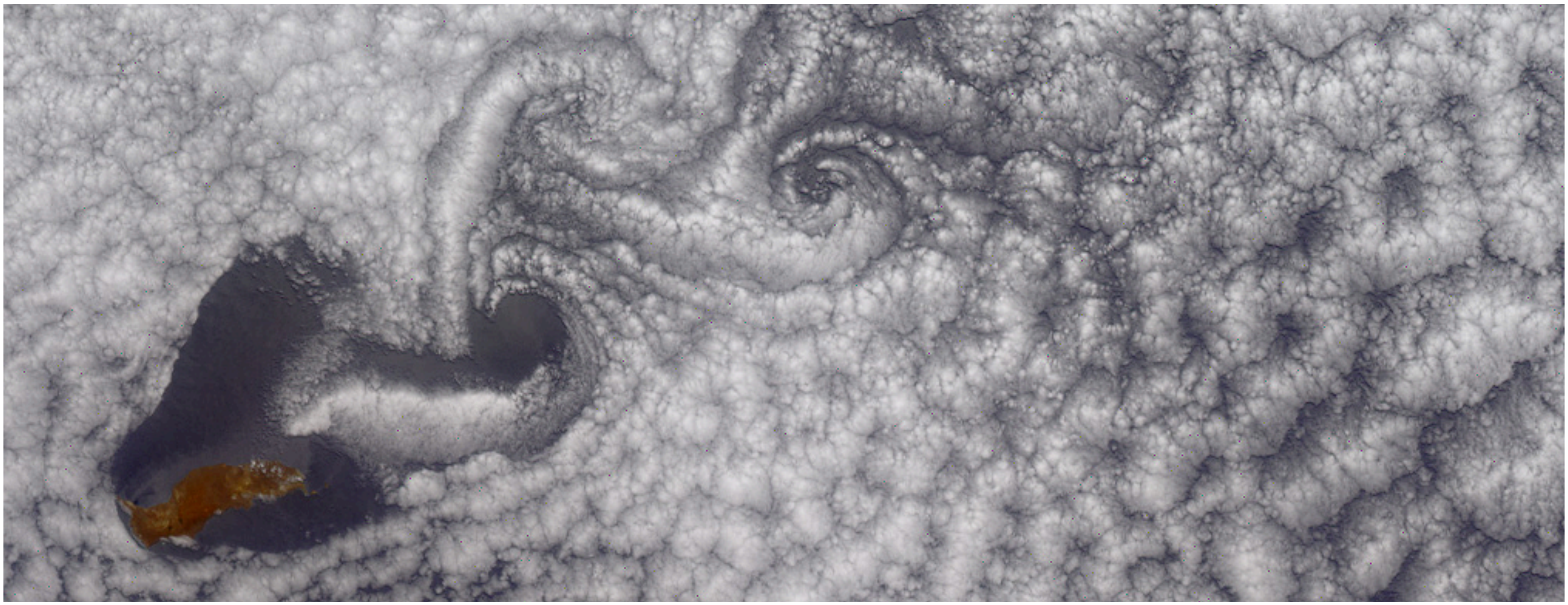
Terrain-Forced Flows



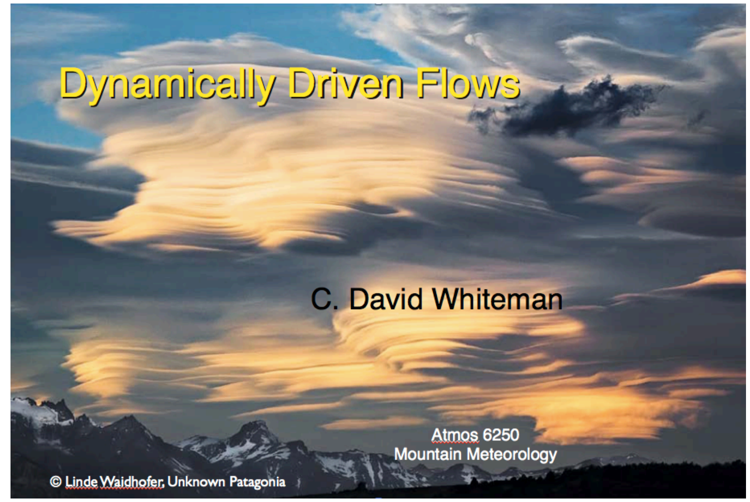
Sebastian W. Hoch

C. David Whiteman

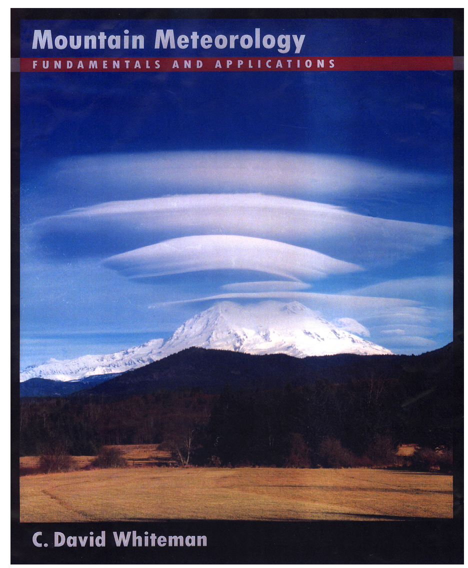
C. David Whiteman

Markowski and Richardson (2010):
“Mesoscale Meteorology in Midlatitudes”

Jim Steenburgh, University of Utah

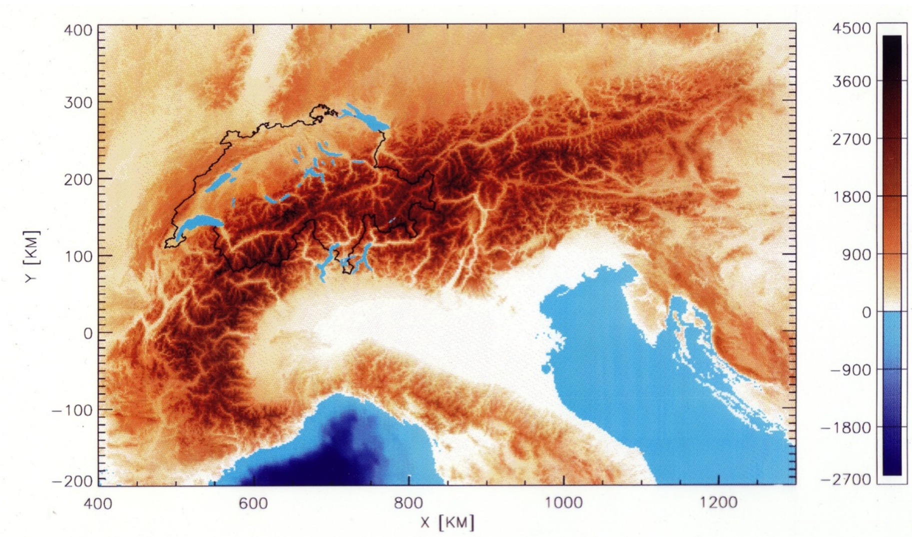


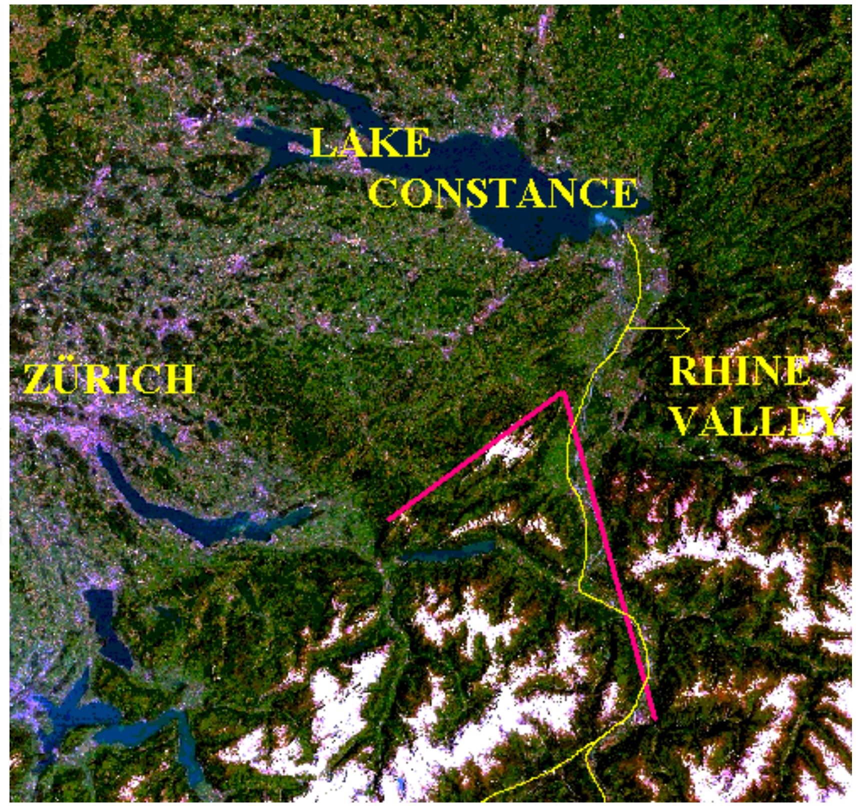
Whiteman; Lecture Atmos. 6250, 2012



Figures: Whiteman (2000) unless otherwise indicated

Video from Hoher Kasten





Provided by Reinhold Steinacker


11-10-99 480H
5:01:5E

Outline

- Introduction
- Topography
- Blocking/Obstruction of Air Masses
- Flow Over Mountains
- Flow Around Mountains
- Flow Through Passes, Channels and Gaps
- Other phenomena

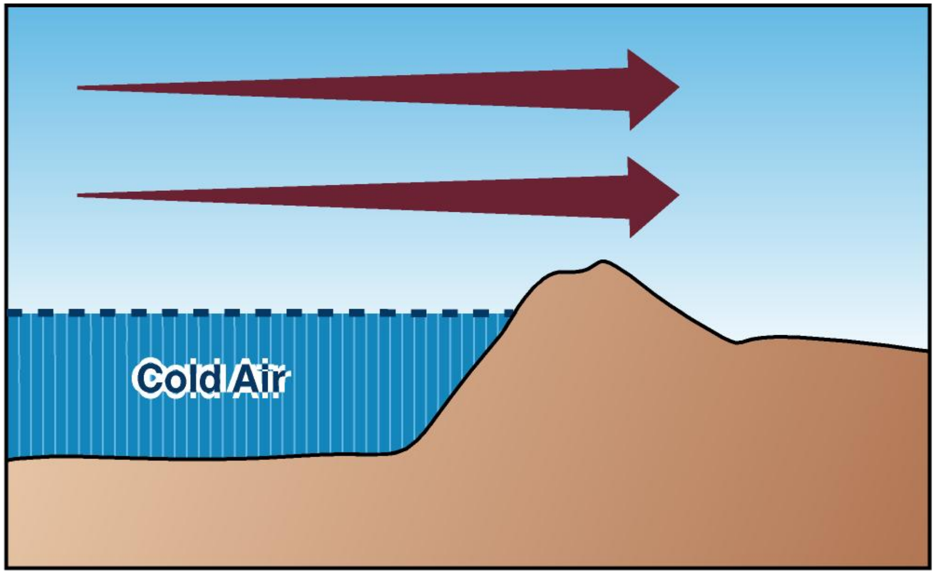
Introduction

- Two types of mountain winds
  - *Diurnal mountain winds* (thermally driven circulations): produced by temperature contrasts that form within mountains or between mountains and surrounding plains [this morning]
  - *Terrain-forced flows*: produced when large-scale winds are modified or channeled by underlying complex terrain
- 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.

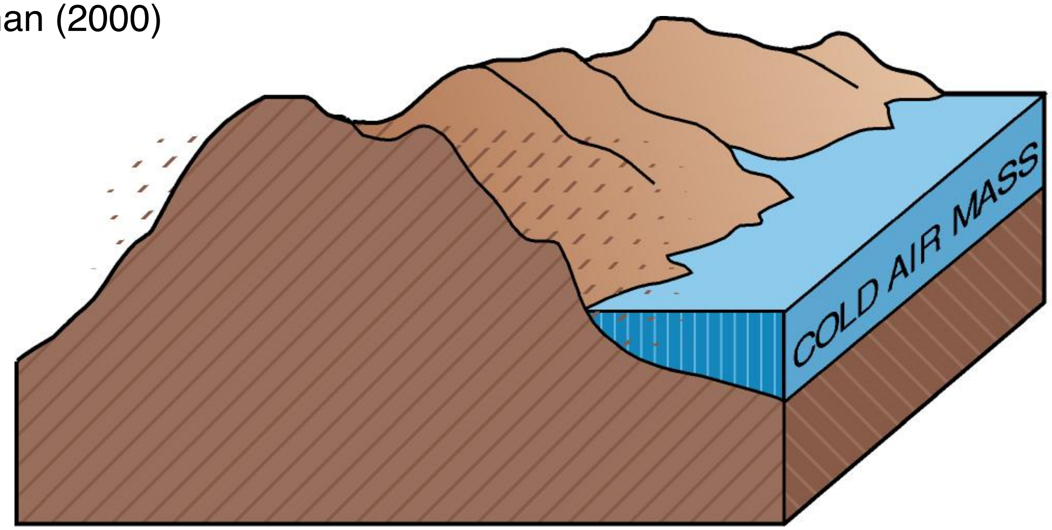
Three main variables determine the reaction of the approach flow with the terrain barrier:

- *Stability* of approaching air (unstable or neutral stability air can be easily forced over a barrier. The more stable, the more resistant to lifting. Concept of dividing streamline height.)
- *Wind speed* (Moderate to strong flows are necessary to produce TFFs. Therefore, most common in areas of cyclogenesis, low pressure, jet streams)
- *Topographic characteristics* of barrier …

Mountains as flow barriers



Whiteman (2000)

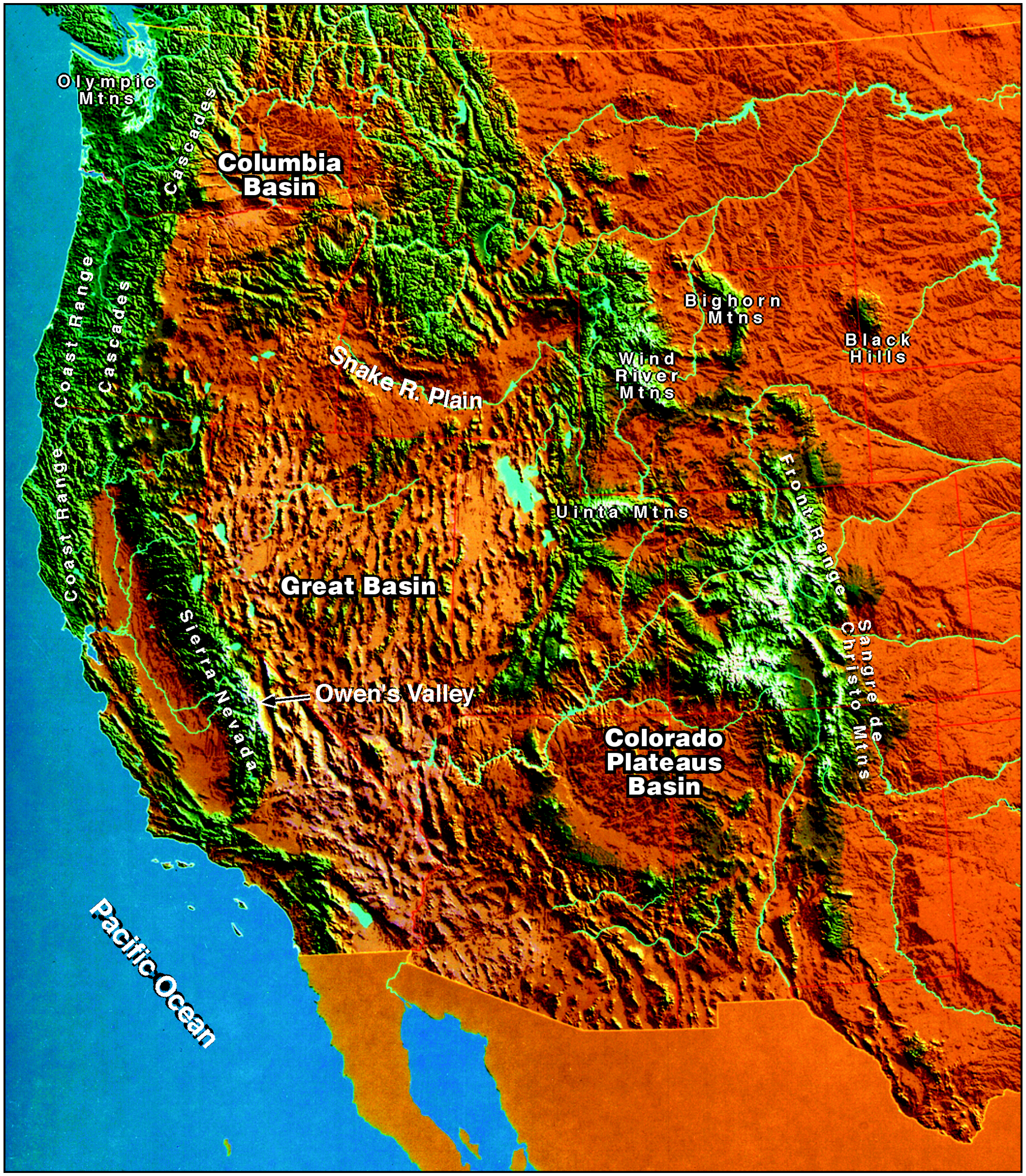


Blocked flow
New Zealand

Whiteman photo

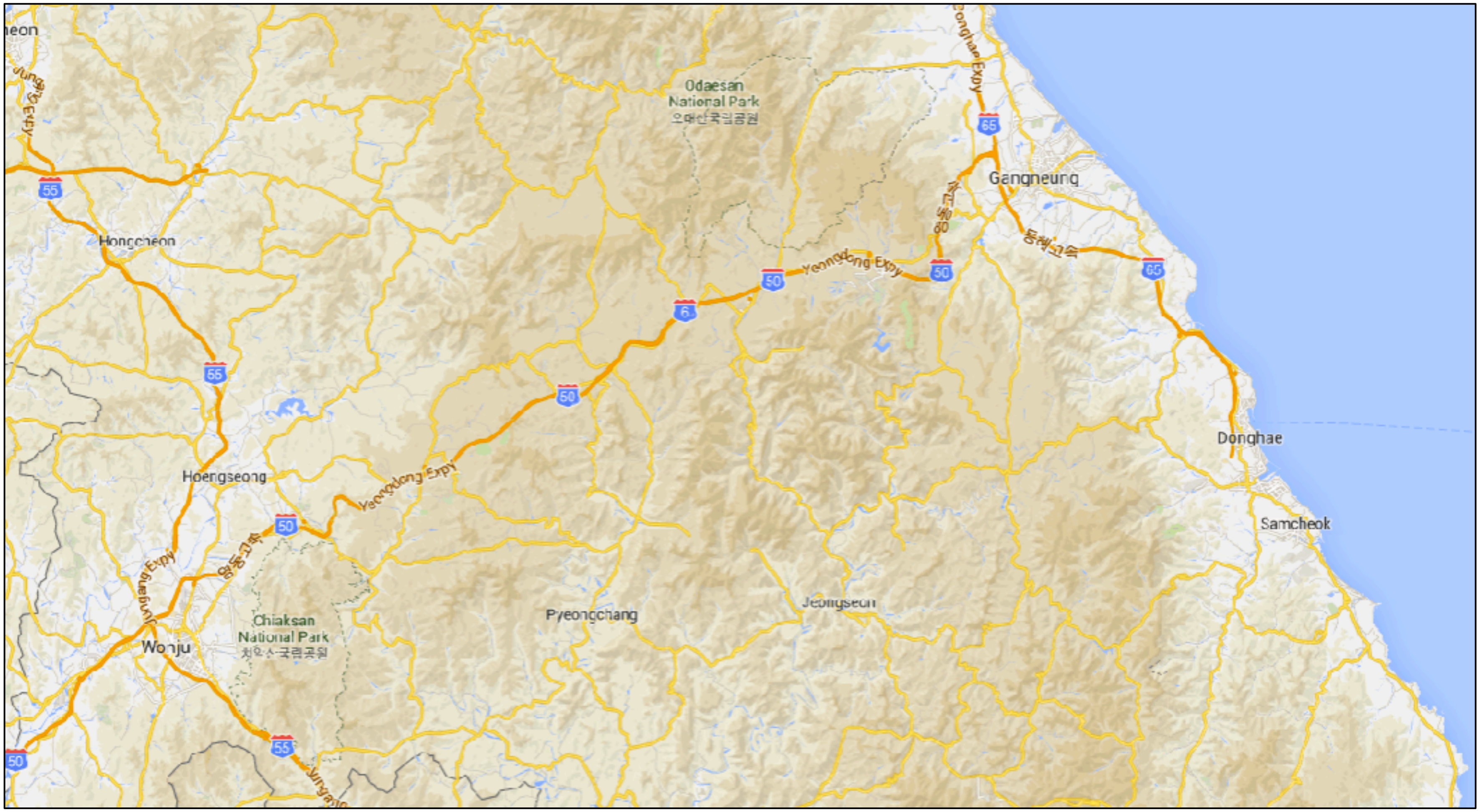
Topography

The Intermountain West



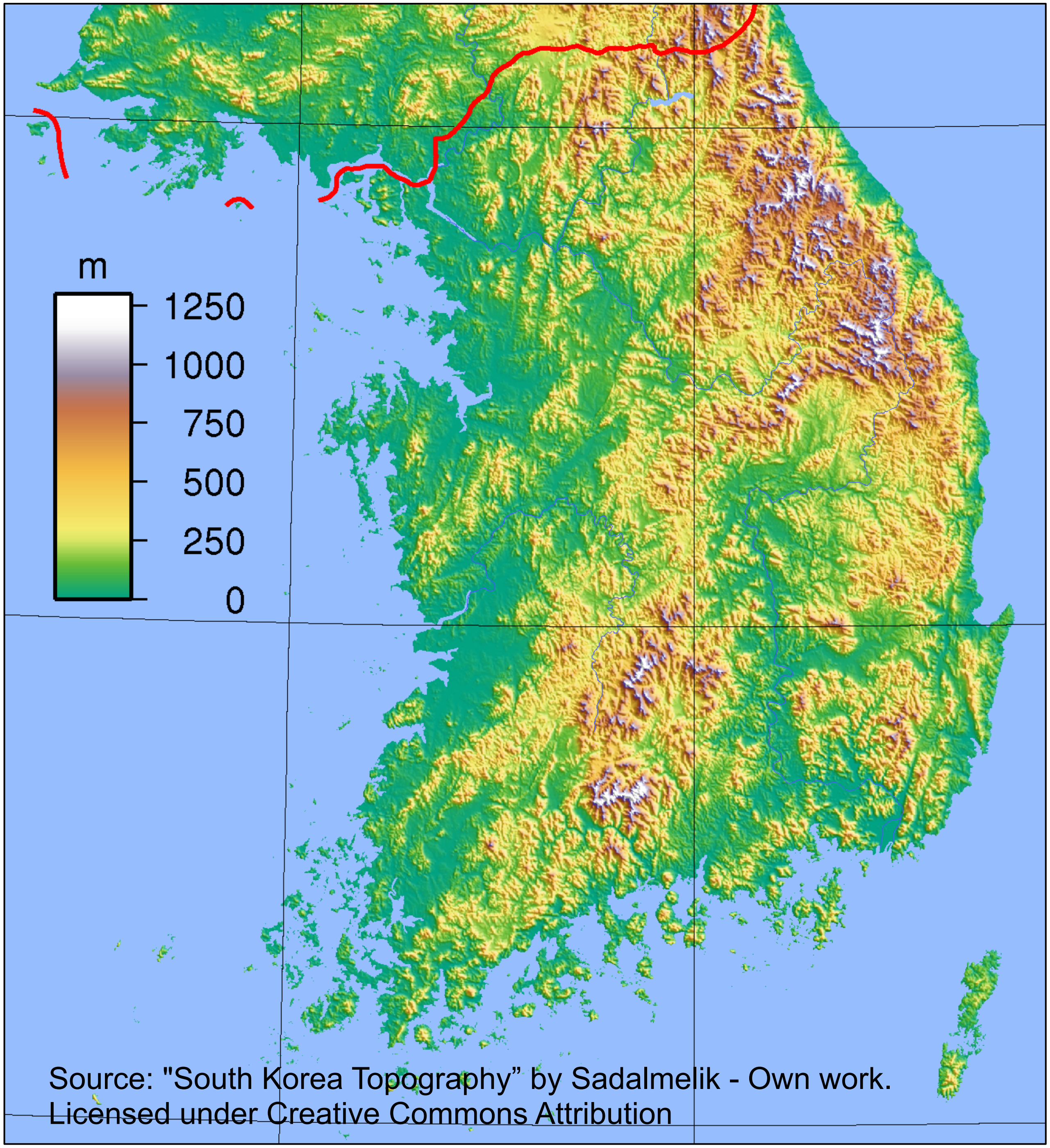
Whiteman (2000)

Topography



Odaesan
National Park
Gangneung
Hongcheon
Yeongdong Expy
Hoengseong
Donghae
Samcheok
Chiaksan
National Park
Wonju
Pyeongchang
Jeongseon

Topography



Own work by Ksiom; Wikimedia Commons

The Basics: Landforms associated with strong and weak surface winds

Expect high winds at sites:
Located in gaps, passes or gorges in areas with *strong pressure gradients*
Exposed directly to strong prevailing winds (summits, high windward or leeward slopes, high plains, elevated plateaus
Located downwind of smooth *fetches*
Expect low wind speeds at sites:
Protected from prevailing winds (low elevations in basins or deep valleys oriented perpendicular to prevailing winds)
Located upwind of mountain barriers or in intermountain basins where air masses are *blocked* by barrier
Located in areas of high *surface roughness* (forested, hilly terrain)

Wind variations with topographic characteristics, continued …

- Wind increases at the **crest of a mountain** (more so for triangular than for rounded or plateau-like hilltops)
- **Separation eddies** can form over steep cliffs or slopes on either the windward or leeward sides
- Speed is affected by **orientation of ridgeline** relative to approaching wind direction (concave, convex)
- Winds can be can be **channeled** through passes or gaps by small topographic features
- Sites low in valleys or basins are often **protected** from strongest winds, but if winds are very strong above valley, **eddies** can form in the valleys or basins bringing strong winds to valley floors.
- Wind speeds are slowed by high **roughness**
- Concept of 'effective topography'
- In complex terrain, winds respond to **landforms** (valleys, passes, plateaus, ridges, and basins) and **roughness elements** (peaks, terrain projections, trees, boulder, etc.)

Non-dimensional numbers

1) Rossby Number R_0

$R_o = U/fL$

U: cross-barrier wind speed
f: Coriolis parameter
(midlatitudes ~10^{-4} s^{-1})
L: Mountain barrier width

2) Non-dimensional Mountain Height ε

aka “inverse Froude number” (more on Froude number later)

$\varepsilon = h_0 N/U$

U: cross-barrier wind speed
N: Brunt-Väisälä Frequency
h_0: Mountain Height

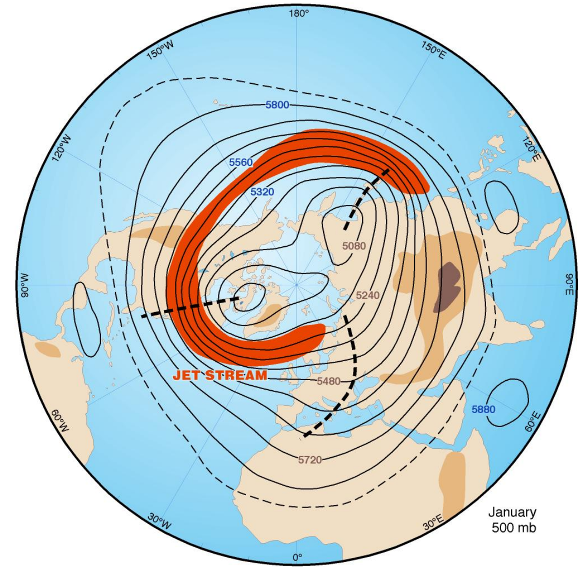
$$N \equiv \sqrt{\frac{g}{\theta}\frac{d\theta}{dz}}$$

Reinecke and Durran (2008)

Rossby Number (R_o); $R_o = U/fL$

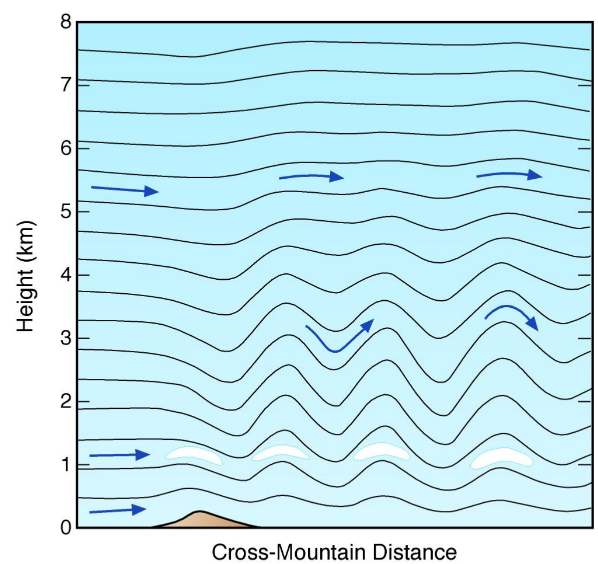
<u>$R_o << 1$</u>

Air takes >> f^{-1} to cross barrier
Coriolis force dominates
Parcels displaced horizontally
Rossby waves produced



<u>$R_o \geq 1$</u>

Coriolis effects negligible
Buoyancy force dominates
Parcels displaced vertically
Mountain waves produced



Images: Whiteman (2000)

Non-Dimensional Mountain Height ε $\varepsilon = h_0 N/U$

"Will the air flow over the barrier?"

ε corresponds to the ratio of the potential energy required to lift air mass over barrier $(N^2 h_0^2/2)$ to the kinetic energy of incoming flow $(U^2/2)$

$$\varepsilon = h_0 N/U = [(N^2 h_0^2/2)/(U^2/2)]^{1/2}$$

ε > 1: Inertia too weak and the flow is ***blocked***

High stability, large mountain; weak cross-barrier flow

ε < 1: Inertia overcomes stability, ***flow surmounts barrier***

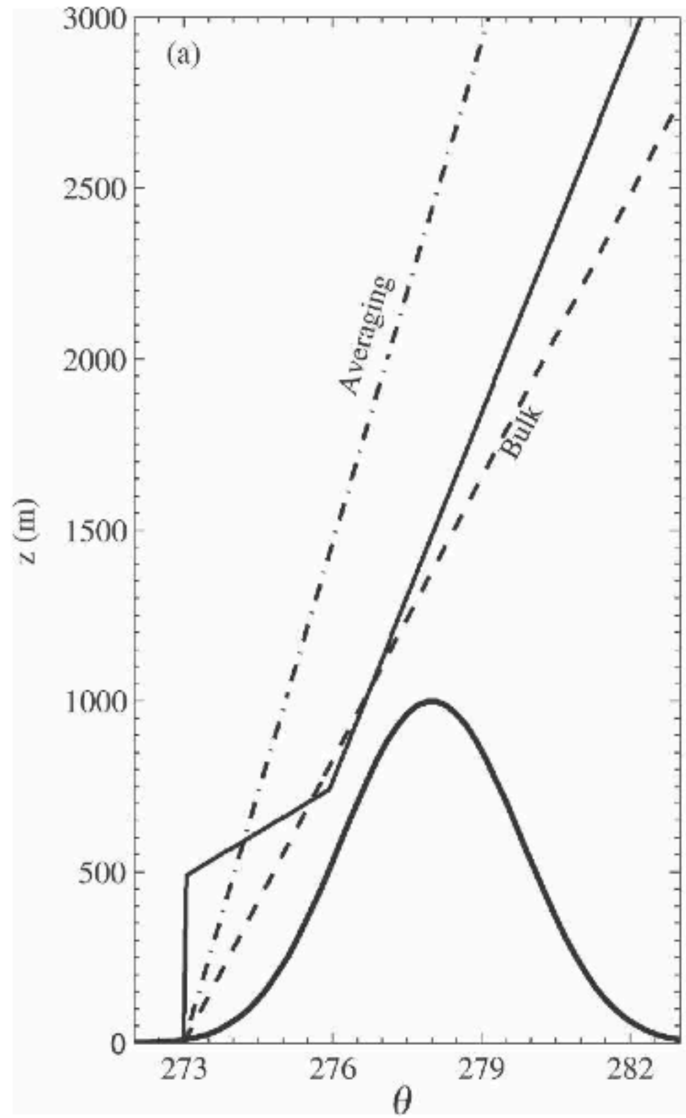
Low stability, small mountain, strong cross-barrier flow

Which is most likely to result in a transition from Blocking to flow over the mountain?

- Flow speed and stability decreasing
- Flow speed and stability increasing
- Flow speed increasing and stability decreasing
- Flow speed decreasing and stability increasing

Non-Dimensional Mountain Height ε

- Useful concepts, but assume uniform upstream wind, *U*, and stratification, *N*
- No variations horizontally or vertically
- Assume no parcel accelerations from large-scale flow or flow adjustment to orography
- Difficult to apply in practice due to non-uniform nature of real world flows and stratification

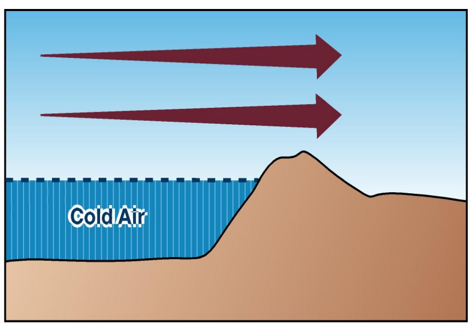


See: Reinecke and Durran (2008)

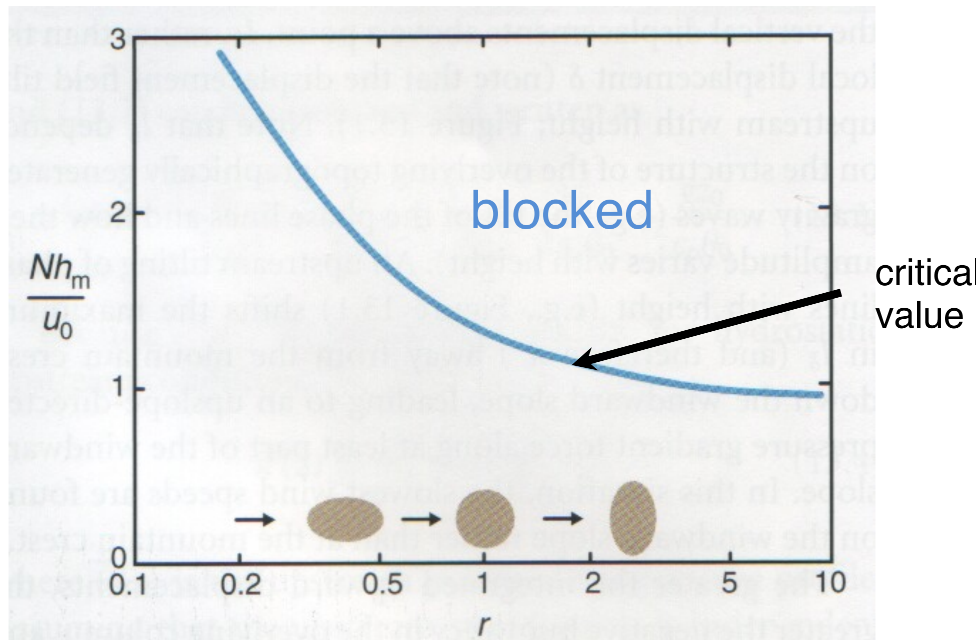
Blocking / Obstruction of Air Masses

- These processes affect stable air masses and occur most frequently in winter.
- The blocked flow upwind of a barrier is usually shallower than the barrier depth. Air above the blocked flow layer may have no difficulty surmounting the barrier and may respond to the ‘effective topography’ including the blocked air mass.
- Onset and cessation of blocking may be abrupt.

Stagnation (blue line) as a function of nondimensional mountain height and mountain aspect ratio r.



r = crosswise / streamwise dimensions



Markowski & Richardson (2010) / Smith 1990

Flow Over Mountains

Approaching flows tends to go over mountains if

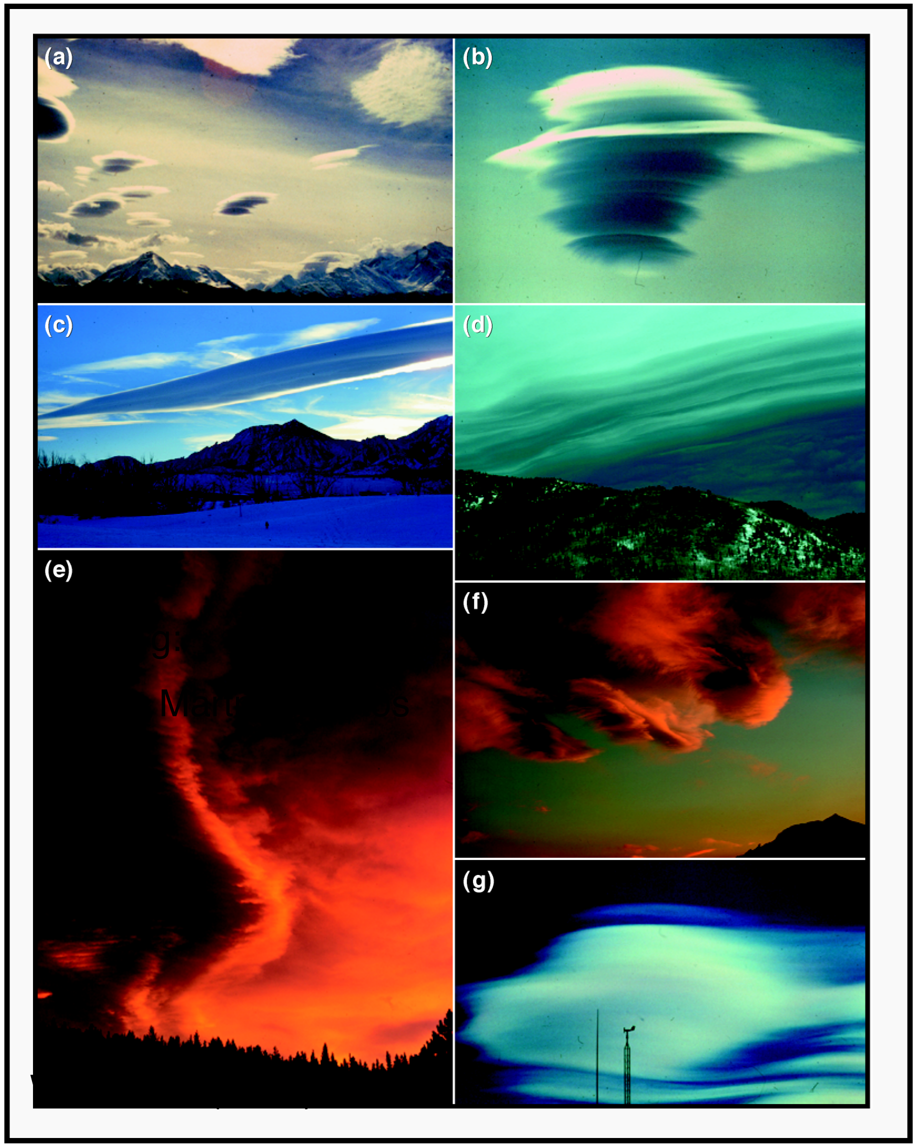
1. Barrier is long,
2. Cross-barrier wind component is strong, and
3. Flow is unstable, neutral or only weakly stable. Common in North American mountain ranges.

Flow over a mountain can be ascertained by **presence of**

- Lenticular clouds
- Cap clouds
- Banner clouds
- Rotors
- Foehn wall
- Chinook arch
- Billow clouds
- Blowing snow,
- Cornice buildup
- Blowing dust
- Downslope windstorms, etc…

30 September 30, 2014, ~ 2 pm

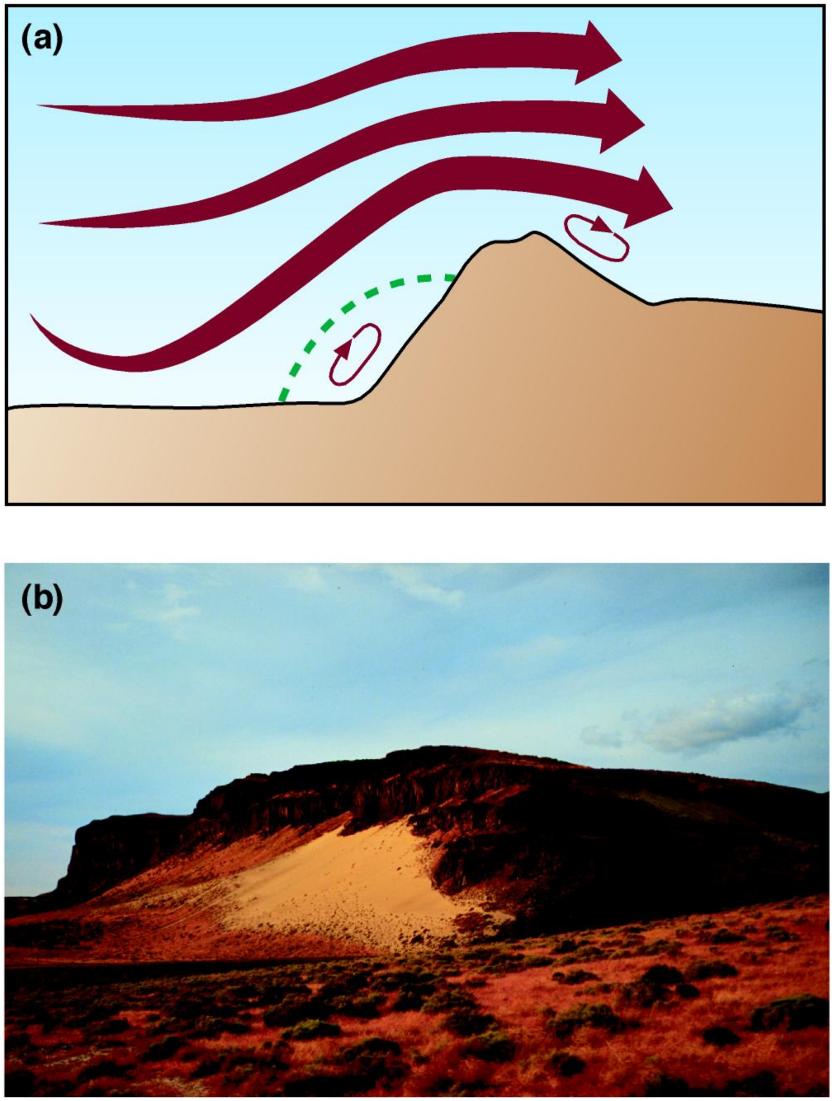
Lenticular and wave clouds



The presence of *orographic waves* is often indicated by lenticular or wave clouds.

Gravity waves that form over mountains are called *mountain waves*. They have a tendency to propagate vertically and can be found not only at low levels over hills but throughout the troposphere and even into the stratosphere.

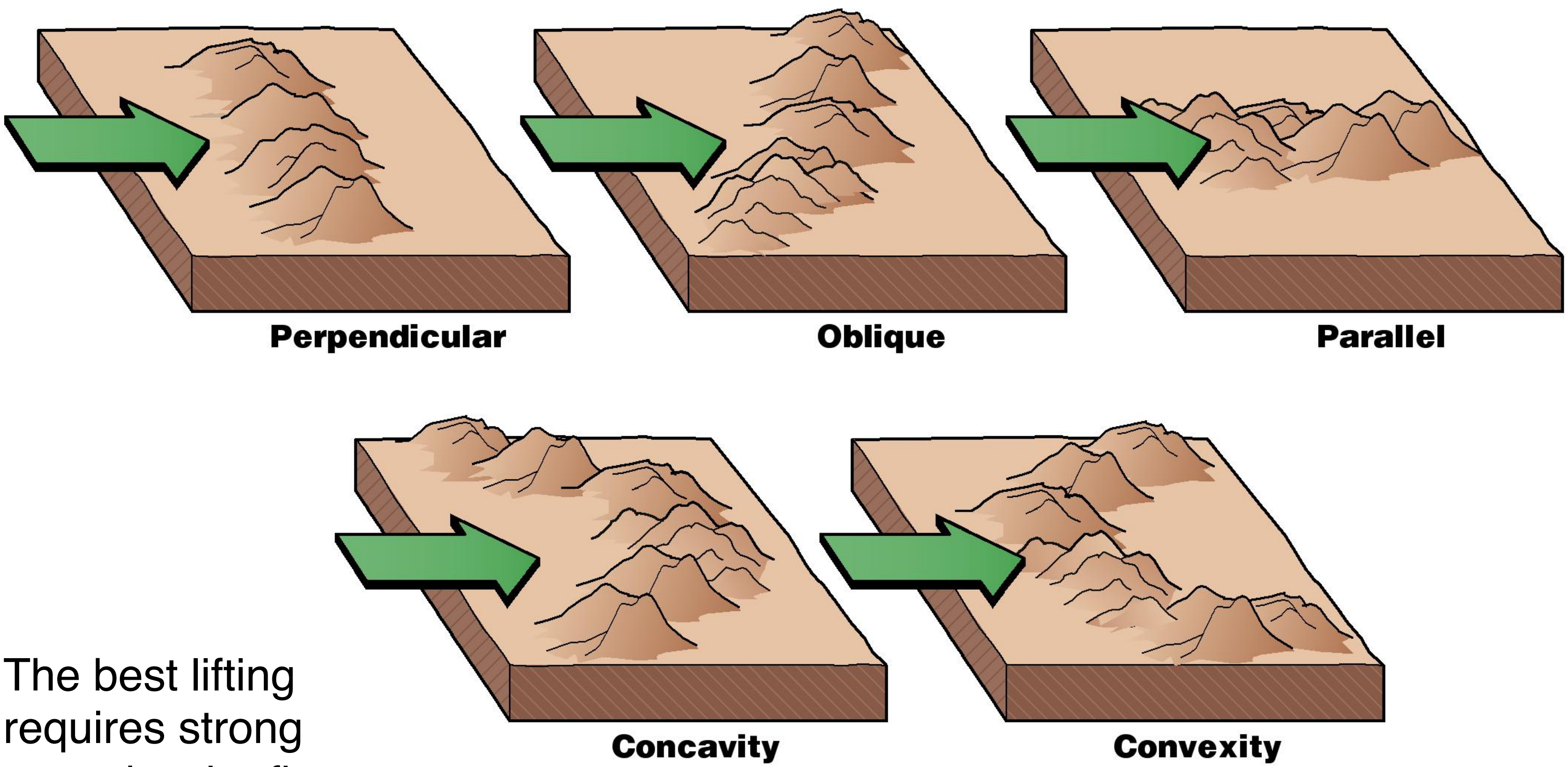
Lee waves, on the other hand, are often confined or trapped in the lee of a barrier by a smooth horizontal flow above. There is a continuum between lee and mountain waves, but mountain waves are generally higher, with longer wavelengths and smaller amplitudes.



Separation eddies

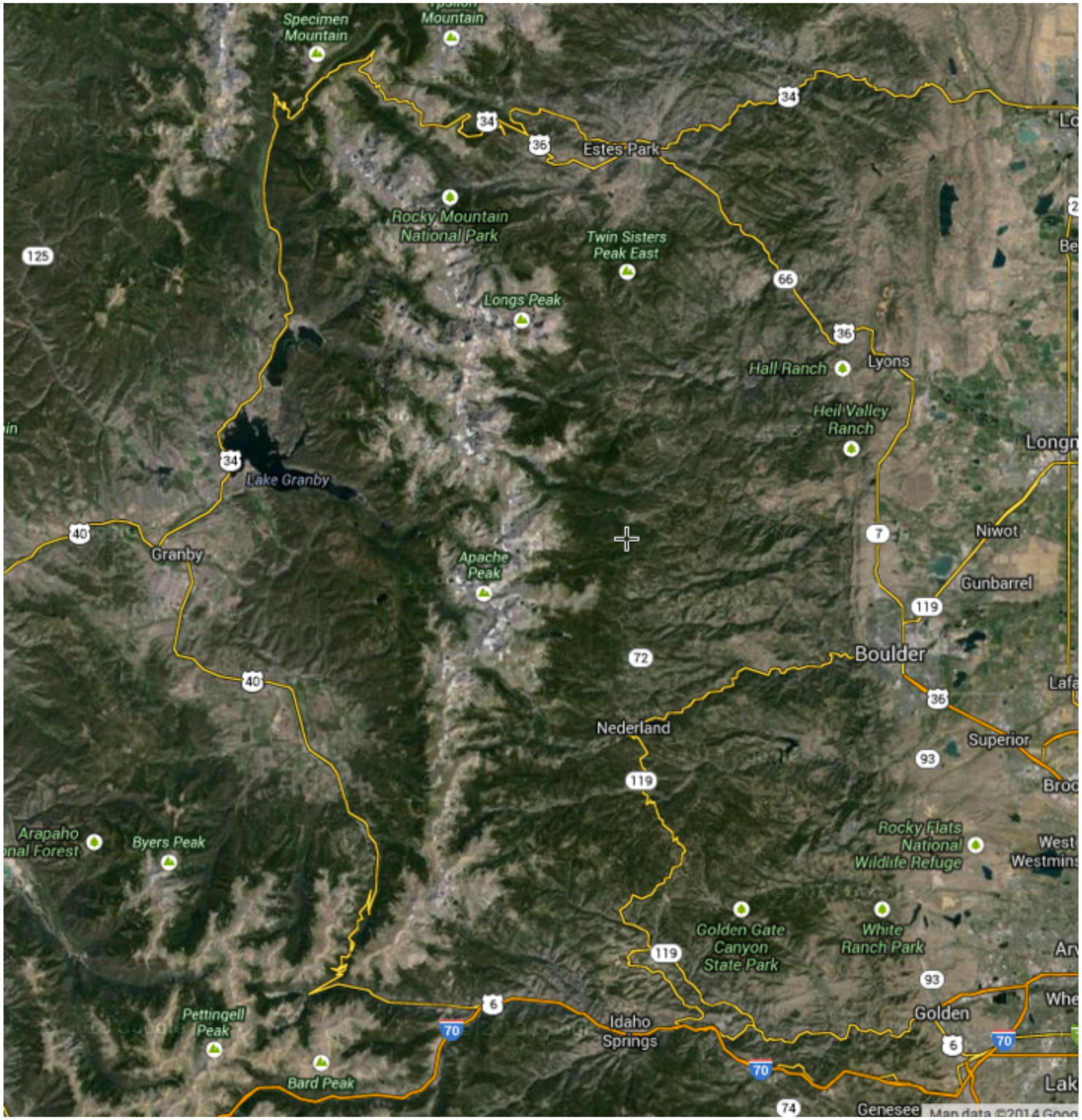
Whiteman (2000)

Angle of attack



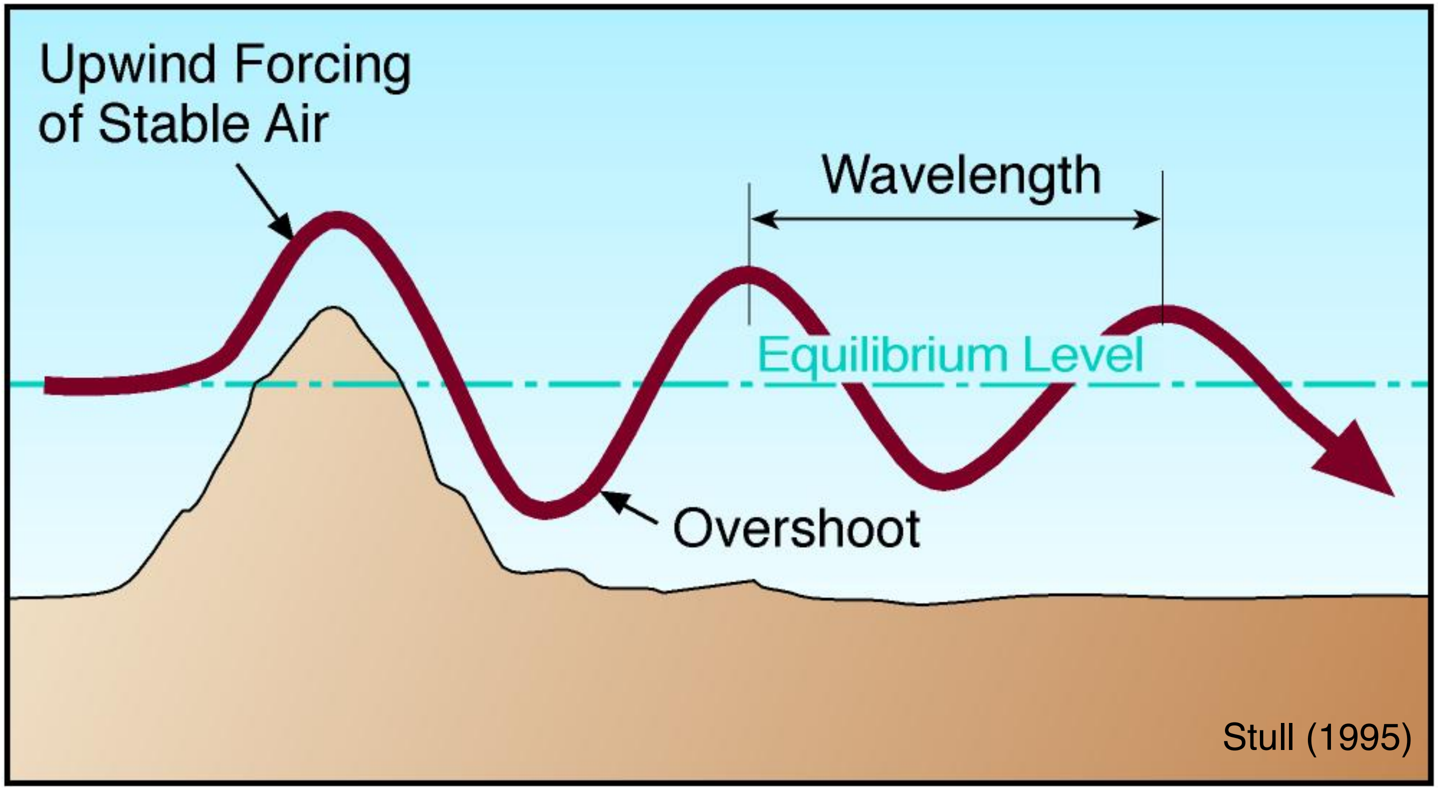
The best lifting requires strong cross-barrier flow

Whiteman (2000)



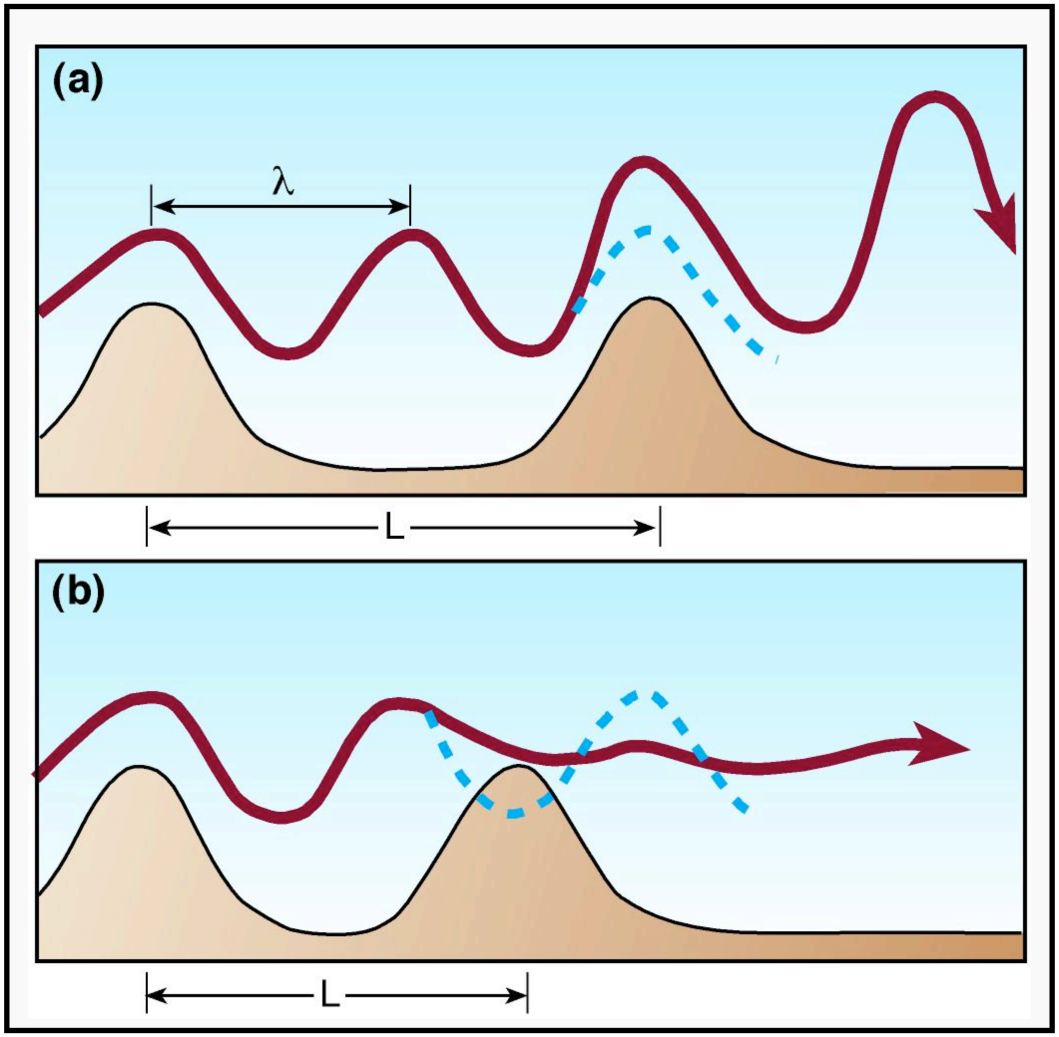
Boulder,
Colorado

Lee waves



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



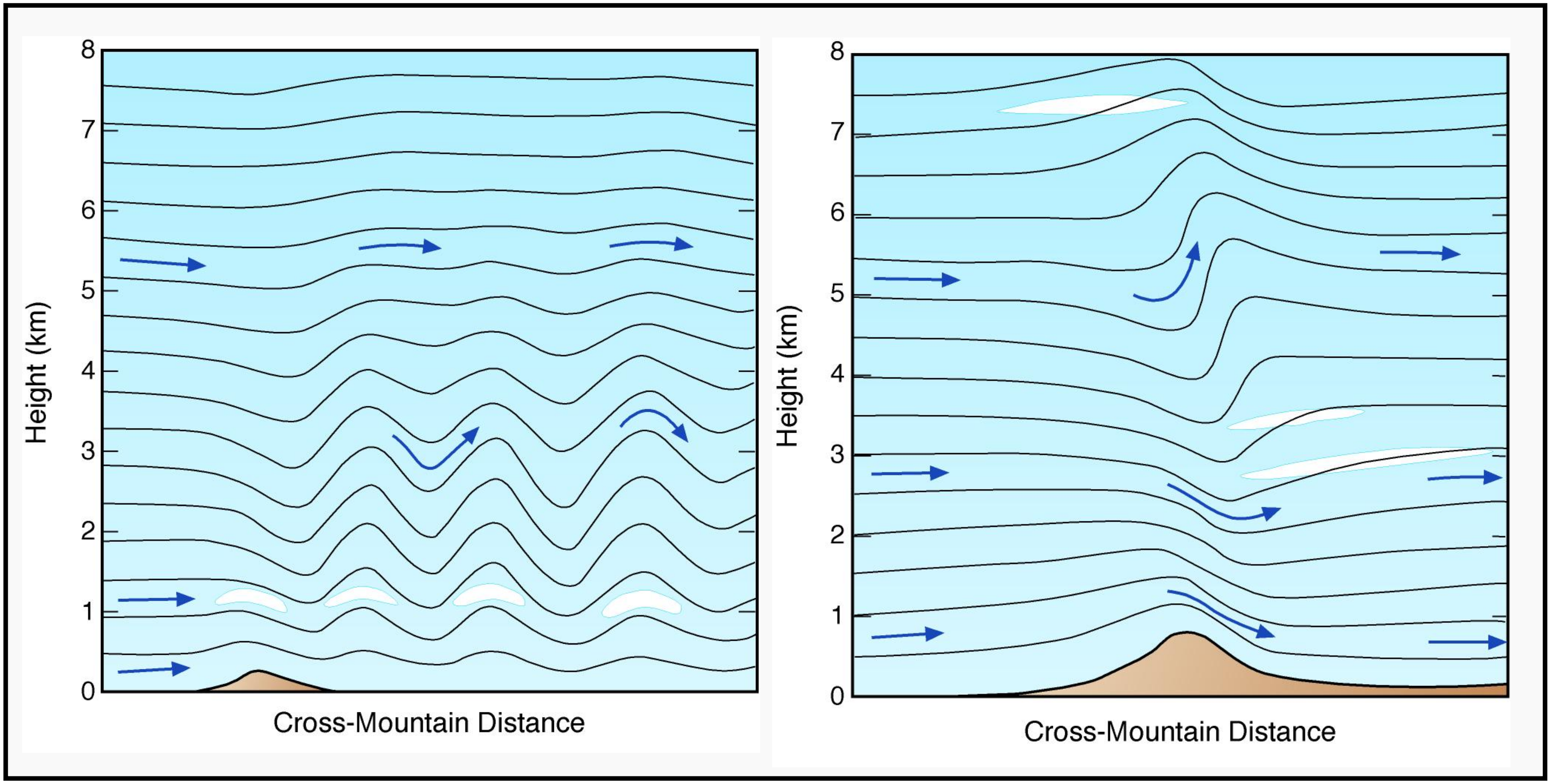
Bérenger & Gerbier (1956)

If the flow crosses more than one ridge crest, the waves generated by the first ridge can be amplified (*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.

Mayr & Gohm (2000)

Trapped and vertically propagating lee waves



Carney et al. (1996)

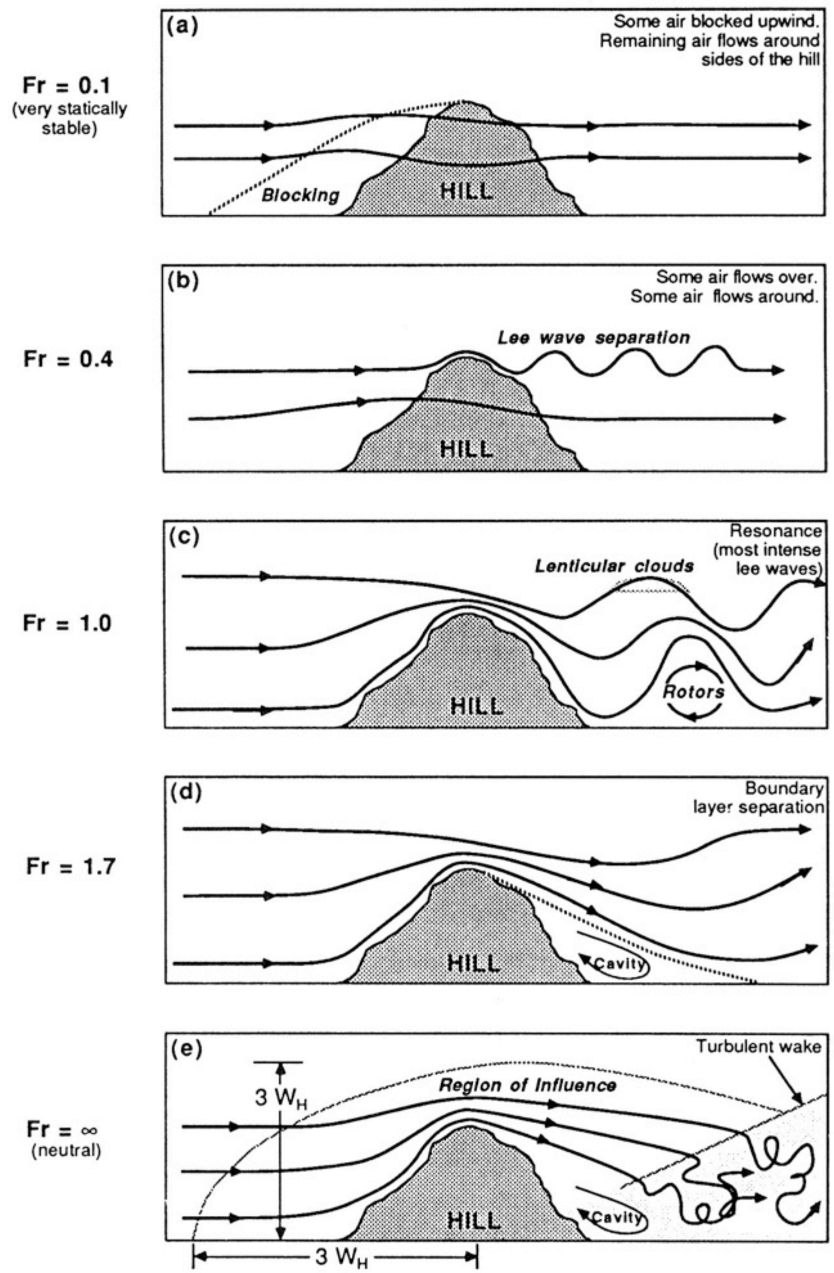


Fig. 14.14 Idealized flow over an isolated hill. The Froude number (Fr) compares the natural wavelength of the air to the width of the hill (W_H).

Froude number

$$Fr = (2\pi U) / (N\ 2W)$$

Natural wavelength of air / effective wavelength of obstacle.

U: mean cross-barrier speed
N: Brunt-Väisälä Frequency
W: Length of obstacle

Stull (1988)

The influence of an elevated inversion in flow over a hill

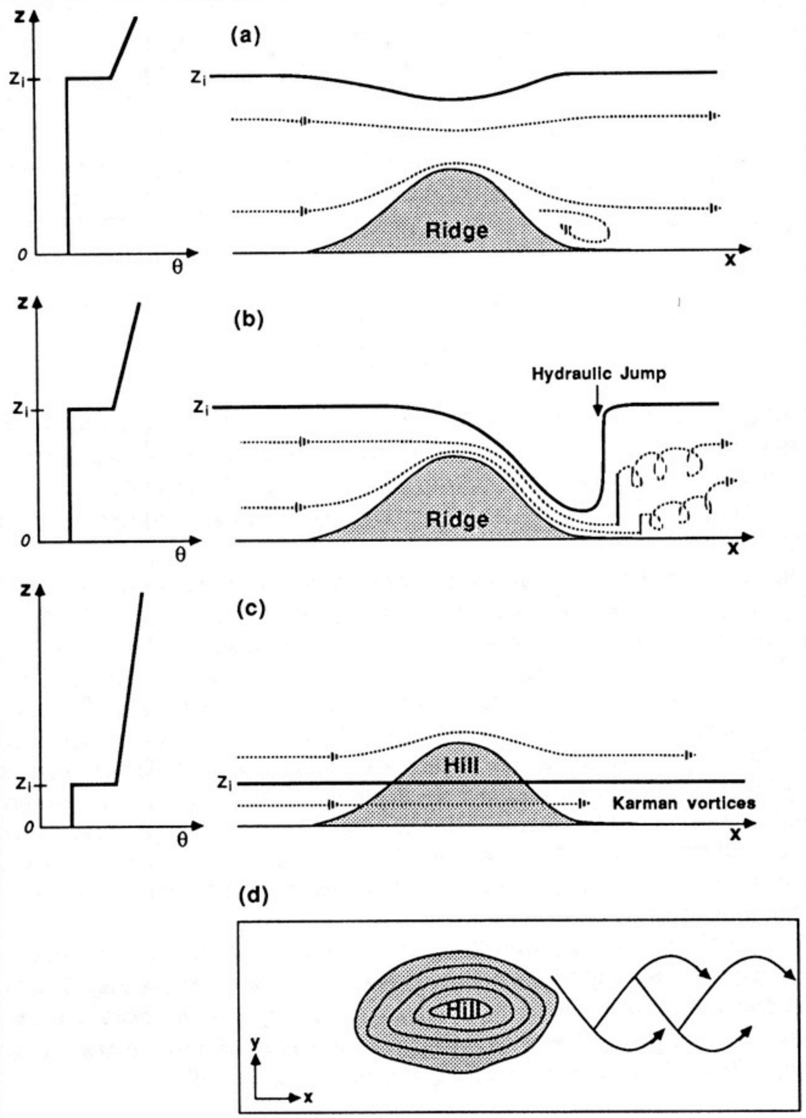
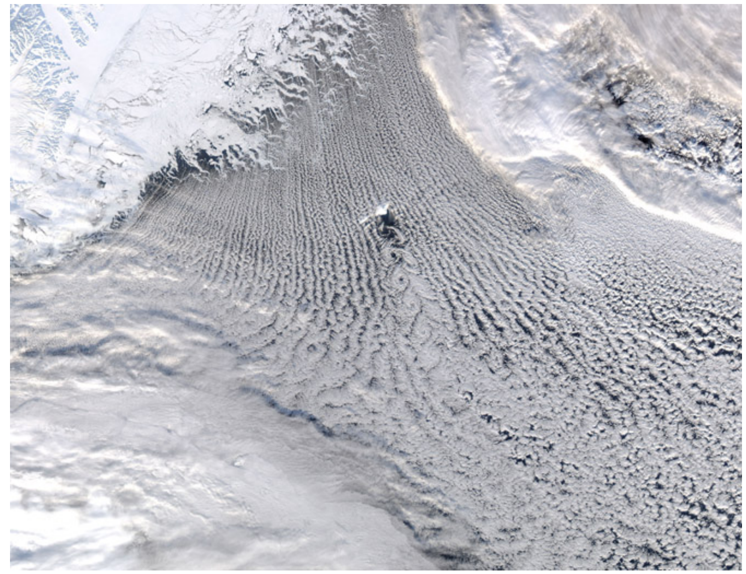
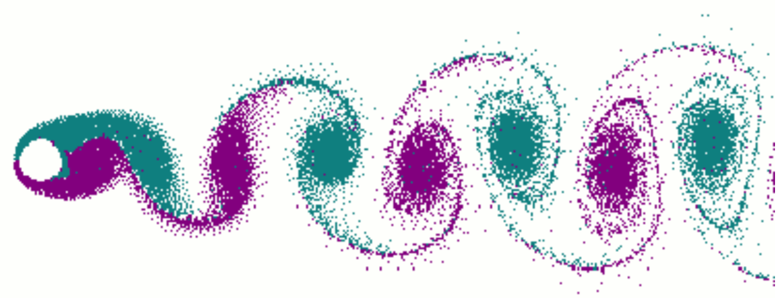


Fig. 14.19 (a) Bernoulli effect as flow accelerates over a 2-D ridge; (b) hydraulic jump downwind of a 2-D ridge for greater ambient wind speed; (c) flow around the sides of an isolated hill; and (d) Karman vortex street downwind of the hill from (c). (After Hunt, 1980.)

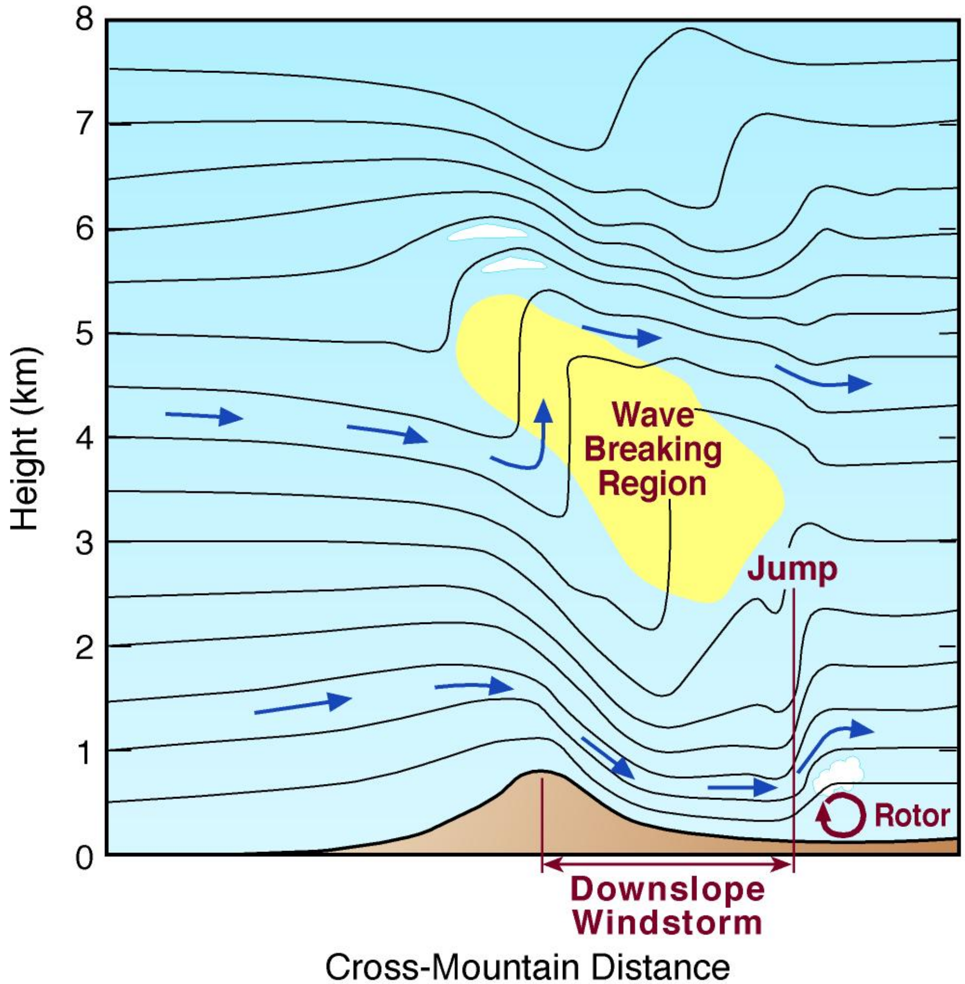


Jan Mayen Island, Greenland Sea



Stull (1988)

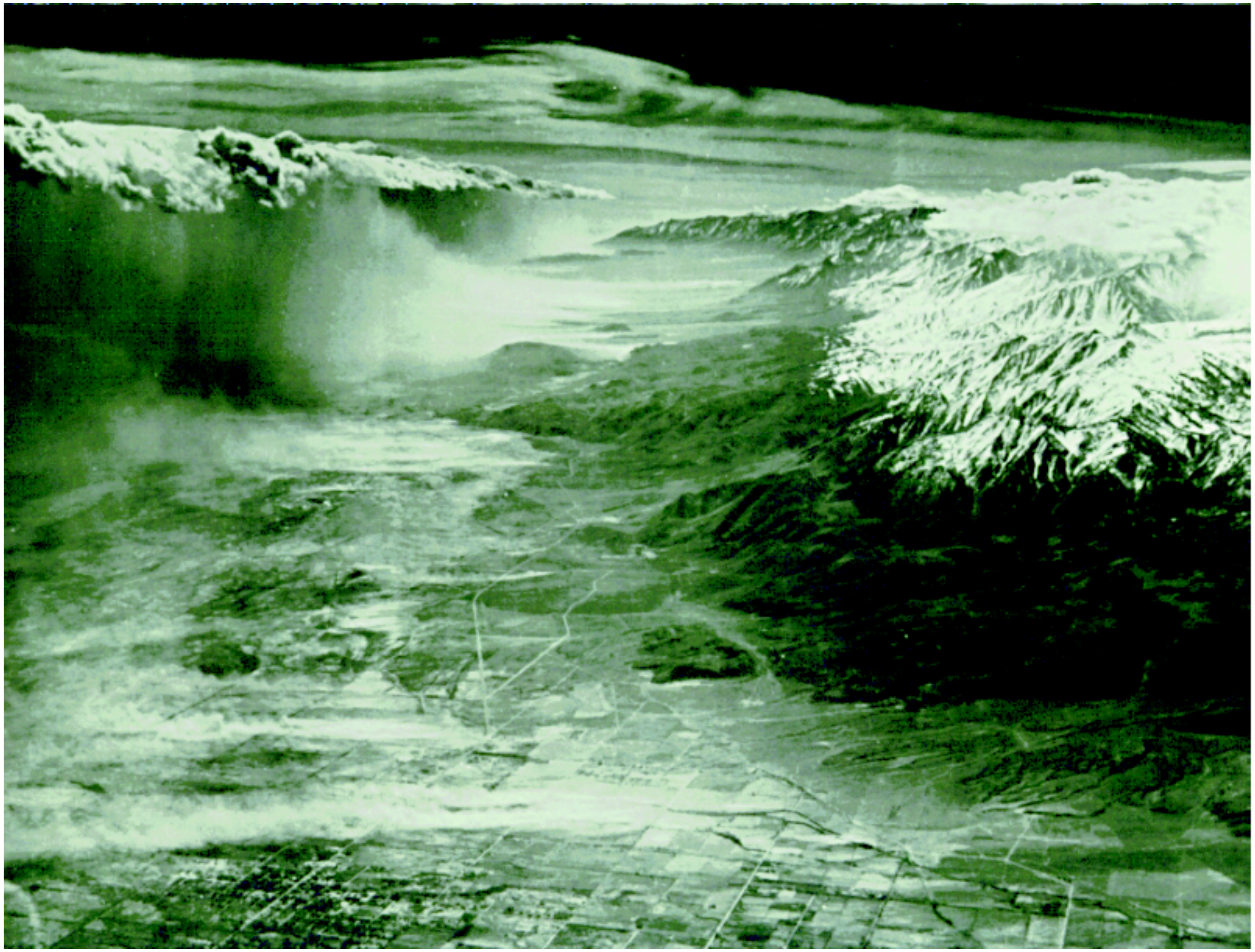
Downslope windstorm



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.

Whiteman (2000) adapted from Carney et al. (1996)

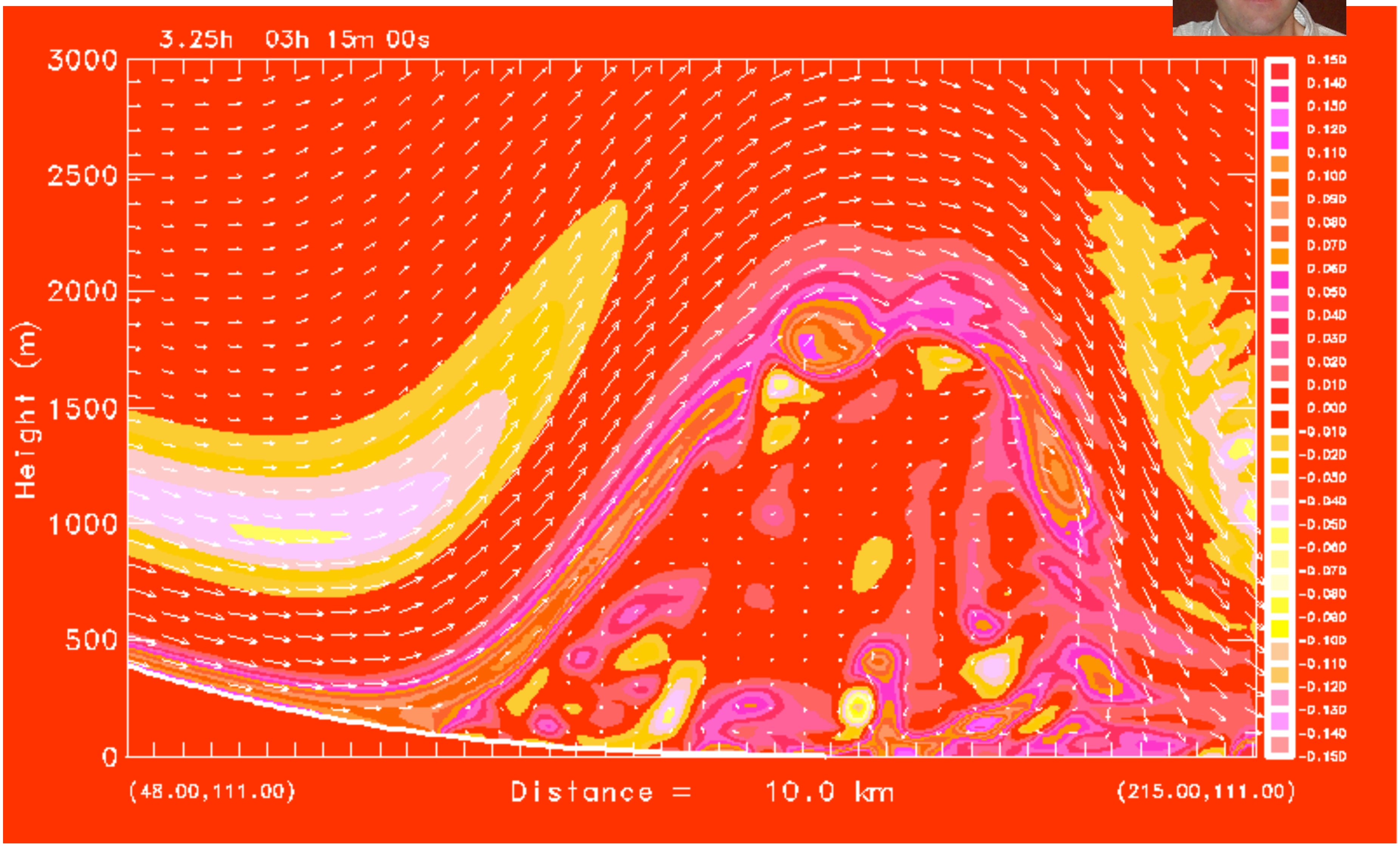
The Sierra Wave



USAF, Robert Symons photo

© Jim Doyle

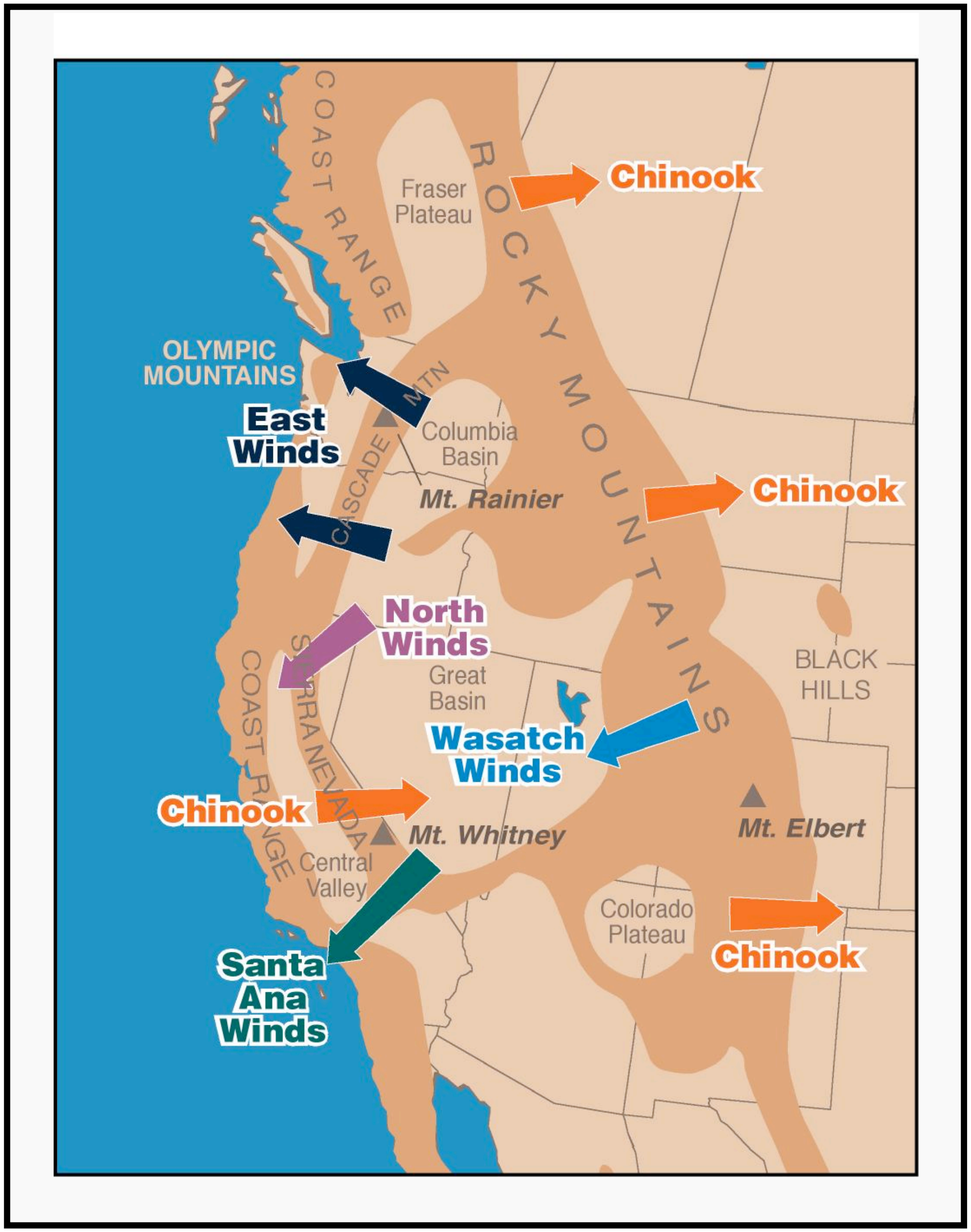
3-D rotor simulation



Horizontal vorticity (s^{-1})

Rotor flow movie, Falkland Islands

Prof. Stephen Mobbs, Umiversity of Leeds, UK



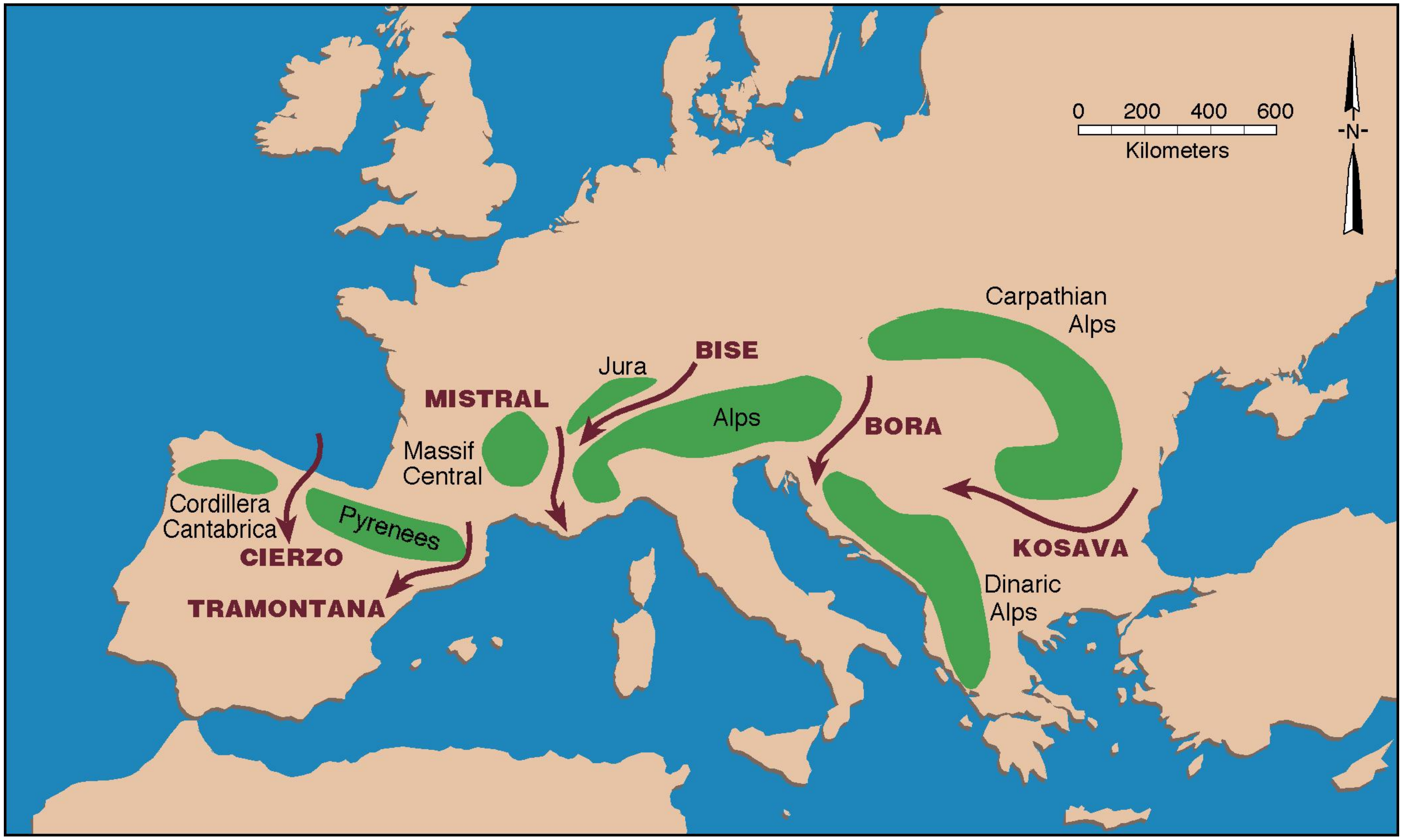
Whiteman (2000), adapted from Schroeder & Buck (1970)

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 or canyon winds - are of two types. Some come through gaps in the Wasatch ridgeline, affecting primarily the canyon exits. Others (less common) affect a more or less contiguous zone along the foothills. These are probably produced by strong mountain waves or hydraulic jumps.

Named Alpine windstorms



Whiteman (2000), adapted from Wanner & Furger (1990)

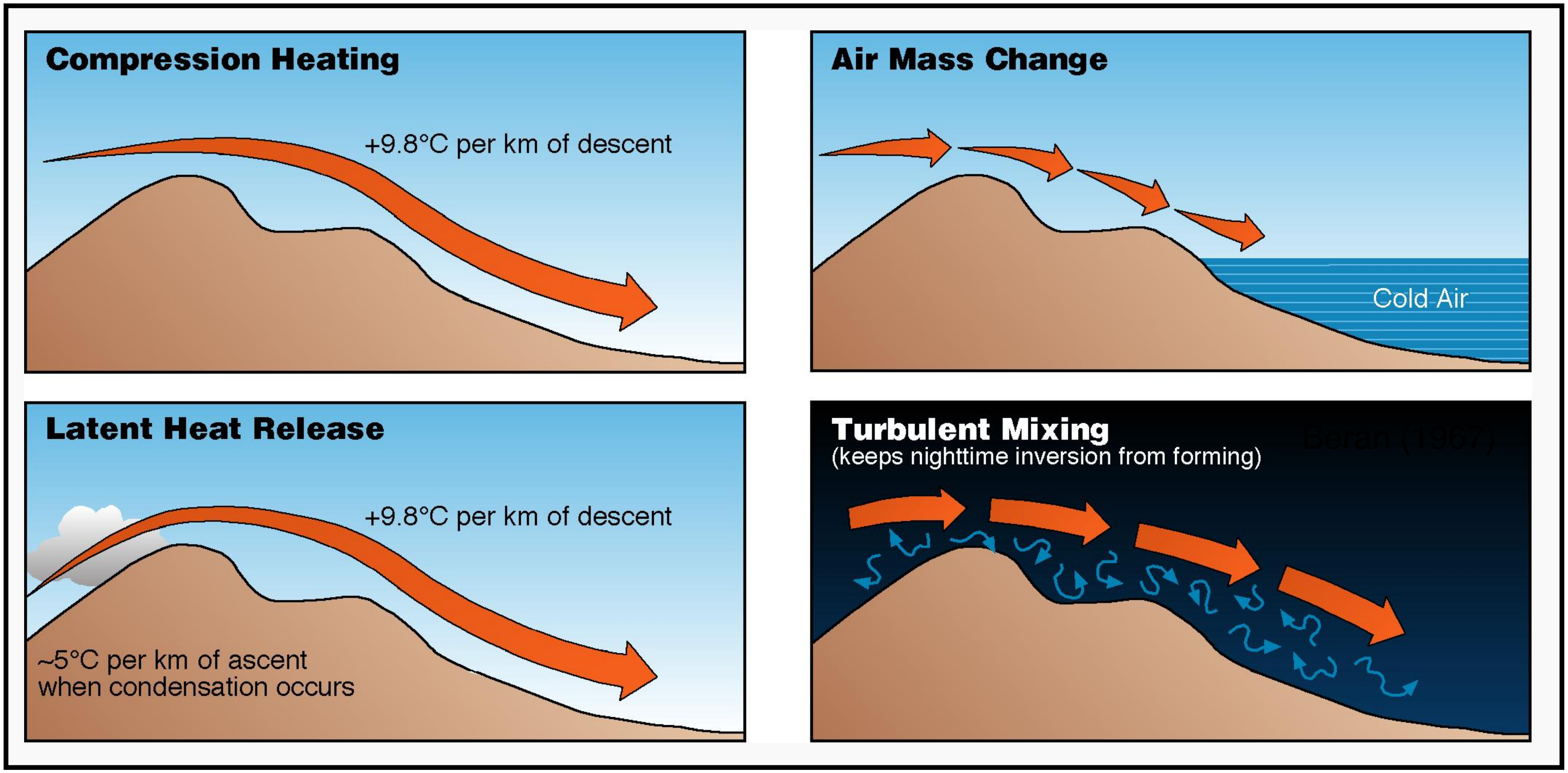
Heinz Wanner

Markus Furger

Downslope windstorms - Bora, Foehn, Chinook

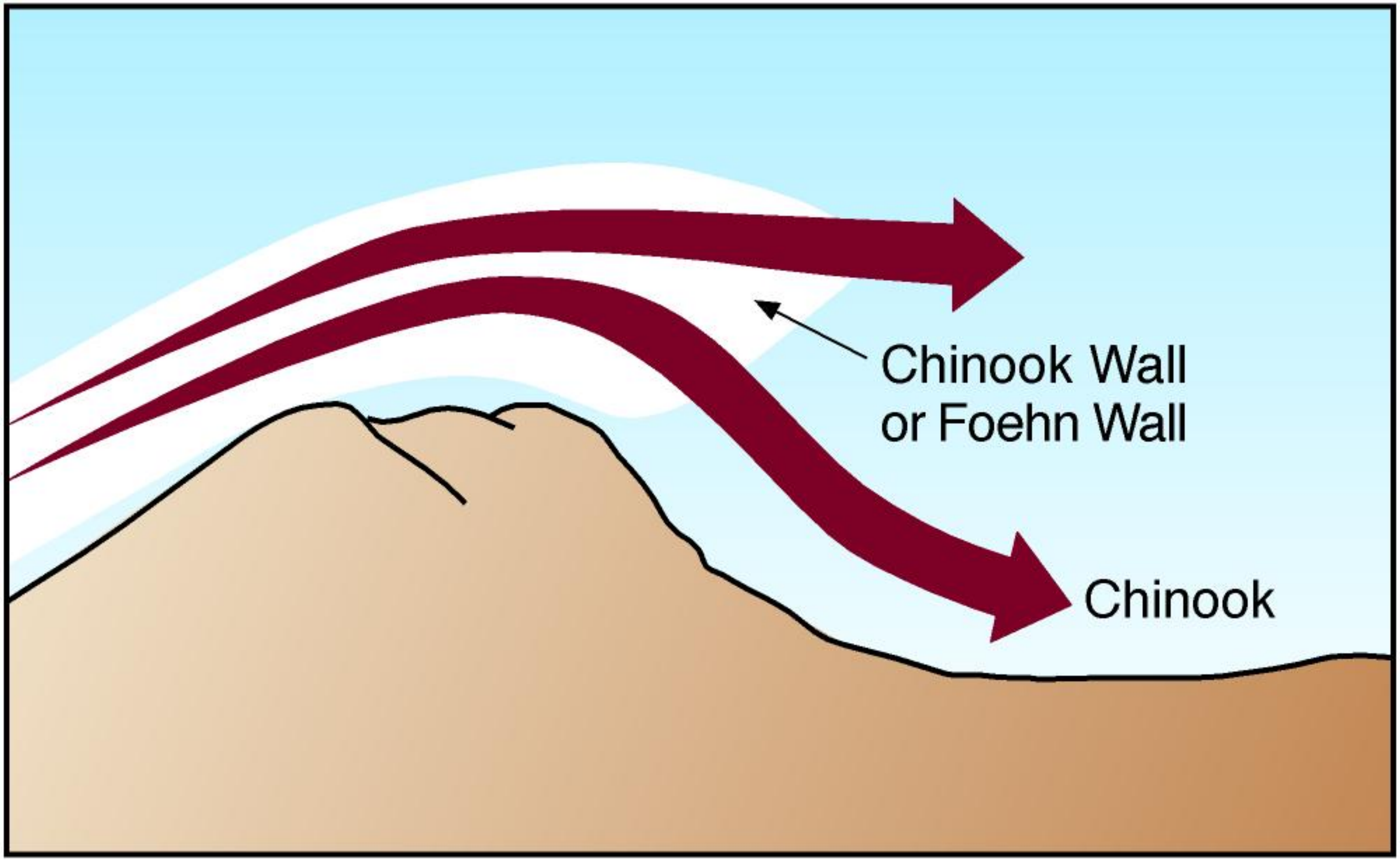
- Are associated with large amplitude lee waves
- Form on the lee side of high-relief mountain barriers when a stable air mass is carried across the mountains by strong cross-barrier winds
- Strong winds are caused by intense surface pressure gradients (high upwind, low pressure trough downwind). Pressure difference is intensified by lee subsidence which produces warming and lower pressure.
- Elevated inversion layers near and just above mountaintop levels appear to play an important role.
- Occur primarily in winter
- 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.

Four Chinook mechanisms



Four factors contribute to the warmth and dryness of Chinook winds

Chinook wall



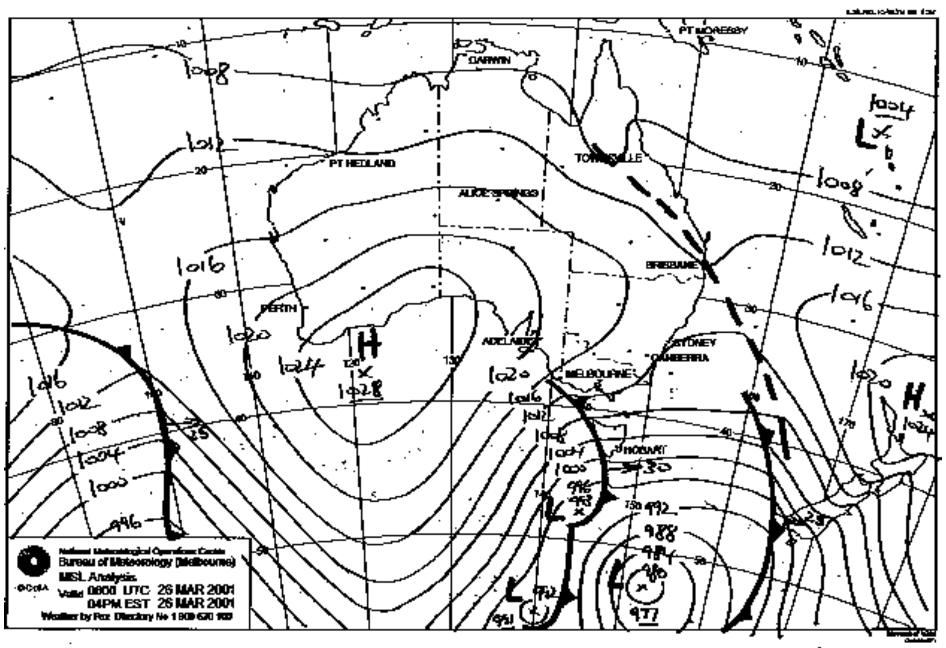
Whiteman (2000)

Chinook wall cloud, RMNP, CO

B. Martner photo

NW arch, Canterbury Plains, Christchurch, NZ

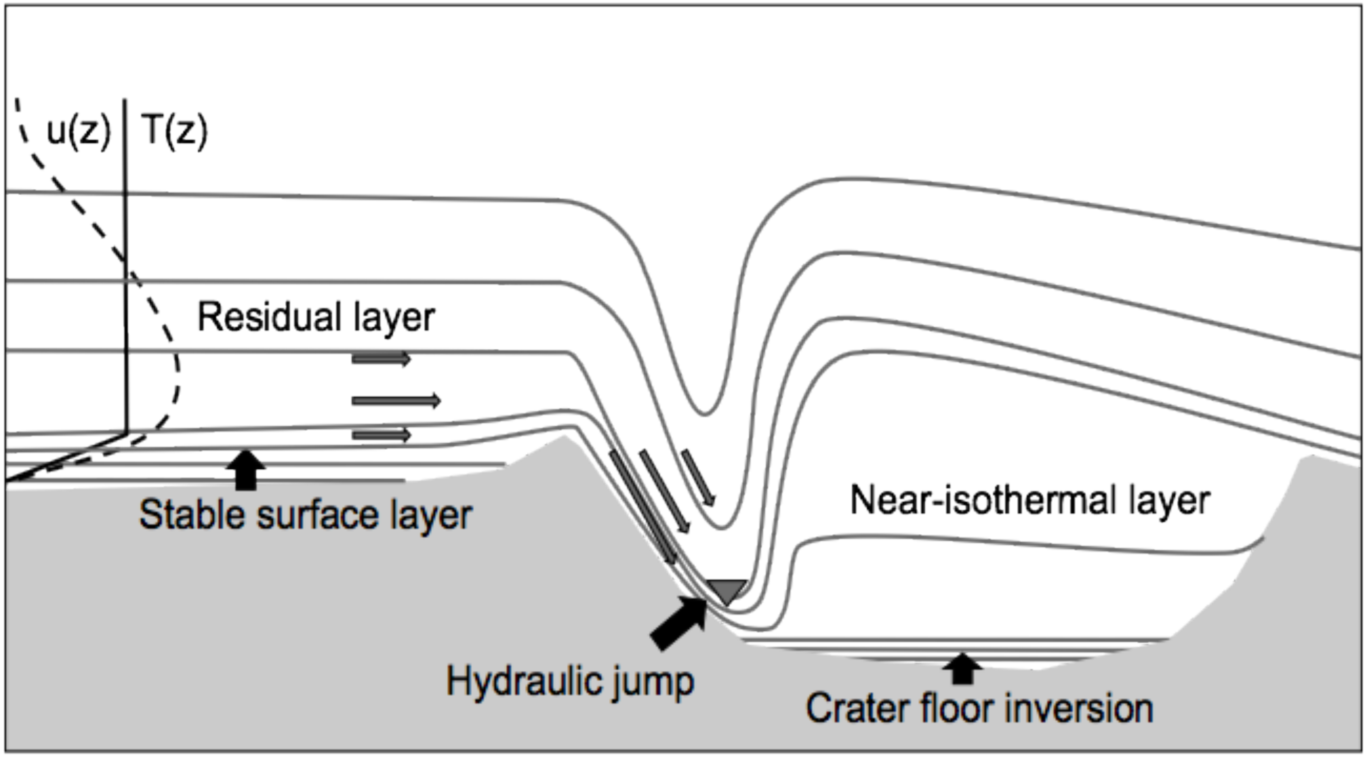
Whiteman photo



26 Mar 01, 0800 UTC

Andy Sturman

METCRAX-II / Conceptual model

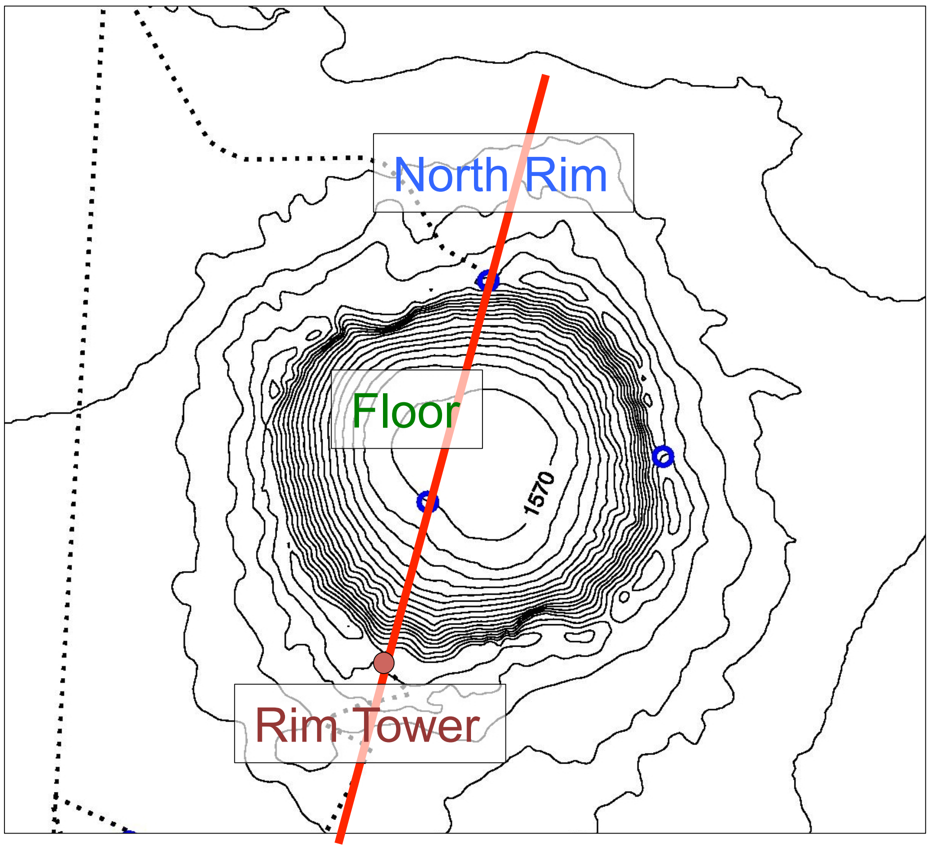


- During METCRAX-I in 2006 we found that intermittent **downslope-windstorm-type flows** developed over the crater's SW sidewall on clear, undisturbed nights. (See Adler et al. 2012)

- METCRAX II, is investigating these flows. Laboratory-like experiment – continuous observations of approach flow and response of crater atmosphere.

Dual-Doppler Retrieval

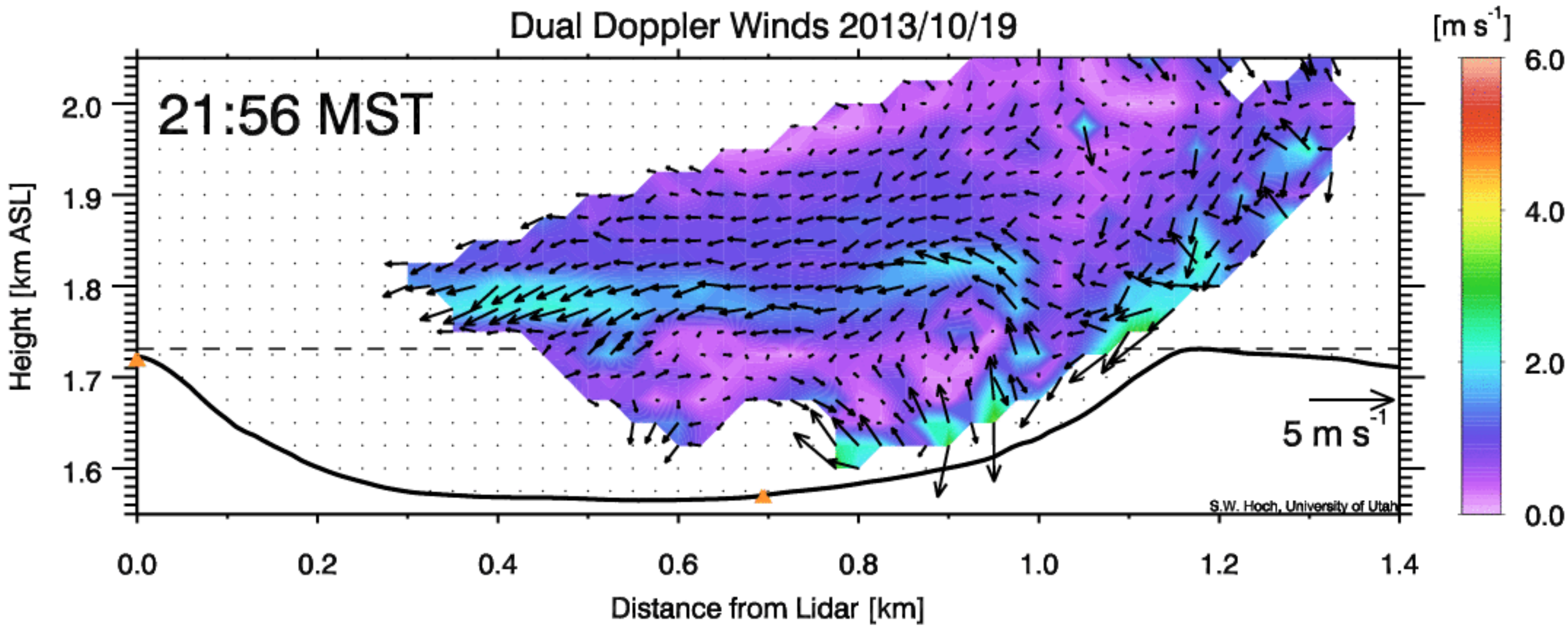
IOP-4 (19-20 October 2013)



Scans within a 2-3 min time window are averaged and used in a dual doppler analysis.

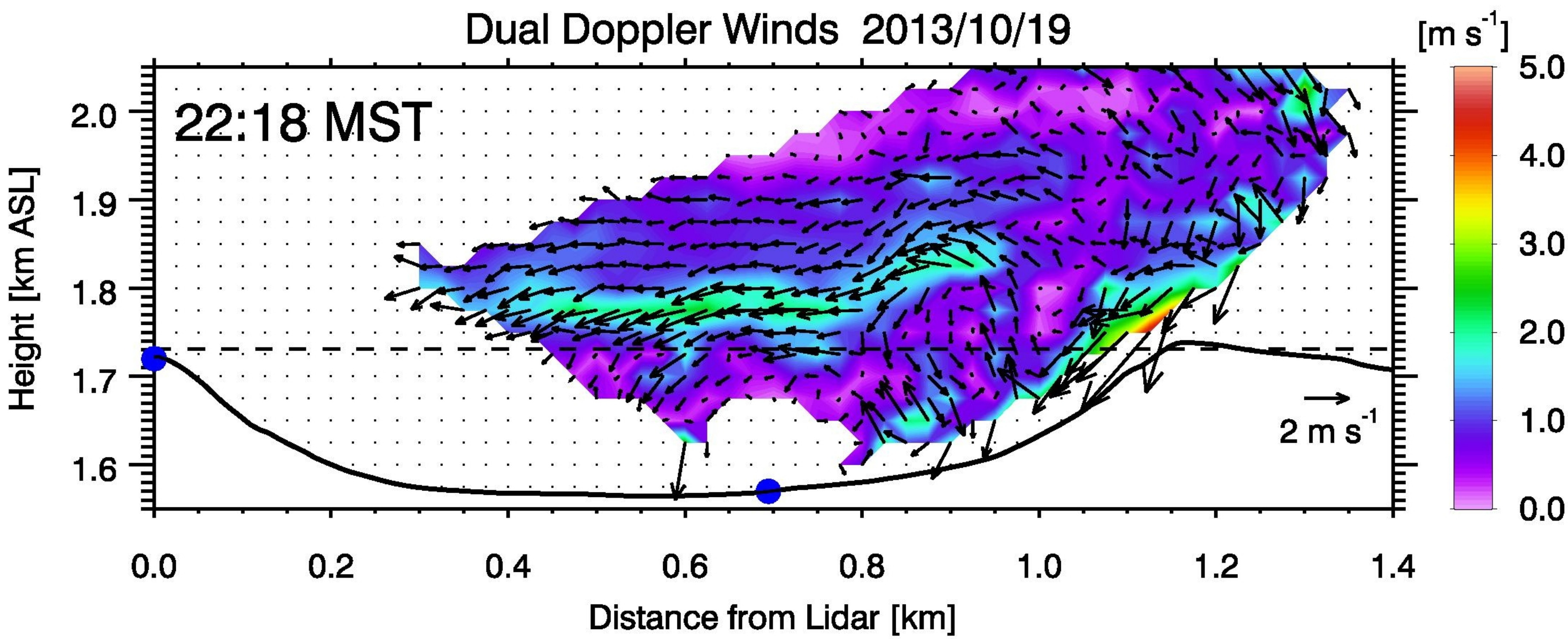
Dual-Doppler Retrieval

IOP-4 (19-20 October 2013)

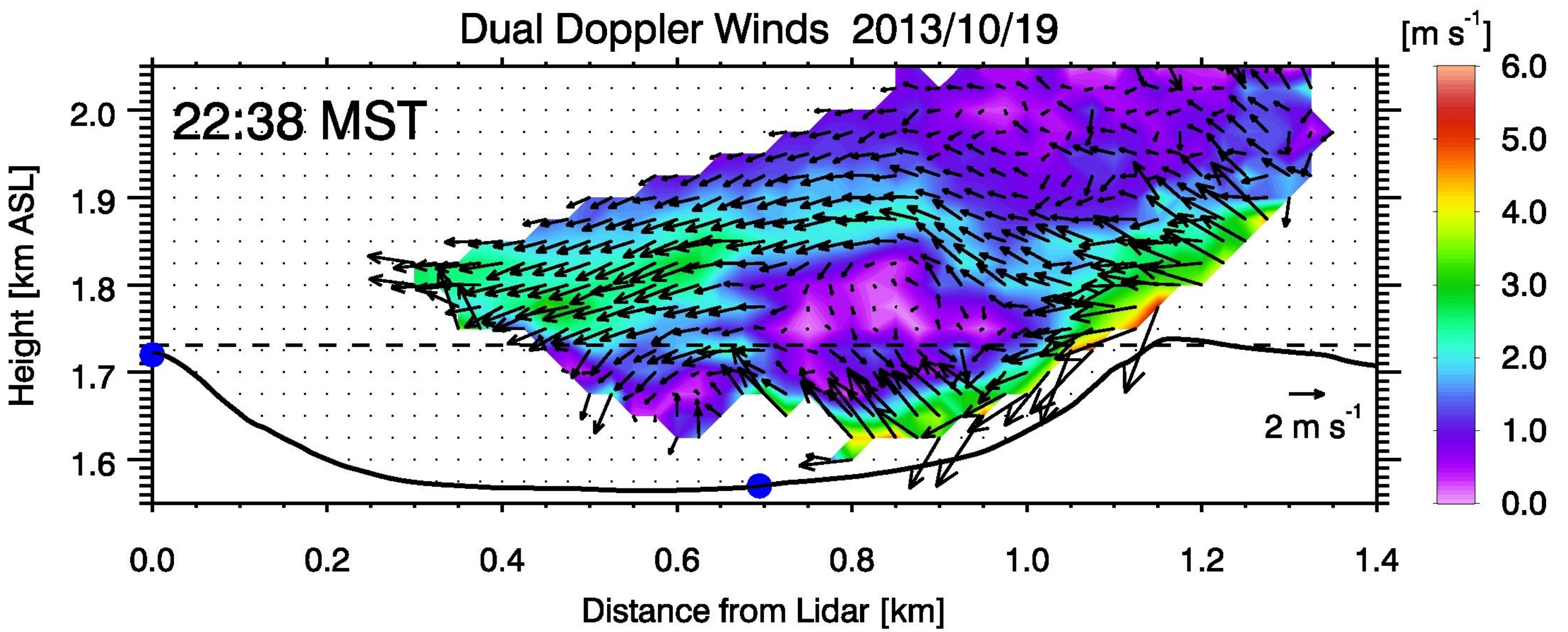


Scans within a 2-3 min time window are averaged and used in a dual doppler analysis.

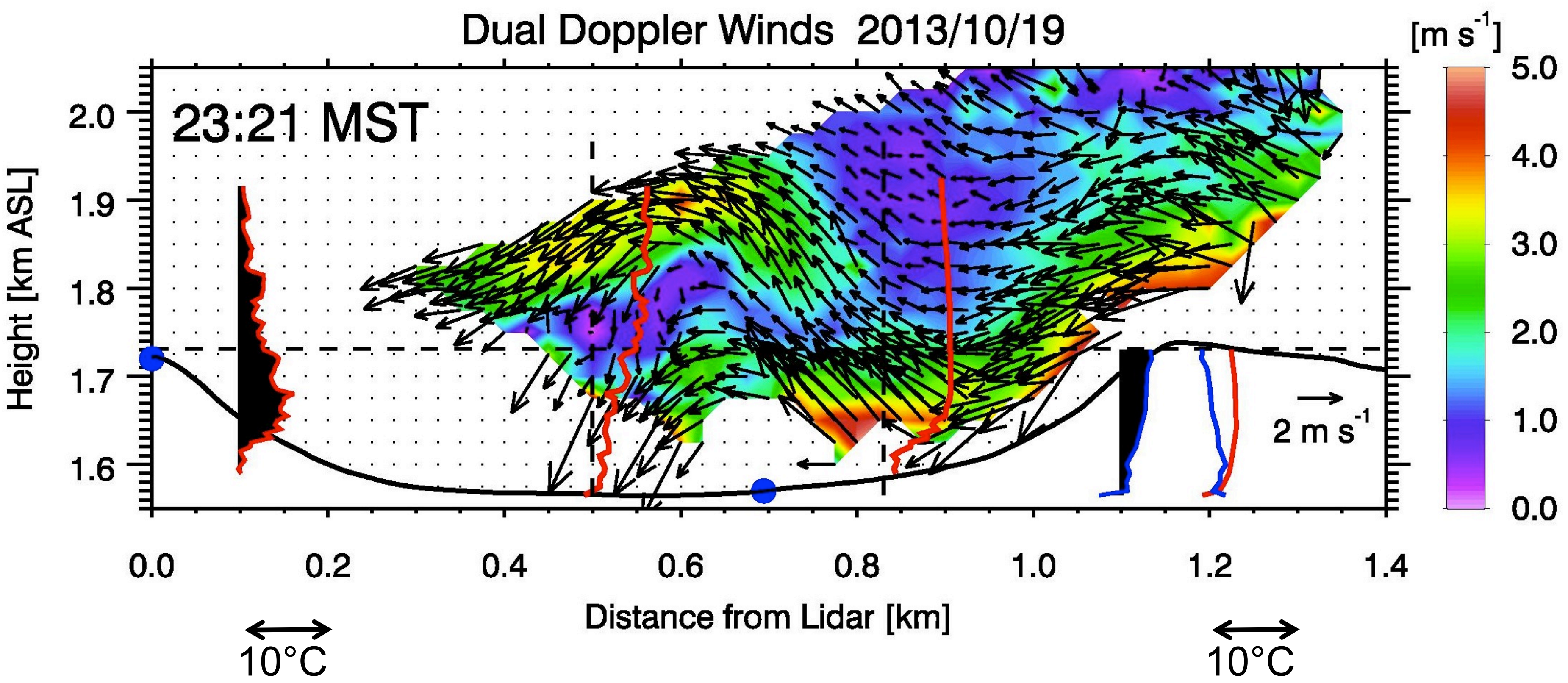
Hydraulic Jumps, rotors, …



Flow Separation



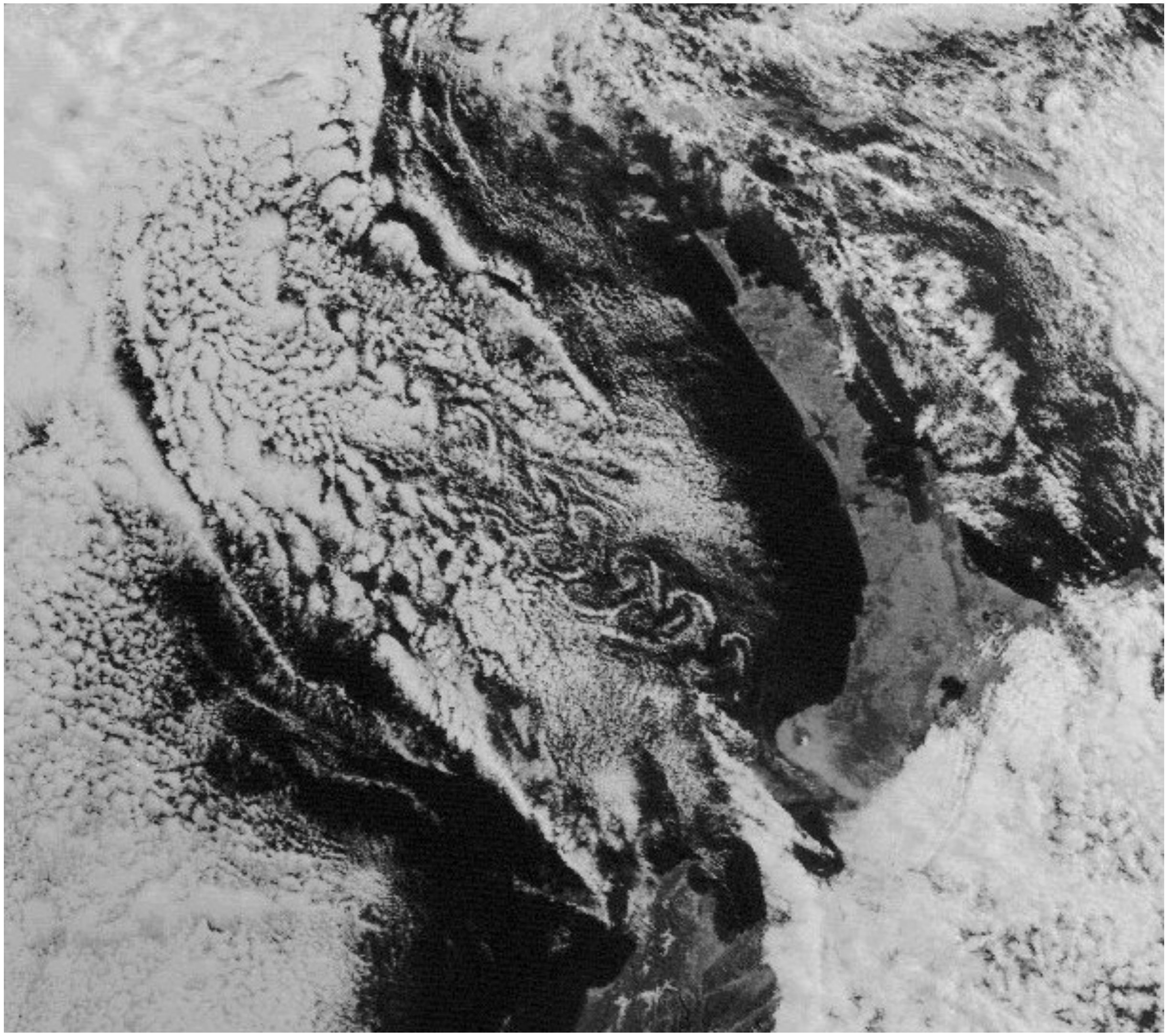
Warm-Air Intrusions & Cold-Air Inflows



Wakes, eddies, vortices

- Wakes, eddies and vortices are common in mountains
- Vertical and horizontal dimensions a function of stability
- They form behind terrain obstacles when the approach flow has sufficient speed
- *Eddy*: swirling current of air at variance with main current
- *Wake*: eddies shed off an obstacle cascading to smaller and smaller sizes. Characterized by low wind speeds and high turbulence.
- *Vortex*: whirling masses of air in form of column or spiral, usually rotate around vertical or horizontal axis.
- Examples: rotors; rotor clouds; drifts behind snow fences, trees and other obstacles; cornices. Winds are slowed to distances of 15 (sometimes 60) times obstacle height.

Kármán vortices in lee of New Zealand volcano

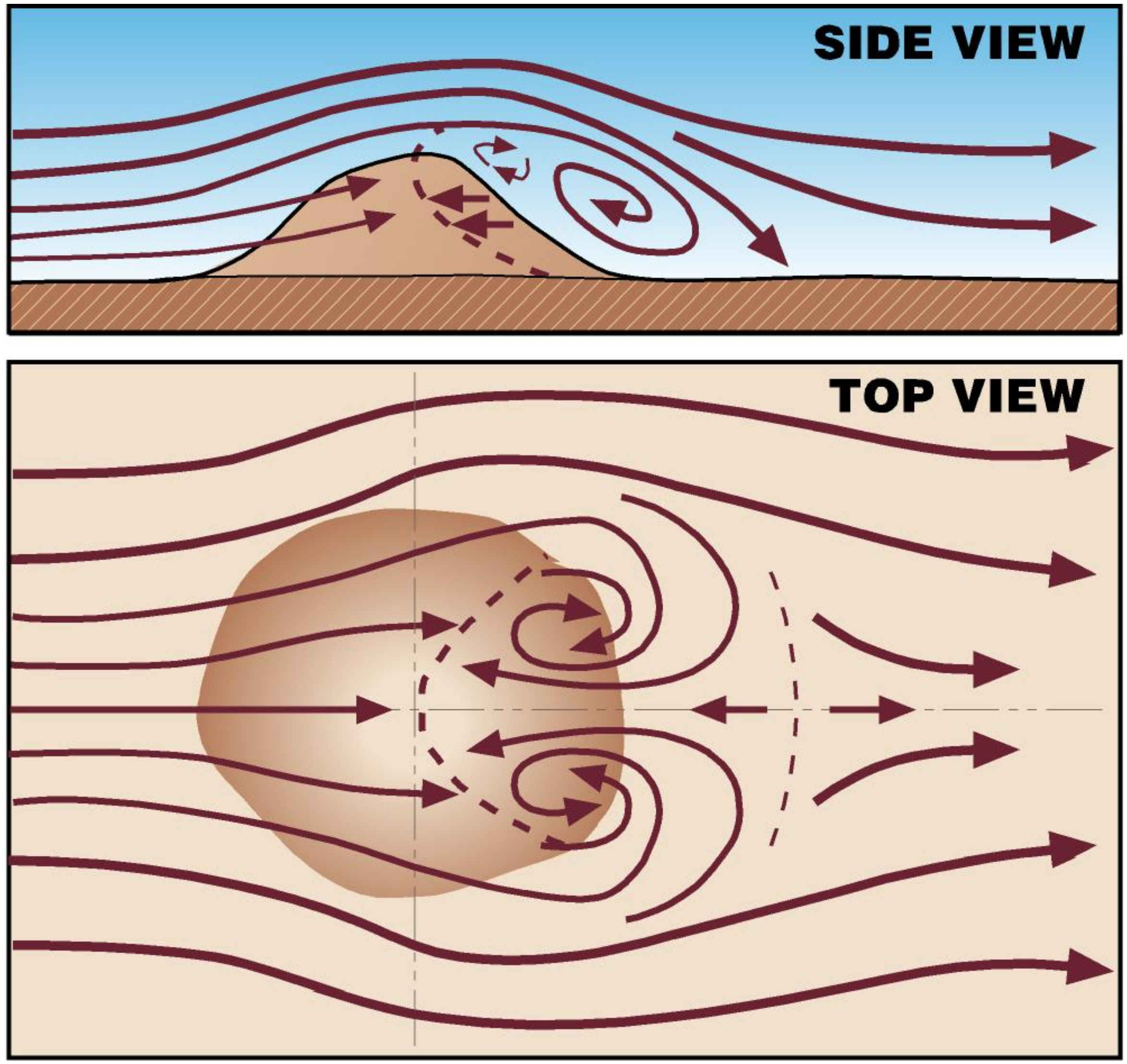


From Erick Brenstrum

Wakes

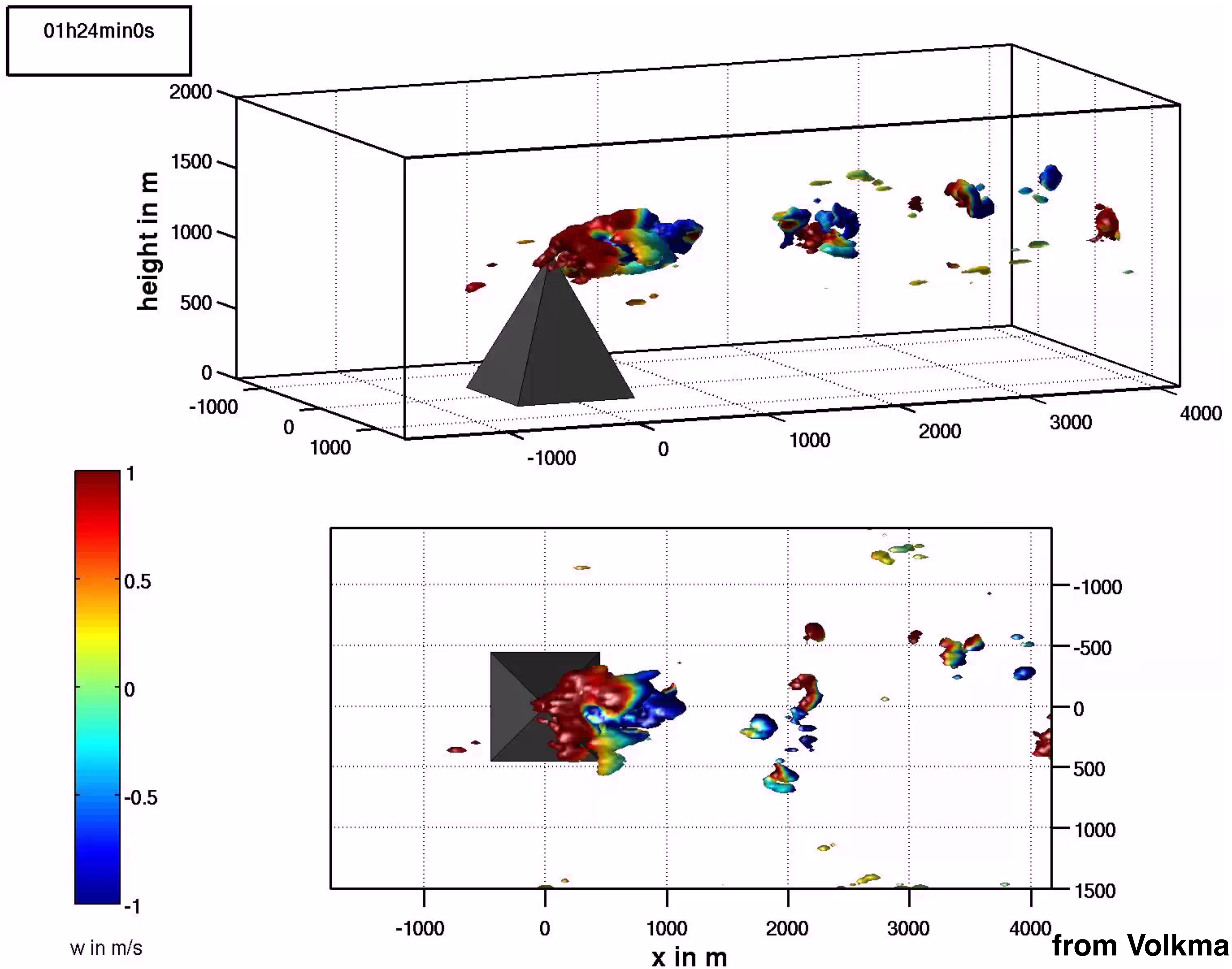
Large, generally isotropic vertical-axis eddies can be produced by the flow around mountains or through gaps as eddies are shed from the vertical edges of terrain obstructions.

Ex.: The Schultz eddy on the north side of the Caracena Strait in CA's Sacramento Valley or on either side of Parley's Canyon (Wasatch Range).



Orgill (1981)

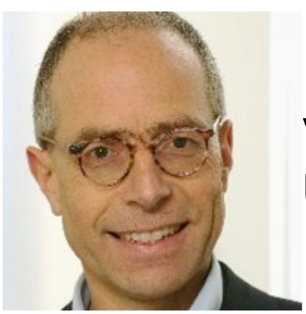

Banner clouds



from Volkmar Wirth

Mt. Zugspitze, Germany

Schween et al. (2007)



Volkmar Wirth
University of Mainz, Germany

Flow Around Mountains

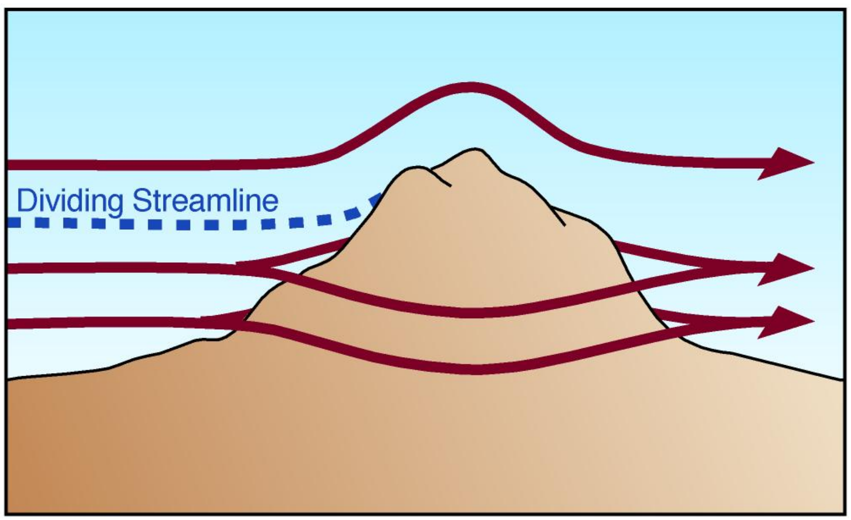
A flow approaching a mountain barrier tends to go around rather than over a barrier if:

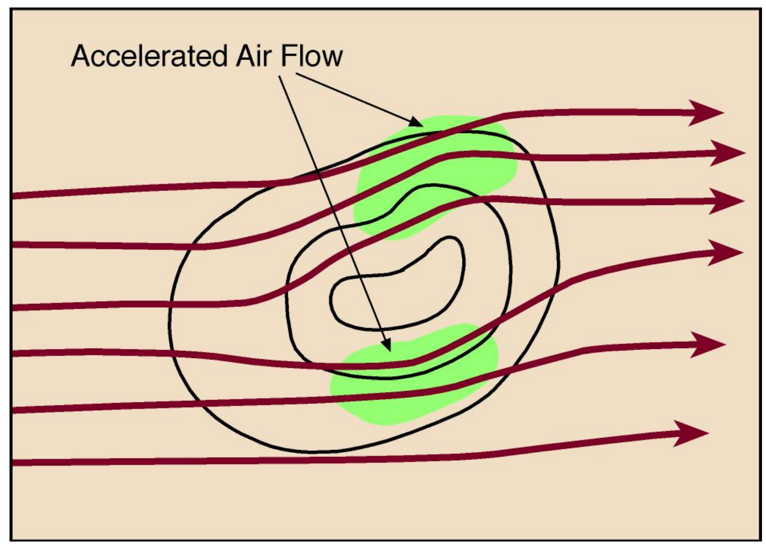
- Ridgeline is ***convex*** on windward side
- Mountains are ***high***
- Barrier is an ***isolated peak*** or a short range
- Cross barrier ***wind*** component is ***weak***
- Flow is ***very stable***
- Approaching low-level ***air mass*** is very ***shallow***

Because Rockies and Appalachians are long, flow around them is uncommon. But these types of flows are seen in the Aleutians, the Alaska Range, the Olympic Mountains and around isolated volcanoes. They should be expected to occur also around the Uintas and in southern Wyoming.

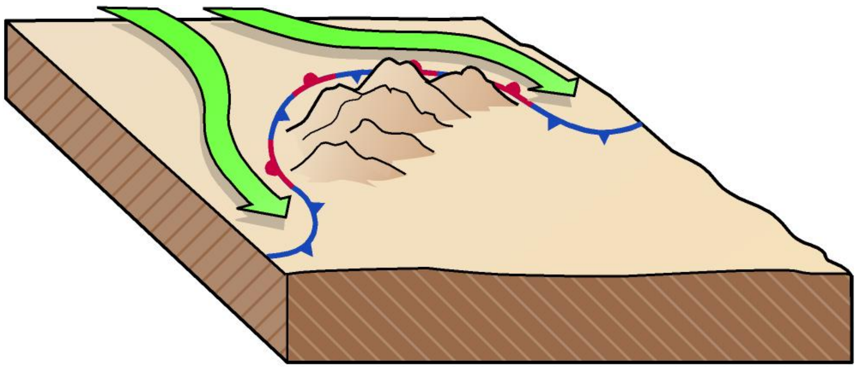
Wind variations with topographic characteristics

- Height and length can determine whether air goes around barrier; to carry air over a high mountain range or around an extended ridge requires strong winds
- When stable air splits around an isolated peak, the strongest winds are usually on the edges of the mountain tangent to the flow



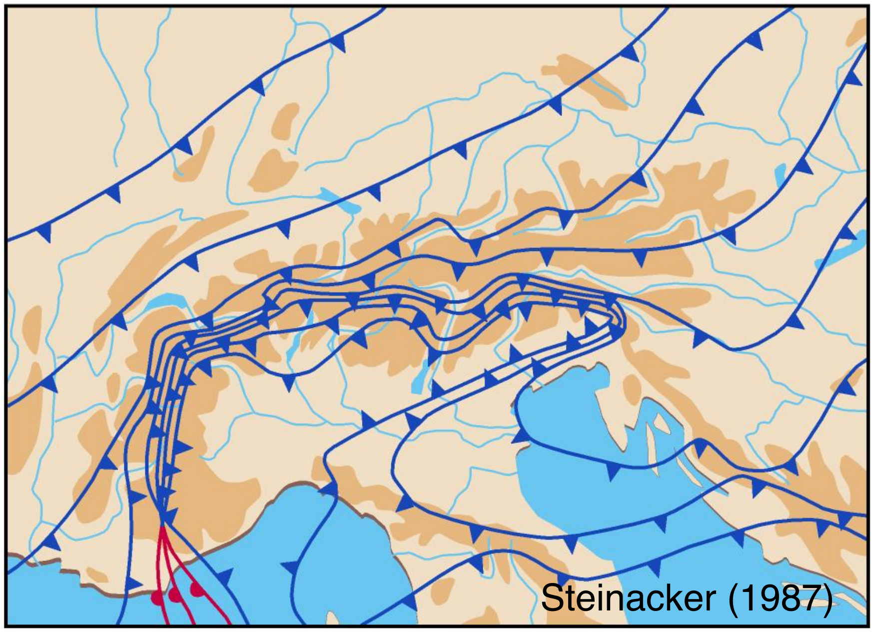


Flow splitting



Whiteman (2000)

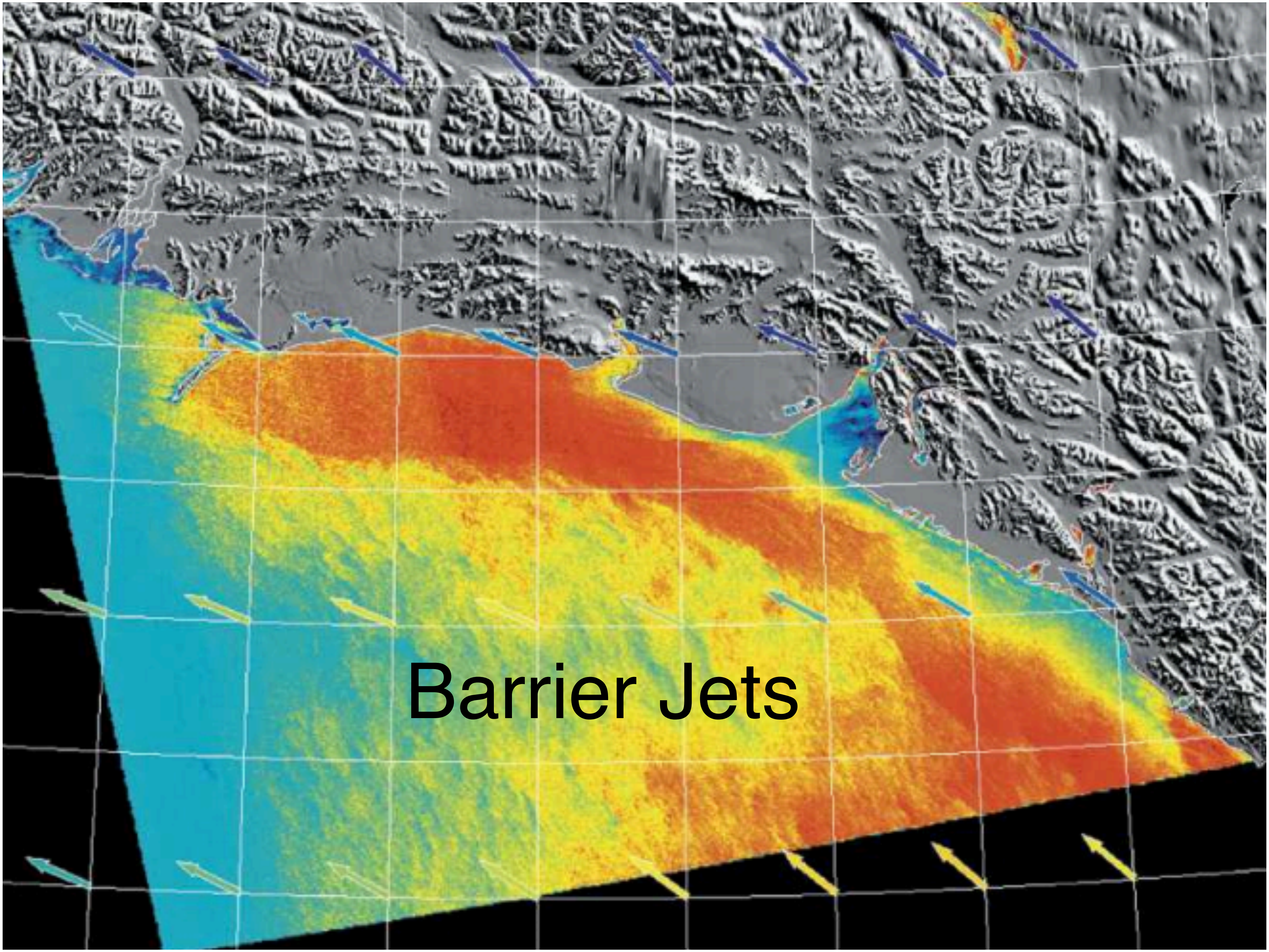
3-hourly frontal positions



Steinacker (1987)

Note: *Convergence zones* often form on the back side of isolated barriers (e.g., Puget Sound)

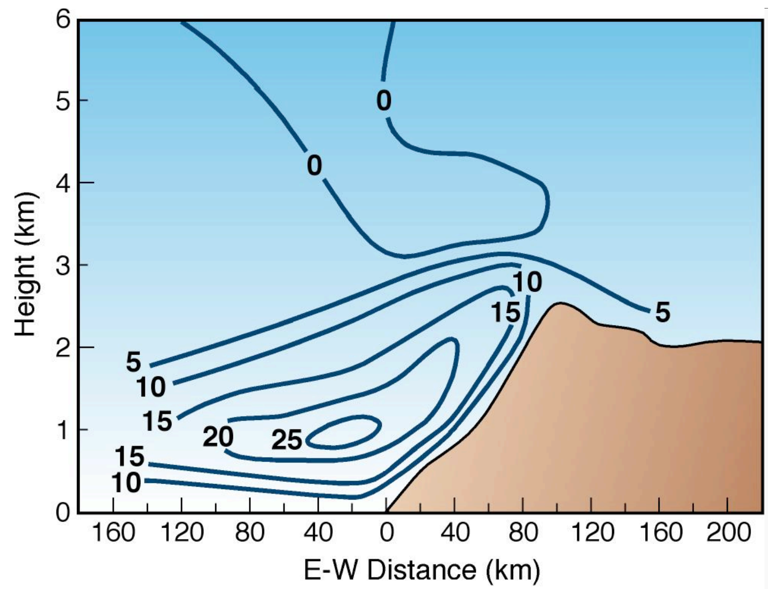
Reinhold Steinacker


Barrier Jets

Barrier jets

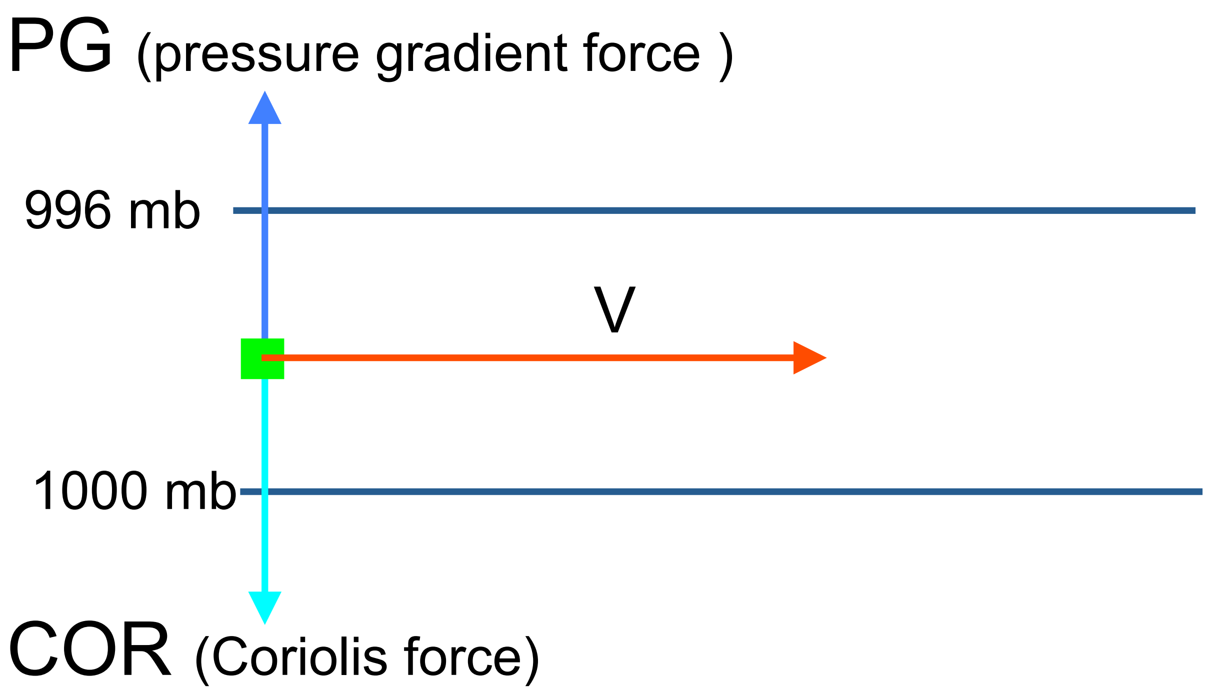
An **elevated wind maximum** on the **windward side of a mountain barrier** blowing **parallel** to the ridgeline.

Occurs in the extratropics when a **stably stratified flow** is **blocked** by a barrier for hours or days. The flow lifted up the barrier is cooled, forming a **high pressure along the slope**, **decelerating** and **blocking** the flow. Geostrophic adjustment occurs between the flow and the high pressure, turning the flow to the left (NH) toward low pressure.



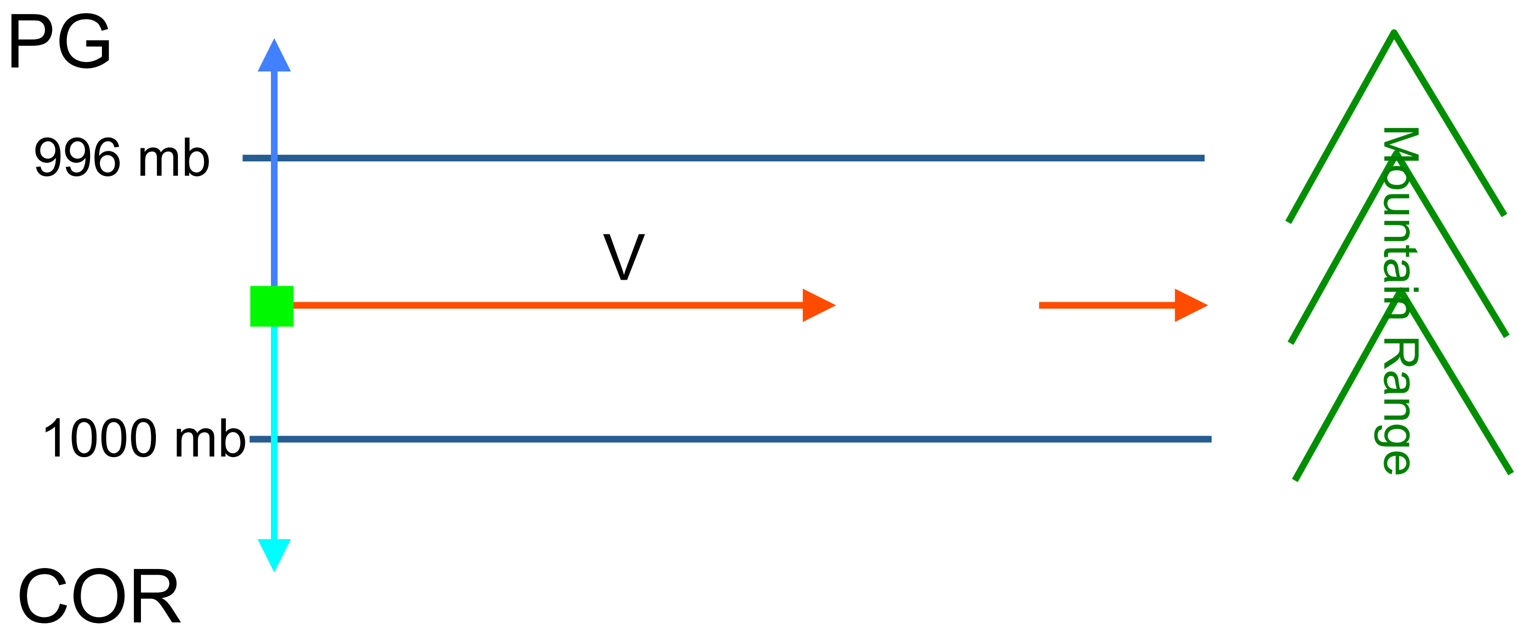
W side of Cascades and Sierras, on E side of Rockies and Appalachians, and on N side of Brooks Range.

Basic Dynamics



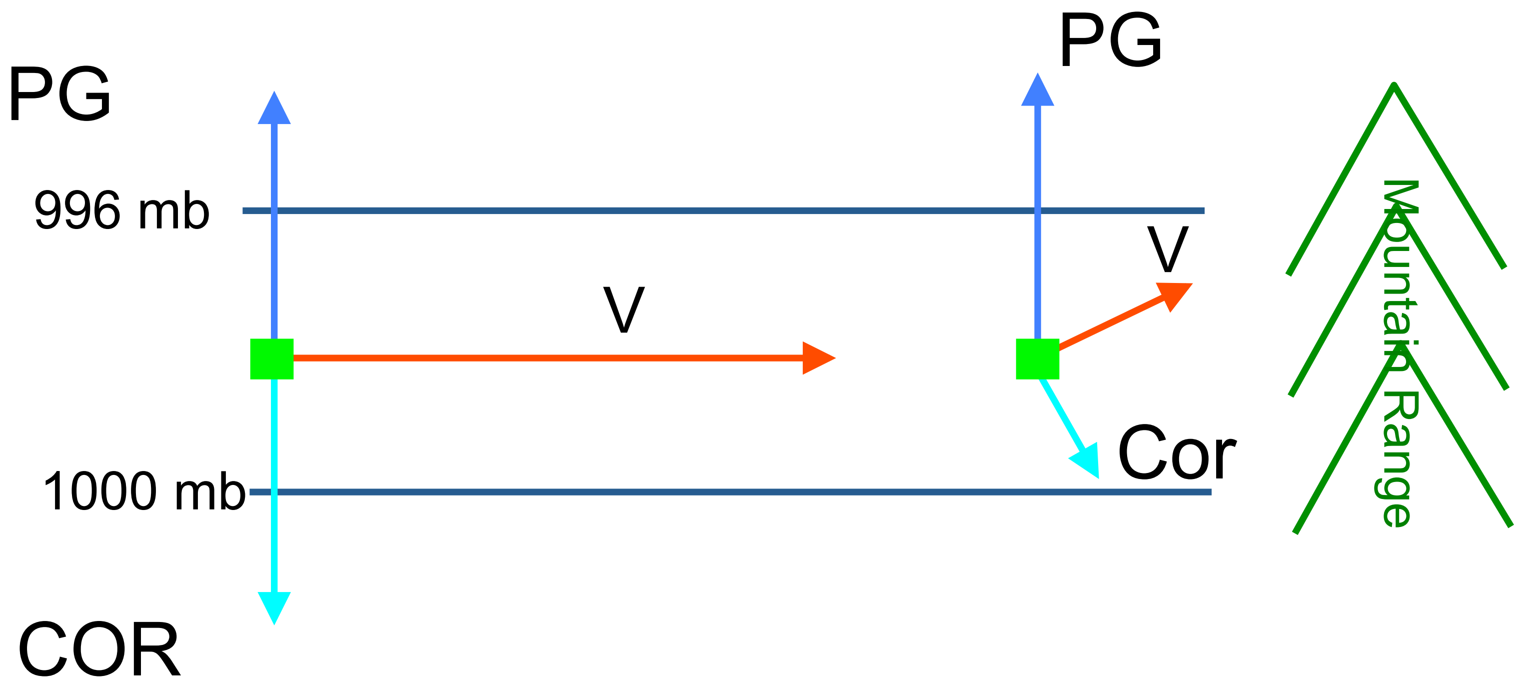
In the absence of topography and friction, the flow exhibits <u>geostrophic balance.</u>

Basic Dynamics



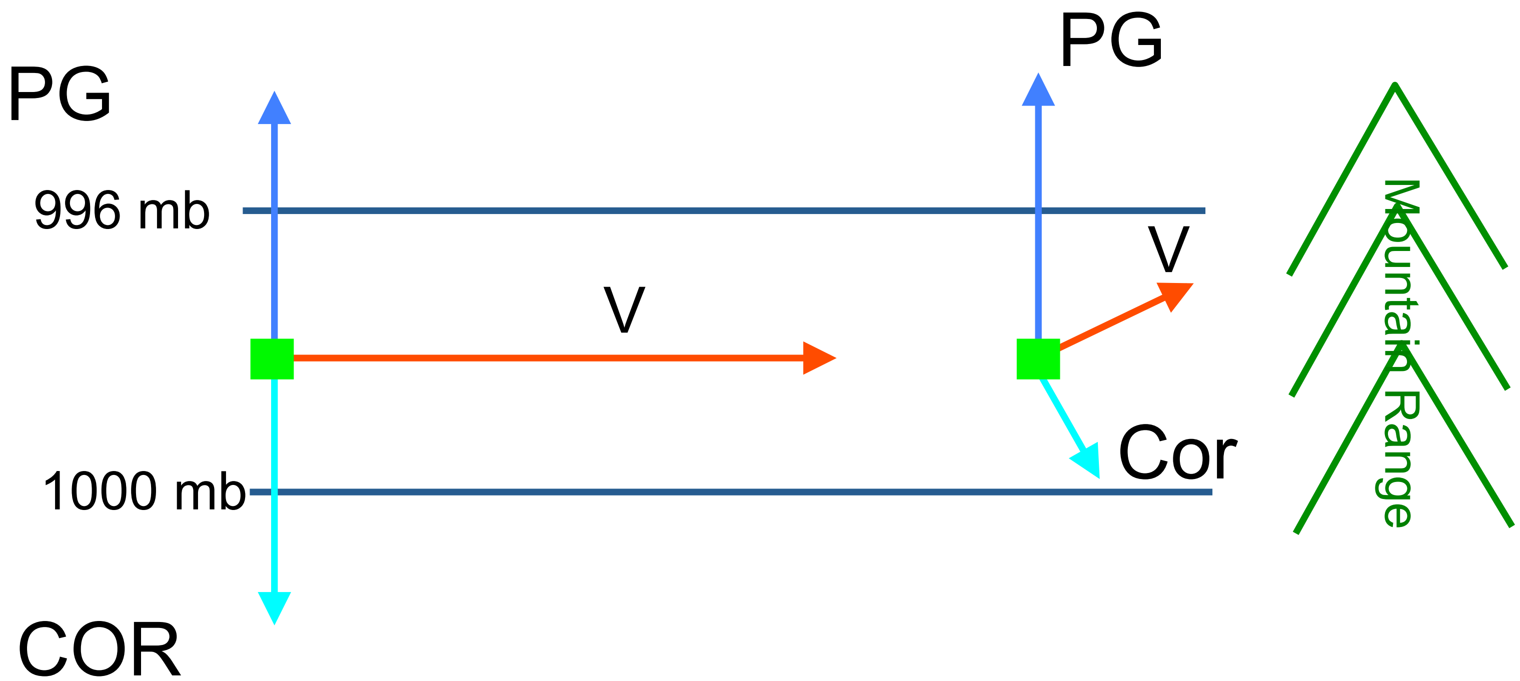
If flow is characterized by a low Froude number (U/NH < 1), the <u>the low-level flow</u> will be <u>blocked</u> and <u>decelerate</u> as it approaches mountains.

Basic Dynamics



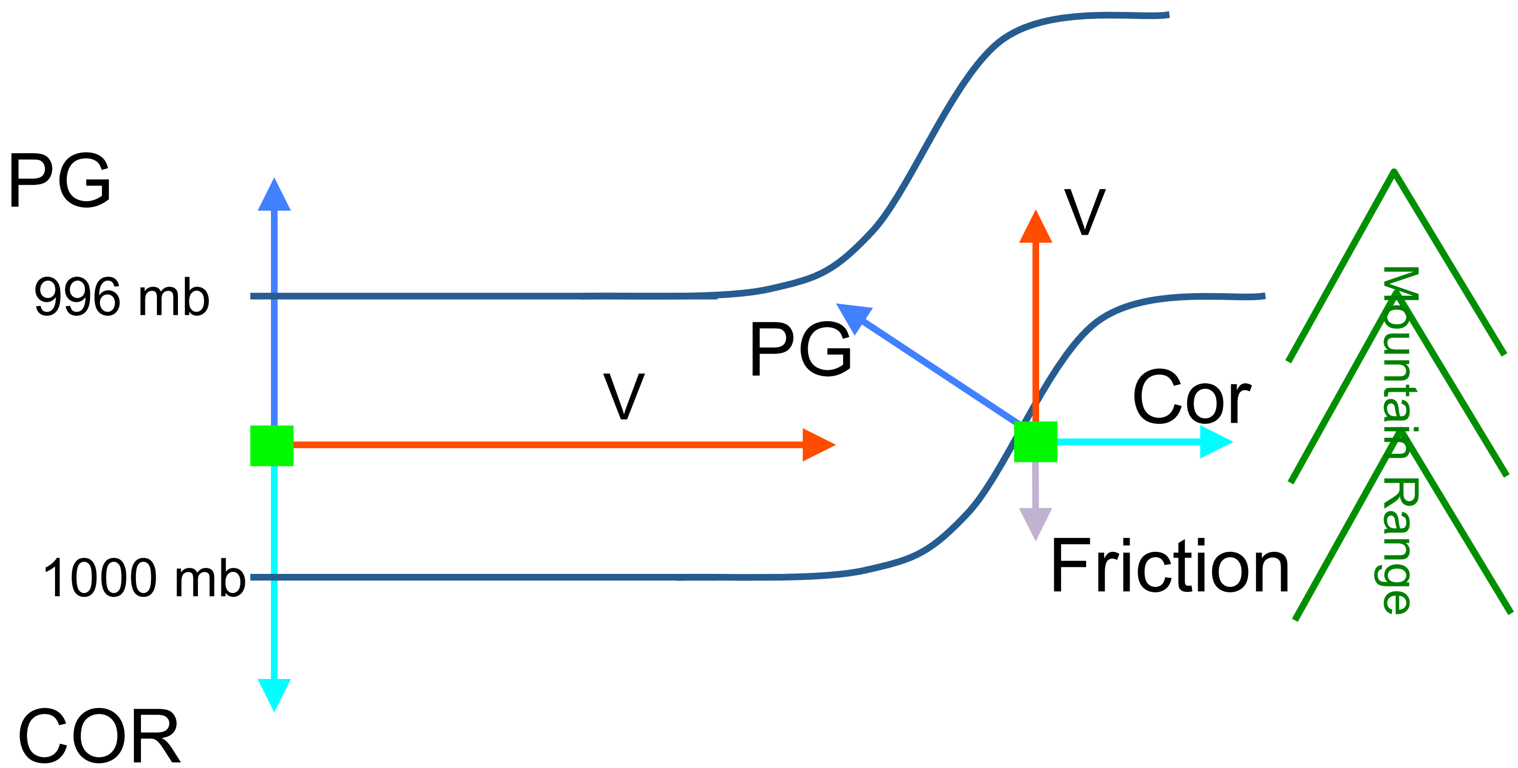
As the flow decelerates, the Coriolis force weakens, and the flow is deflected toward lower pressure.

Basic Dynamics



Flow deceleration results in a <u>piling up of mass</u> and development of a <u>mesoscale pressure ridge</u> near the mountains (mutual adjustment of mass and momentum)

Basic Dynamics

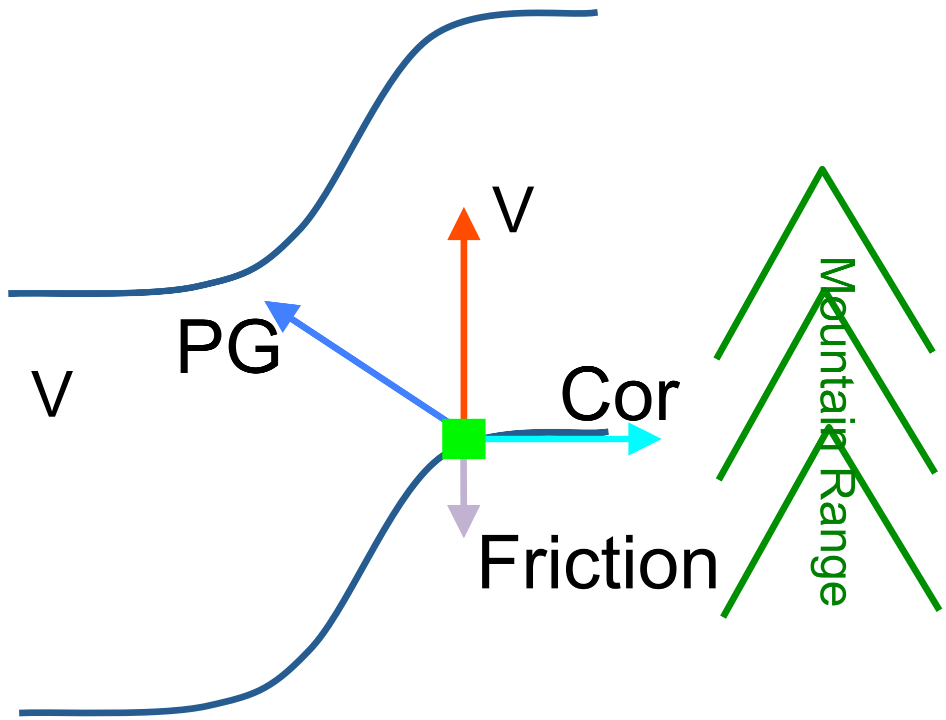


The final near-barrier force balance.

Mature Force Balance

- Along-barrier **antitriptic**
  - Pressure gradient balances friction

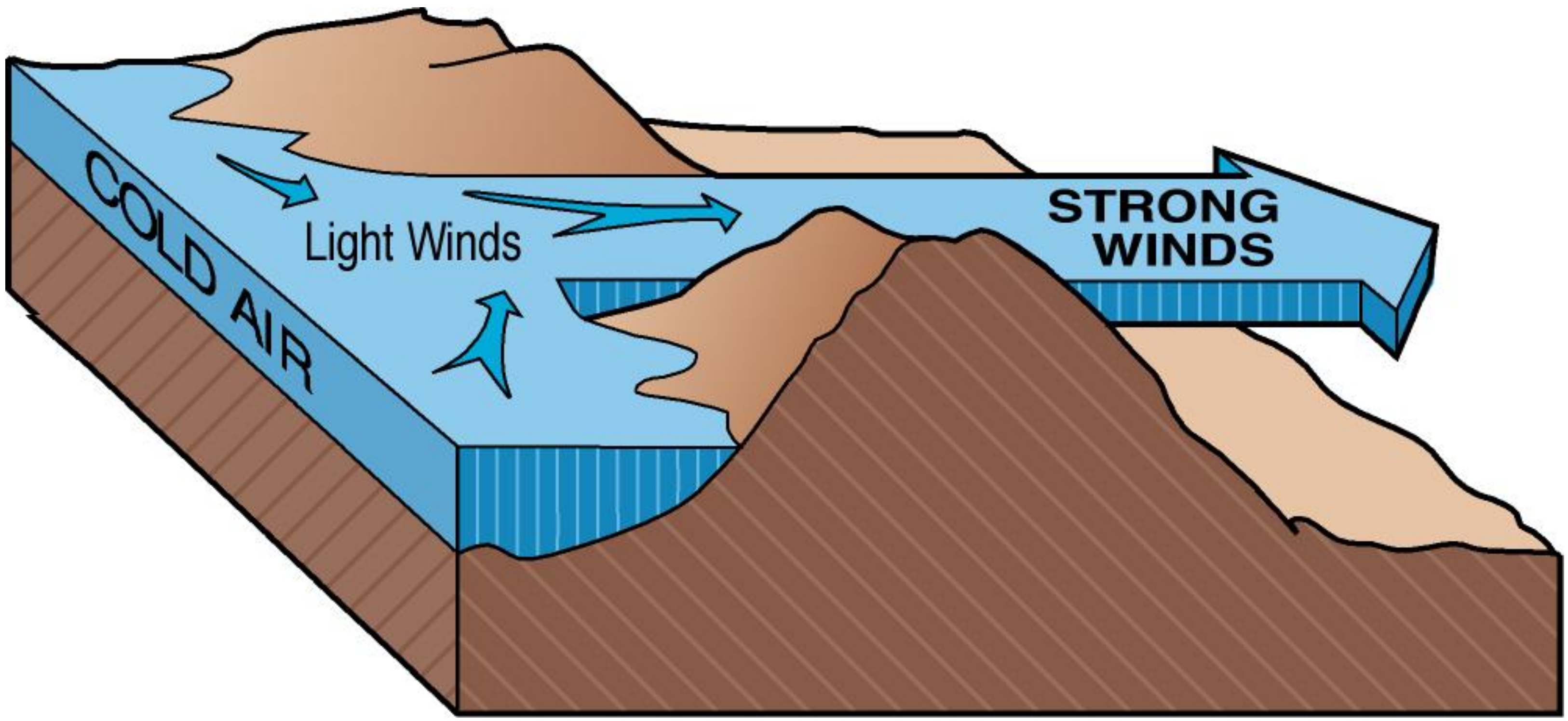
- Cross-barrier geostrophic



Flow through Passes, Channels and Gaps

- ***Gaps*** - major erosional openings through mountain ranges
- ***Channels*** - low altitude paths between mountain ranges (usually with the sea as the base of the channel)
- ***Mountain passes*** - routes over or through mountains
- Strong winds in a gap, channel or pass are usually ***pressure driven*** - i.e., caused by a strong pressure gradient across the gap, channel or pass.
- Regional pressure gradients occur frequently across *coastal mountain ranges* because of the differing characteristics of *marine and continental air*. These pressure gradients usually reverse seasonally.

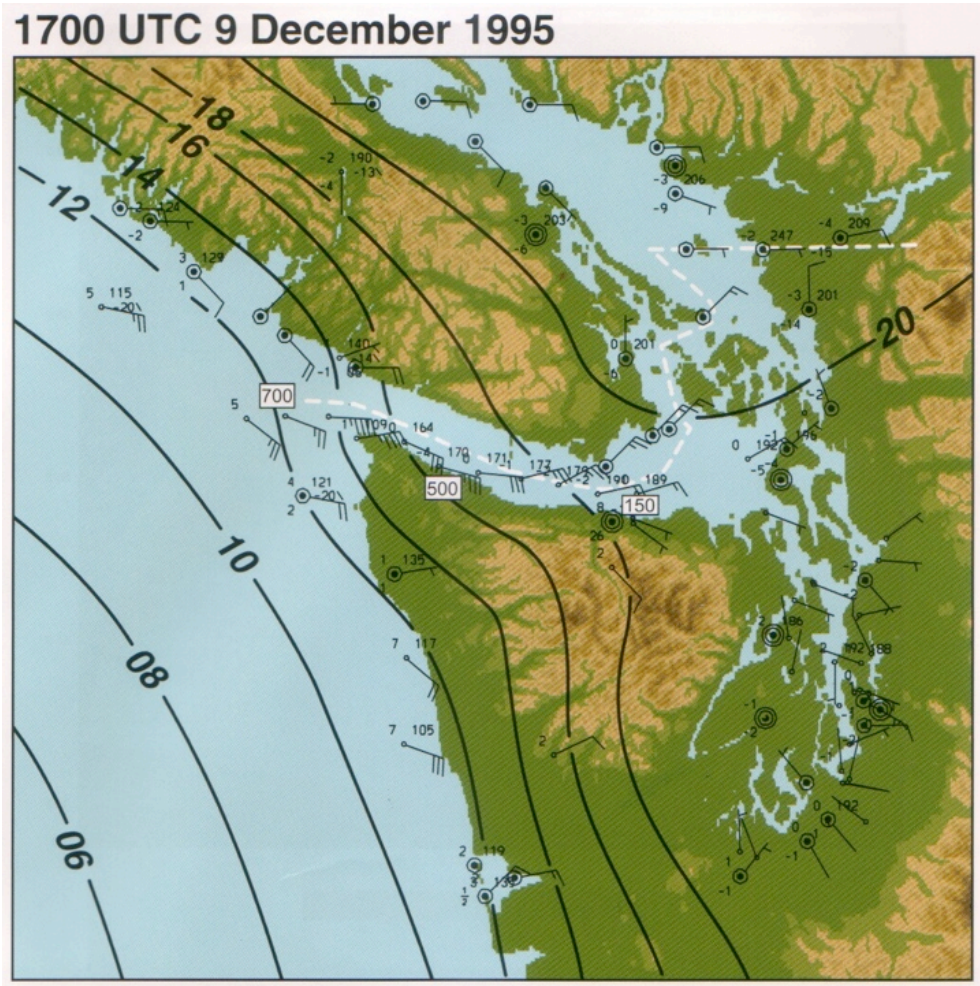
Flow through passes and gaps



Whiteman (2000)

Waterfall clouds

Gap flow



Markowski and Richardson (2010)

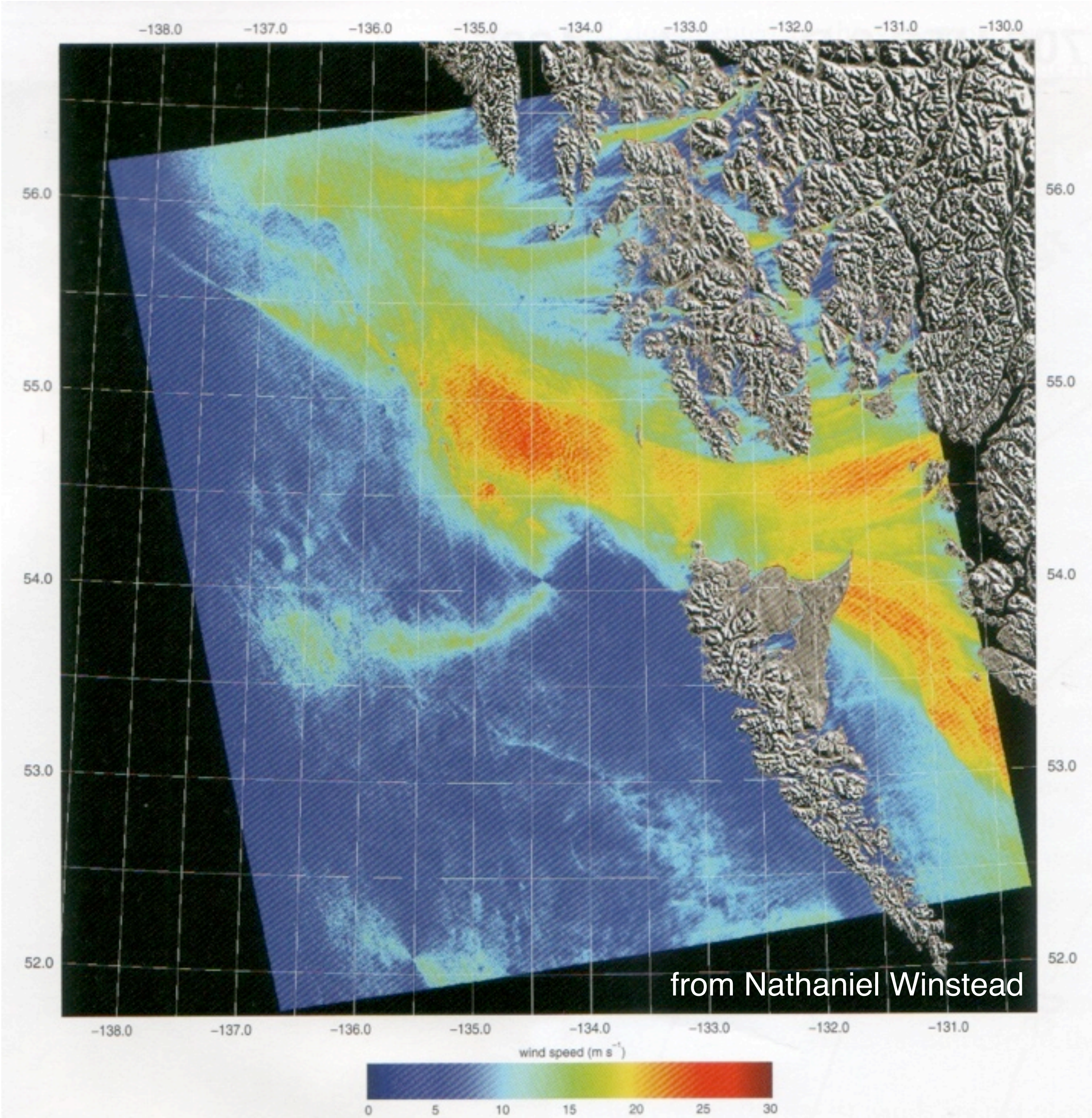
Strait of Juan de Fuca

Gap flows are associated with **along-gap pressure gradient forces**, but also arise from low-level temperature differences between **air masses** on different sides of the gap.

The fastest winds are not generally within the gap, but at the **gap exit**.

An inversion is often present below the crest.

Gap flow

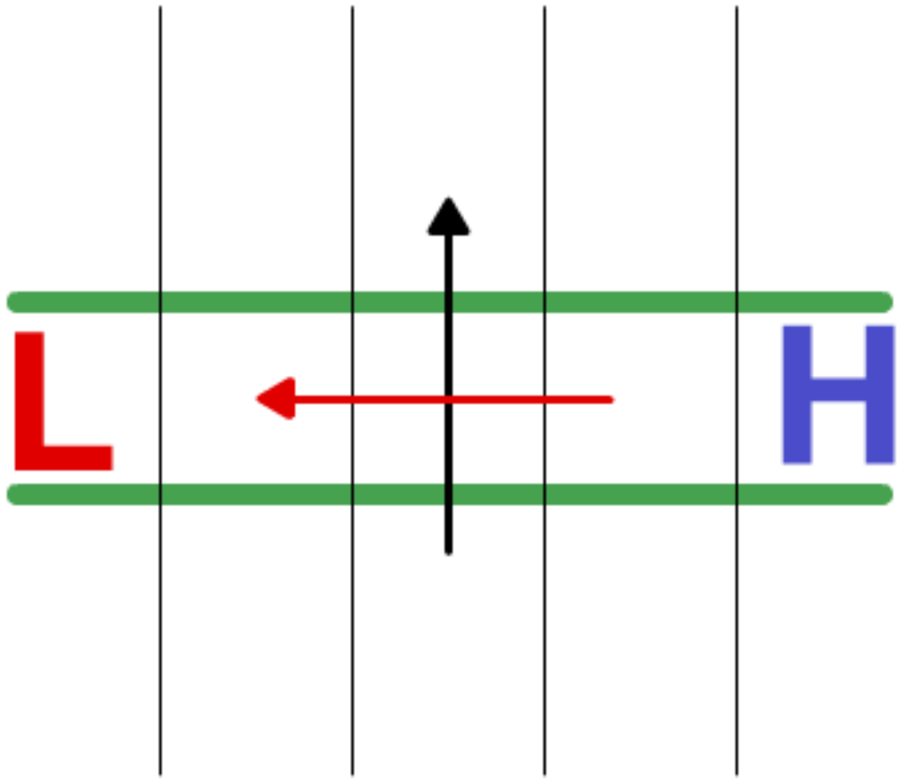


Markowski and Richardson (2010)

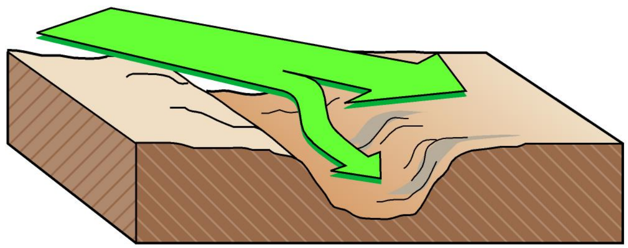
Gap flows observed by synthetic aperture radar (SAR) in the Dixon Entrance between Grand Island, BC, and Prince of Wales Is, AK. (From Nathaniel Winstead)

Other Phenomena

Pressure driven channeling versus **forced channeling**

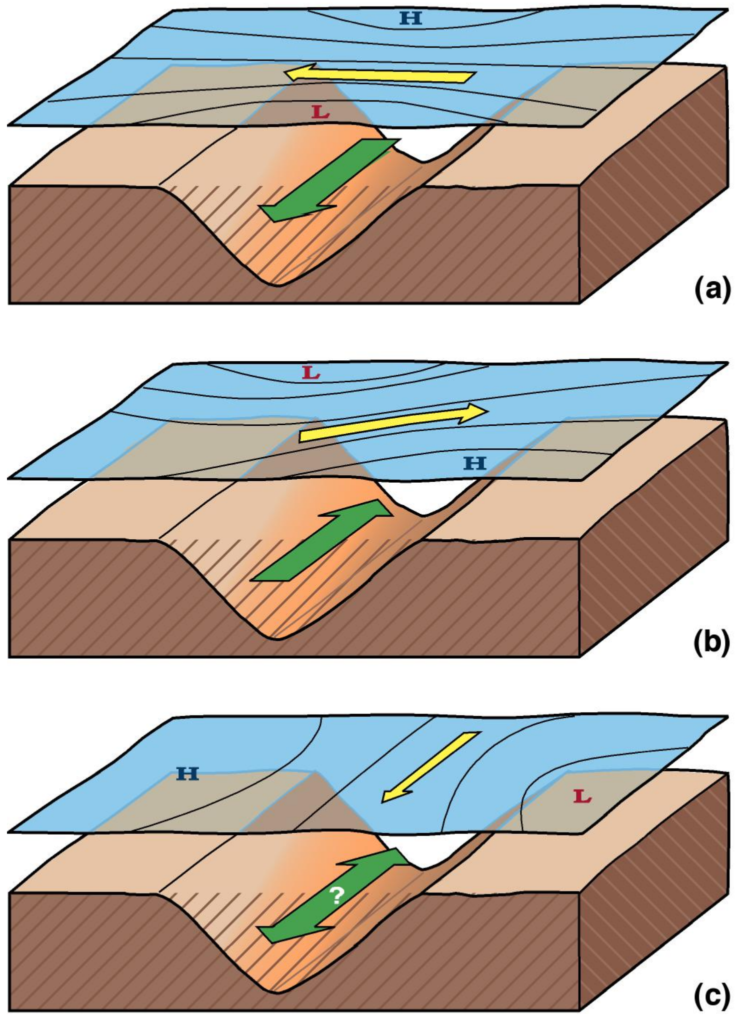


Pressure driven channeling



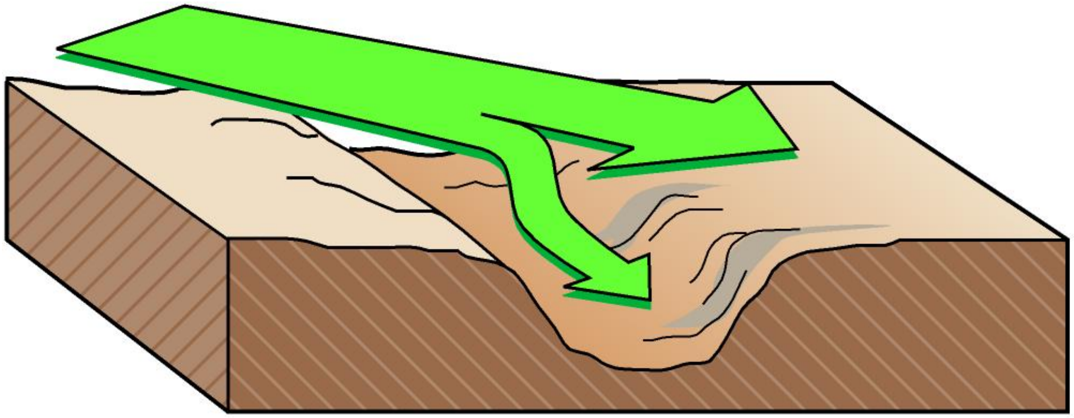
Forced Channeling

Pressure driven channeling

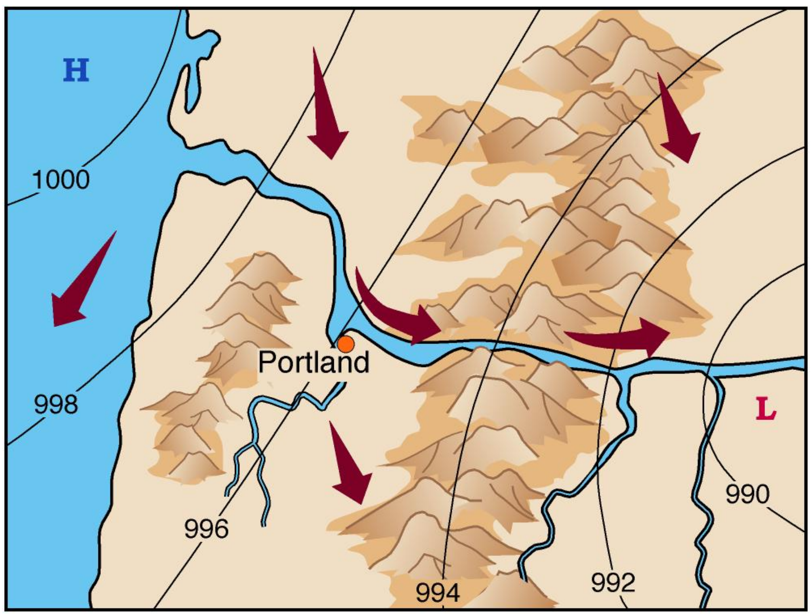


Whiteman (2000)

Channeling

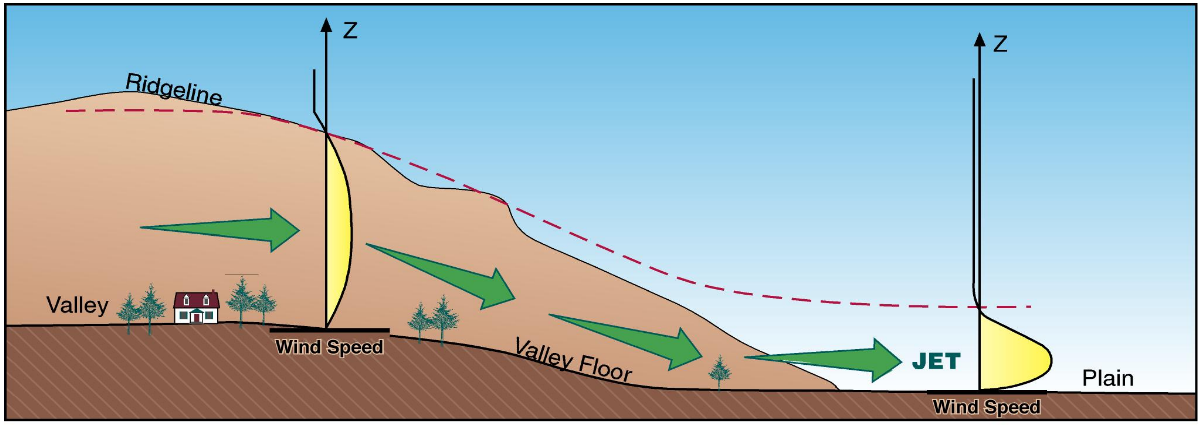


Forced Channeling

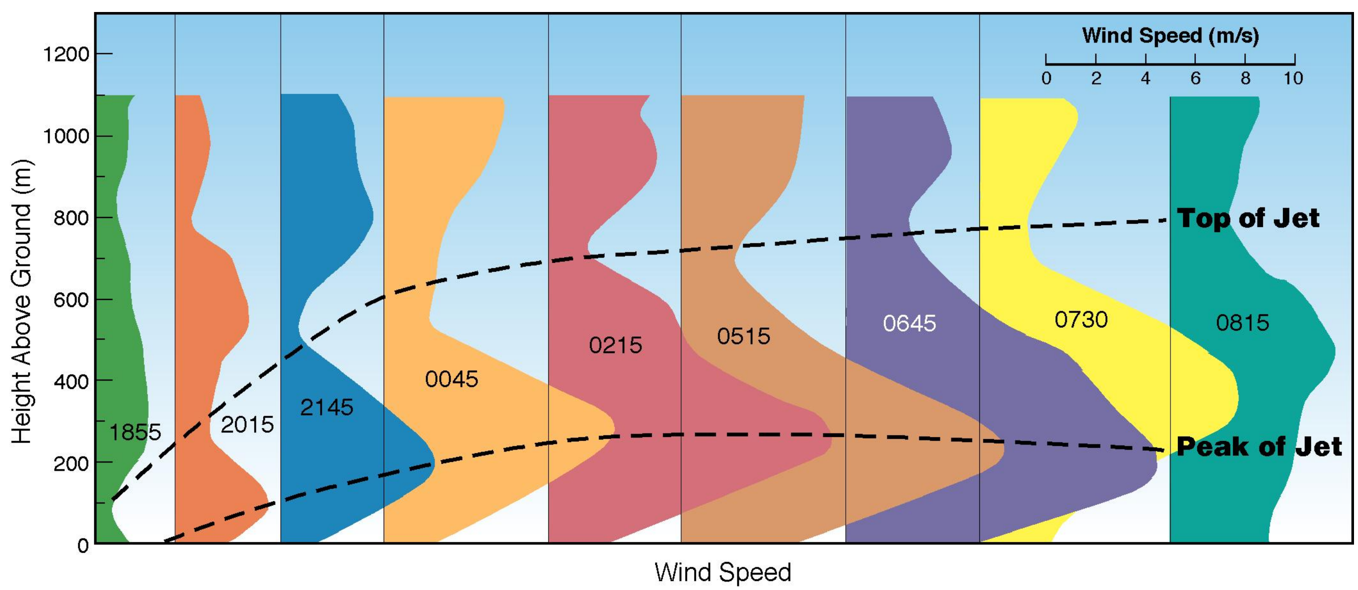


Pressure Driven Channeling

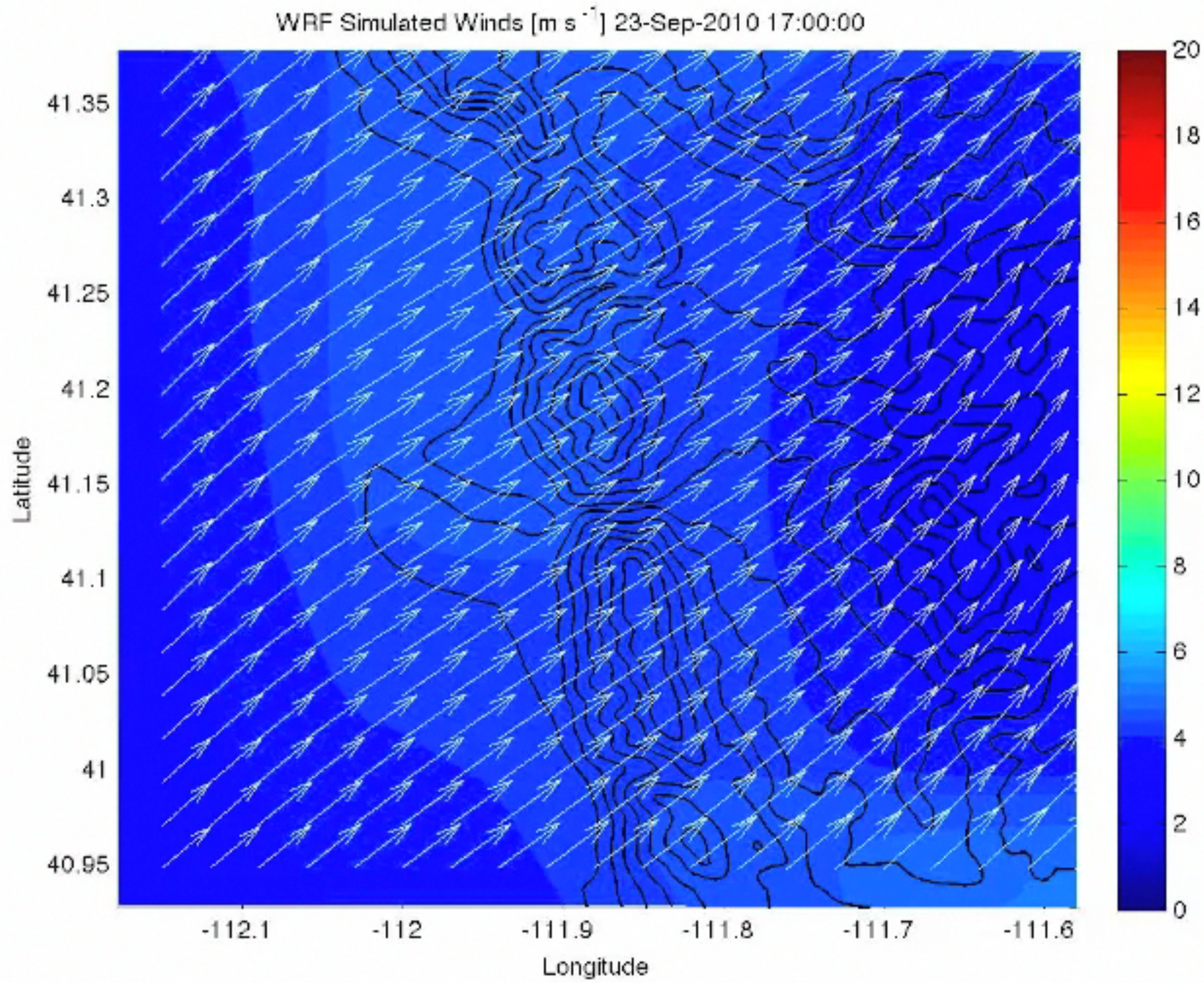
Valley exit jet



adapted from Pamperin & Stilke (1985)



Weber Canyon, UT


WRF Simulated Winds [m s⁻¹] 23-Sep-2010 17:00:00
Latitude
41.35
41.3
41.25
41.2
41.15
41.1
41.05
41
40.95
Longitude
-112.1
-112
-111.9
-111.8
-111.7
-111.6
20
18
16
14
12
10
8
6
4
2
0


The End
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