Terrain-forced vs. Thermally Driven Flows

Thermally Driven Circulations

– produced by temperature contrasts that form within mountains or between mountains and surrounding plains

Terrain-forced flows

– produced when large-scale winds are modified or channeled by underlying complex terrain

Over or Around?

- Terrain forcing can cause an air flow approaching a barrier to be carried over or around the barrier, to be forced through gaps in the barrier or to be blocked by the barrier.
  - See http://meted.ucar.edu/mesoprim/flowtopo/
  - See http://meted.ucar.edu/mesoprim/gapwinds/
  - See http://meted.ucar.edu/mesoprim/mtnwave/

Critical Factors

- Three factors determine the behavior of flow approaching barrier
  - Stability of approaching air
    - Unstable or neutral stability air can be easily forced over a barrier
    - The more stable, the more resistant to lifting
  - Wind speed
    - Moderate to strong flows are necessary
  - Topographic characteristics of barrier

Kinetic Energy vs. Potential Energy

- Kinetic energy
  - Energy due to motion of air
  - $\frac{1}{2} U^2$
- Potential energy
  - Energy due to location of air parcel in gravitational field
  - Greater the stability (N-Brunt-Vaisala frequency), stronger the restoring force due to gravity
  - Higher the obstacle (h_m), greater the displacement required
  - $\frac{1}{2} N h_m / U$

Froude Number

- Froude Number
  - Ratio of kinetic energy to potential energy
  - $U/(N\ h_m)$
  - U: Speed of wind approaching mountain
  - N: stability of atmospheric flow
  - h_m: height of obstacle
- FR<1: KE<PE; upstream flow blocked by terrain
- FR= 1: KE=PE; upstream flow reaches crest
- FR>1: KE>PE; upstream flow continues over mountain

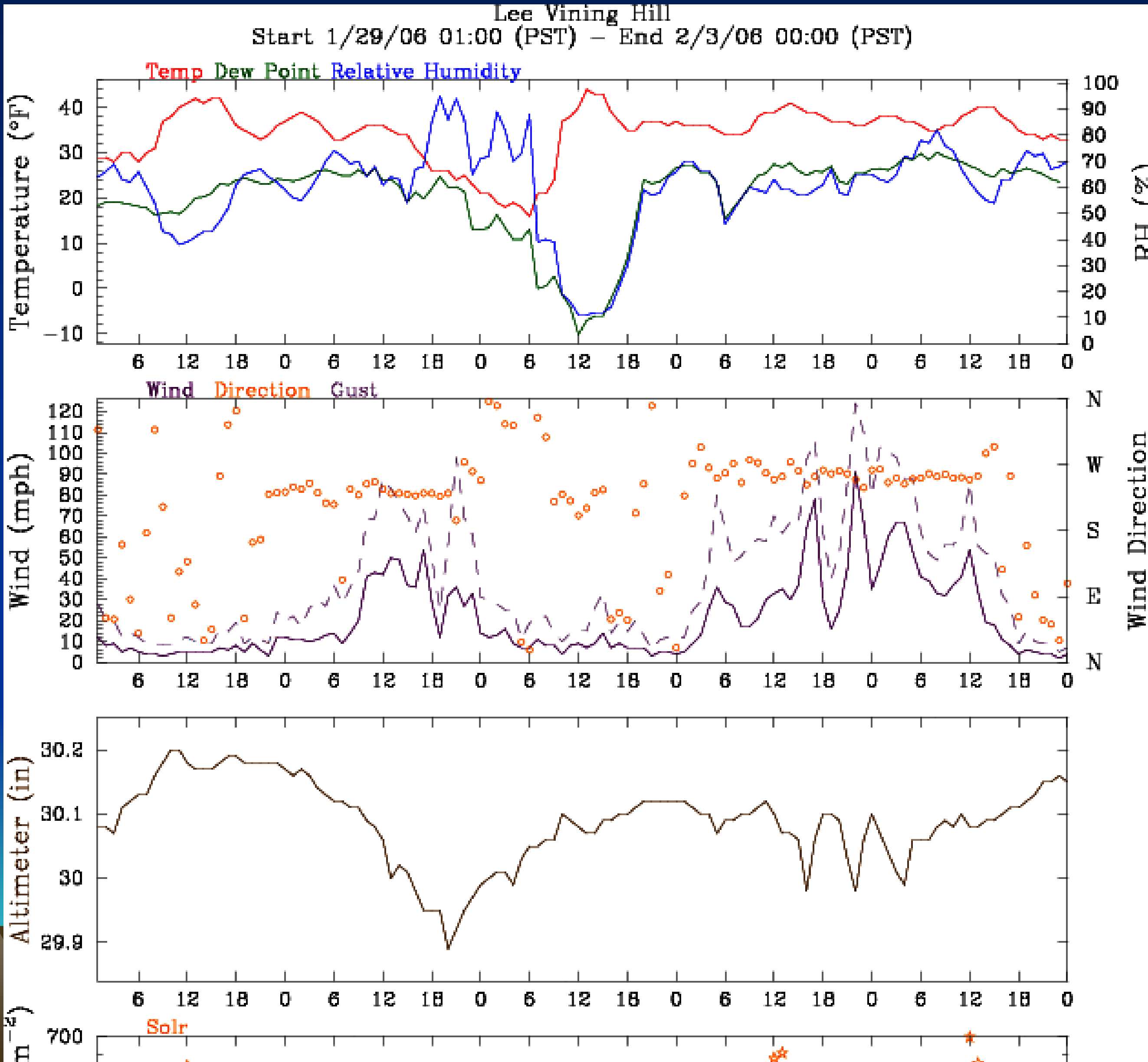
Flow Over Mountains

- Approaching flows tends to go over mountains if
  - –1) barrier is long
  - –2) cross-barrier wind component is strong
  - –3) flow is unstable, neutral or only weakly stable
- Common in North American mountain ranges
- Evident by presence of lenticular clouds, cap clouds, banner clouds, rotors, foehn wall, chinook arch, and billow clouds as well as blowing snow, cornice buildup, blowing dust, downslope windstorms, etc.

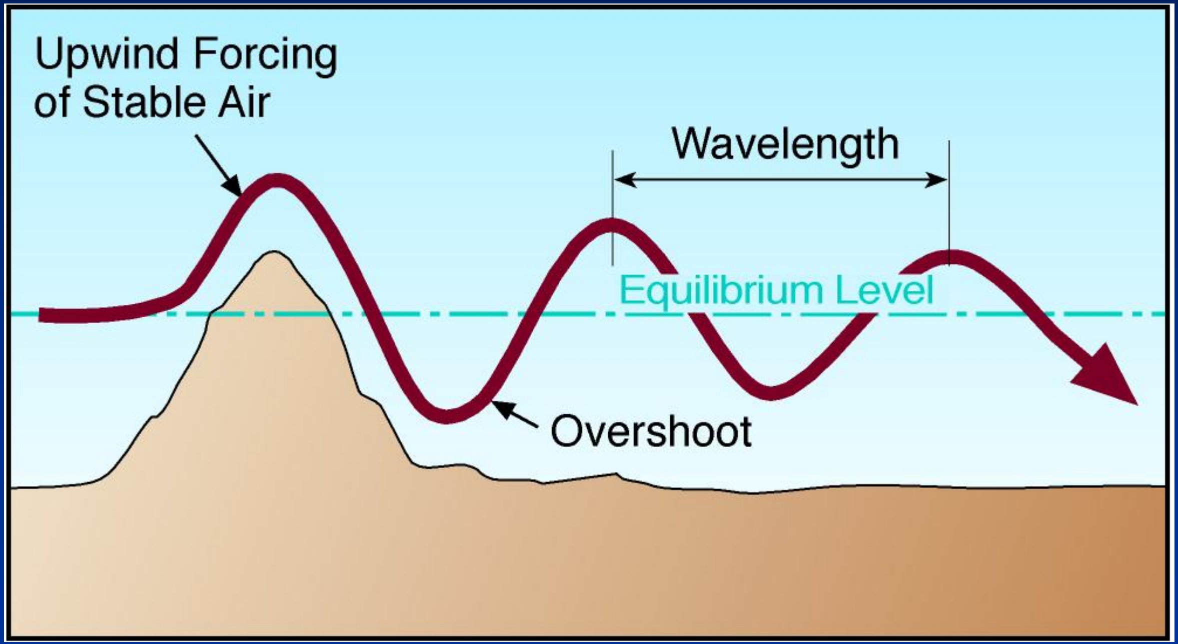
The Intermountain West

Whiteman (2000)

Lee Vining, CA (eastern Sierras)



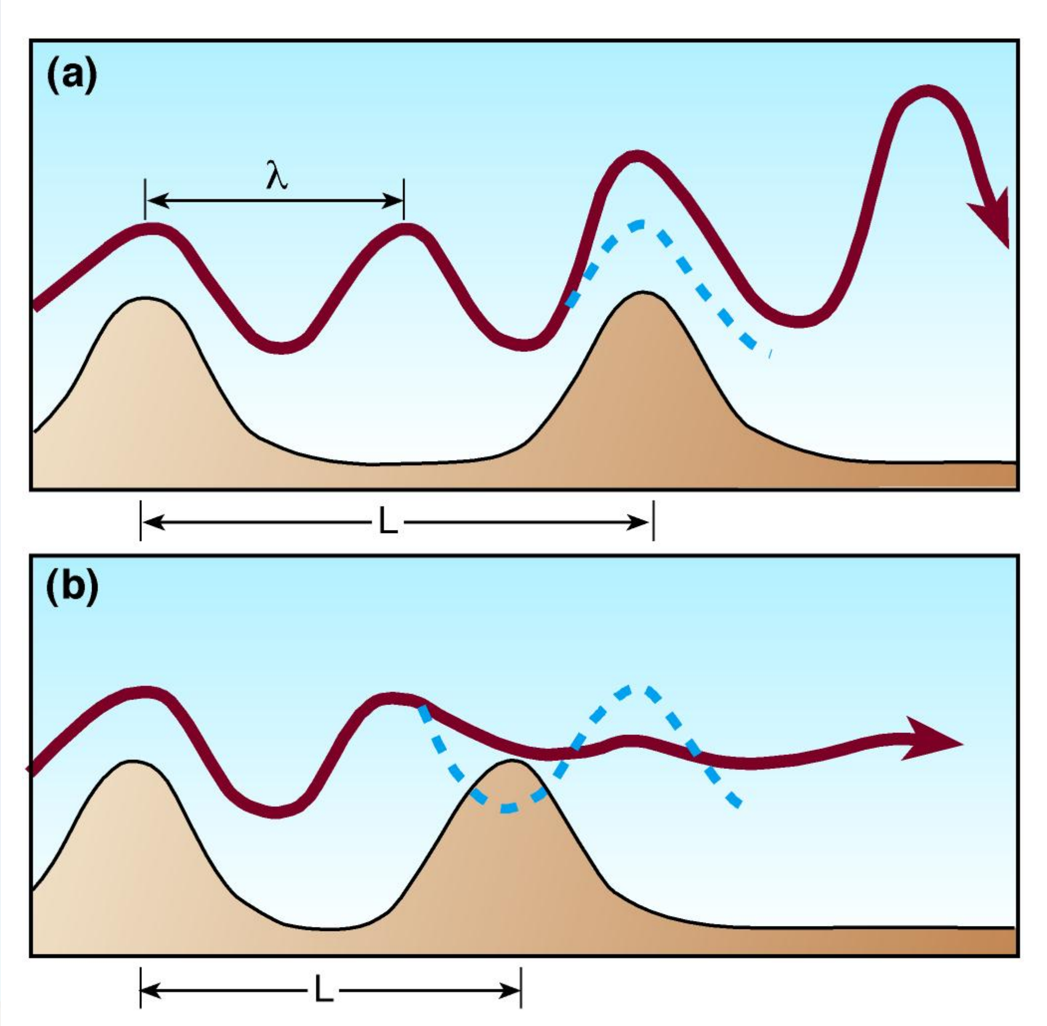
Lee waves



Stull (1995)

Lee waves are *gravity waves* produced as stable air is lifted over a mountain. The lifted air cools and becomes denser than the air around it. Under gravity's influence, it sinks again on the lee side to its equilibrium level, overshooting and oscillating about this level.

Amplification and cancellation of lee waves



If the flow crosses more than one ridge crest, the waves generated by the first ridge can be amplified (a process called *resonance*) or canceled by the second barrier, depending on its height and distance downwind from the first barrier.

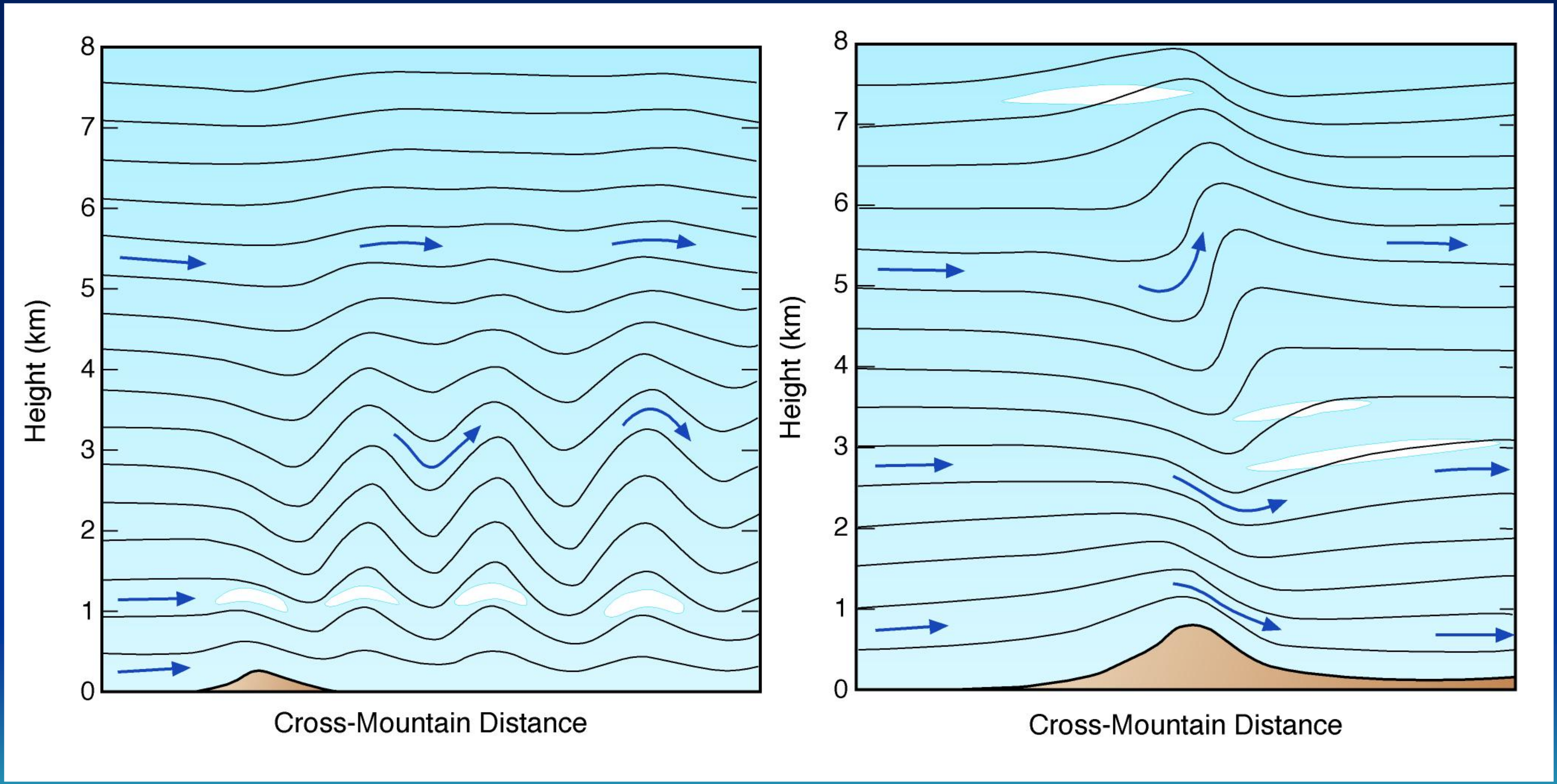
Orographic waves form most readily in the lee of steep, high barriers that are perpendicular to the approaching flow.

Bérenger &Gerbier (1956)

Formation of waves

- The basic form of a wave (trapped or vertically propagating) and its wavelength depend on variations of speed and stability of the approach flow. One of 3 flow patterns results depending on the characteristics of the vertical profile of the horizontal wind.
  - If winds are weak and change little with height, shallow waves form downwind of the barrier.
  - When winds become stronger and show a moderate increase with height, air overturns on the lee side of the barrier, forming a standing (i.e., non-propagating) lee eddy with its axis parallel to the ridgeline.
  - When winds become stronger still and show a greater increase in speed with height, deeper waves form and propagate farther downwind
- The wavelengths of orographic waves increase when wind velocities increase or stability decreases.

Trapped and vertically propagating lee waves



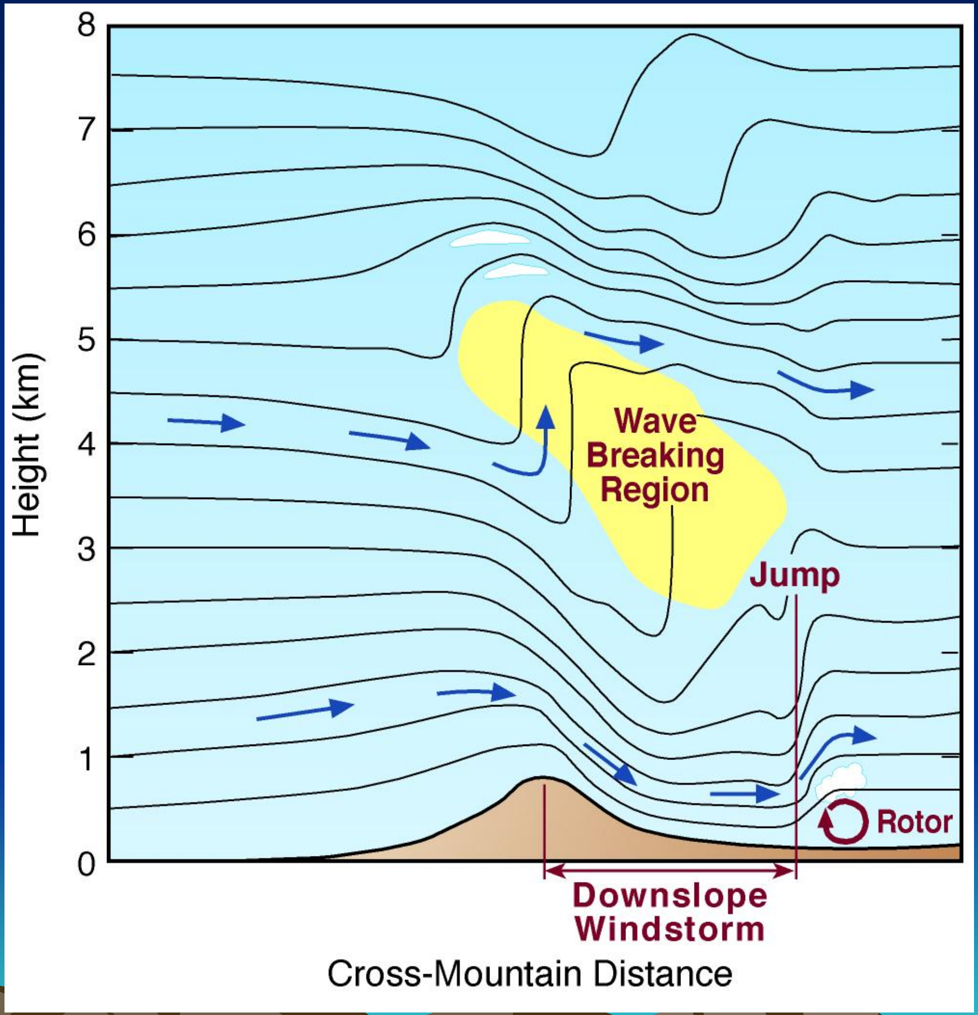
Carney et al. (1996)

Lenticular with rotor

Whiteman photo

- Campbell Scientific

Hydraulic flow



Under certain stability, flow and topography conditions, the entire mountain wave can undergo a sudden transition to a *hydraulic flow* involving a *hydraulic jump* and a turbulent *rotor*. This exposes the lee side of the barrier to sweeping, high speed turbulent winds that can cause forest blowdowns and structural damage.

Carney et al. (1996)

Sierra wave
http://www.met.utah.edu/whiteman/T_REX/

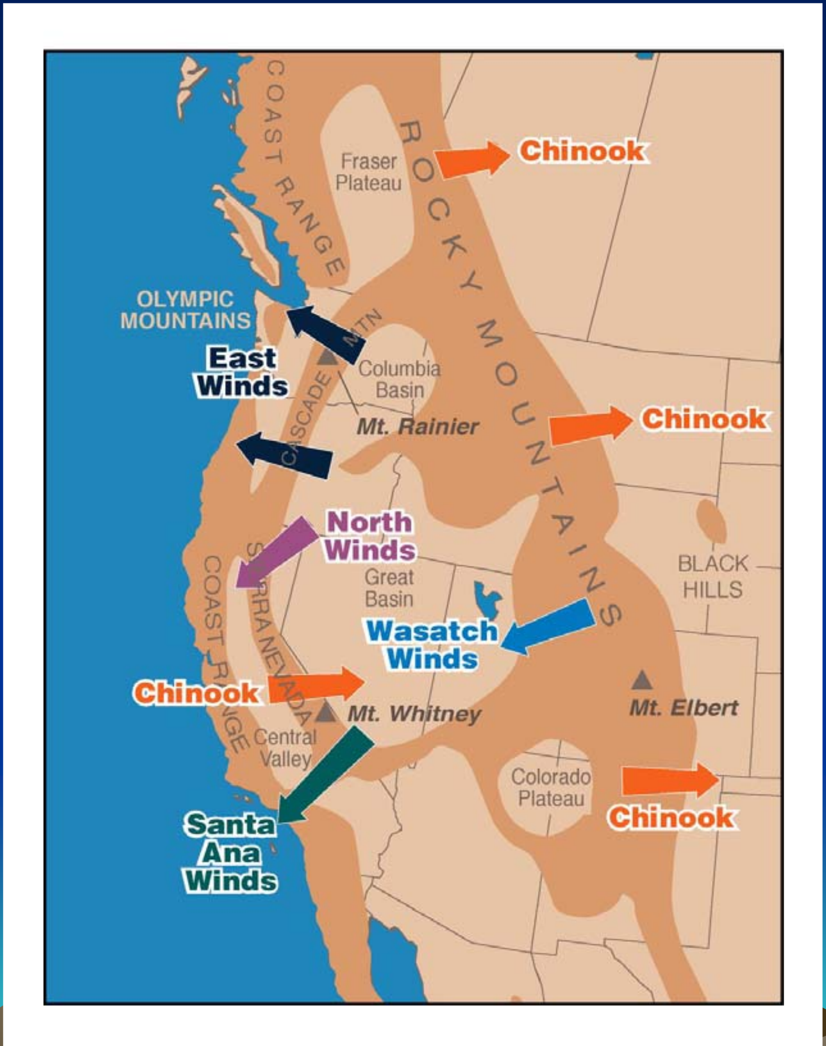
View is toward south from 11 km height. Airflow is from right to left. The cloud mass on the right is plunging down the lee slope of the Sierra Nevada; the near-vertical ascending cloud wall of the mountain wave is on the left. The turbulent lower part of the cloud wall is a "rotor”; the smooth upper part is the "lenticular" or "wave cloud". The cloud mass to the right is a "cap cloud" (= Föhn-Mauer); the cloud-free gap (middle) is the "Foehn gap" (= Föhn-Lücke).

Kuettner/
Klieforth 1952

Downslope windstorms - Bora, Foehn, Chinook

- Form on the lee side of high-relief mountain barriers when a stable air mass is carried across the mountains by strong cross-barrier winds that increase in strength with height.
- Strong winds are caused by intense surface pressure gradients (high upwind, low pressure trough downwind). Pressure difference is intensified by lee subsidence which produces warming and lower pressure.
- Elevated inversion layers near and just above mountaintop levels play a role that is now under investigation.
- Occur primarily in winter
- Are associated with large amplitude lee waves
- May be associated with wave trapping, or wave breaking regions aloft.
- Local topography often plays an important role (Ex: Boulder, CO and Livingston, MT). Steep leeside slopes, canyons, concave ridgeline.
- Can bring cold (Bora) or warm (Foehn, Chinook) air to leeward foothills.

Foehn winds of the intermountain west



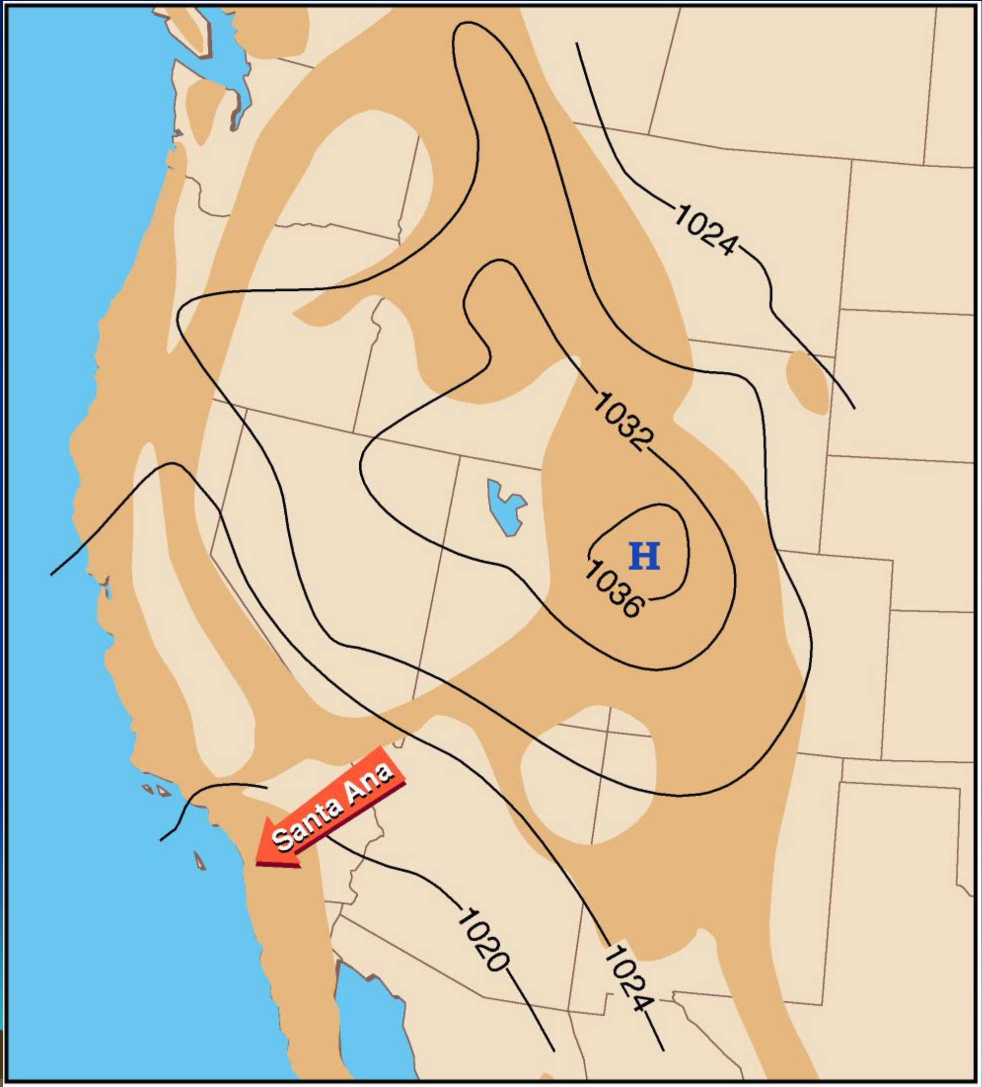
Schroeder & Buck (1970)

Chinook winds usually occur on the east side of N American mountain ranges since winds aloft are usually westerly. But, they can occur on the west sides when upper-level winds are from the east (Ex: Santa Ana and Wasatch winds).

Santa Ana winds - late Fall and Winter, cause horrendous wildfires.

Wasatch downslope winds - affect a more or less contiguous zone immediately adjacent to the foothills. These are produced by hydraulic jumps and interaction with flows in vicinity of canyon mouths

Synoptic conditions for Santa Ana winds

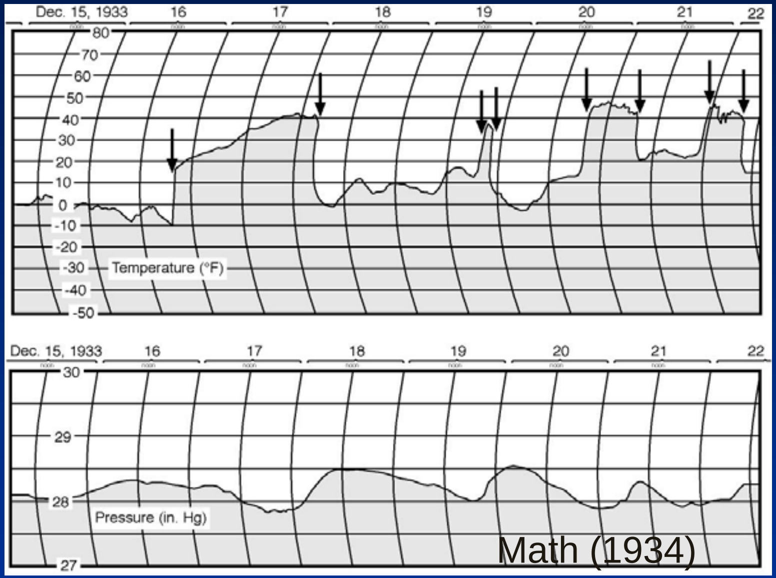


Ahrens (1994)

Santa Ana winds (e.g., 02/11/02)

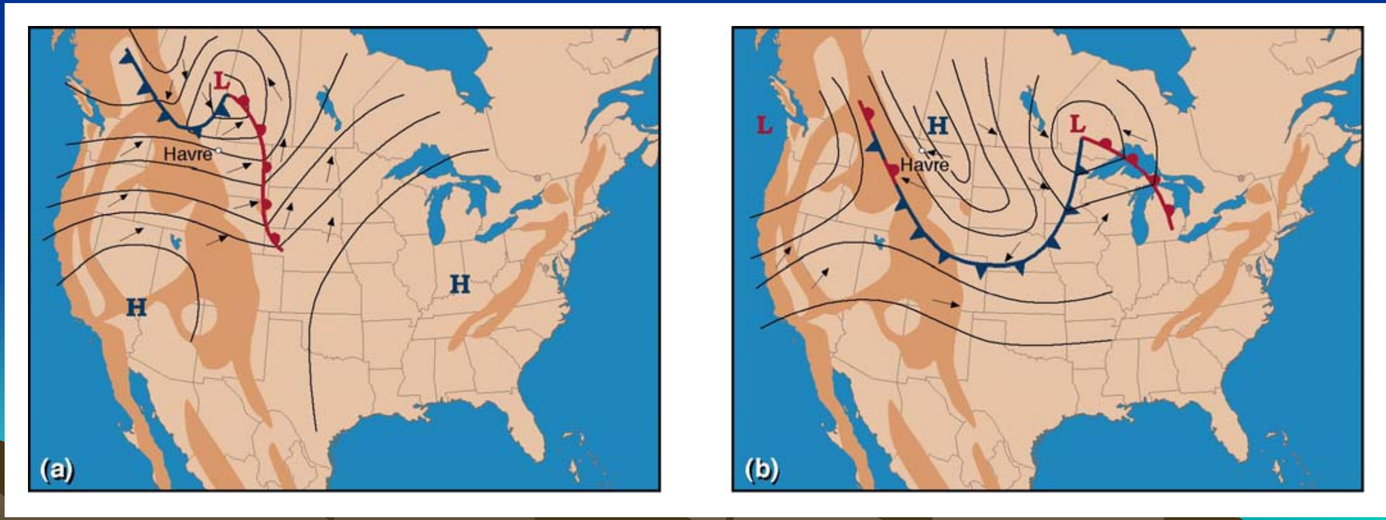
Rosenthal (1972)

Foehn pauses & rapid T changes, Havre, MT



Foehn (Chinook) pause: abrupt cessation of downslope winds.

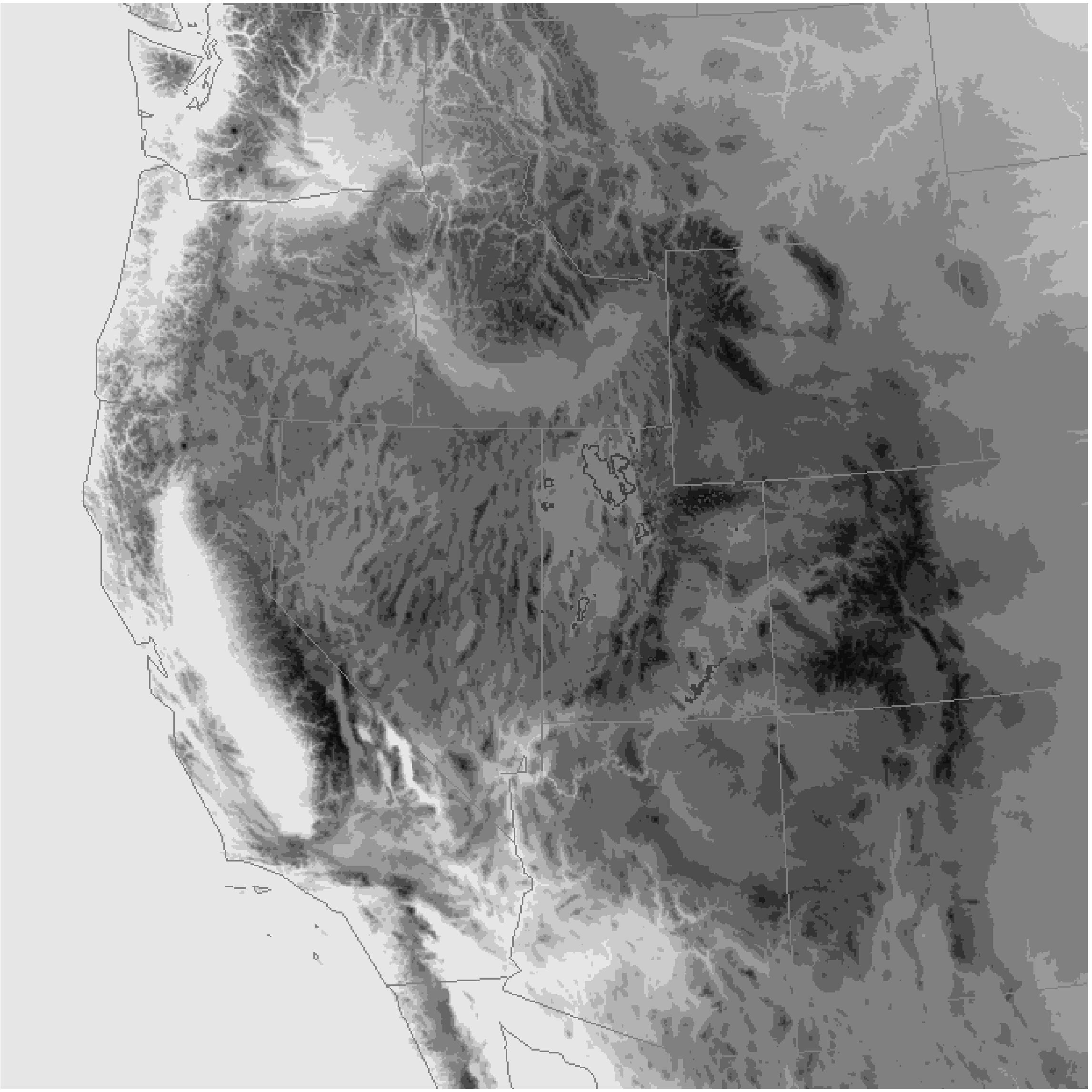
Alternating strong wind break-ins and foehn pauses can cause temperatures to oscillate wildly.



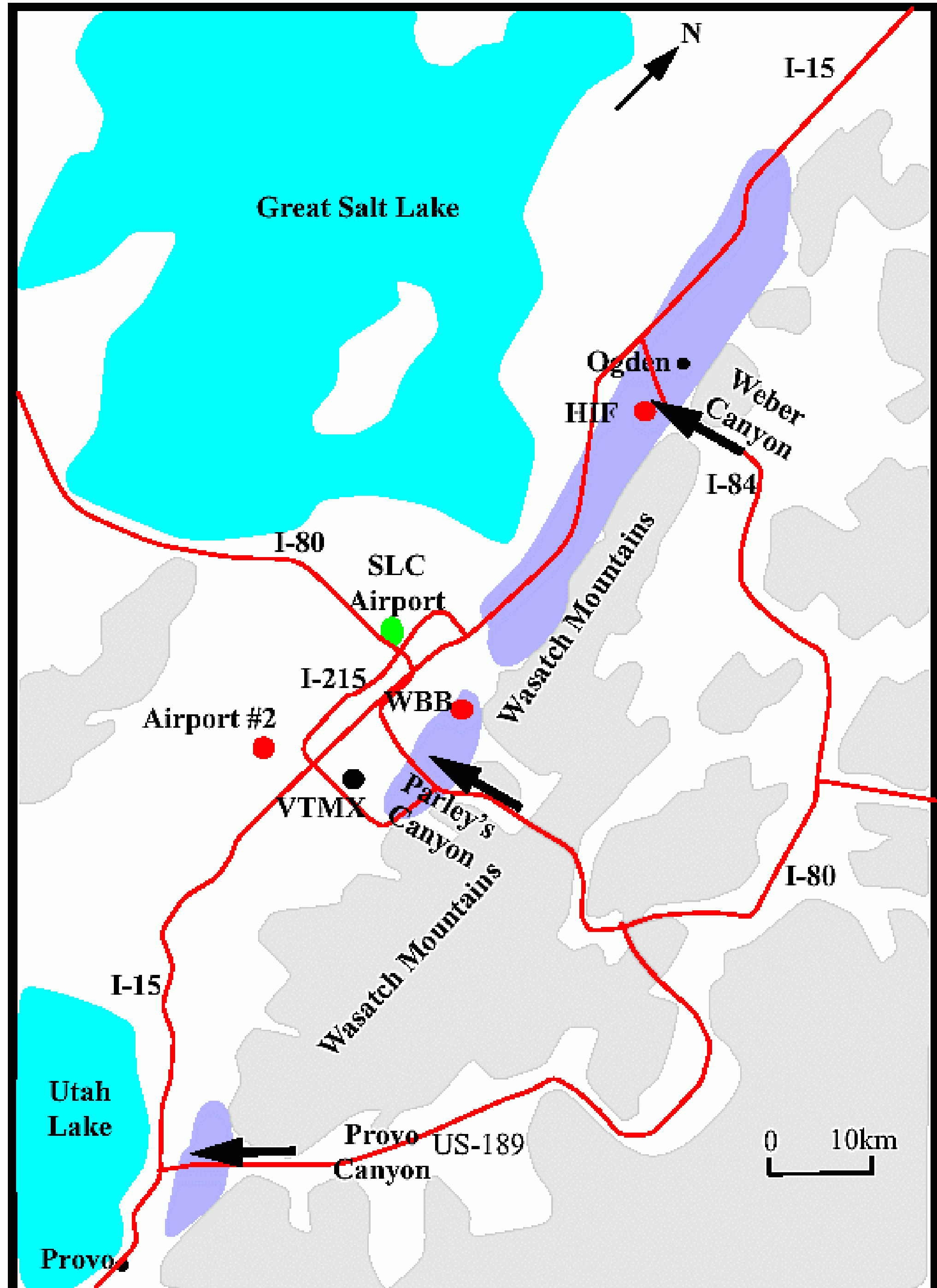
Chinook wall cloud

Ronald L. Holle photo

Western U.S. terrain



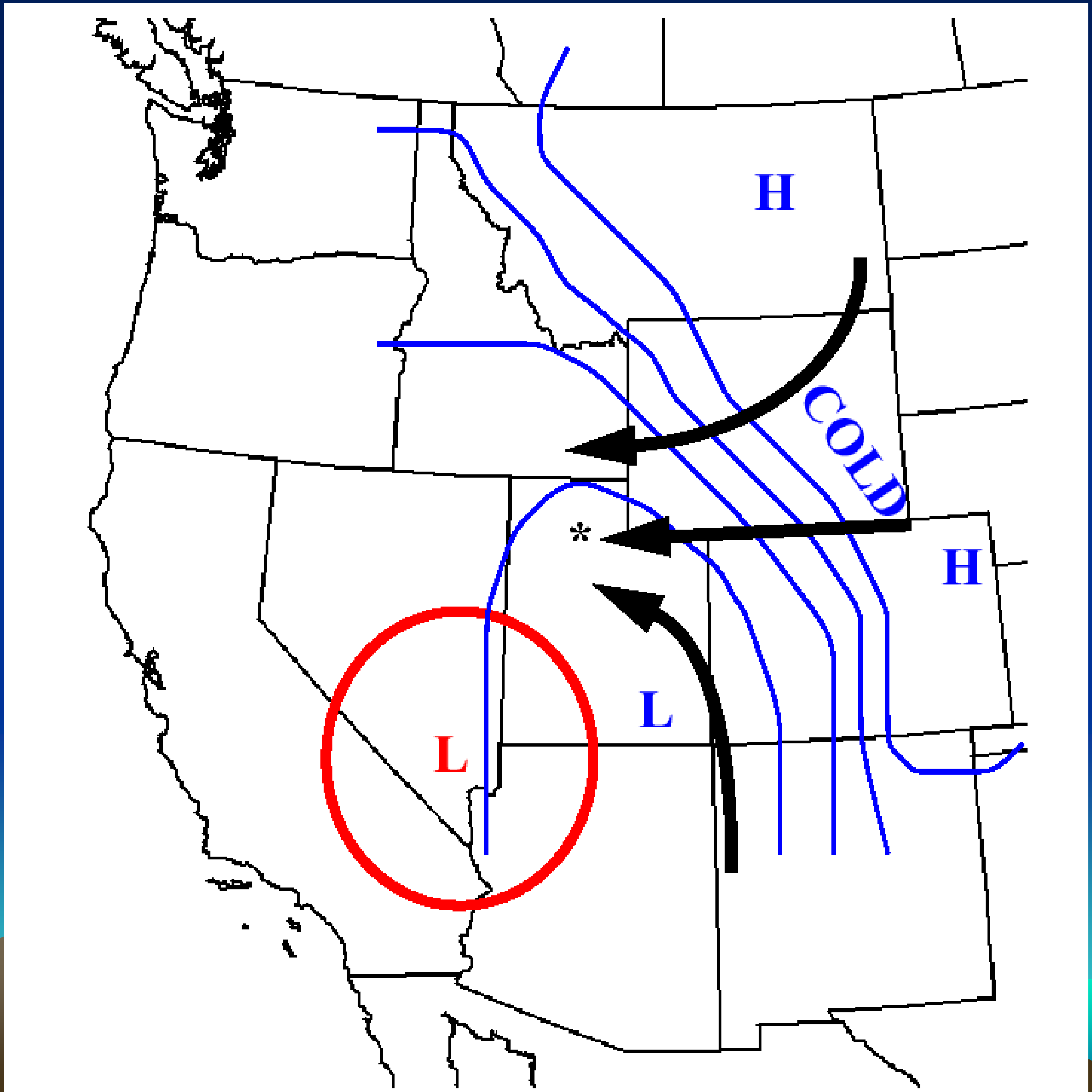
Areas affected by Wasatch downslope windstorms



Conditions favorable for downslope windstorms along the Wasatch Front

- Strong cross-barrier flow at crest-level (700 mb closed low to SSW)
- Pool of cold air to the ENE (relatively high pressure over Wyoming)
- Wind reversal above crest-level (presence of a critical level) and elevated stable layer

Synoptic conditions favorable for downslope windstorms

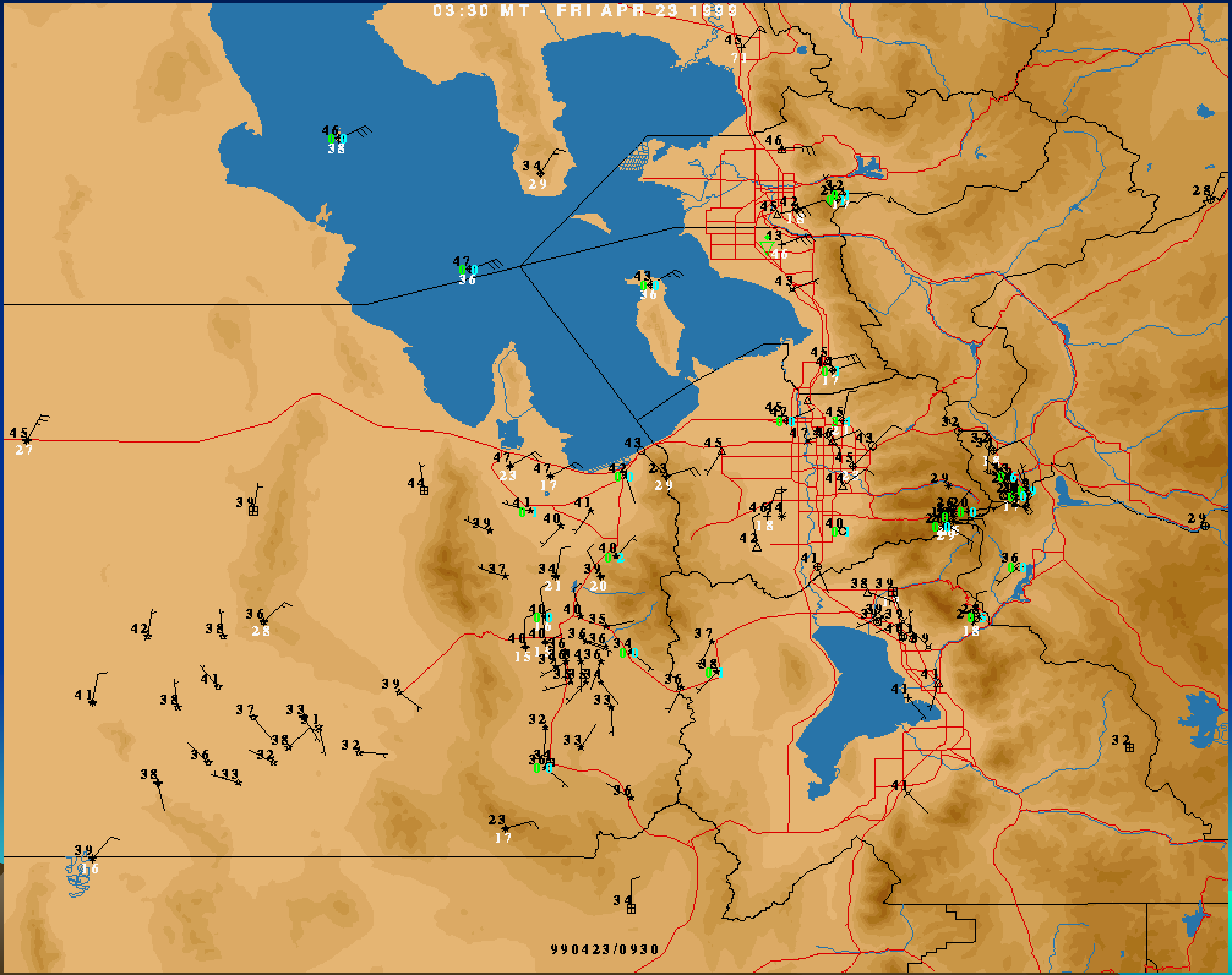


Ten Strongest Downslope Windstorms at HIF (1947-1999)

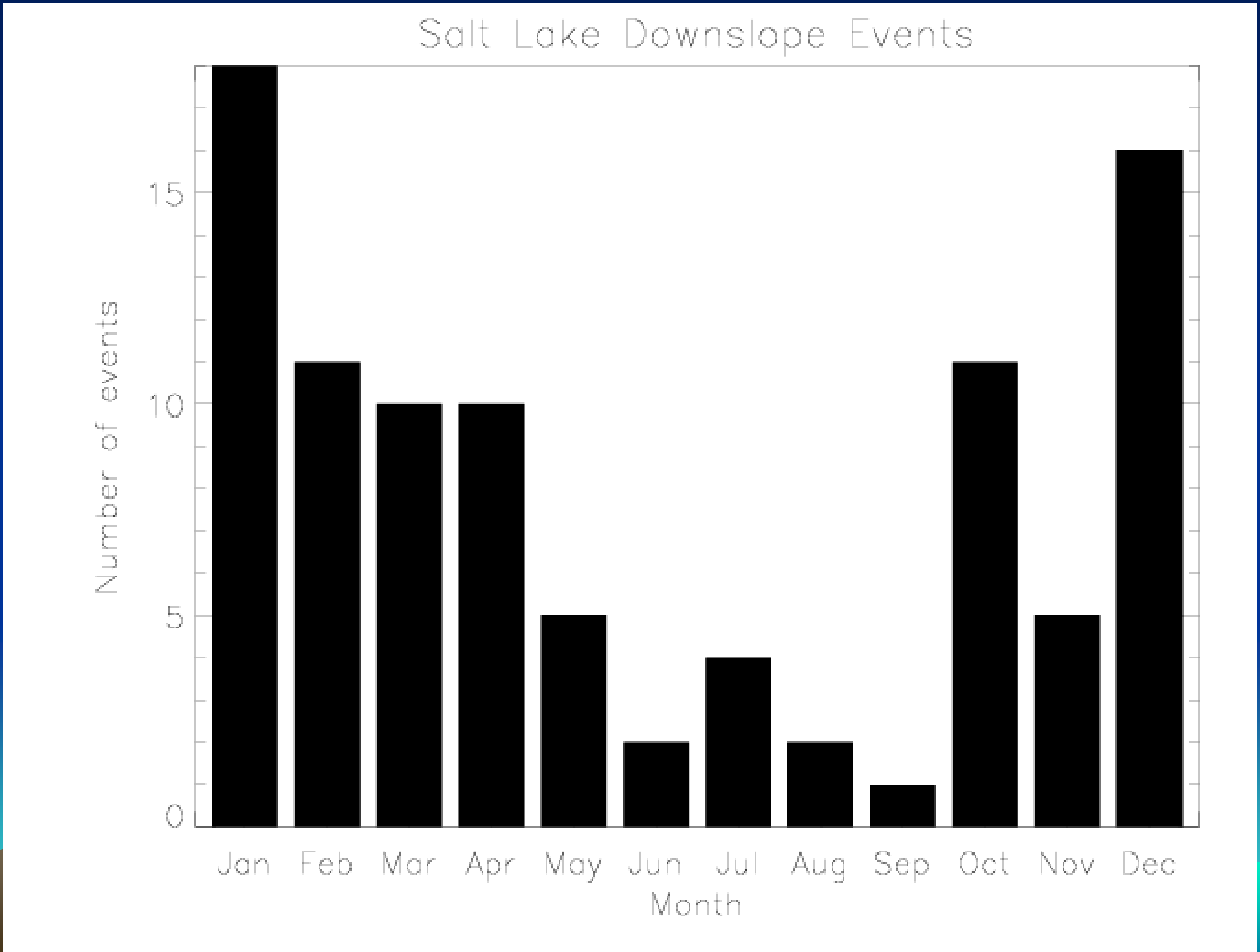
- 4 Apr 1983 (46 m/s)
- 16 May 1952 (42 m/s)
- 20 Feb 1971 (38 m/s)
- 22 Oct 1953 (38 m/s)
- 18 Mar 1961 (37 m/s)
- 3 June 1949 (35 m/s)
- 11 Nov 1978 (35 m/s)
- 6 May 1949 (34 m/s)
- 16 Nov 1964 (34 m/s)
- 26 Jan 1957 (33 m/s)

*23 April 1999 ranks 20th

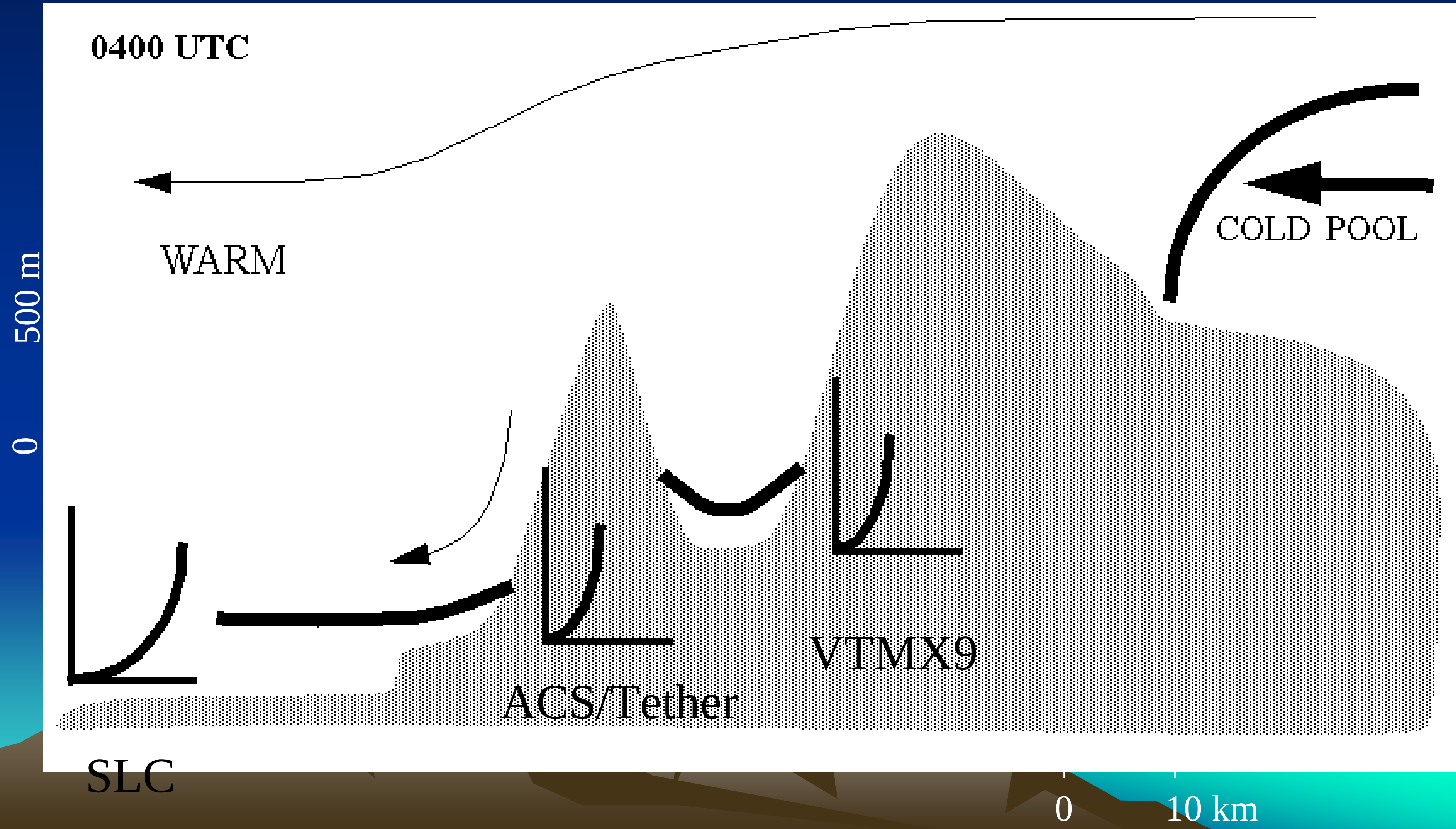
23 April 1999, 0930 UTC– example of an extreme event



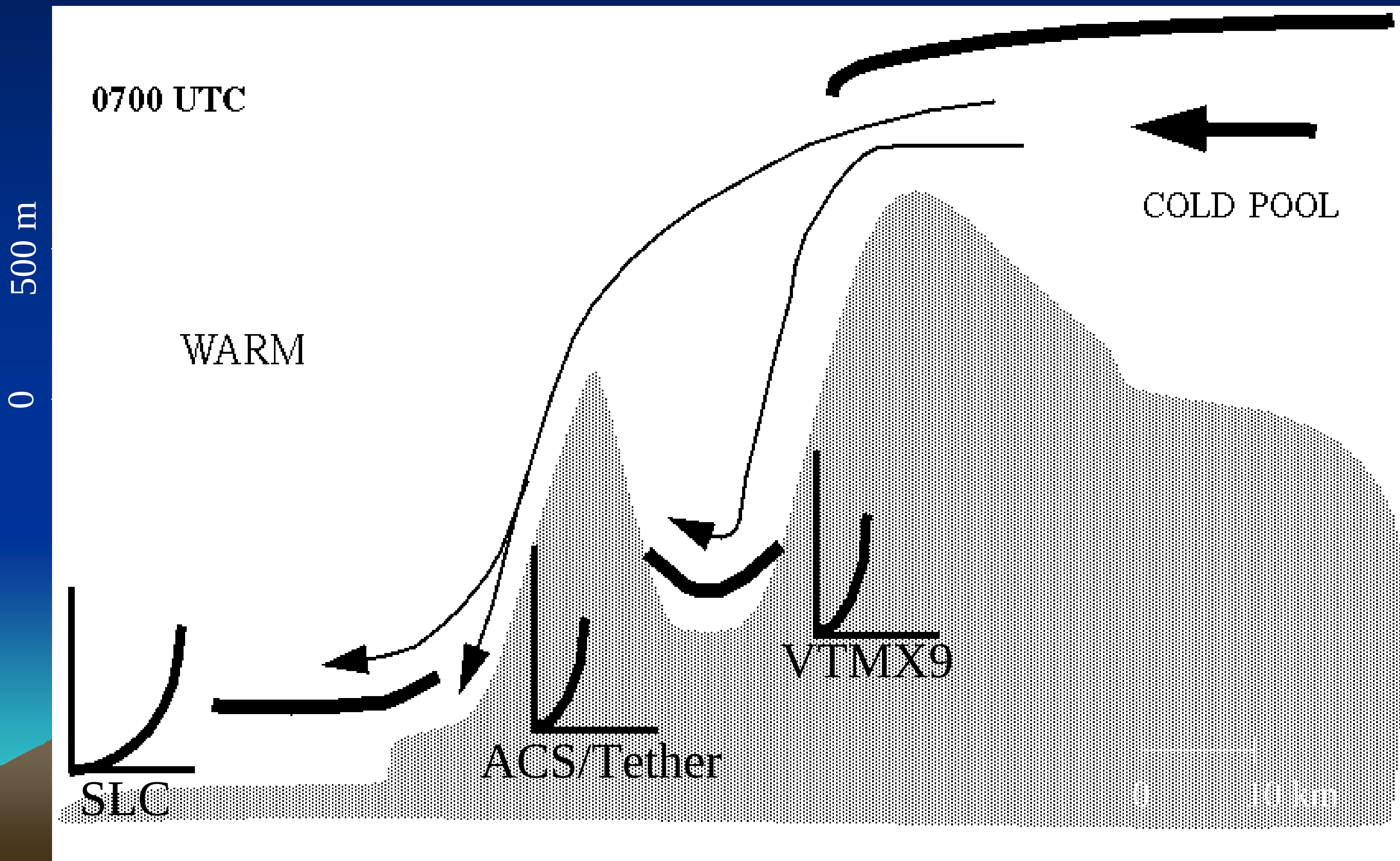
Wasatch Downslope Windstorms by Month (strongest 0.5%, 1947-1999)



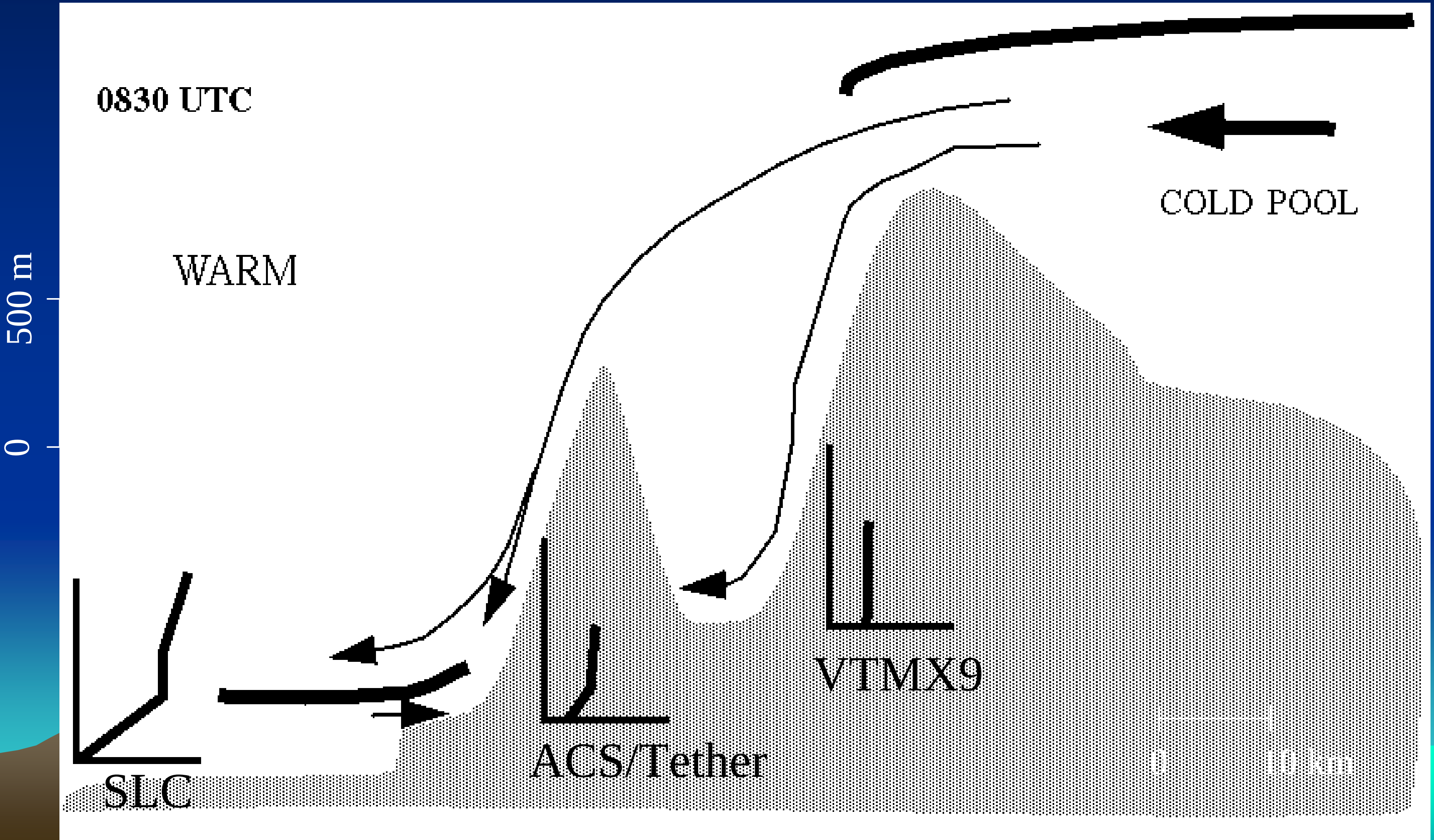
Conceptual model of 7 Oct 2000



Conceptual Model



Conceptual Model



Conceptual Model