped lee wave formation. Trapped lee waves assume the form of a series of waves running parallel to the ridges, and the crests of these waves often contain altocumulus, stratocumulus, wave clouds, or rotor clouds in parallel bands that can be very striking in satellite pictures. Because wave energy is trapped within the stable layer, these waves (and accompanying cloud bands) may dissipate only very slowly downwind, and they can continue downstream for many wavelengths spanning many tens of kilometers. Flow beneath the wave crests, occasionally made visible by rotor clouds, is often turbulent, thus presenting a significant hazard to low-level aviation. Vertically propagating mountain waves and trapped lee waves can coexist, and sometimes lee waves are incompletely trapped or “leaky,” leading to a variety of complex rotor interactions. This complexity of rotor patterns often produces interesting variations in cloud forms. As mountain waves propagate upward, the rotor's amplitude can grow to the point that the rotor “breaks,” that is, the rotor becomes convectively unstable and

overturns. Wave breaking can have an important role in vertically redistributing horizontal atmospheric momentum, as it slows the atmosphere by turbulent transport of the earth's momentum upward.

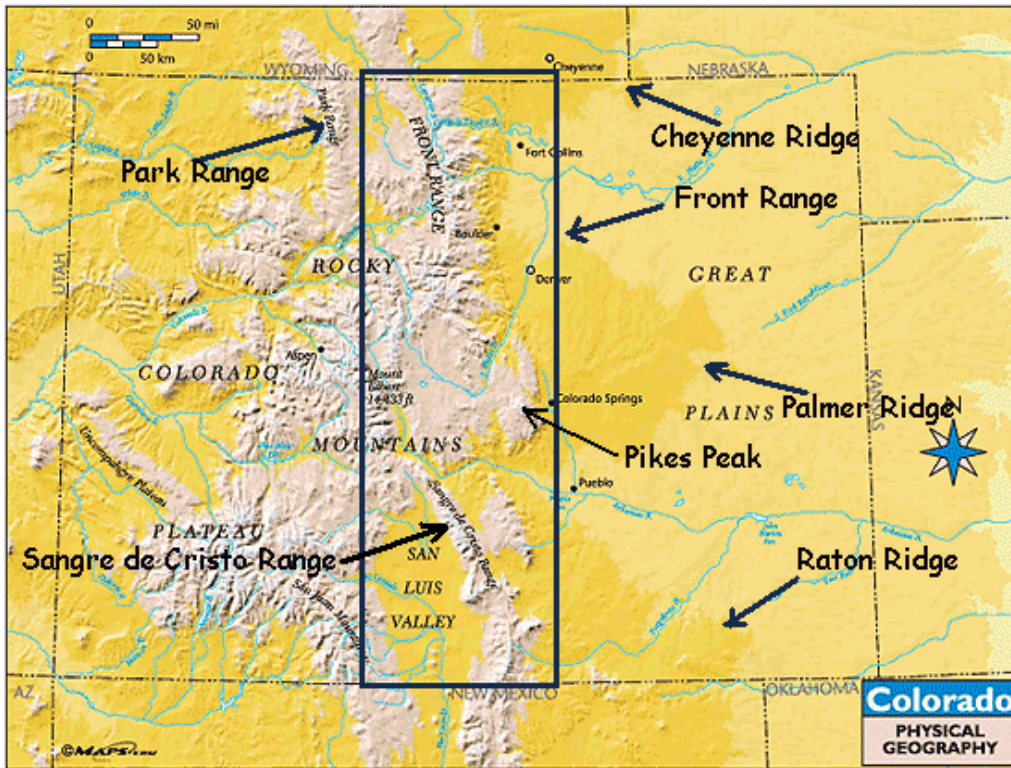
**mountain-wave cloud**—A cloud that forms in the rising branches of mountain waves and occupies the crests of the waves. The most distinctive are the sharp-edged, lens-, or almond-shaped lenticular clouds, but a variety of stratocumulus, altocumulus, and cirrocumulus forms appear in both the main, vertically propagating waves and in the lee waves.

## Maps

### Arizona



Colorado



## Montana

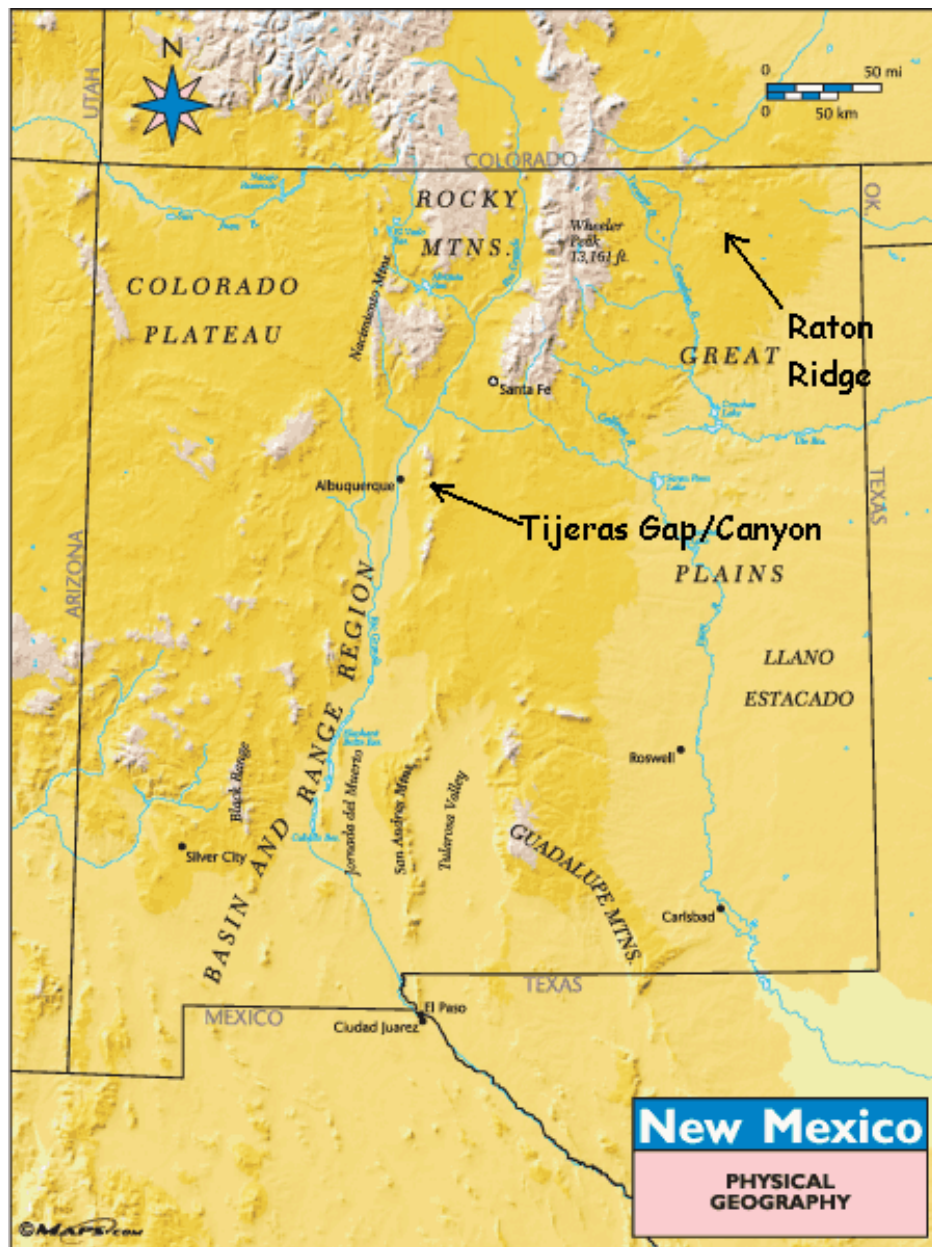


## Idaho



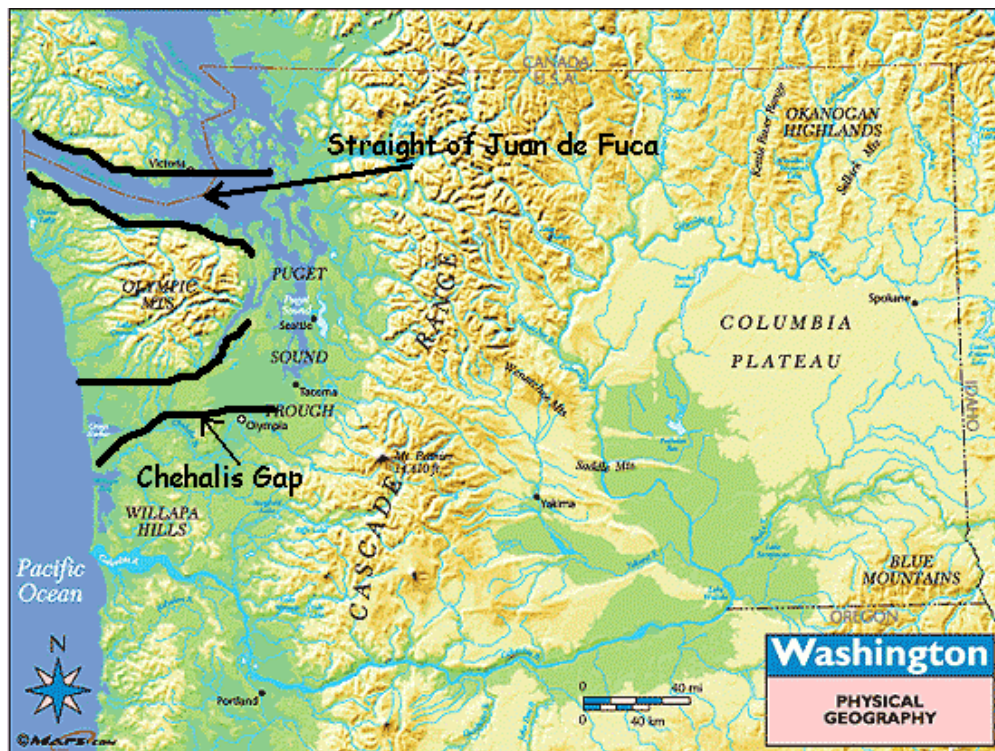


New Mexico



Washington





## Wyoming

