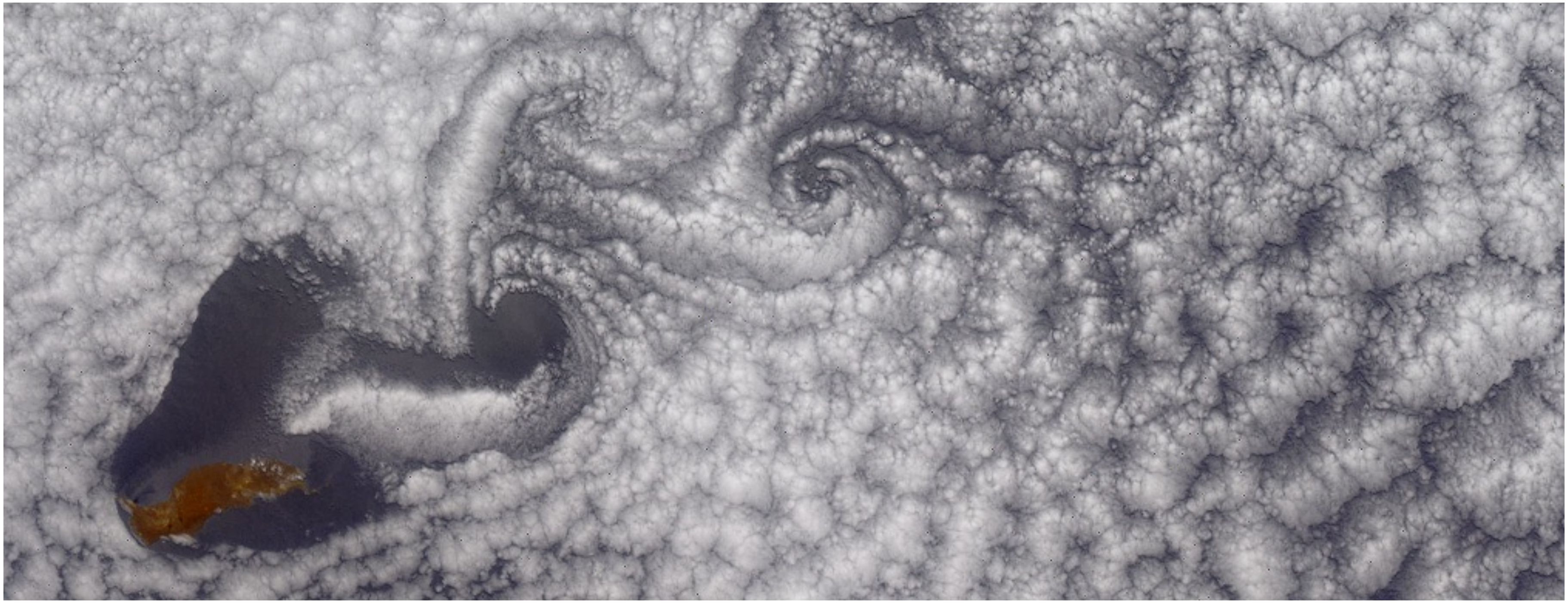
Terrain-Forced Flows



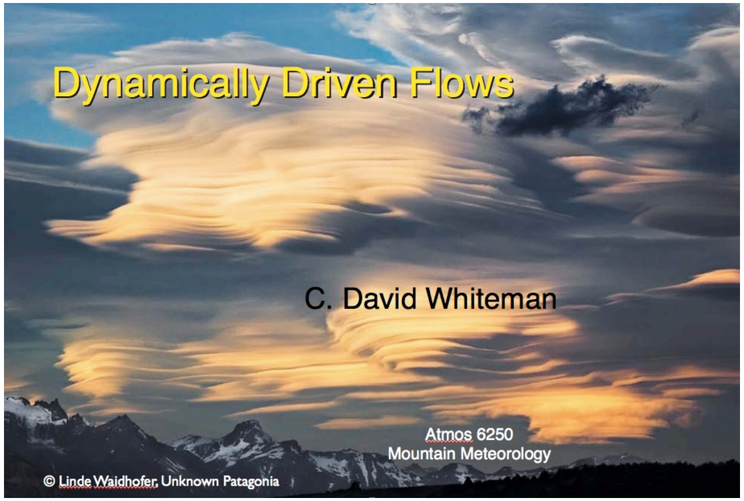
Selkirk Island, Landsat 7 satellite in September 1999. Credit: Bob Cahalan / NASA, USGS

Sebastian W. Hoch
C. David Whiteman

C. David Whiteman

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

Jim Steenburgh, University of Utah



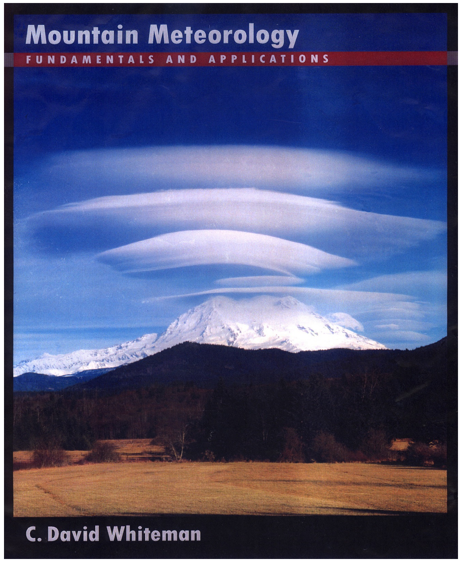
Dynamically Driven Flows

C. David Whiteman

Atmos 6250
Mountain Meteorology

© Linde Waidhofer, Unknown Patagonia

Whiteman; Lecture Atmos. 6250, 2012



Mountain Meteorology
FUNDAMENTALS AND APPLICATIONS

C. David Whiteman

**Figures: Whiteman (2000)
unless otherwise indicated**

Outline

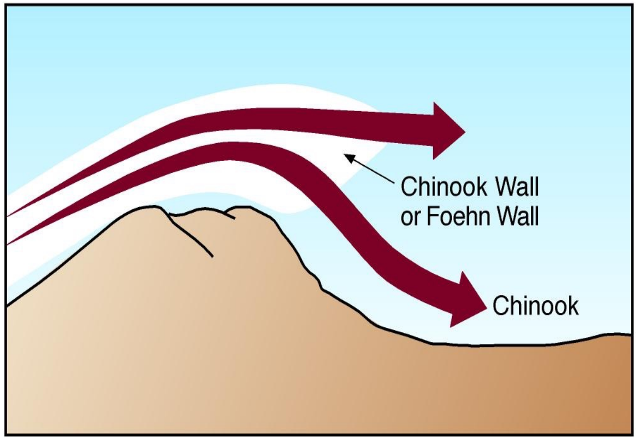
- Introduction
- Topography
- Blocking/Obstruction of Air Masses
- Flow Over Mountains
- Flow Around Mountains
- Flow Through Passes, Channels and Gaps
- Other phenomena

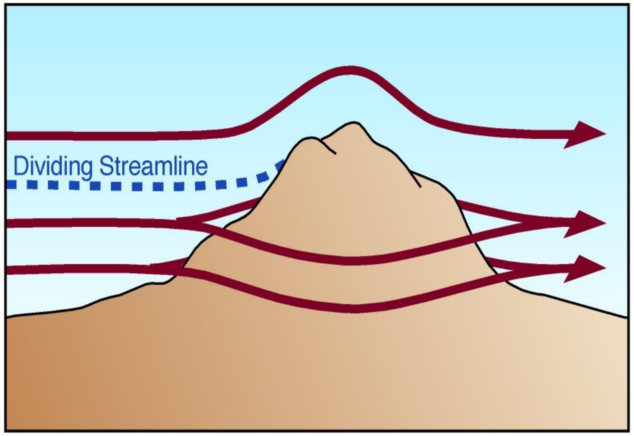
Introduction

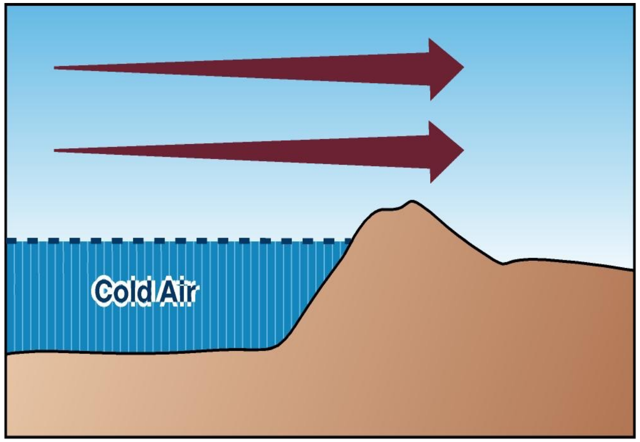
- Two types of **mountain winds**
  - *Diurnal mountain winds* (thermally driven circulations): produced by temperature contrasts that form within mountains or between mountains and surrounding plains [covered this morning/yesterday]
  - *Terrain-forced flows*: produced when large-scale winds are modified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

What options does air have when it approaches a mountain barrier?







Terrain forcing can cause an air flow approaching a barrier to …

- … be carried *over* the barrier (downslope windstorms, mountain waves)
- … be forced *through gaps* in the barrier (gap flows)
- … be forced *around* the barrier (barrier jets, flow splitting, leeside convergence, vortices, wakes)
- … be *blocked* by the barrier (blocking)

What characteristics of the incident flow and the topography are likely to determine the outcome?

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

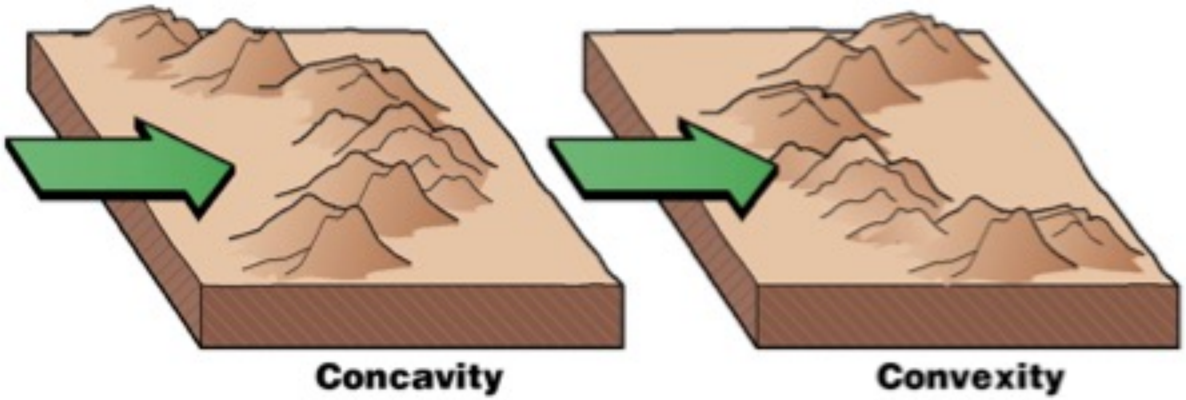
- ***Stability*** of approaching air (unstable or neutral stability air can be easily forced over a barrier. The more stable, the more resistant to lifting. Concept of dividing streamline height.)

- ***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 …

Terrain Forced Flows &

Topographic Characteristics



Topography

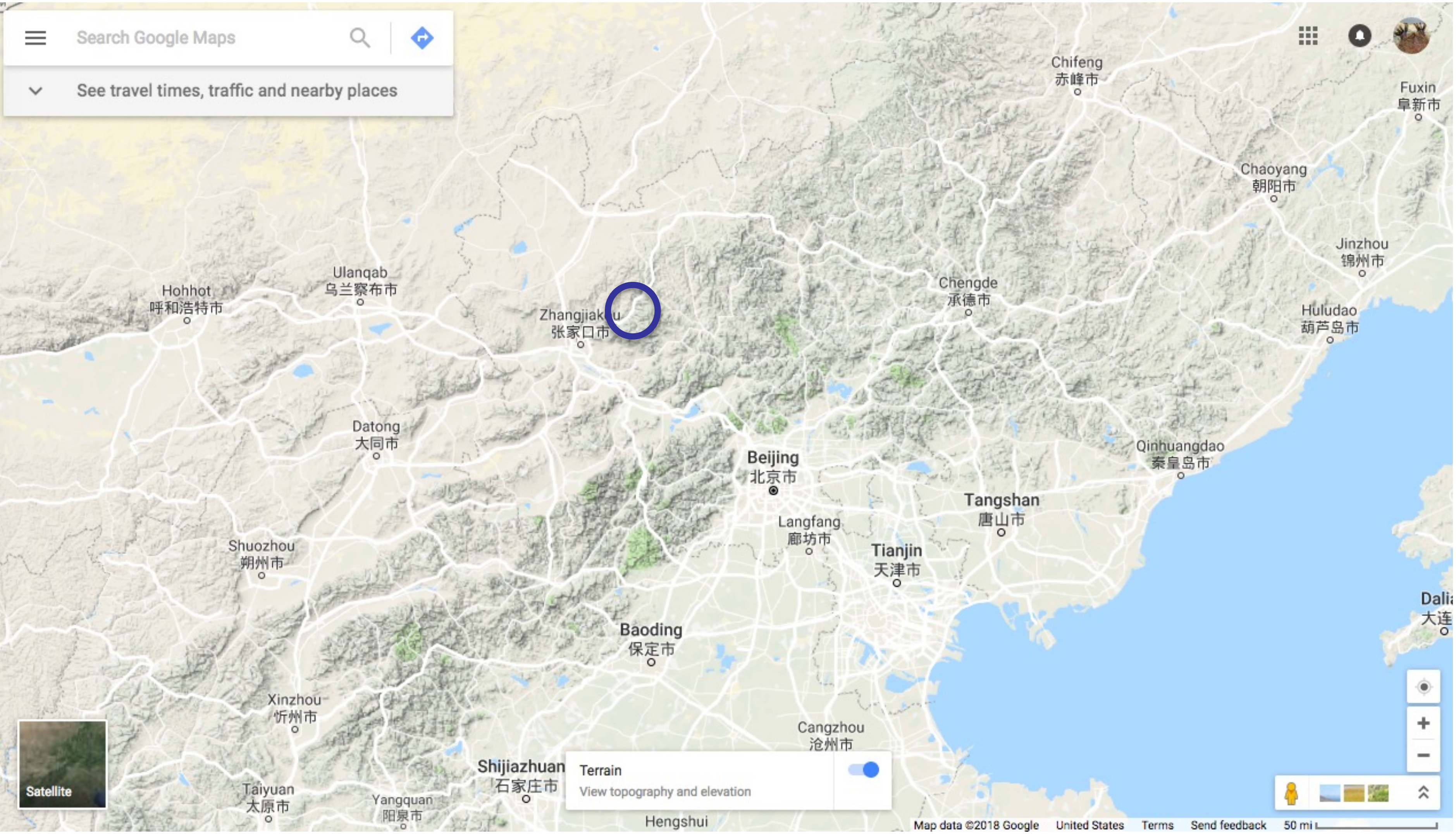
The Intermountain West

Whiteman (2000)

Topography


Ulaanbaatar
Улаанбаатар
Mongolia
HEILONGJIANG
Vladivostok
Владивосток
JILIN
INNER
MONGOLIA
LIAONING
Sea of Japan
North Korea
Beijing
北京
Pyongyang
평양
HEBEI
Tianjin
天津
GANSU
QINGHAI
NINGXIA
SHANXI
South Korea
Hiroshima
広島
Osak
大阪
SHAANXI
SHANDONG
Yellow Sea
Busan
부산
China
Xi'an
西安
Fukuoka
福岡
HENAN

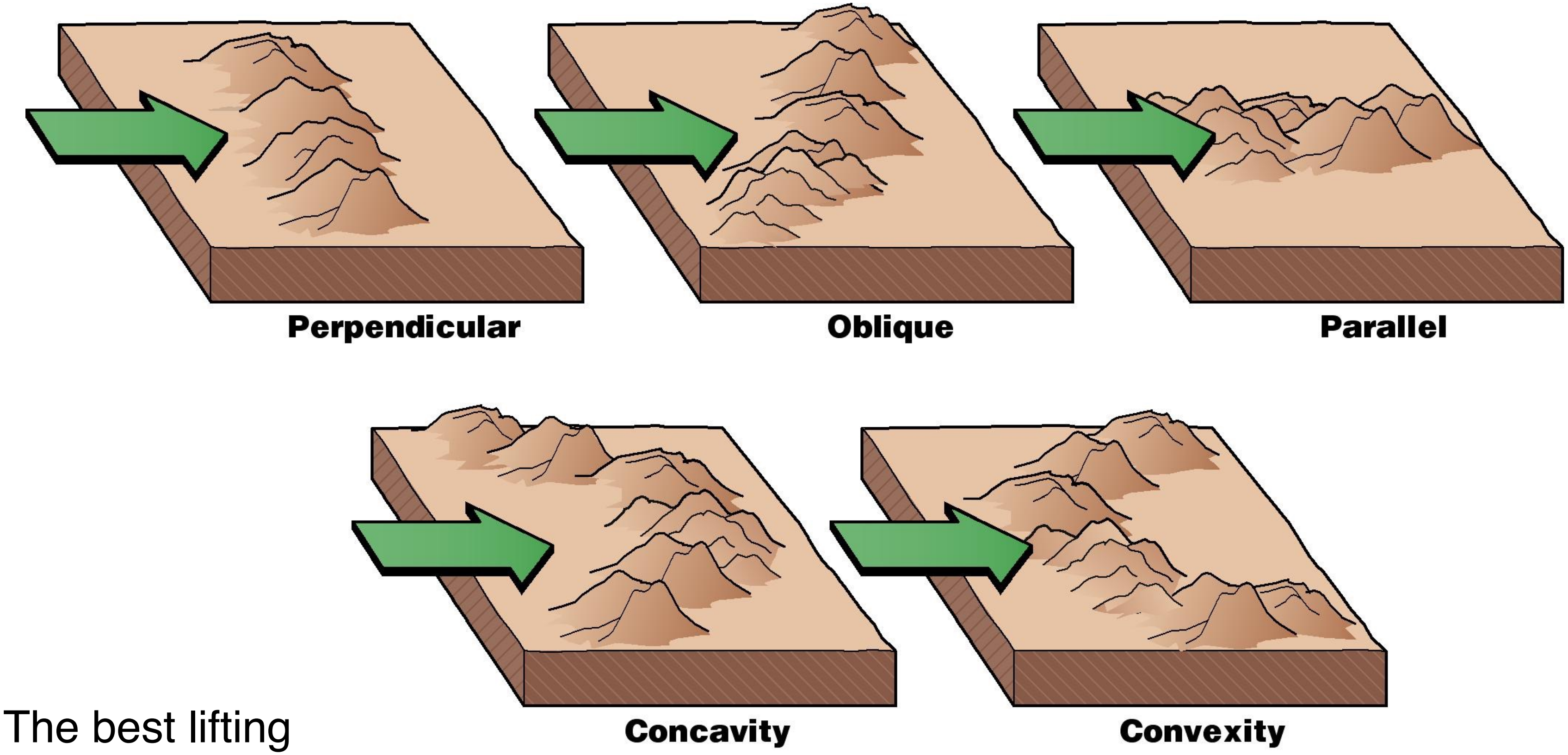
Topography


Search Google Maps
See travel times, traffic and nearby places
Chifeng
赤峰市
Fuxin
阜新市
Chaoyang
朝阳市
Jinzhou
锦州市
Chengde
承德市
Huludao
葫芦岛市
Ulanqab
乌兰察布市
Hohhot
呼和浩特市
Zhangjiakou
张家口市
Datong
大同市
Beijing
北京市
Qinhuangdao
秦皇岛市
Tangshan
唐山市
Langfang
廊坊市
Tianjin
天津市
Shuozhou
朔州市
Baoding
保定市
Dalian
大连
Xinzhou
忻州市
Cangzhou
沧州市
Shijiazhuang
石家庄市
Taiyuan
太原市
Yangquan
阳泉市
Hengshui
Satellite
Terrain
View topography and elevation
Map data ©2018 Google
United States
Terms
Send feedback
50 mi

Topography

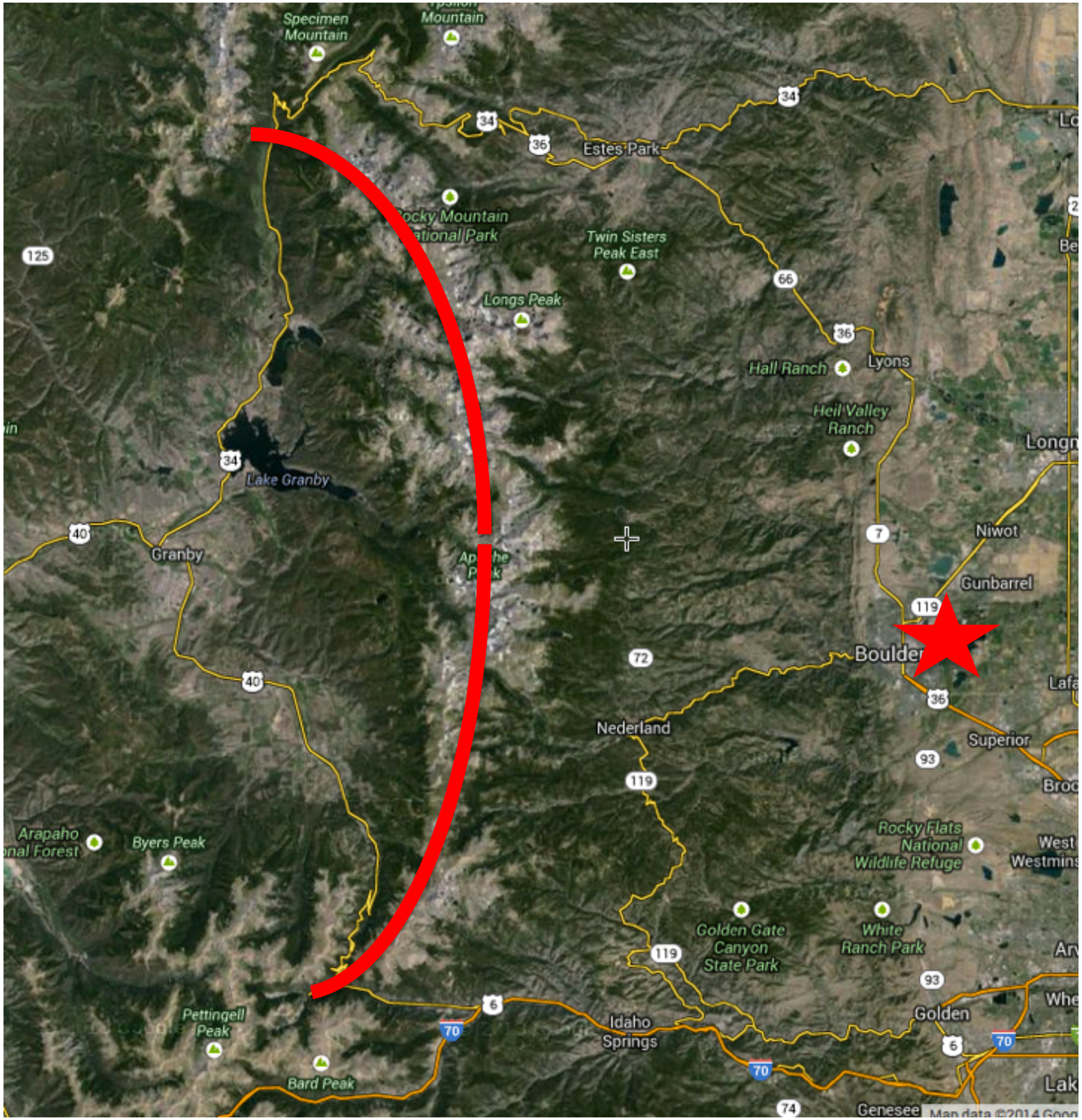
Image Landsat / Copernicus
Image © 2018 CNES / Airbus
Image © 2018 DigitalGlobe
Google Earth
2009
eye alt 2.02 km
N

Angle of attack



The best lifting
requires strong
cross-barrier flow

Whiteman (2000)



Boulder, Colorado

The Basics: Landforms associated with strong and weak surface winds

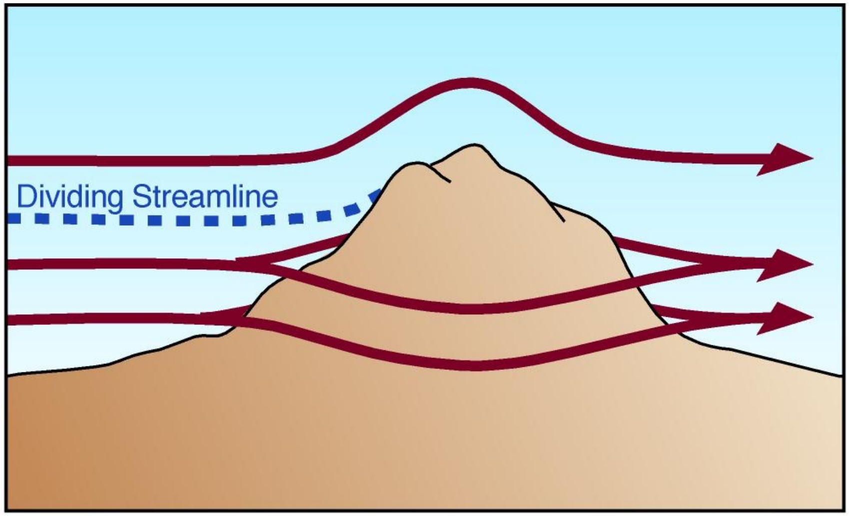
Expect high winds at sites:
Located in gaps, passes or gorges in areas with *strong pressure gradients*
Exposed directly to strong prevailing winds (summits, high windward or leeward slopes, high plains, elevated plateaus
Located downwind of smooth *fetches*
Expect low wind speeds at sites:
Protected 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)

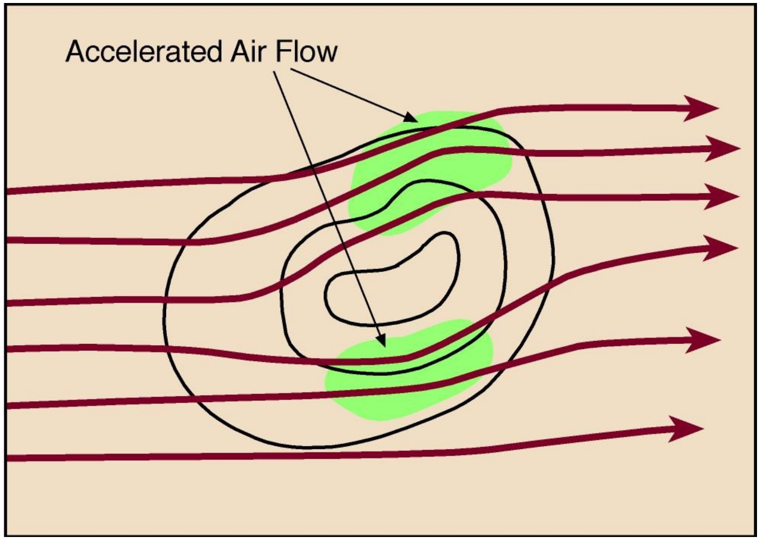
Wind variations with topographic characteristics, continued …

- In complex terrain, winds respond to **landforms** (valleys, passes, plateaus, ridges, and basins) and **roughness elements** (peaks, terrain projections, trees, boulder, etc.)
- Wind increases at the **crest of a mountain** (more so for triangular than for rounded or plateau-like hilltops)
- Speed is affected by **orientation of ridgeline** relative to approaching wind direction (concave, convex)
- **Separation eddies** can form over steep cliffs or slopes on either the windward or leeward sides
- 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’ Winds can be can be **channeled** through passes or gaps by small topographic features

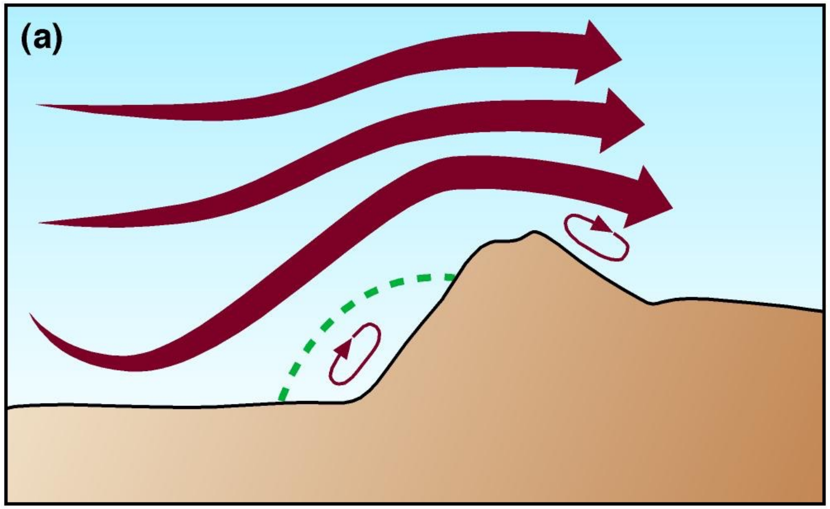
Wind variations with topographic characteristics

- **Barrier 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.





Separation eddies



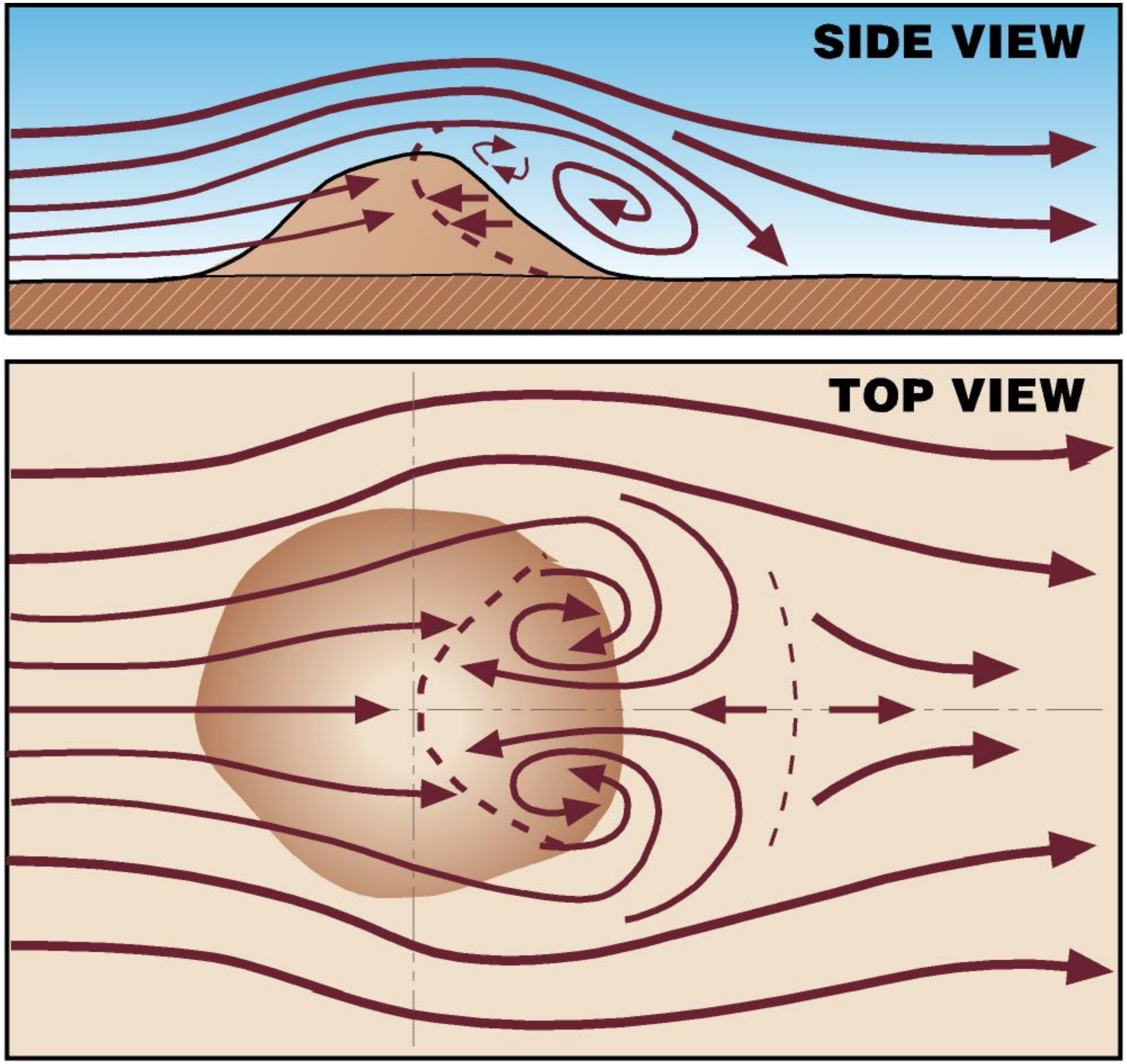
Separation eddies can form over steep cliffs or slopes on either the windward or leeward sides

Whiteman (2000)

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 Parleys Canyon (Wasatch Range).



Orgill (1981)

CMA/COMET 2019

Terrain Forced Flows & their basic

Dynamics

Marc Thunis / unsplash

Key non-dimensional parameters

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

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

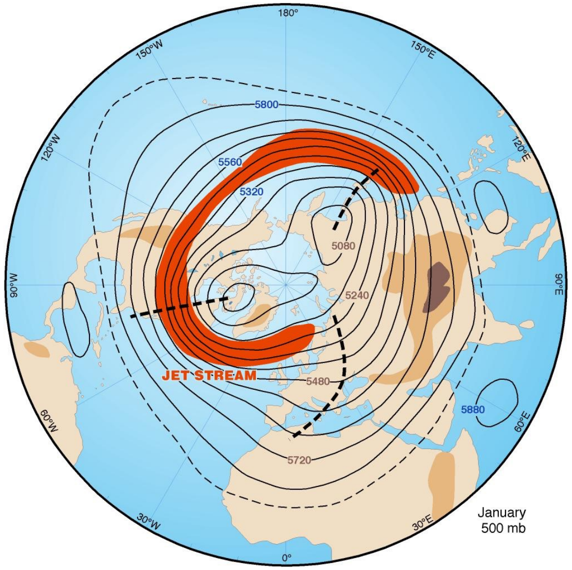
Reinecke and Durran (2008)

Rossby Number (R_o);

$$\boxed{R_o = U/fL}$$

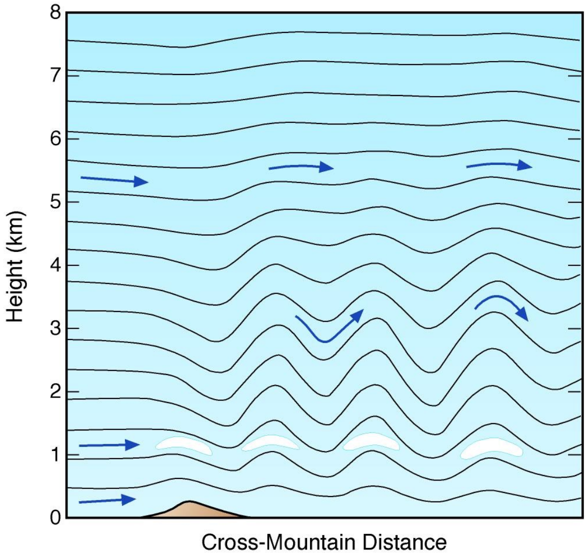
$R_o \ll 1$

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



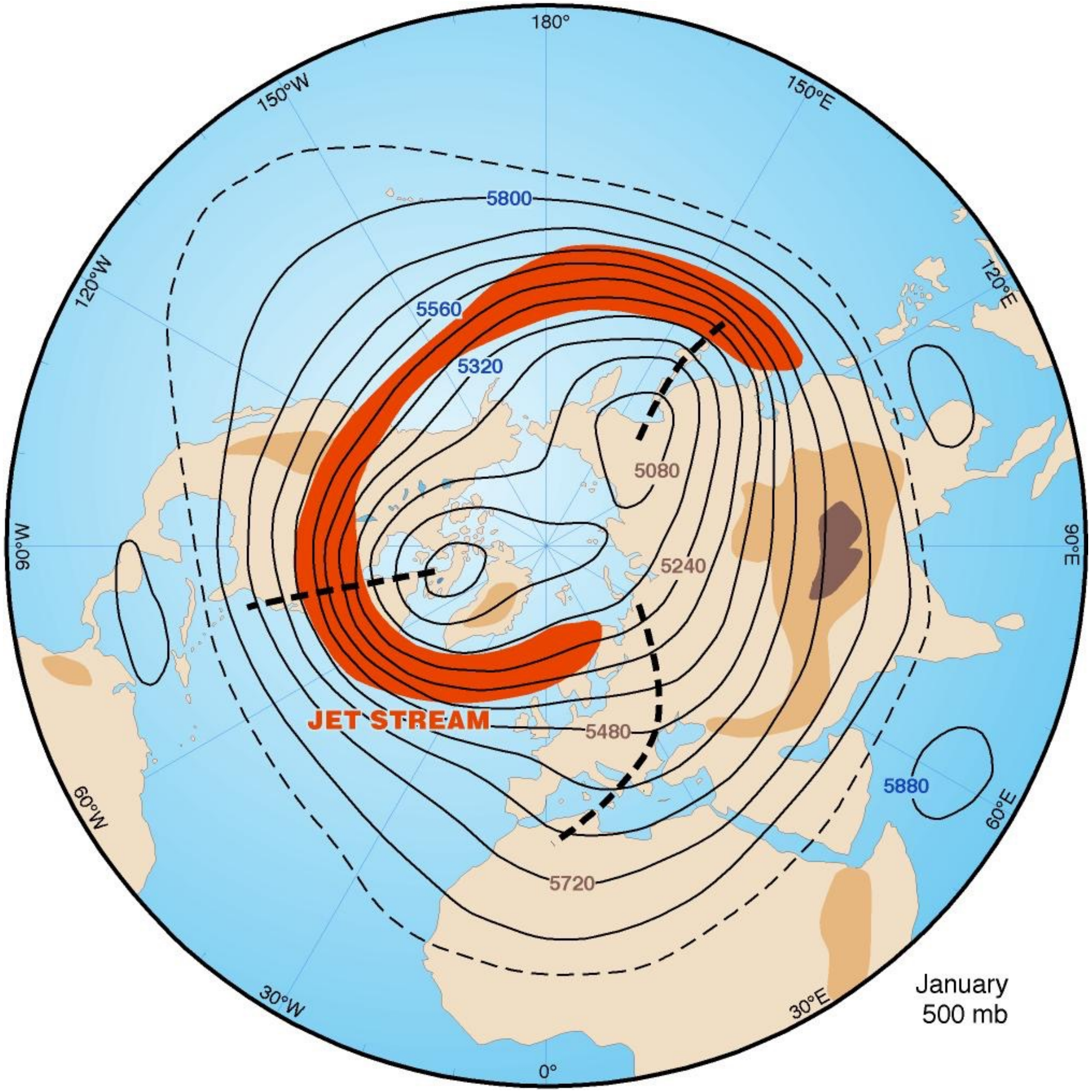
$R_o \geq 1$

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



Images: Whiteman (2000)

Mean January 500 mb hemispheric map

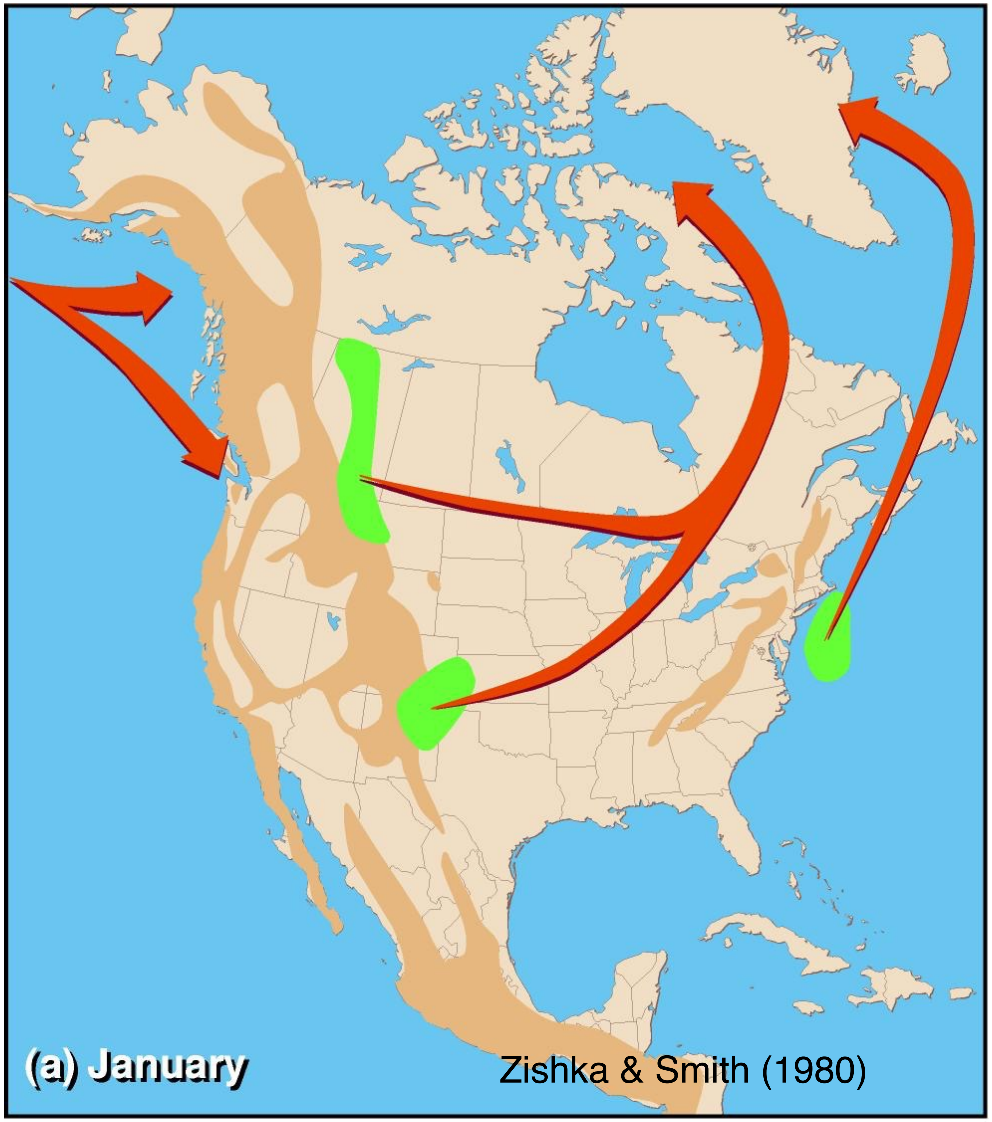


January
500 mb

Mean troughs form down-wind of major mountain barriers

Wallace & Hobbs (1977)

January cyclogenesis areas and paths



Zishka & Smith (1980)

Cyclogenesis: formation and intensification of low pressure systems or cyclones.

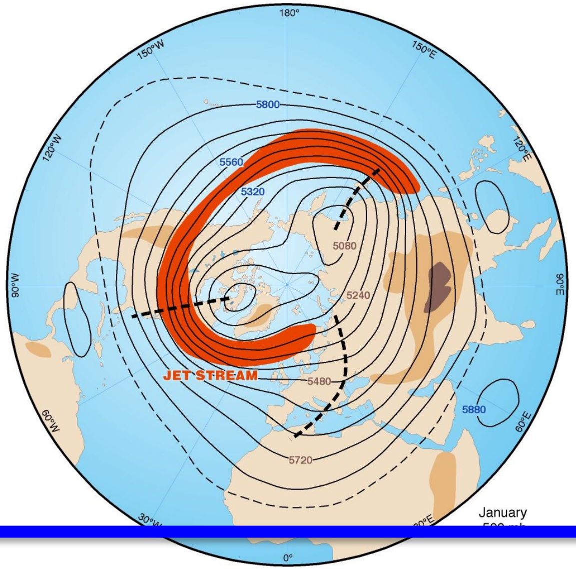
“Lee cyclogenesis”

Rossby Number (R_o);

$$\boxed{R_o = U/fL}$$

$R_o << 1$

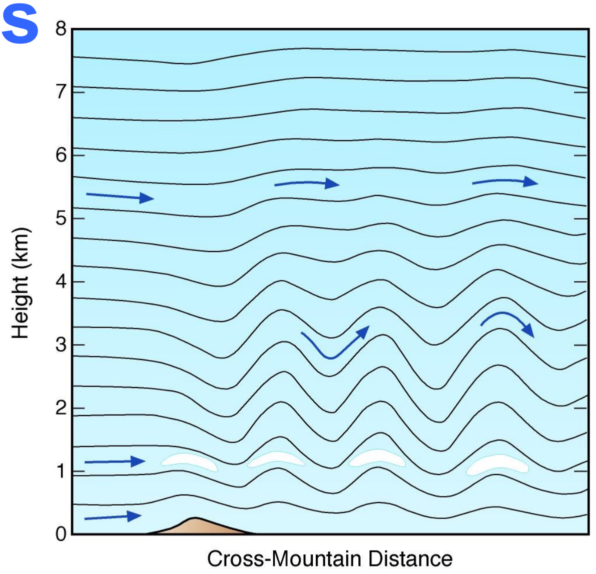
Air takes >> f^{-1} to cross barrier
Coriolis force dominates
Parcels displaced horizontally
Rossby waves produced



Terrain-Forced Flows

$R_o \geq 1$

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



Images: Whiteman (2000)

Non-Dimensional Mountain Height ε

$\boxed{\varepsilon = h_0N/U}$

"Will the air flow over the barrier?"

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

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

ε > 1: Inertia too weak and the flow is ***blocked***
High stability, large mountain; weak cross-barrier flow

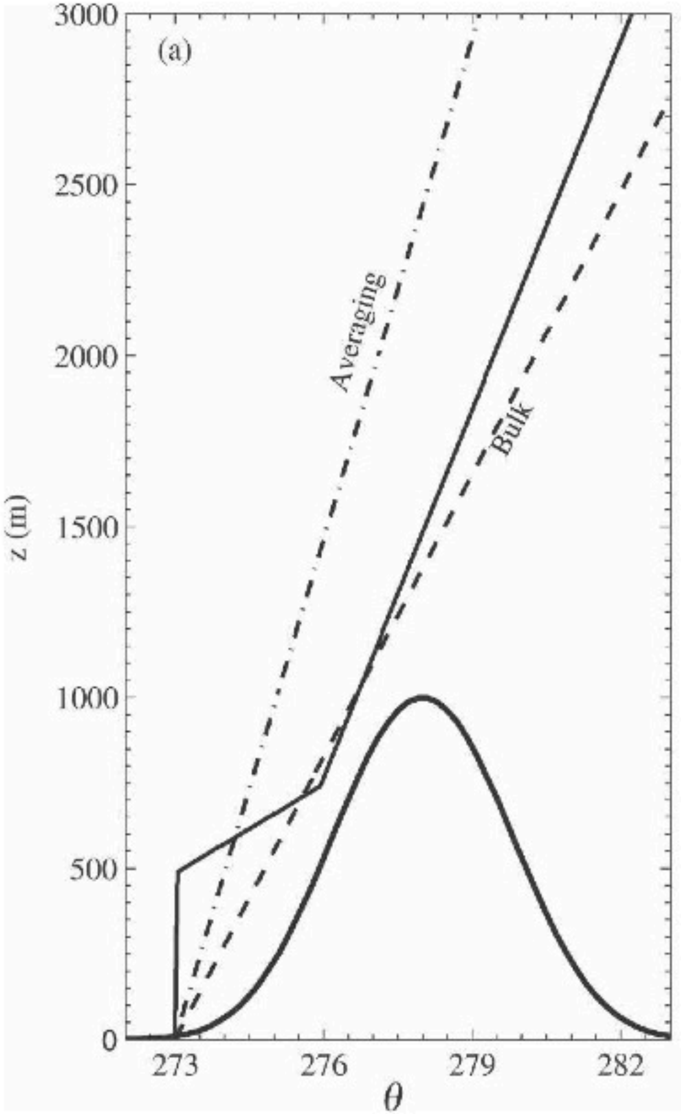
ε < 1: Inertia overcomes stability, ***flow surmounts barrier***
Low stability, small mountain, strong cross-barrier flow

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)

Terrain Forced Flows & Stability

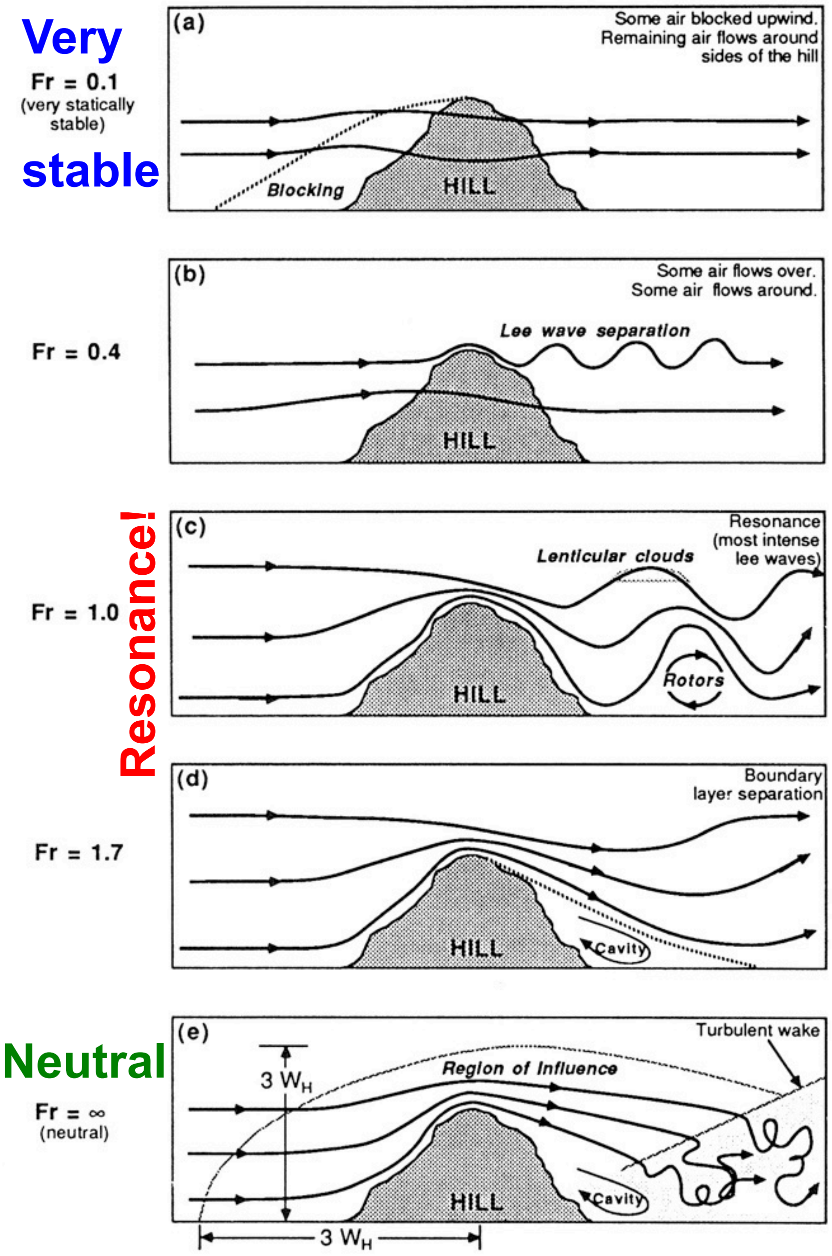


Fig. 14.14 Idealized flow over an isolated hill. The Froude number (Fr) compares the natural wavelength of the air to the width of the hill (W_H).

Stull (1988)

Froude number

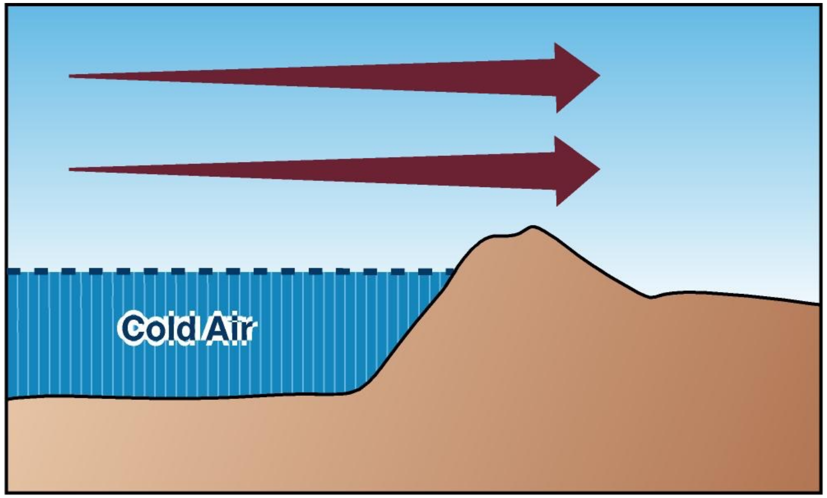
Non-dimensional mountain height = "Inverse" Froude number

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

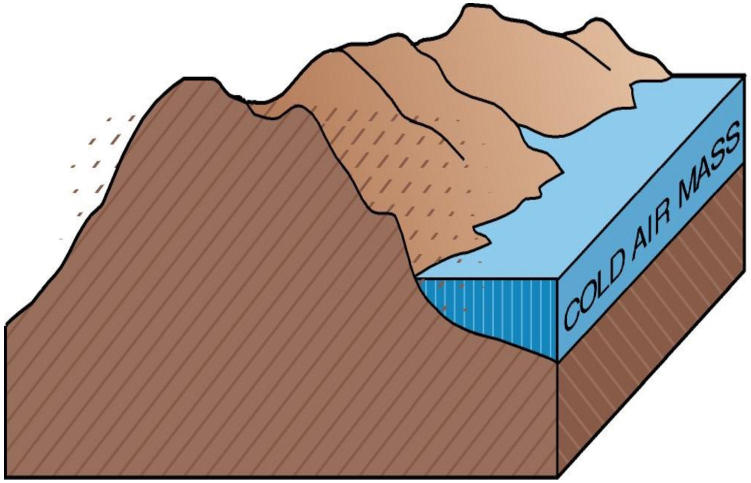
Natural wavelength of air / effective wavelength of obstacle.

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

Blocking - Mountains as flow barriers



Whiteman (2000)



Blocked flow

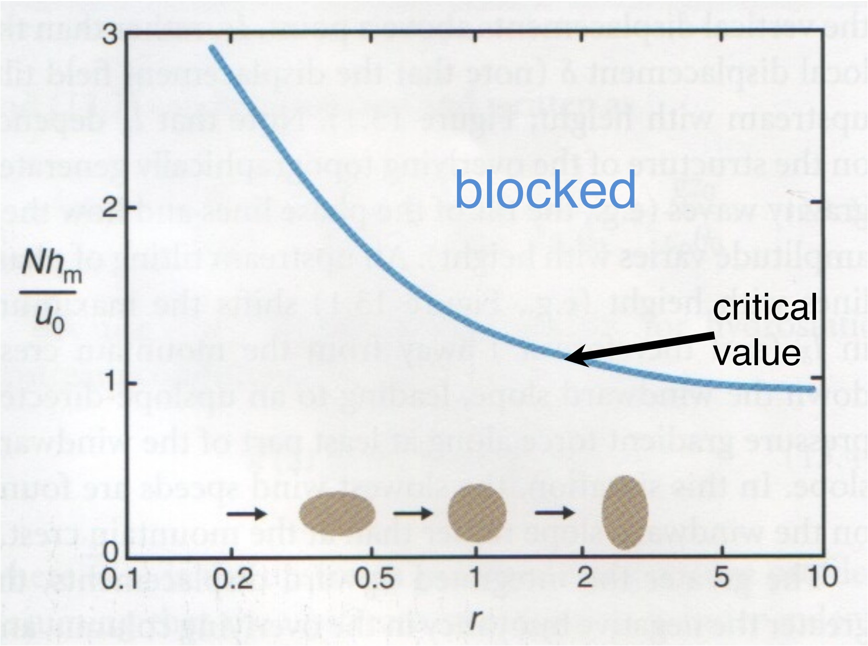
New Zealand

© C. D. Whiteman

Blocking / Obstruction of Air Masses

- Blocking of **stable** air masses 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 *non-dimensional mountain height ε* and mountain aspect ratio r.



r = crosswise / streamwise dimensions

Markowski & Richardson (2010) / Smith 1990

Flow Over Mountains

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!

Descent into DIA 30 September 30, 2014, ~ 2 pm

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

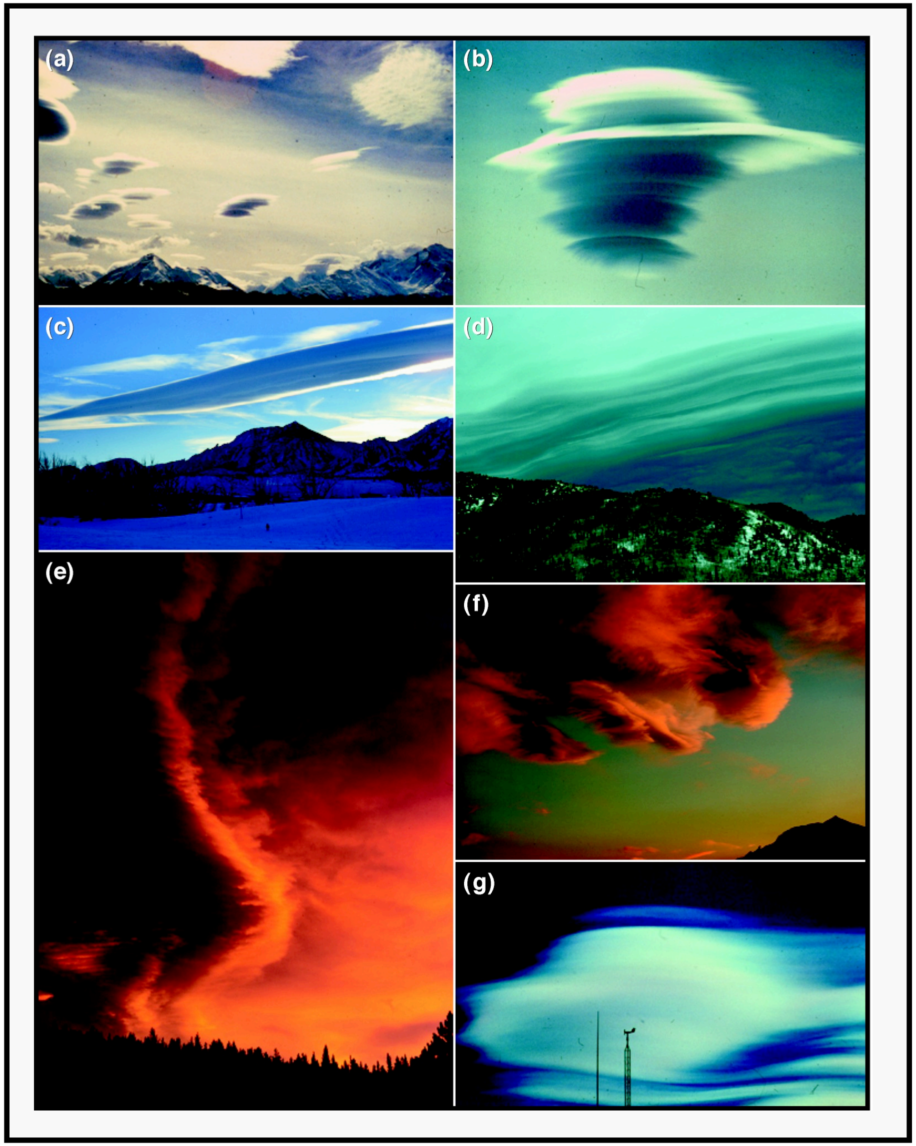
- Lenticular clouds
- Cap clouds
- Banner clouds
- Rotors
- Foehn wall
- Chinook arch
- Billow clouds
- Blowing snow
- Cornice buildup
- Blowing dust
- Downslope windstorms, etc…

Mountain Waves (Orographic Waves)

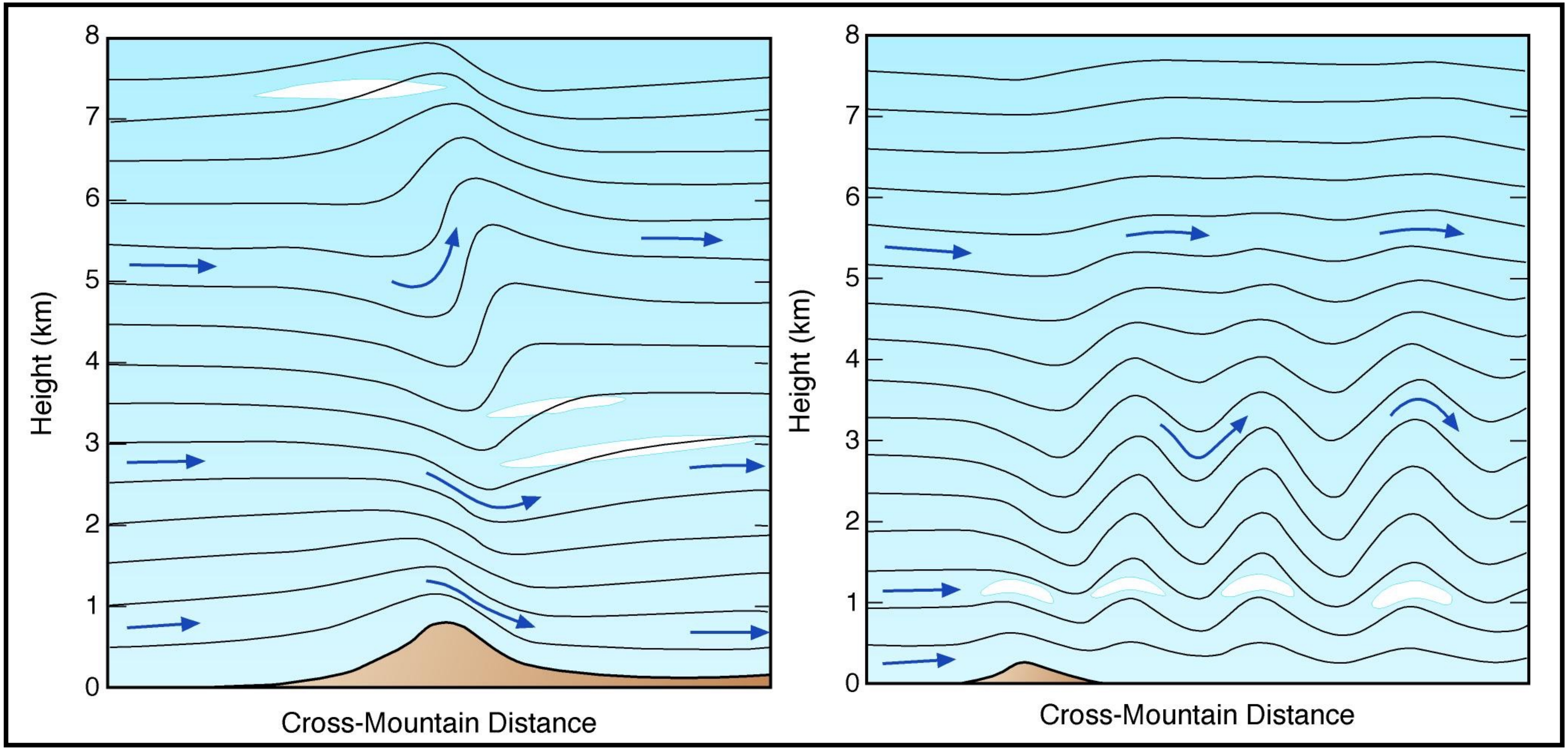
Mountain waves are atmospheric **gravity waves**, formed when stable air flow passes over a mountain or mountain barrier.

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

We can distinguish between **vertically propagating waves** and **trapped lee waves**.



Vertically propagating and trapped lee waves

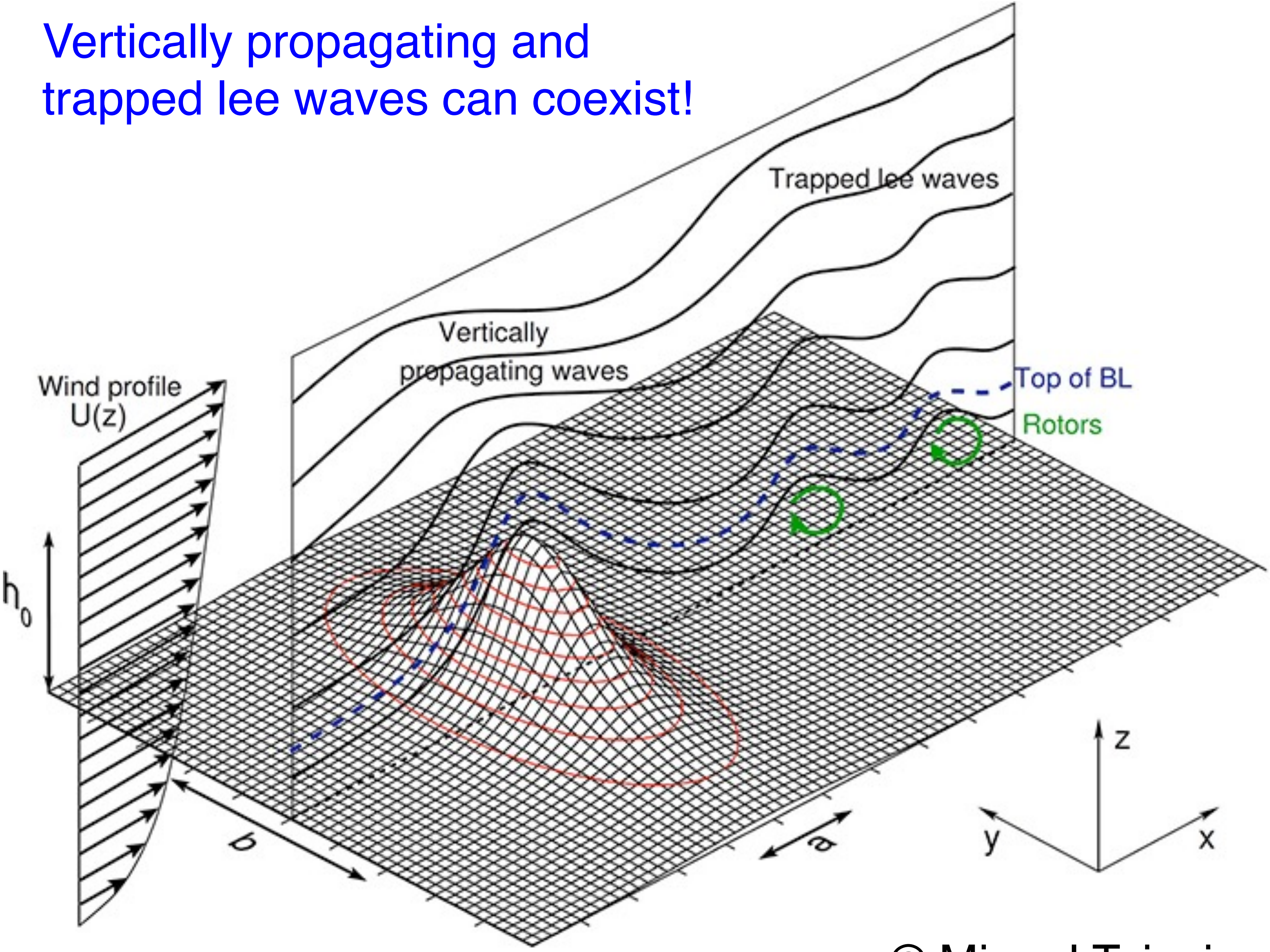


Carney et al. (1996)

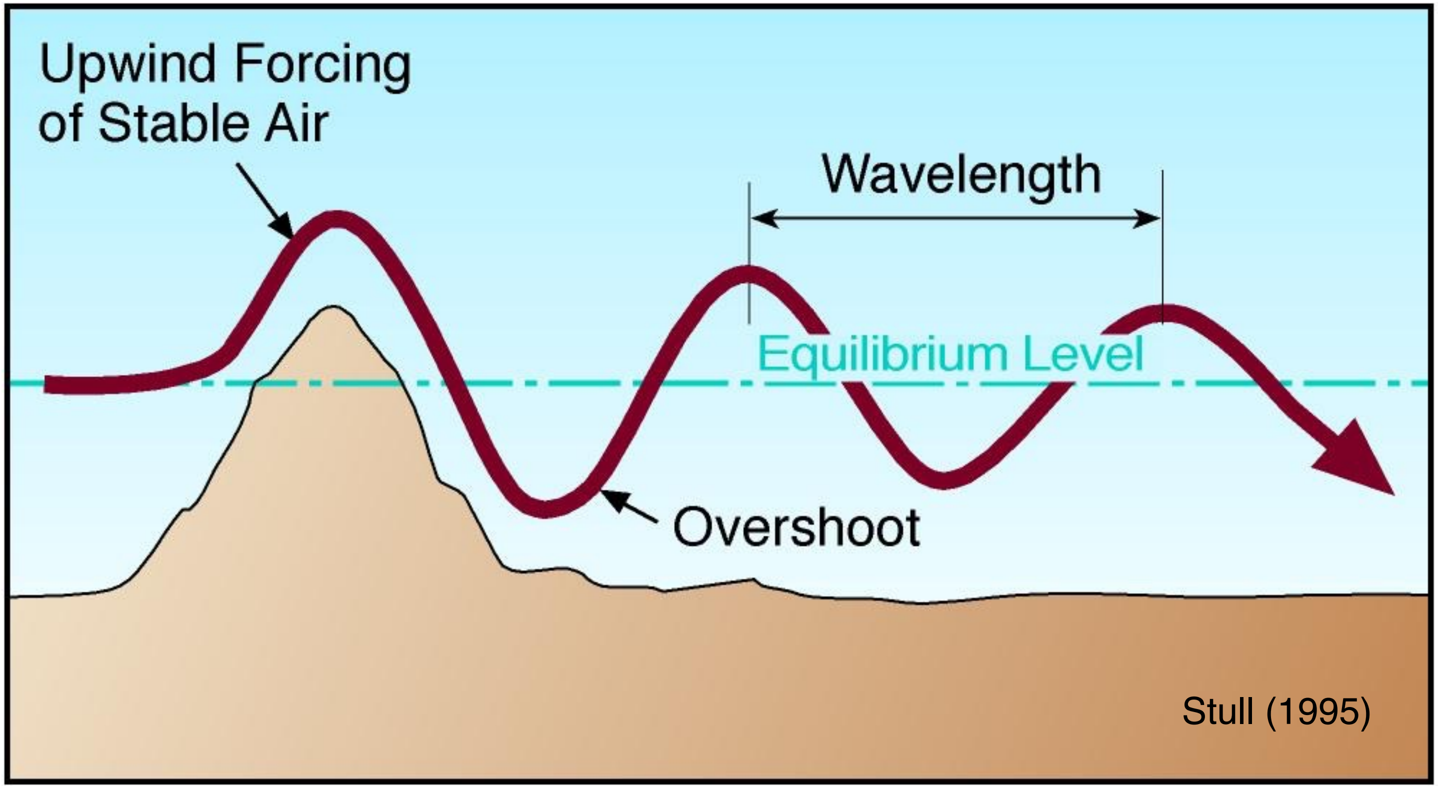
- Wavelengths of 10s of km
- Extend into lower stratosphere
- Often accompany foehn, chinook or bora
- Capability of concentrating energy on lee slopes (see downslope windstorms)
- Clear air turbulence

- Wavelengths of 5–35 km
- Occur within or beneath stable layer
- Strong vertical wind shear
- Turbulence / hazard for low-level aviation

Vertically propagating and trapped lee waves can coexist!



Trapped Lee Waves

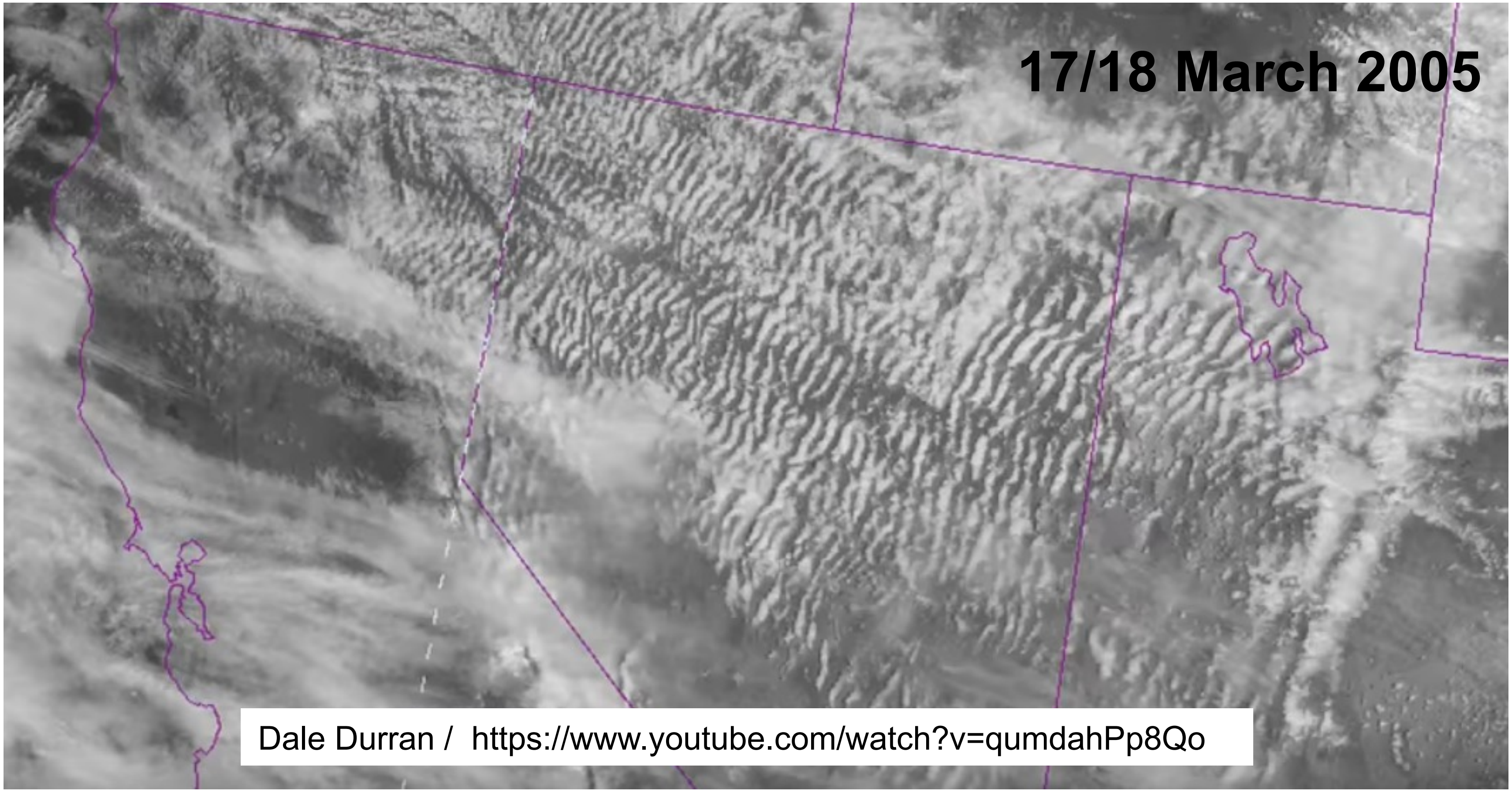


Stull (1995)

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.

Wavelength increases as speed increases and stability decreases!

Trapped Lee Waves


17/18 March 2005

Dale Durran / https://www.youtube.com/watch?v=qumdahPp8Qo

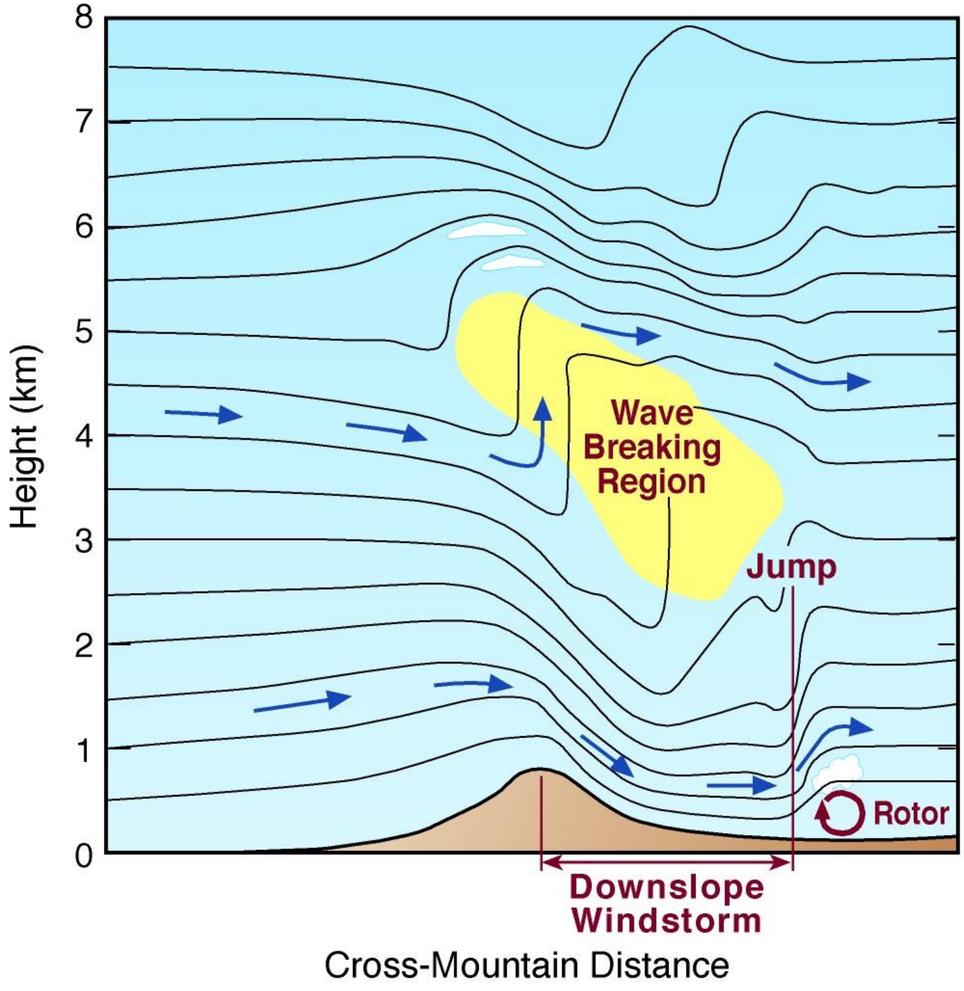
Factors that promote trapped lee waves:

- Increase of flow with height (unidirectional shear)
- Decrease in stability with height (elevated stable layer)

Downslope windstorms

https://www.youtube.com/watch?v=XPSK6ods58Q

Downslope windstorms



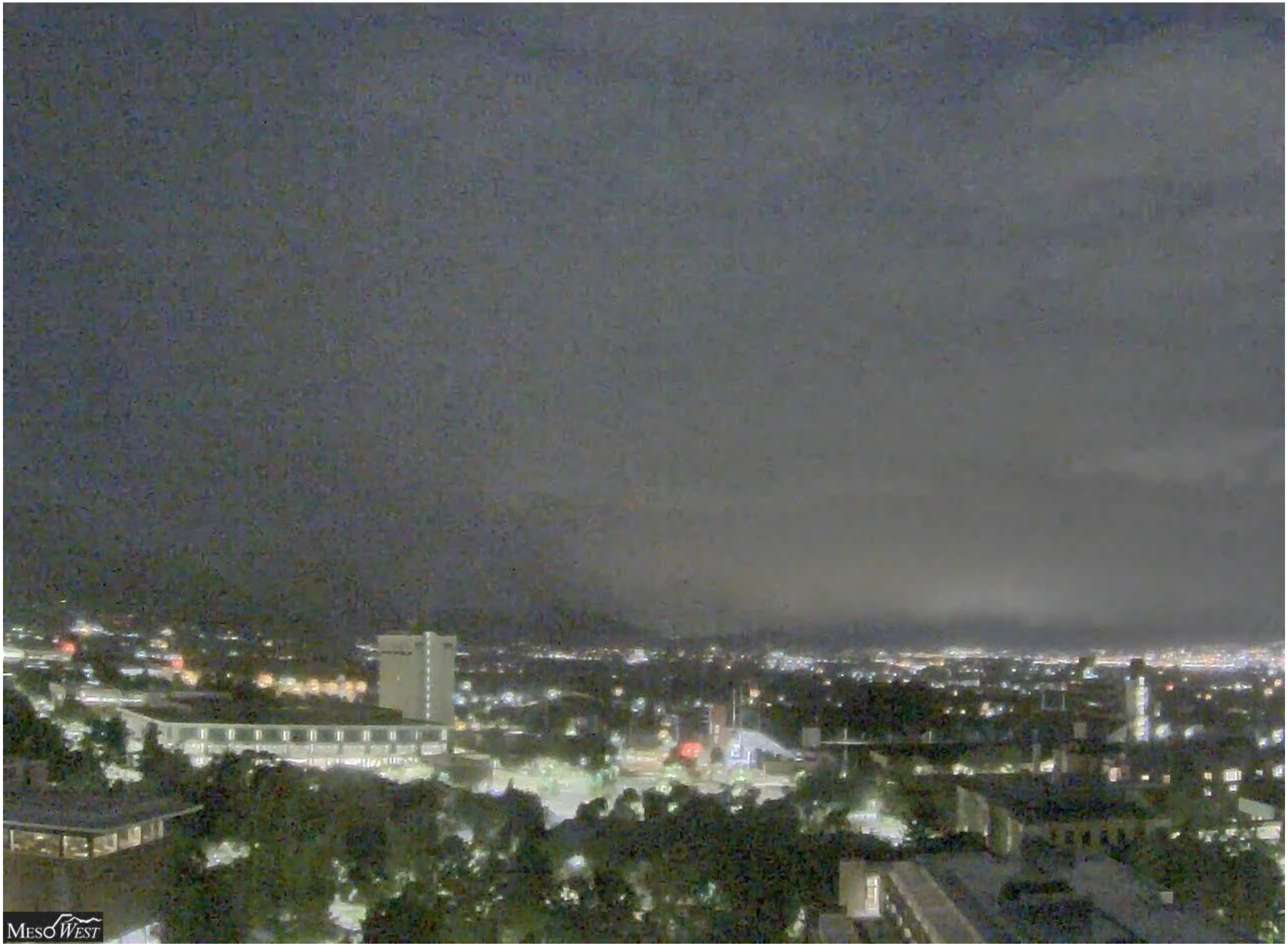
Under certain stability, flow and topography conditions, the entire mountain wave can undergo a sudden transition to a hydraulic flow involving a **hydraulic jump** and a **turbulent rotor**.

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)

Wasatch Front Windstorm 8 Sept 2020

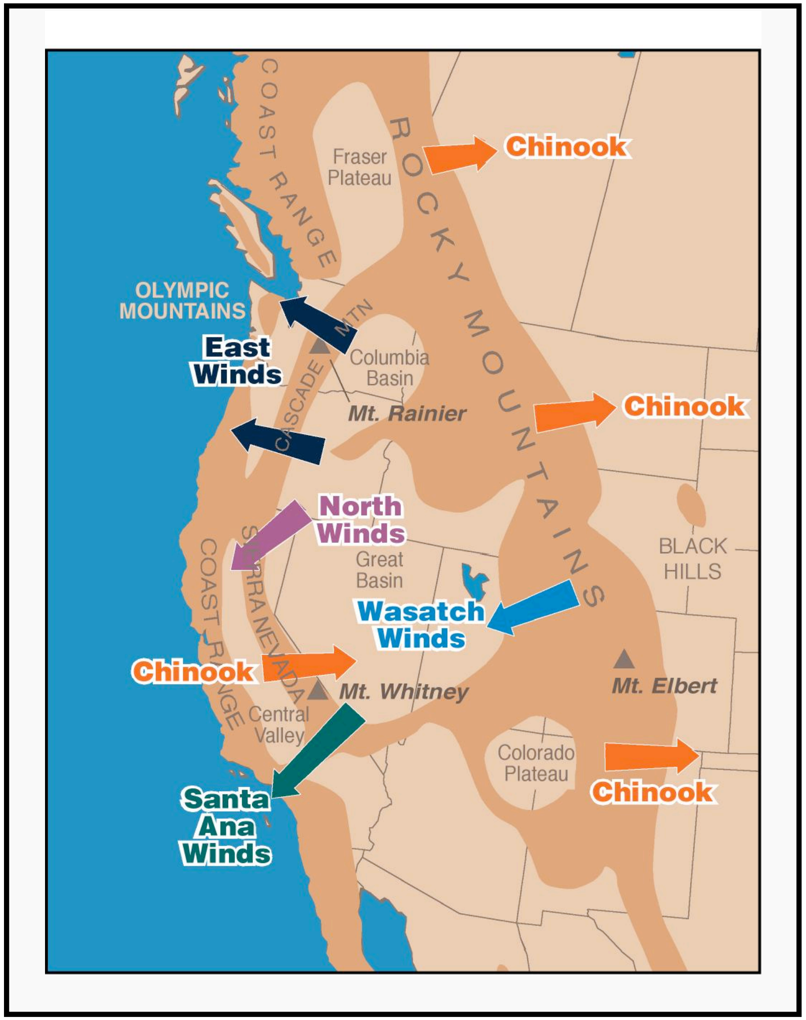
WBB South 2020-09-08 06:13:33



Wasatch Front Windstorm 8 Sept 2020

Zack Shutt
@ZackShutt

Wild and windy day in northern Utah. Power still out at my place for the for what appears to be at least another day. Sad seeing all these old trees topple over. #utahwind #utah

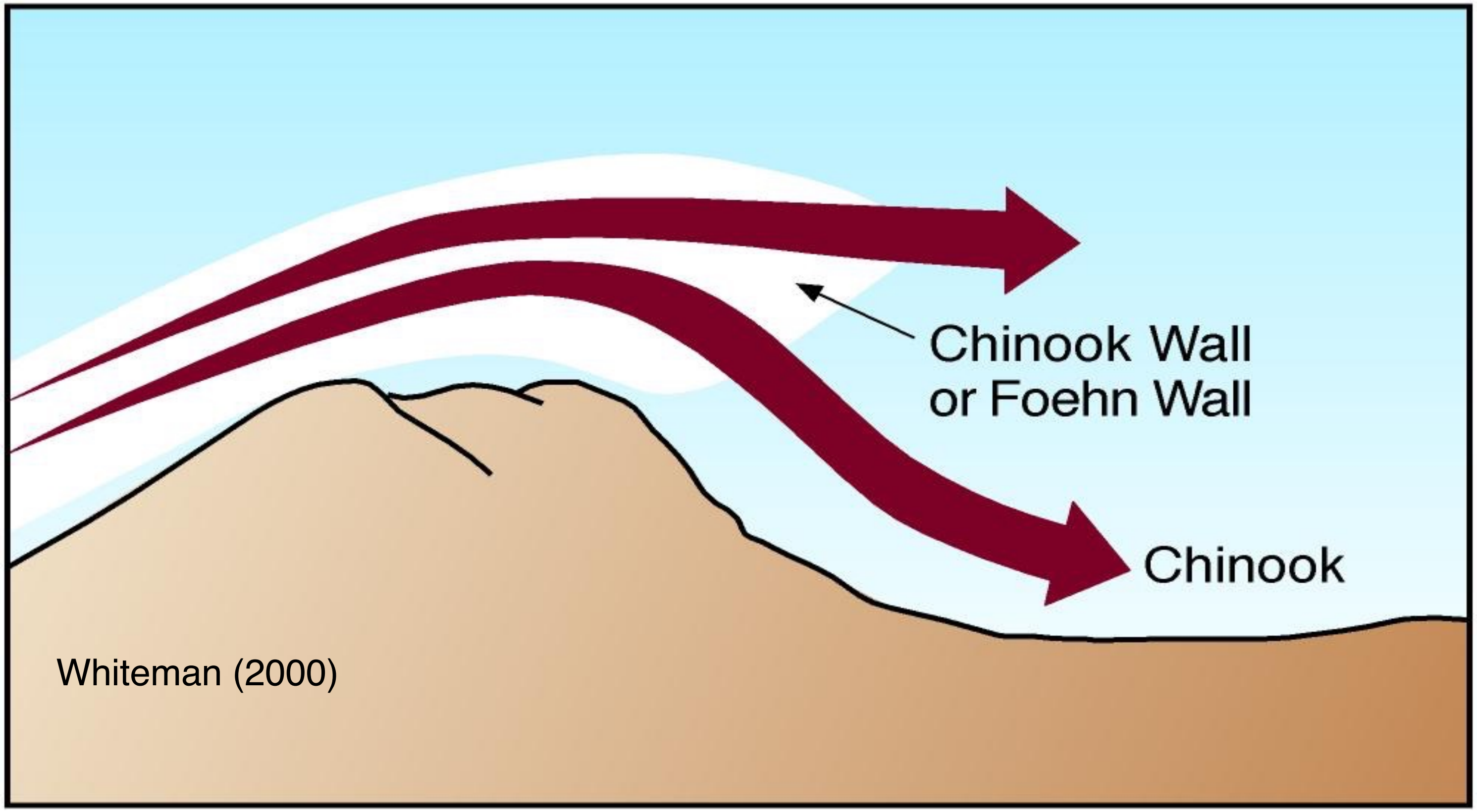


Whiteman (2000), adapted from Schroeder & Buck (1970)

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.
- May be associated with wave trapping, or wave breaking regions aloft.
- Can bring cold (Bora) or warm (Foehn, Chinook) air to leeward foothills.

Chinook of Foehn wall

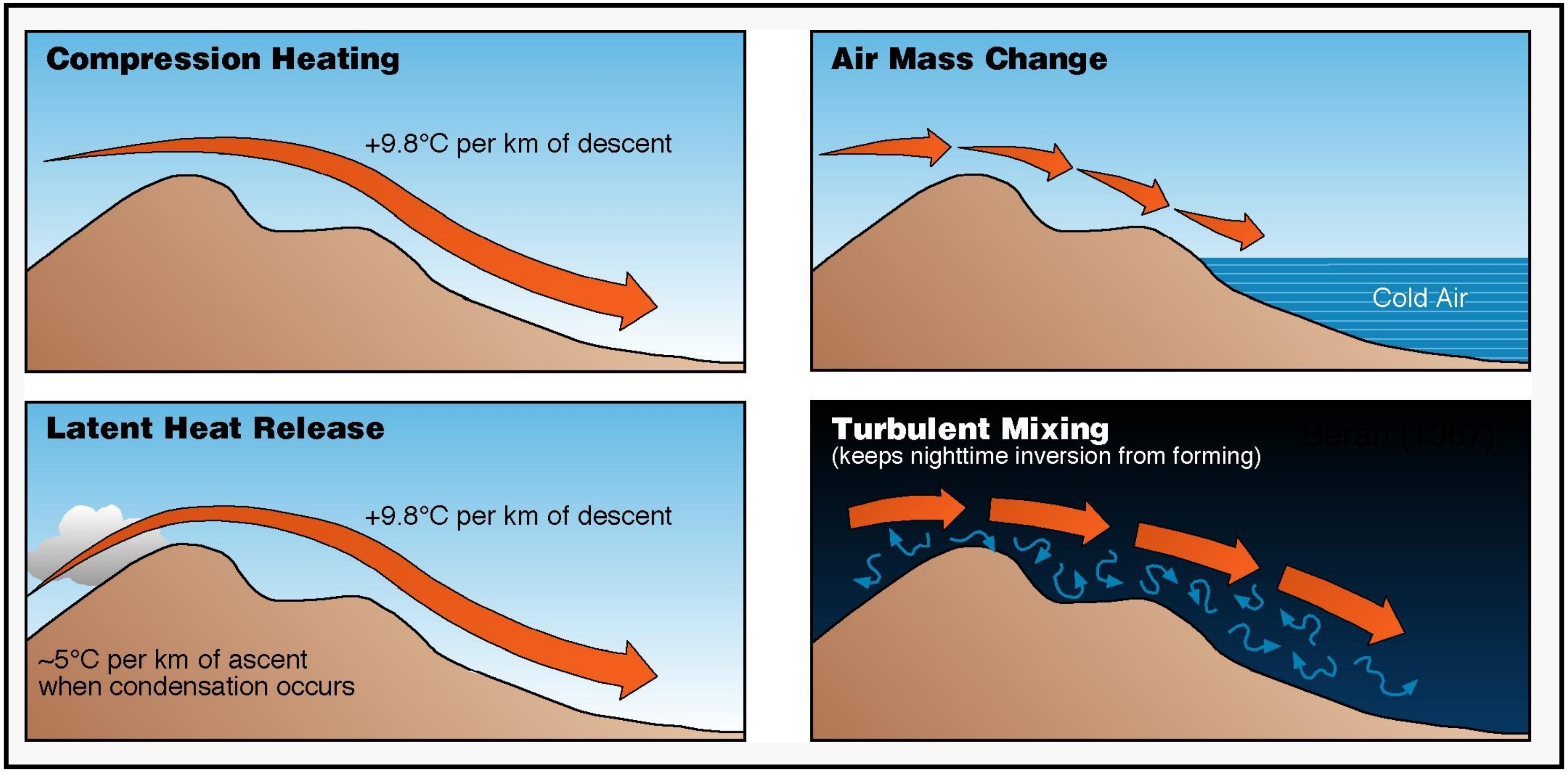


Whiteman (2000)

Prof. Stephen Mobbs, University of Leeds, UK

Rotor flow movie, Falkland Islands

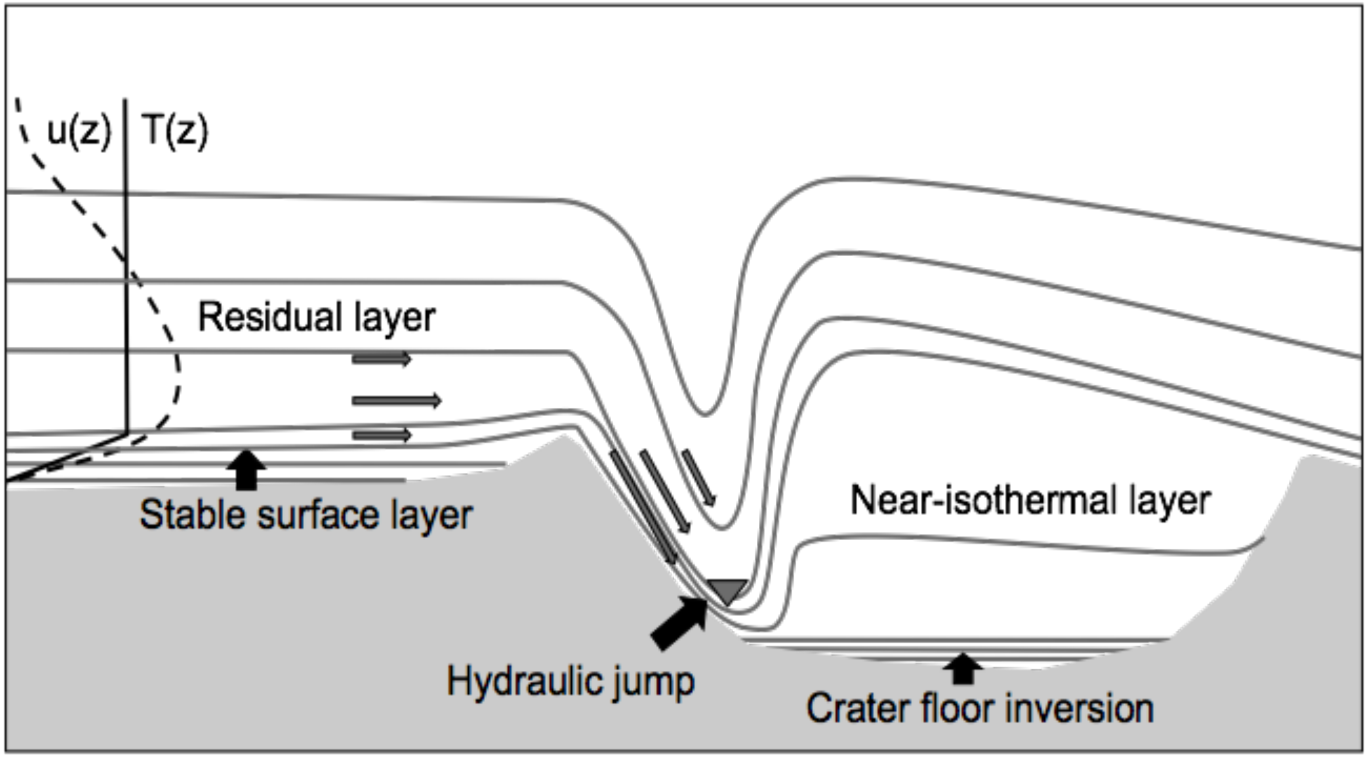
Four Chinook mechanisms



Beran (1967)

Four factors contribute to the warmth and dryness of Chinook winds

DWF – METCRAX-II / Conceptual model

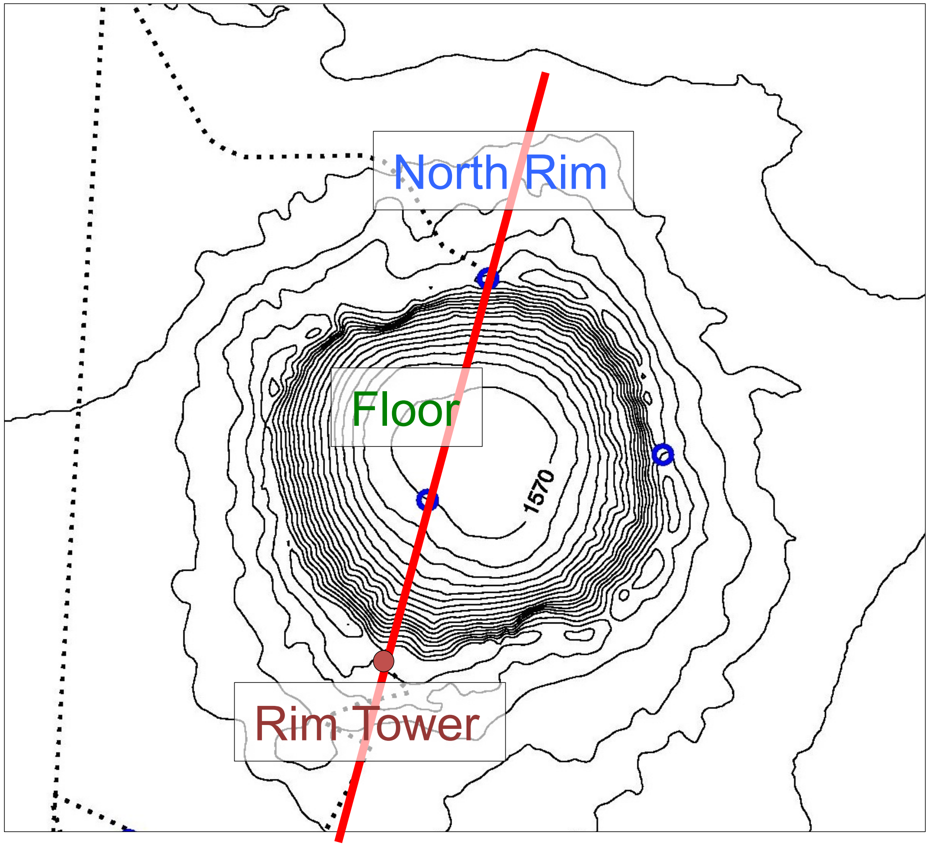


- During METCRAX-I in 2006 we found that intermittent downslope-windstorm-type flows developed over the crater's SW sidewall on clear, undisturbed nights. (See Adler et al. 2012)

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

Dual-Doppler Retrieval

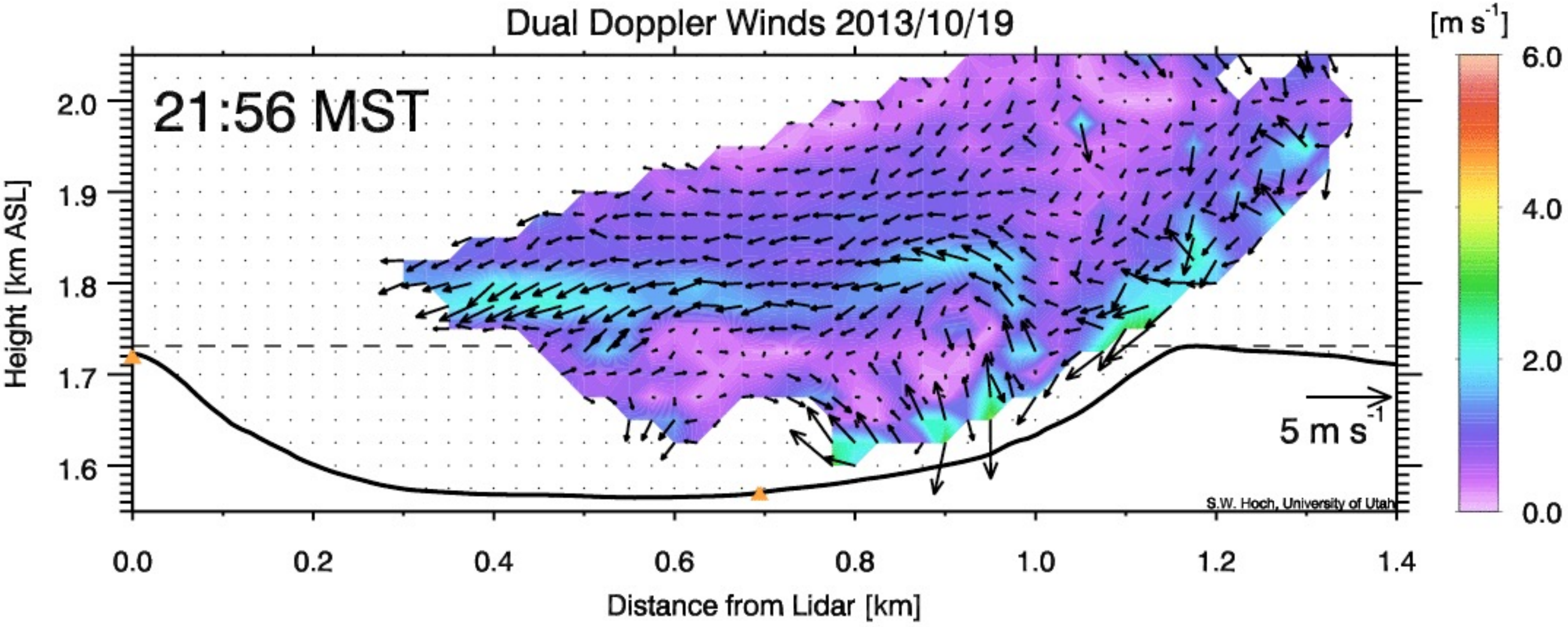
IOP-4 (19-20 October 2013)



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

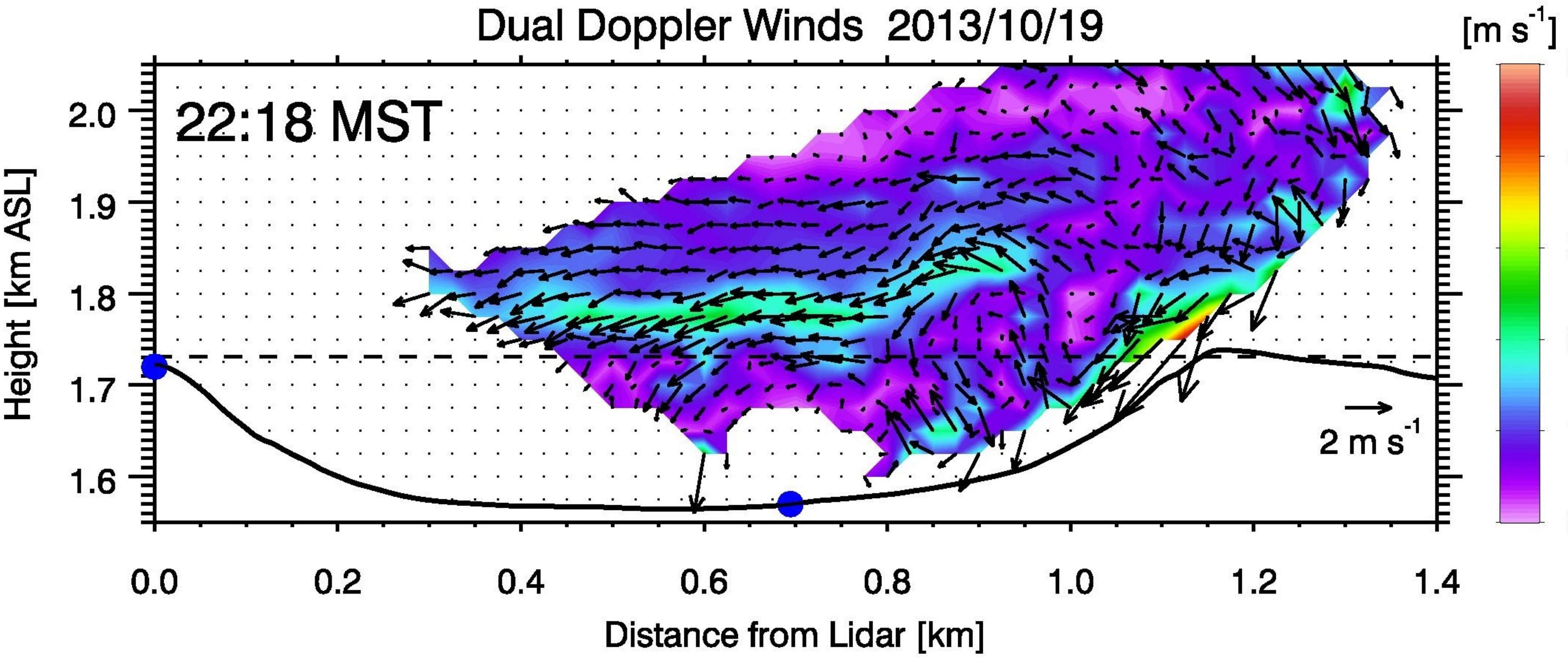
Dual-Doppler Retrieval

IOP-4 (19-20 October 2013)

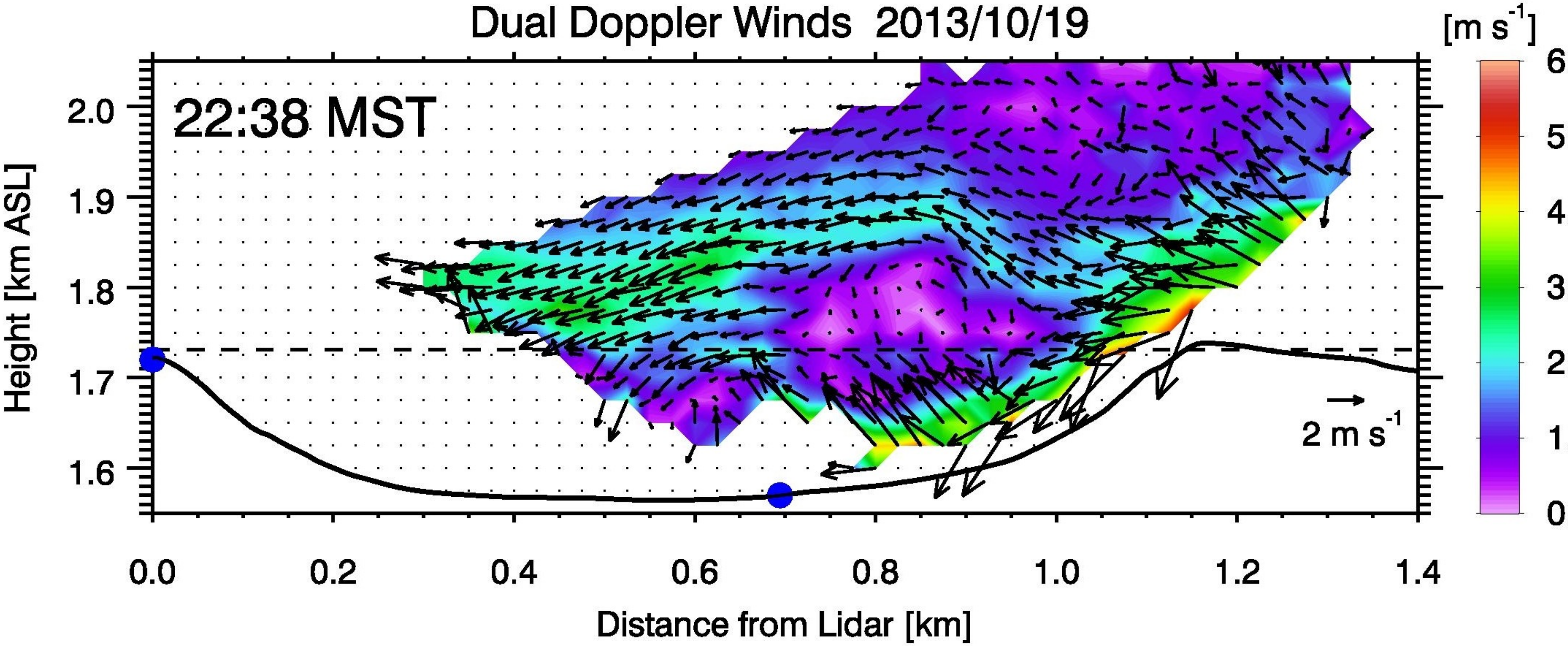


Scans within a 2-3 min time window are averaged and used in a dual doppler analysis.

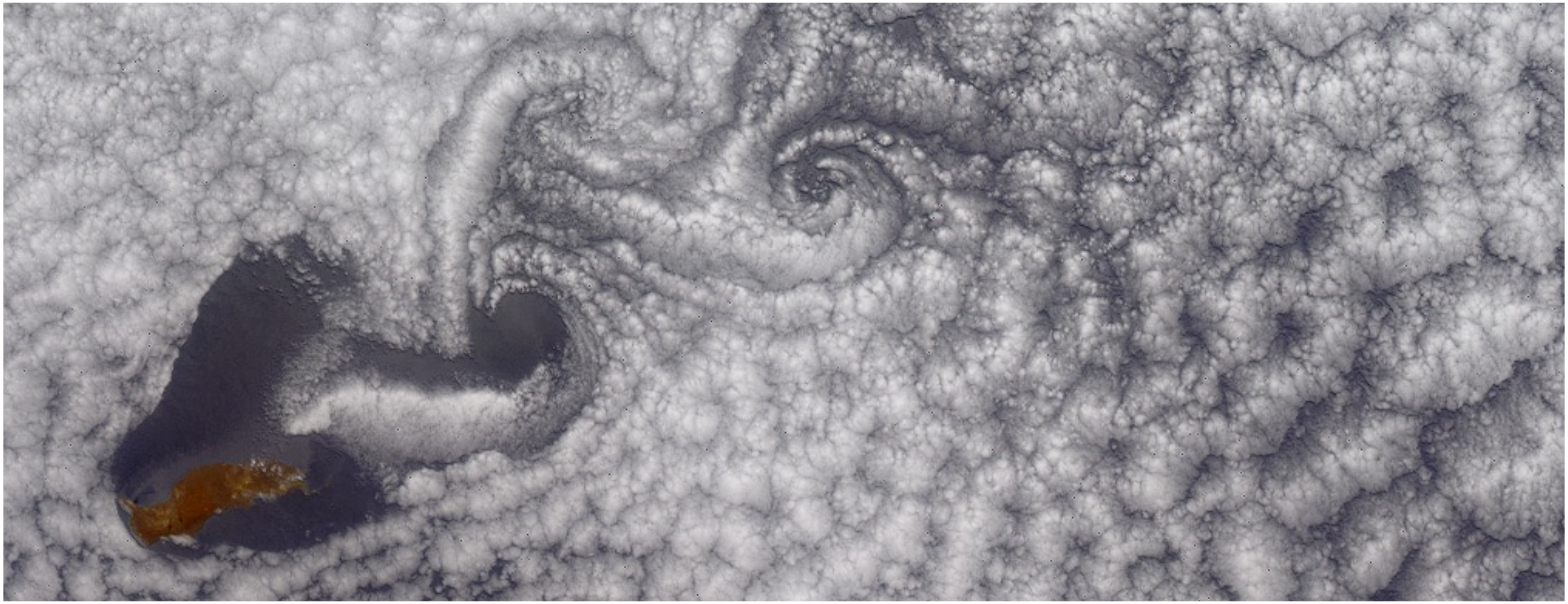
Hydraulic Jumps, rotors, …



Flow Separation



Flow around



Selkirk Island, Landsat 7 satellite in September 1999. Credit: Bob Cahalan / NASA, USGS

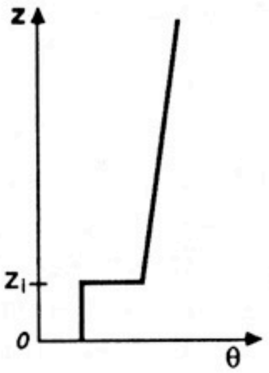
Flow Around Mountains

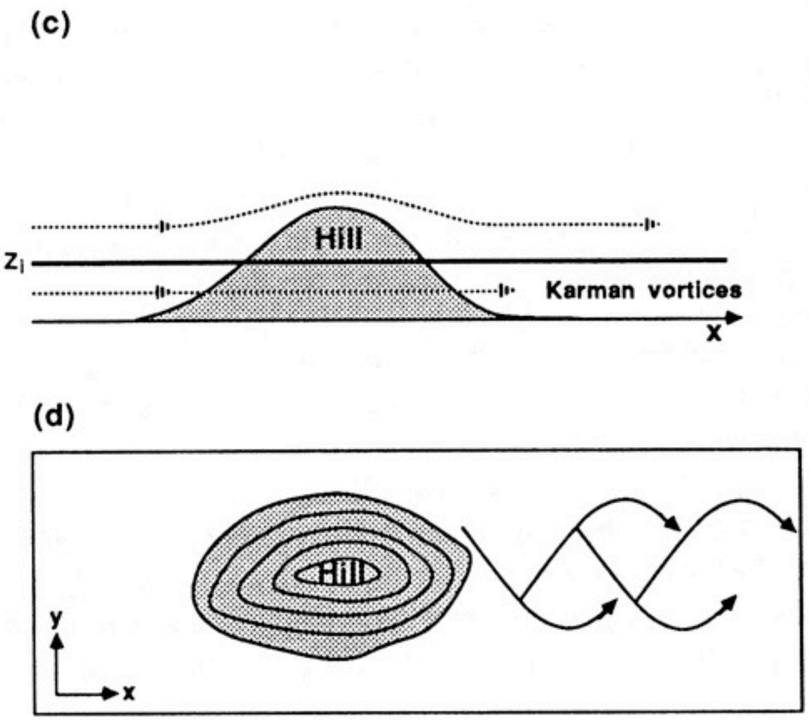
A flow approaching a mountain barrier tends to go around rather than over a barrier if:

- 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 (blocking)***
- Approaching low-level ***air mass*** is very ***shallow***

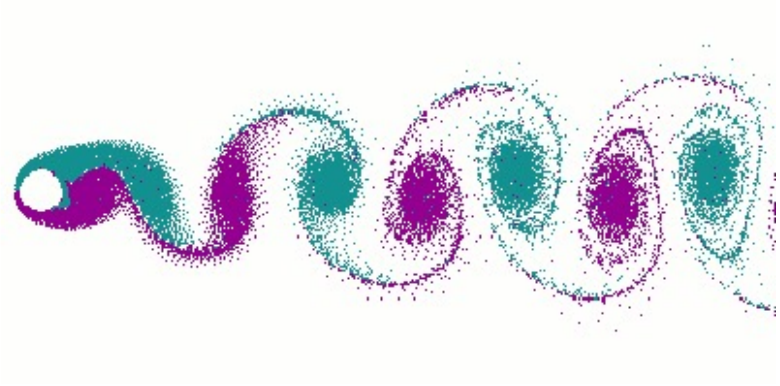
Because Rockies and Appalachians are long, flow around them is uncommon. But these types of flows are seen in the Aleutians, the Alaska Range, the Olympic Mountains and around isolated volcanoes. They should be expected to occur also around the Uintas and in southern Wyoming.

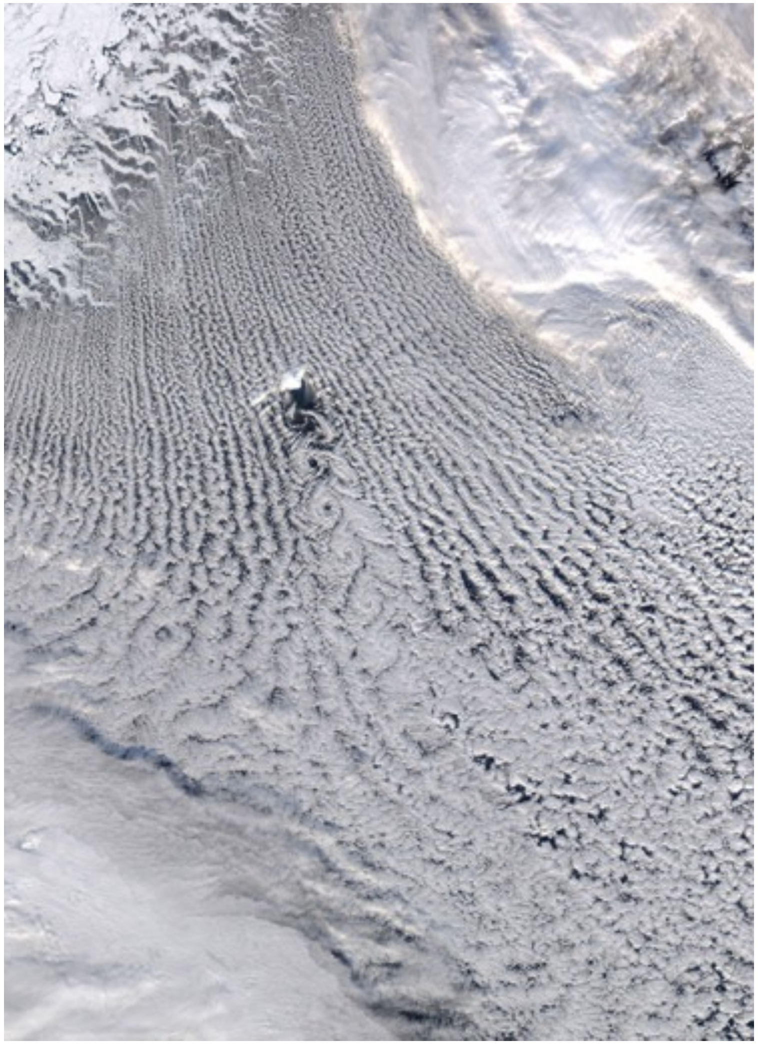
The influence of an elevated inversion in flow over a hill





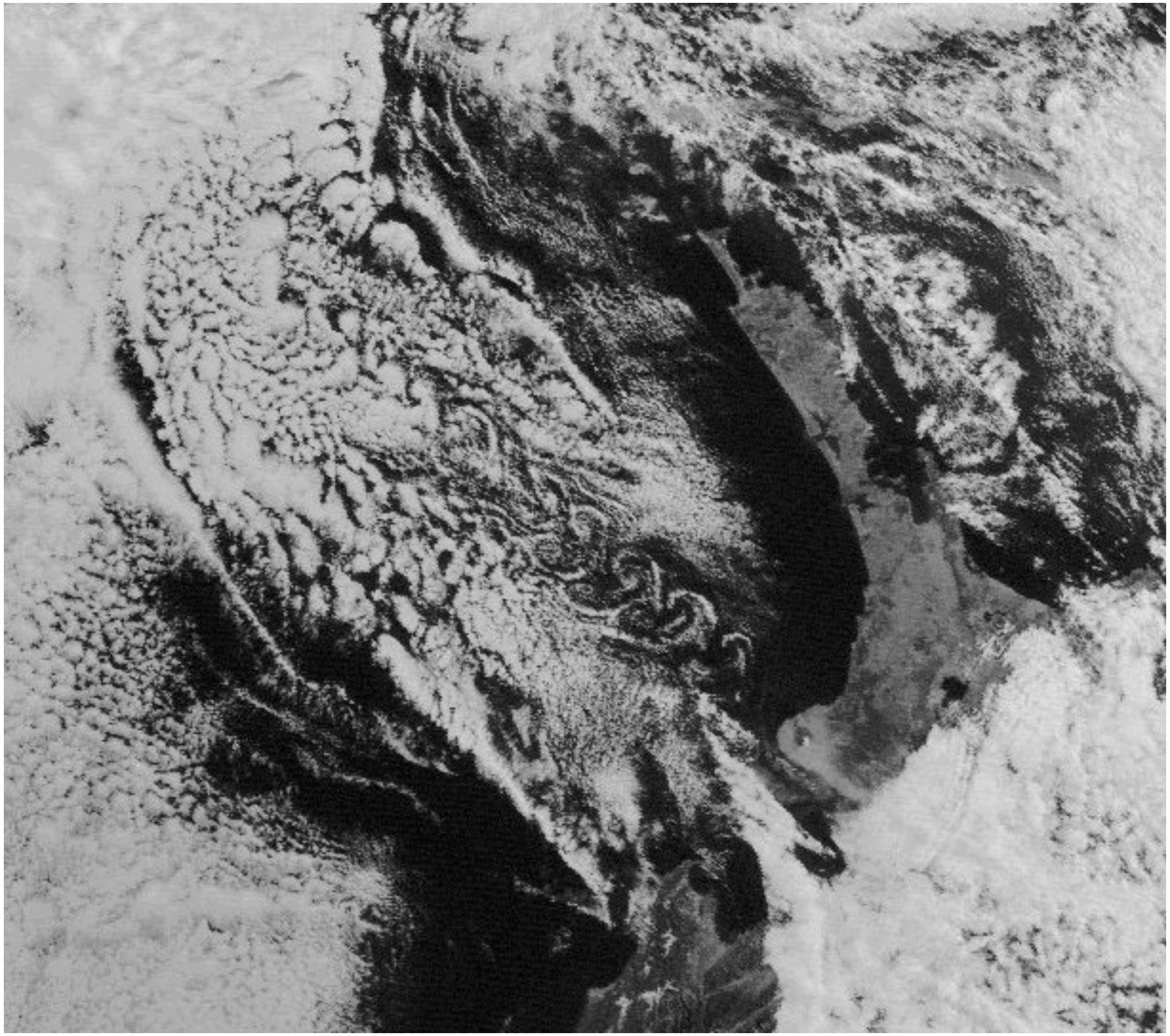
Stull (1988)





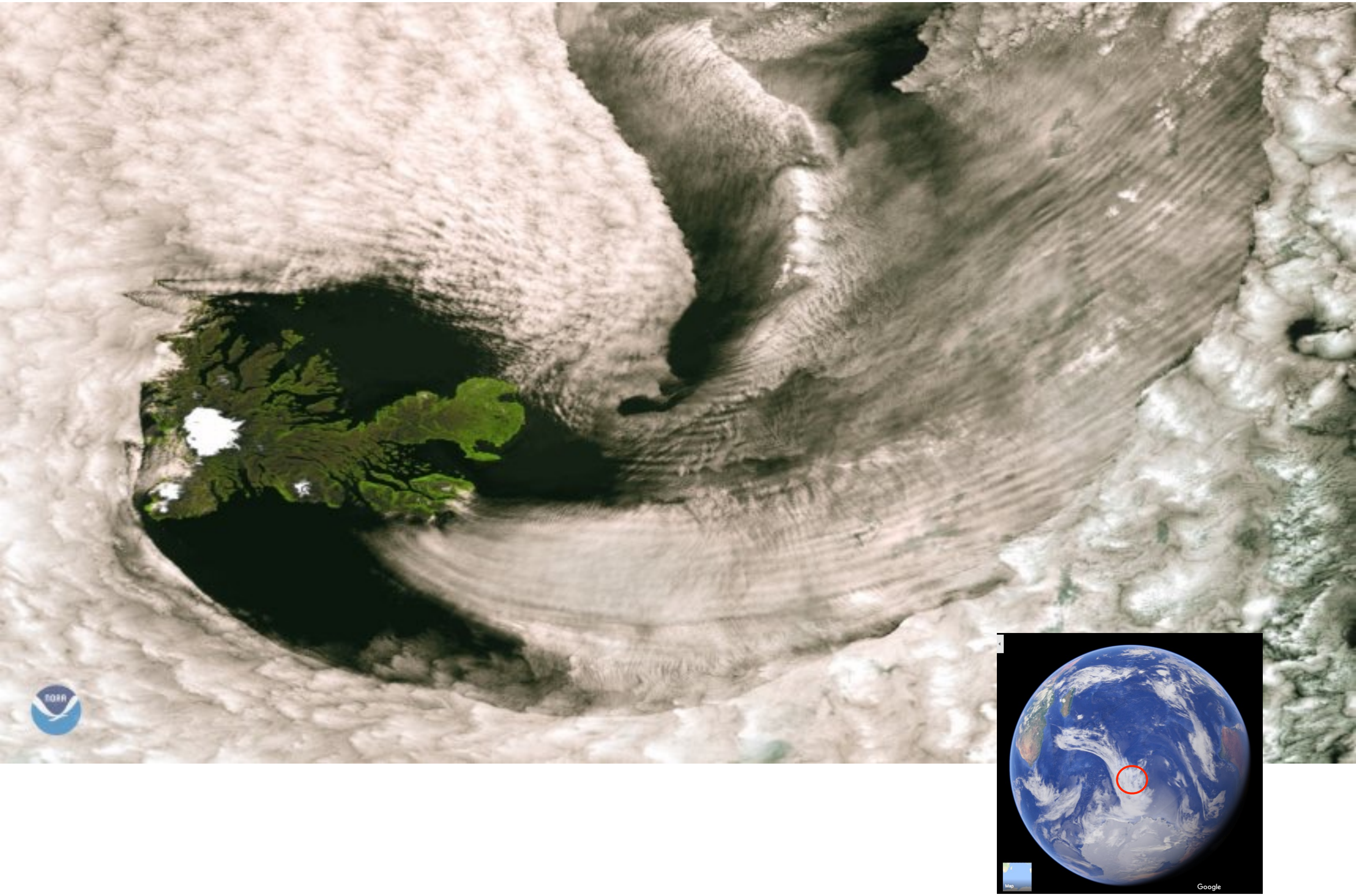
Jan Mayen Island, Greenland Sea

Kármán vortices in lee of New Zealand volcano



From Erick Brenstrum

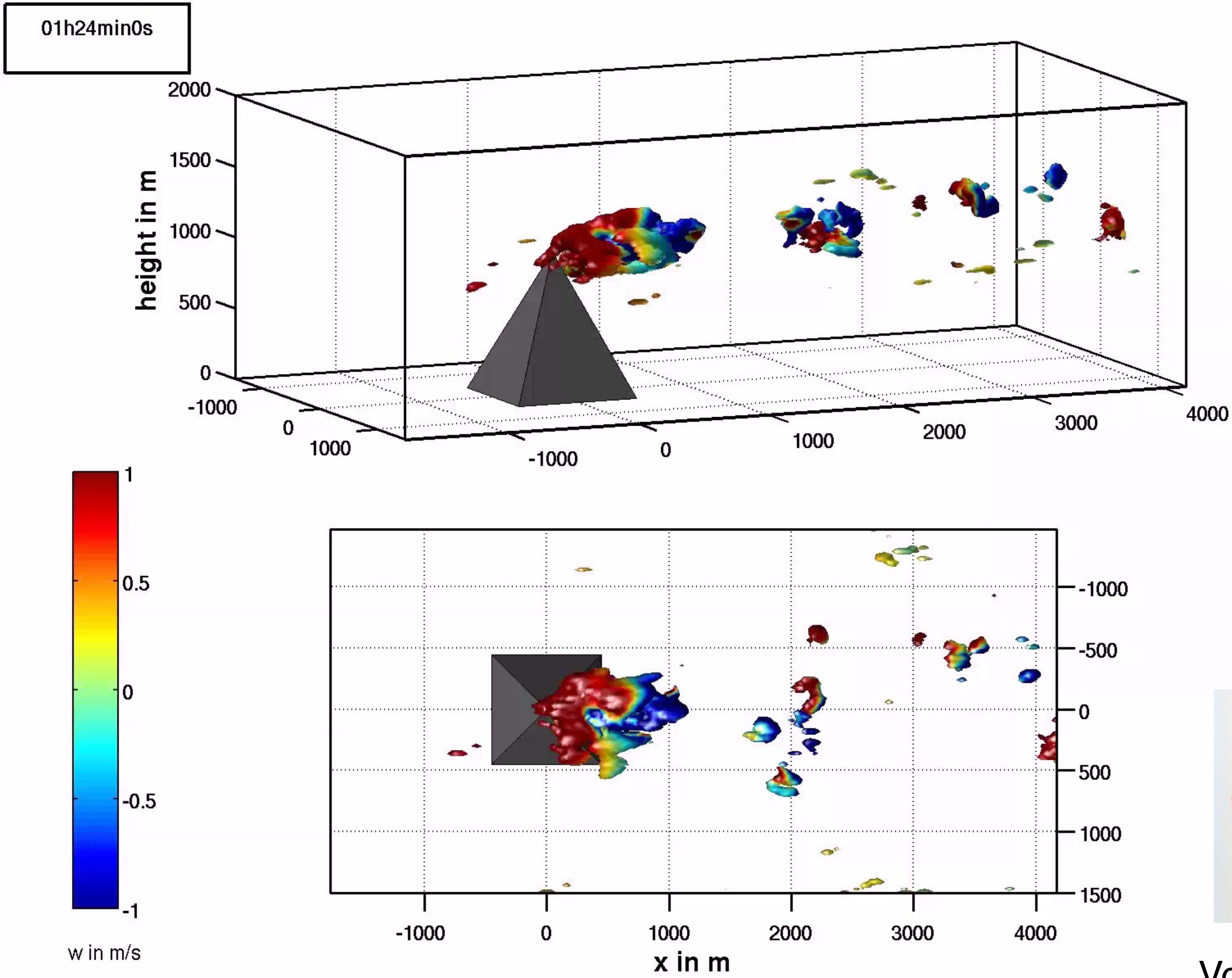
Kerguelen Islands



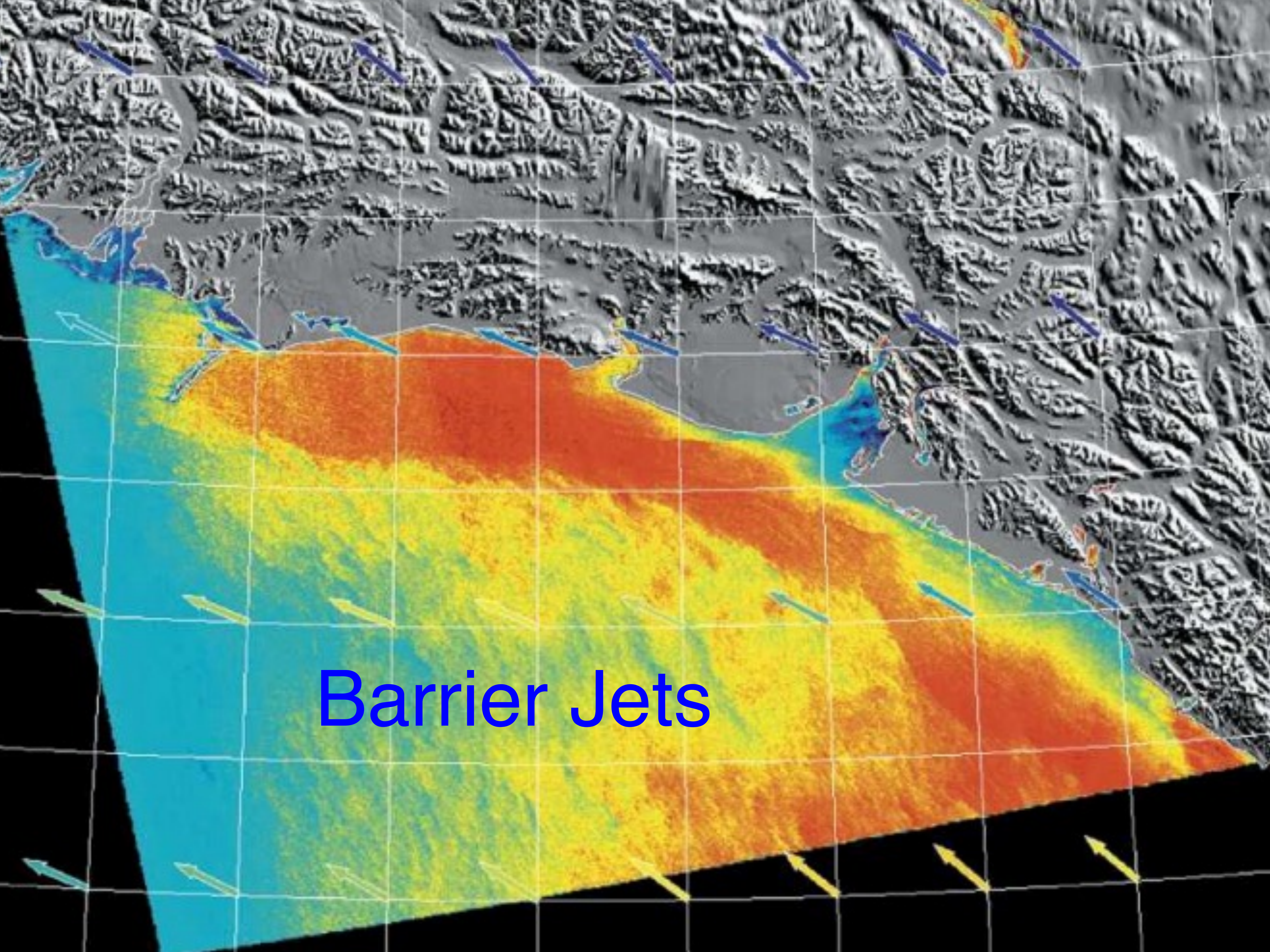
Banner clouds

© Zacharie Grossen

Banner Cloud, Mt. Olympus, Utah



Volkmar Wirth
University of
Mainz, Germany

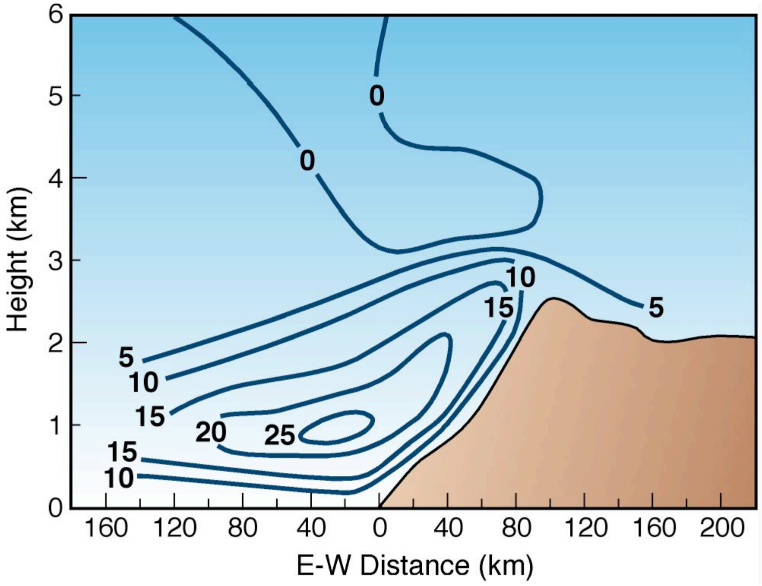


Barrier Jets

Barrier jets

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

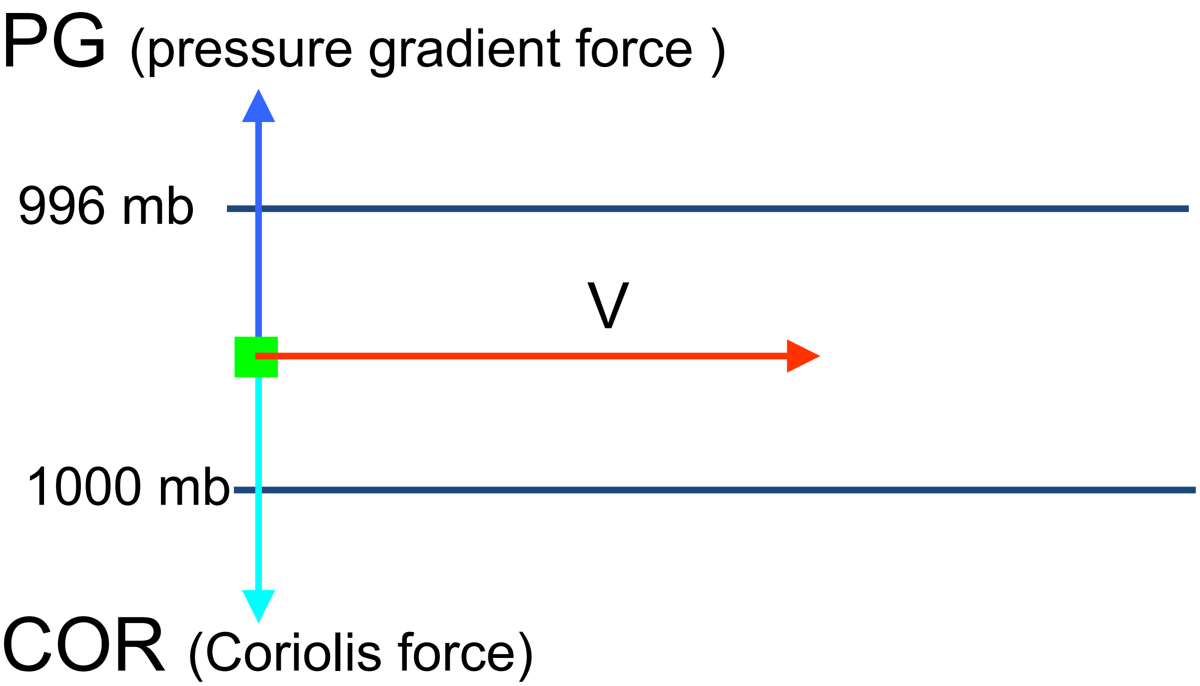
Occurs in the extratropics when a **stably stratified flow** is **blocked** by a barrier for hours or days. The flow lifted up the barrier is cooled, forming a **high pressure along the slope**, **decelerating** and **blocking** the flow. Geostrophic adjustment occurs between the flow and the high pressure,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



Typical locations:

- West side of Cascades and Sierras
- East side of Rockies and Appalachians
- North side of Brooks Range.

Barrier Jets - Basic Dynamics



PG (pressure gradient force)

996 mb

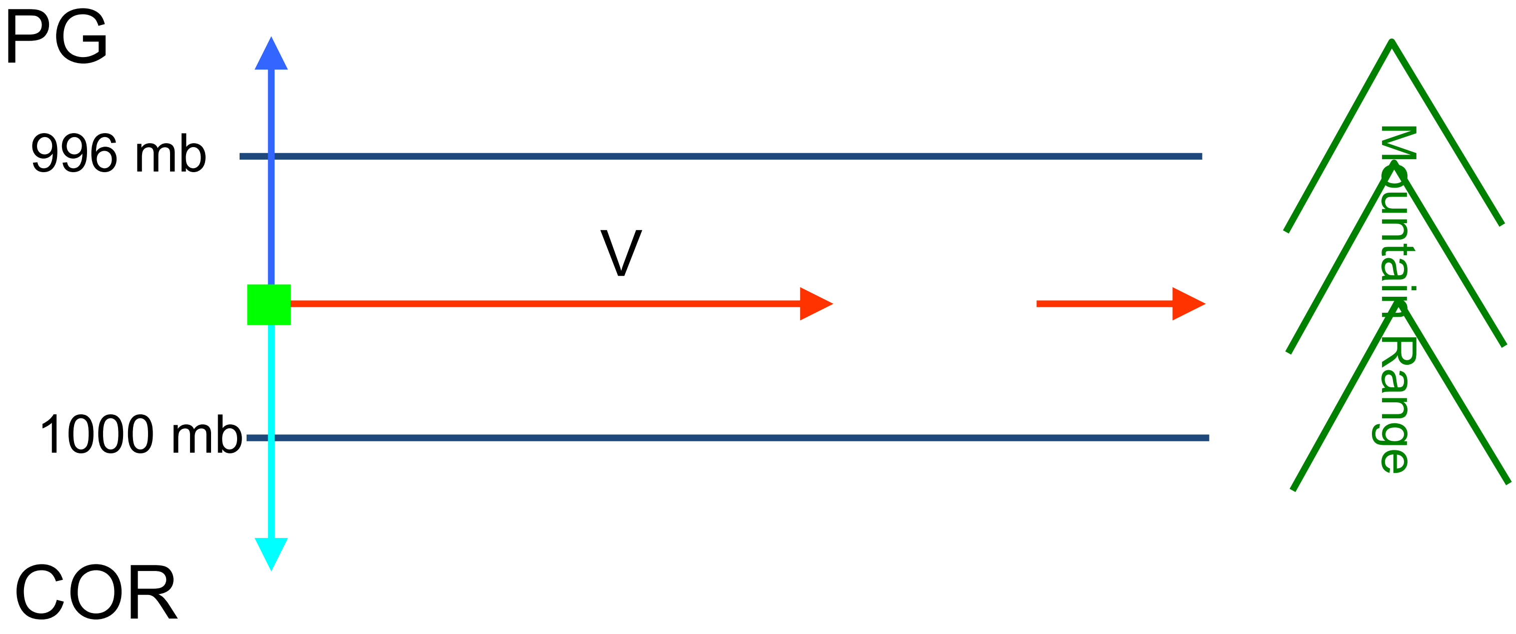
V

1000 mb

COR (Coriolis force)

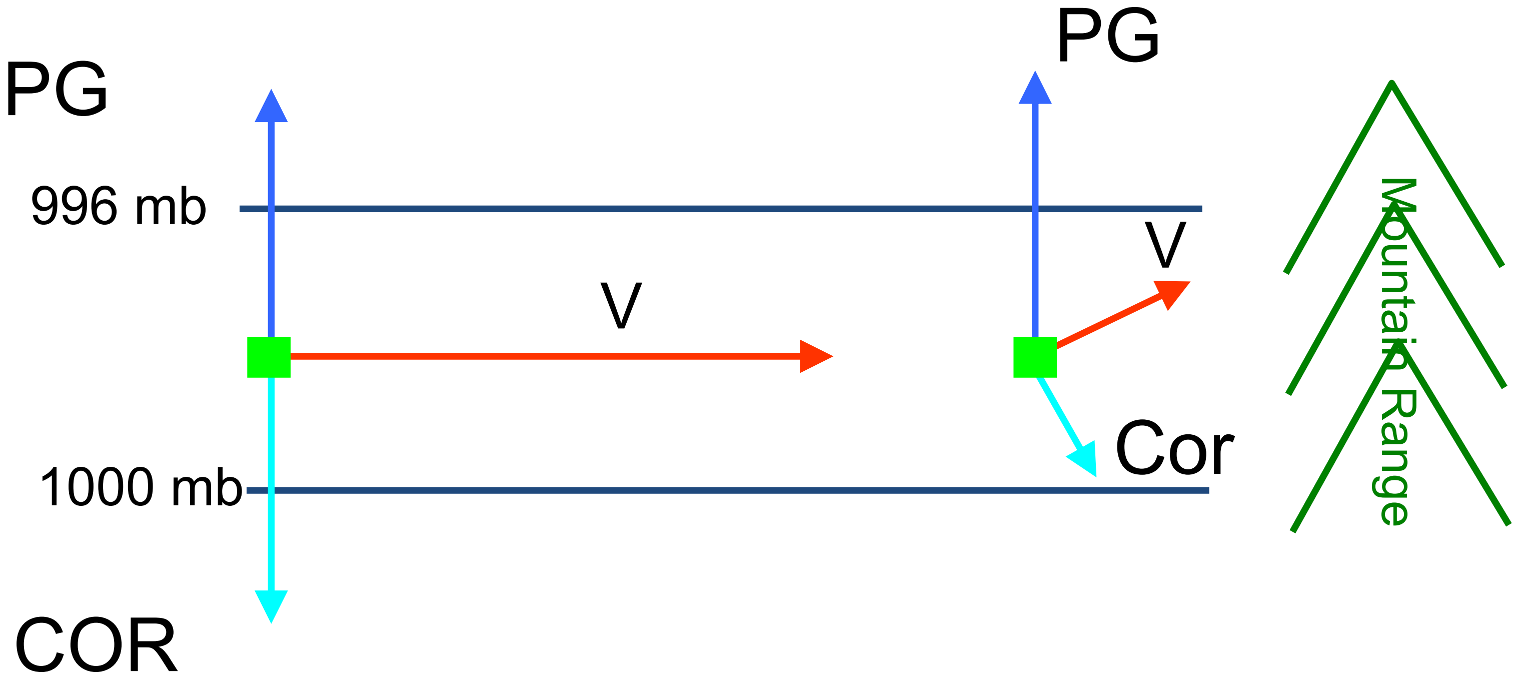
In the absence of topography and friction, the flow exhibits *geostrophic balance*.

Barrier Jets - Basic Dynamics



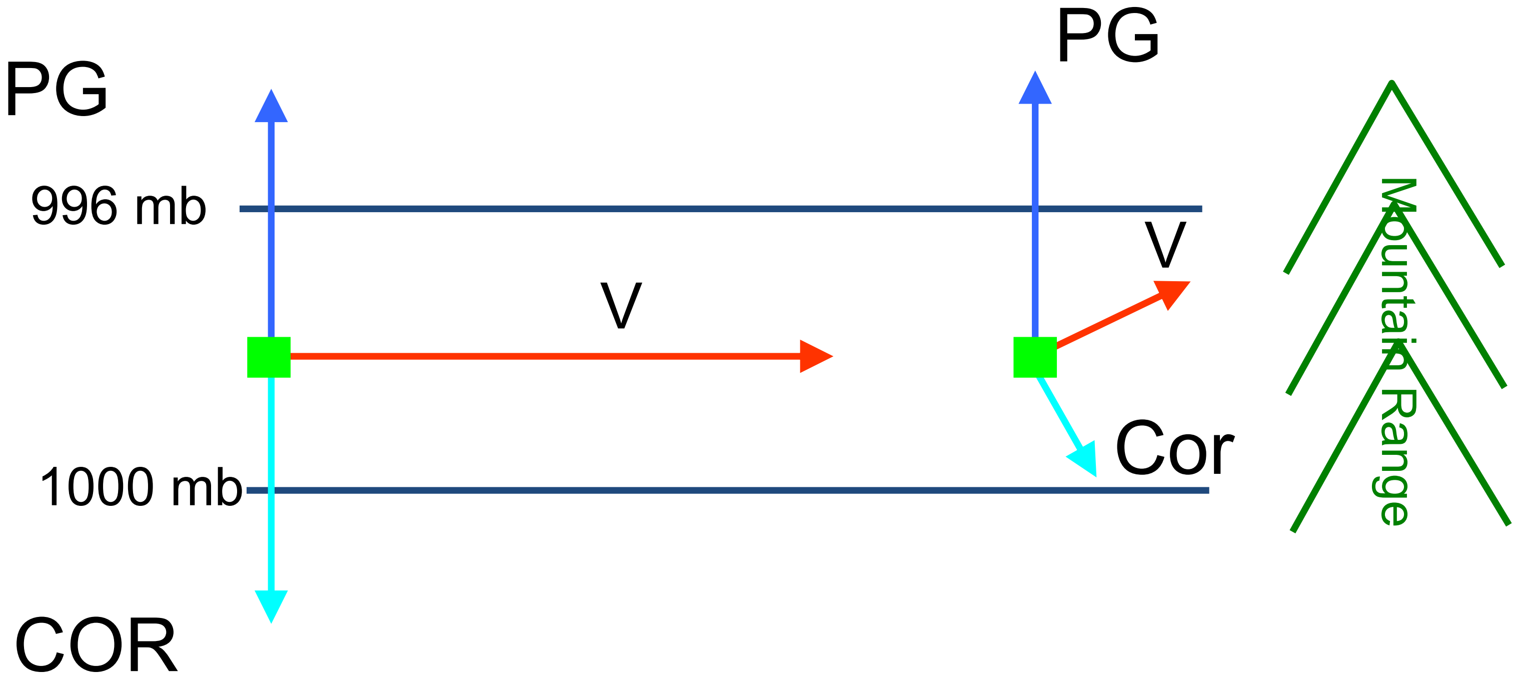
If flow is characterized by a low Froude number (U/NH < 1), the the low-level flow will be blocked and will decelerate as it approaches mountains.

Barrier Jets - Basic Dynamics



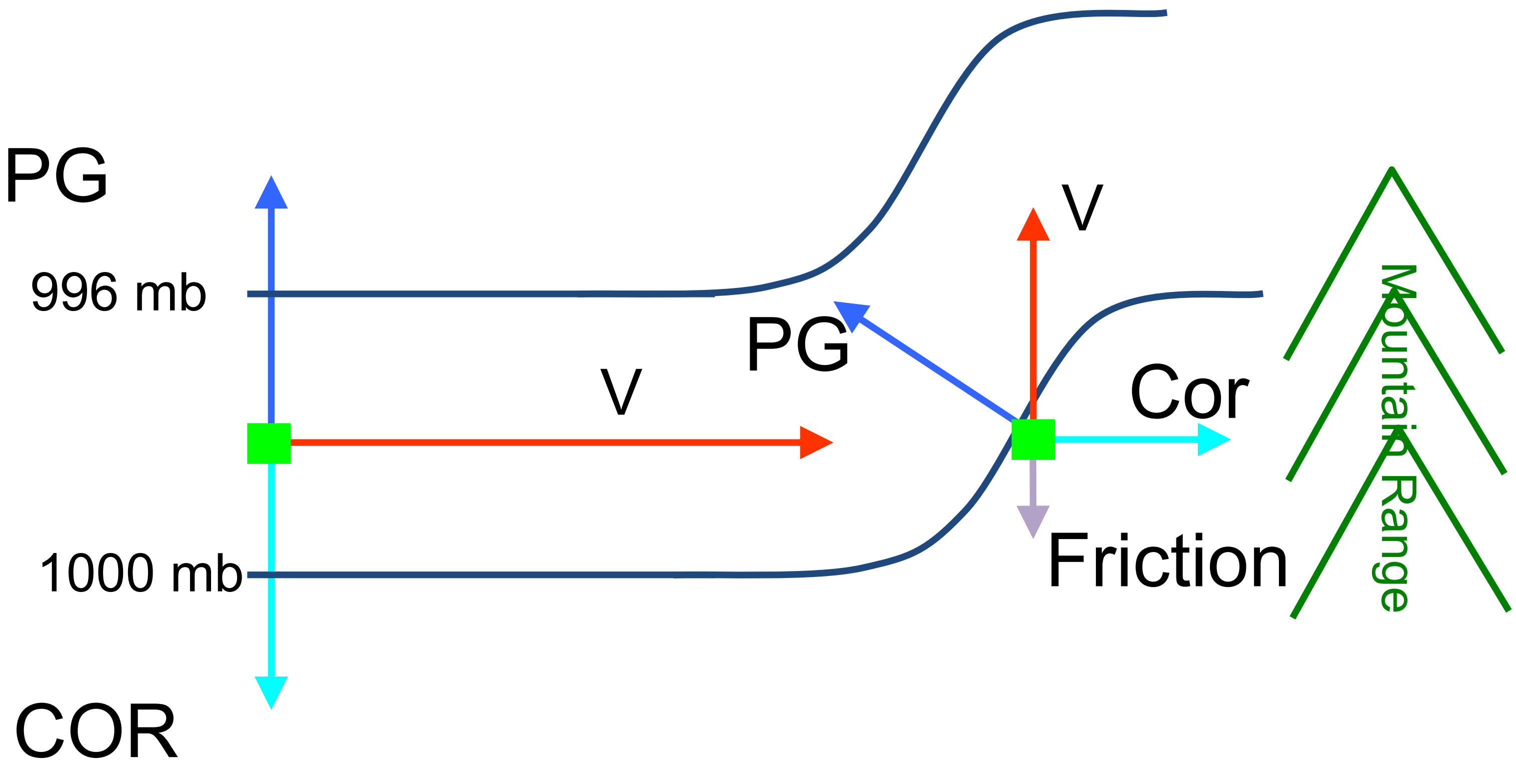
As the flow decelerates, the Coriolis force weakens, and the flow is deflected toward lower pressure.

Barrier Jets - 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).

Barrier Jets - Basic Dynamics



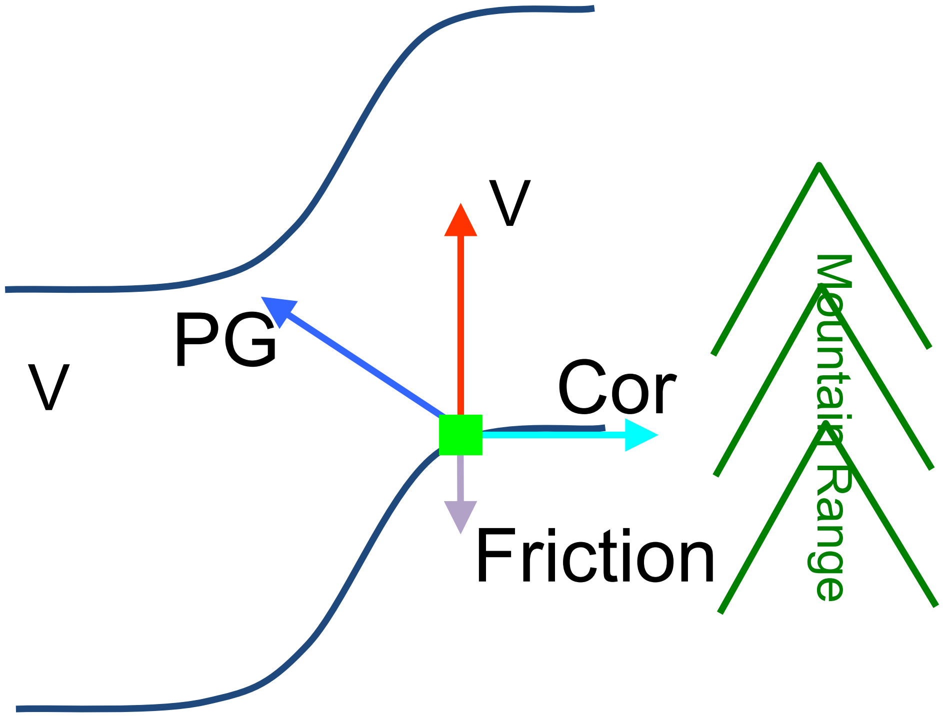
The final near-barrier force balance.

Barrier Jets – Mature Force Balance

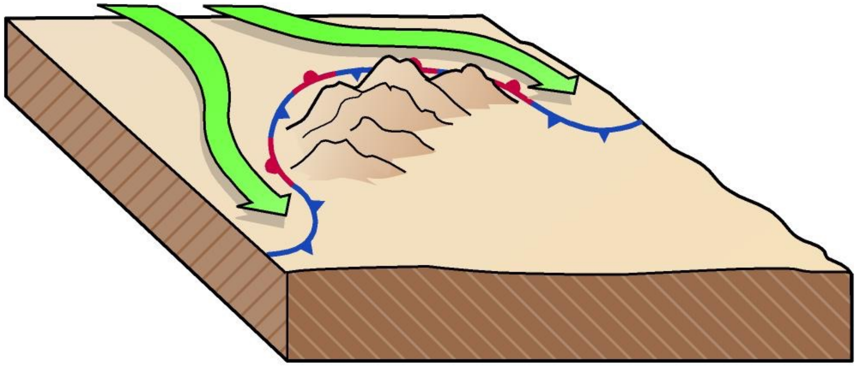
- Along-barrier **antitriptic:**

  Pressure gradient balances friction

- Cross-barrier geostrophic

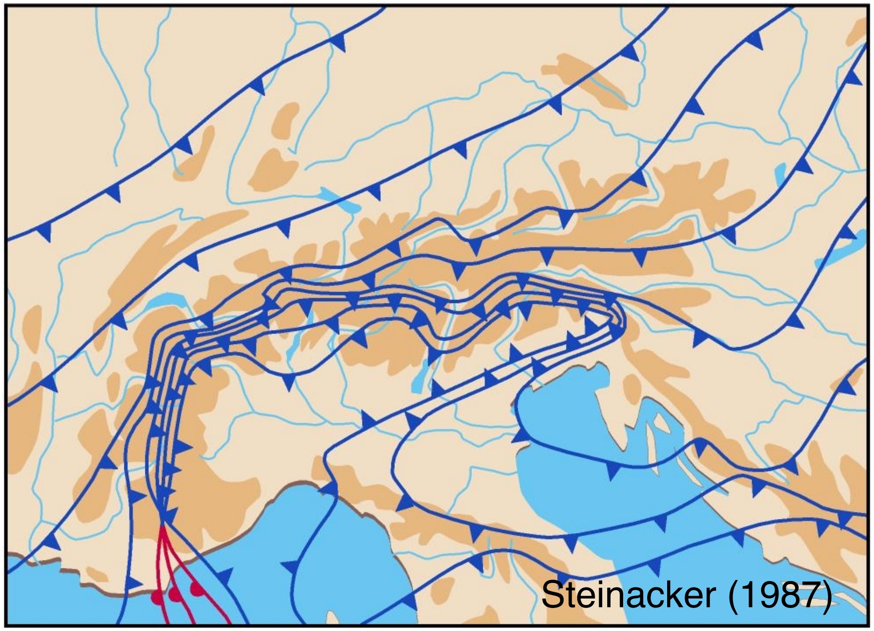


Flow splitting



Whiteman (2000)

3-hourly frontal positions



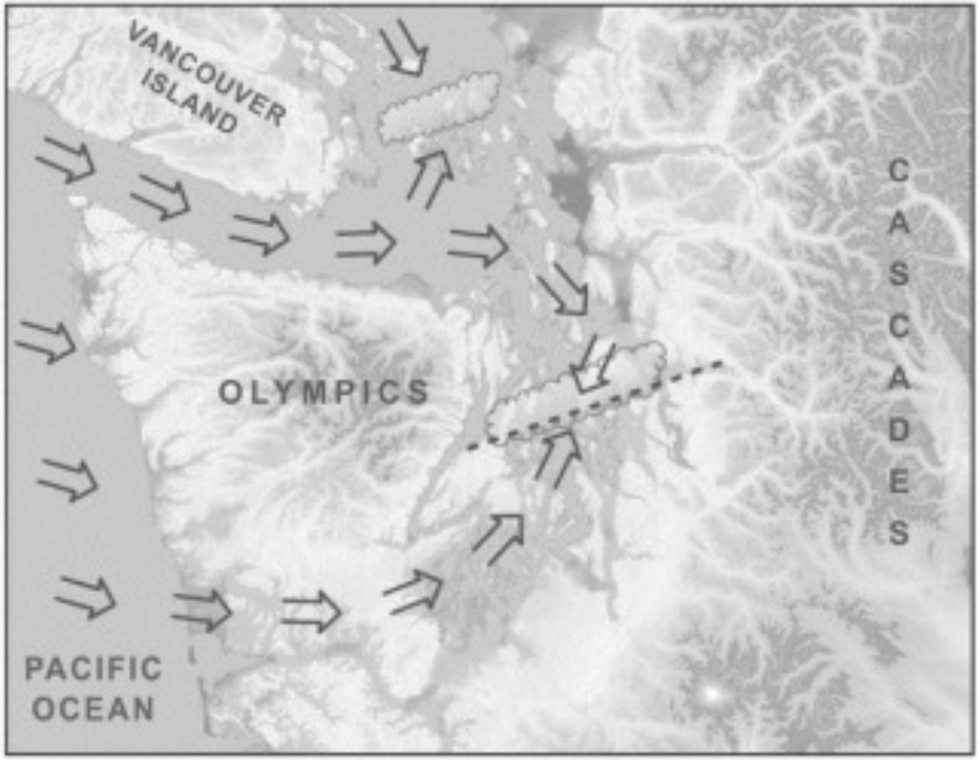
Steinacker (1987)

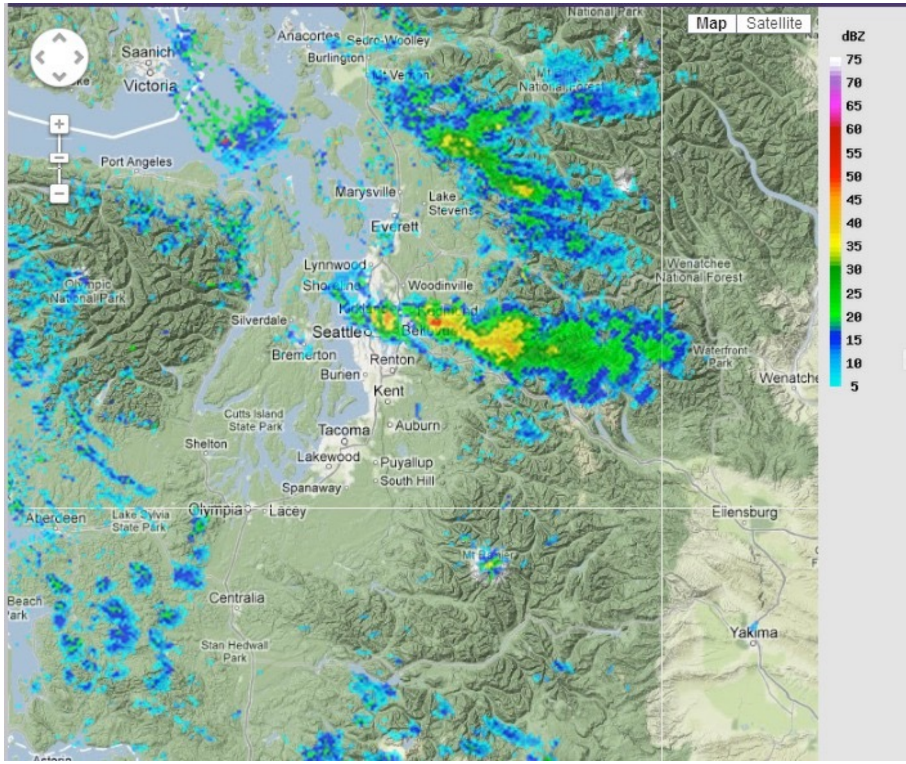
Note: *Convergence zones* often form on the back side of isolated barriers (e.g., Puget Sound)

Reinhold Steinacker

Leeside Conversion Zones

Example: Puget Sound Convergence Zone





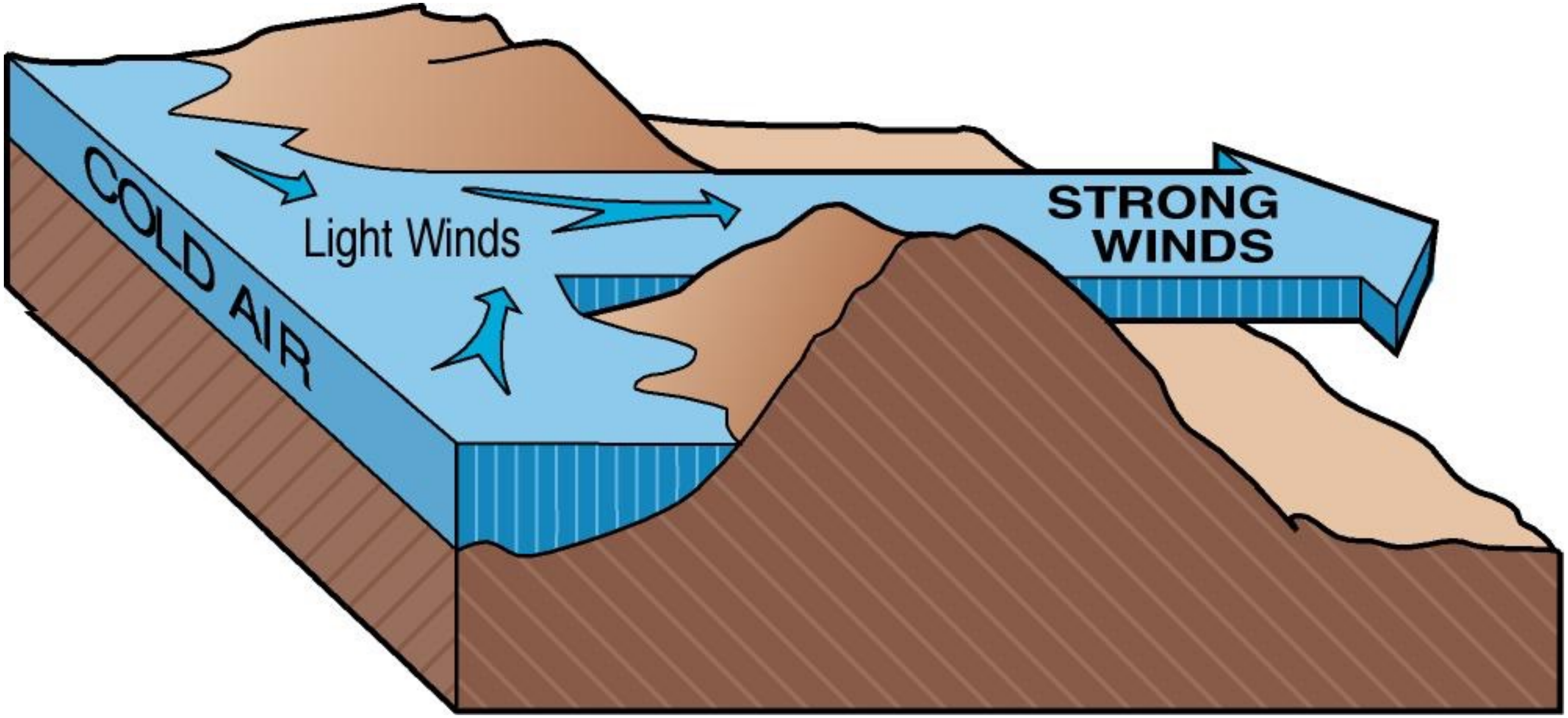
https://charliesweatherforecasts.blogspot.com/2013_04_01_archive.html

Gaps/Passes

Flow through Passes, Channels and Gaps

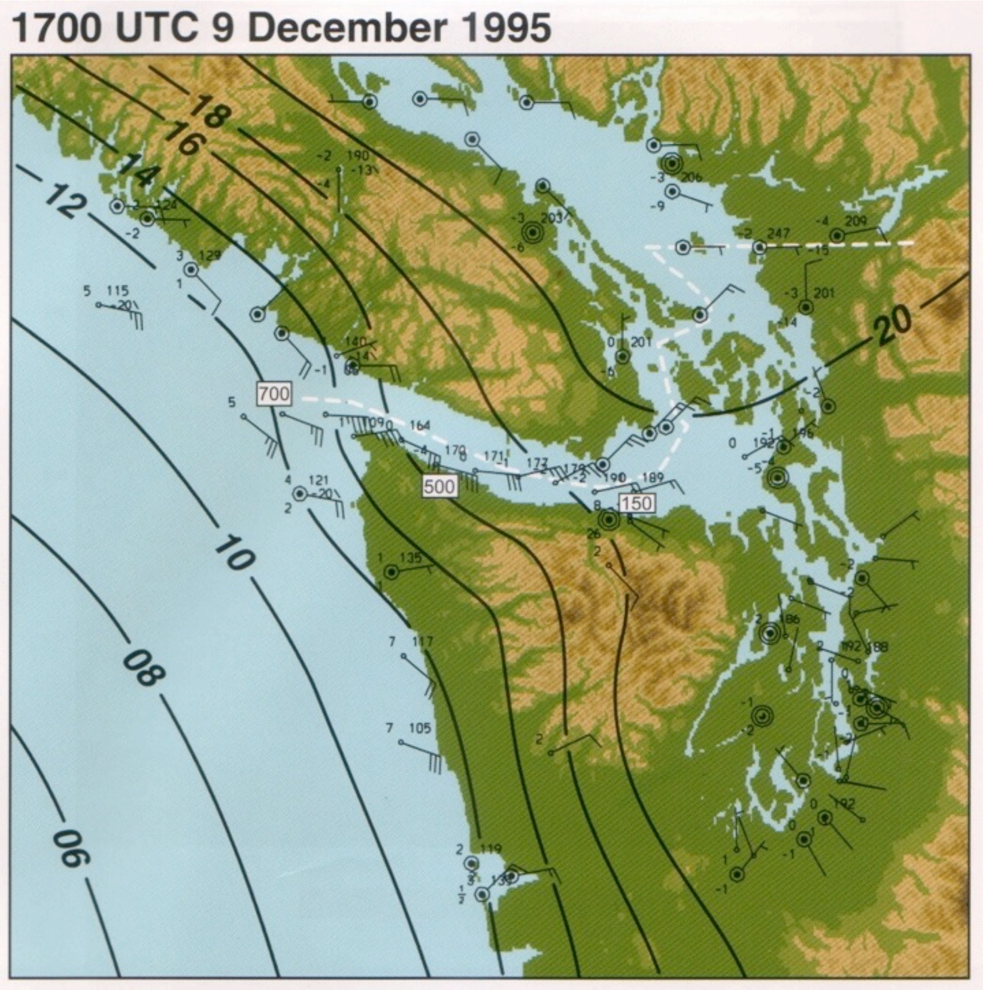
- ***Gaps*** - major erosional openings through mountain ranges
- ***Channels*** - low altitude paths between mountain ranges (usually with the sea as the base of the channel)
- ***Mountain passes*** - routes over or through mountains
- Strong winds in a gap, channel or pass are usually ***<u>pressure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

Flow through passes and gaps



Whiteman (2000)

Gap flow



1700 UTC 9 December 1995

Markowski and Richardson (2010)

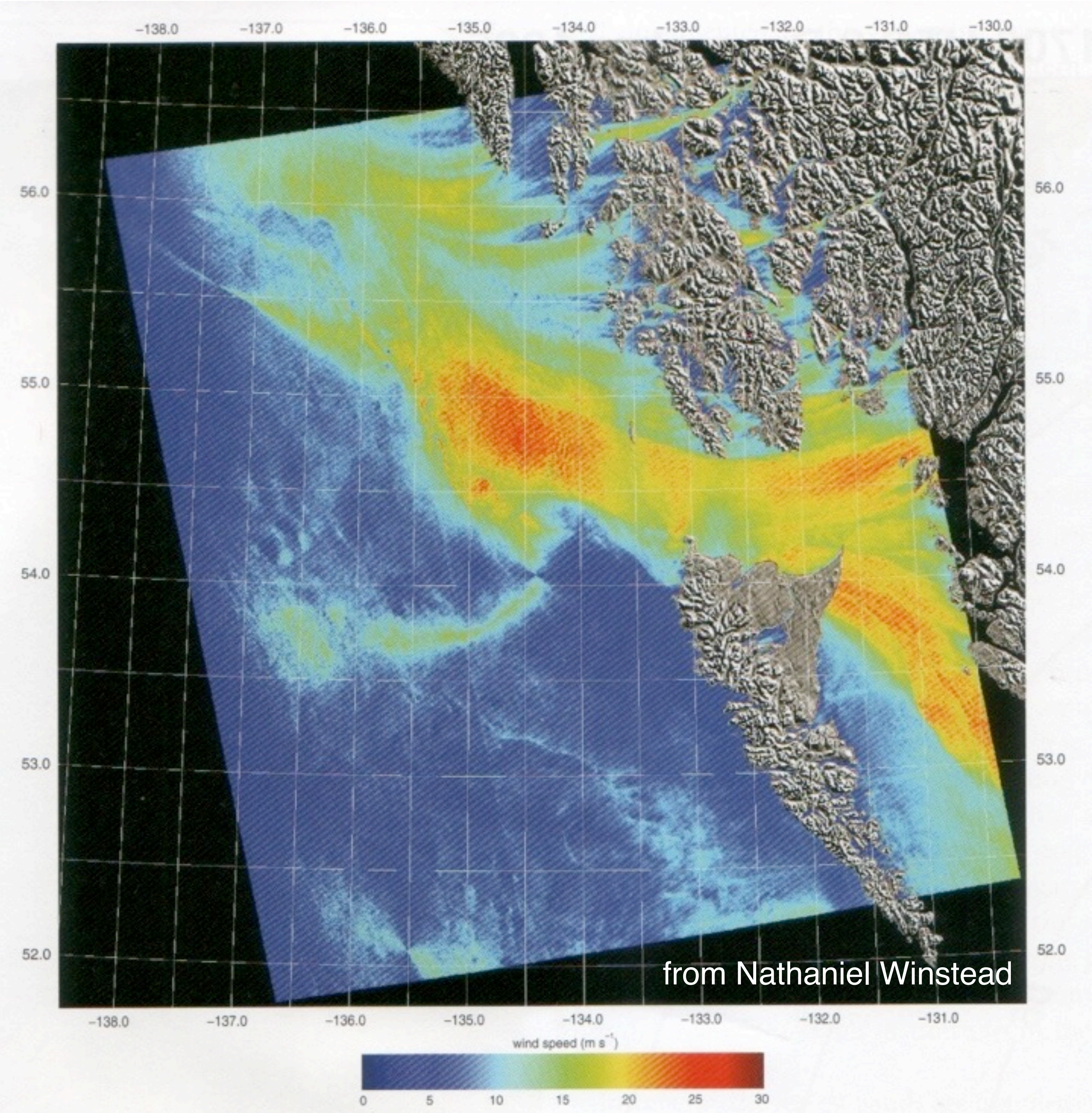
Strait of Juan de Fuca

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

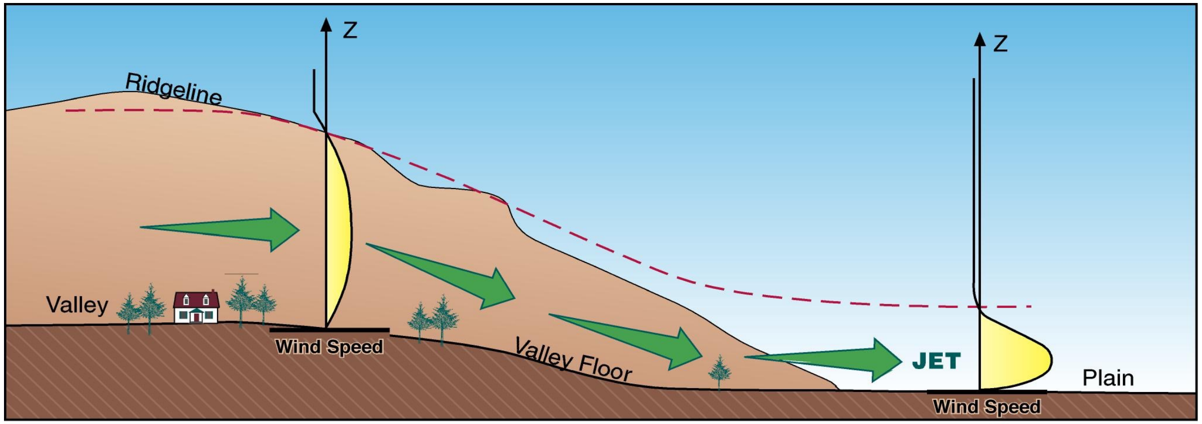


from Nathaniel Winstead

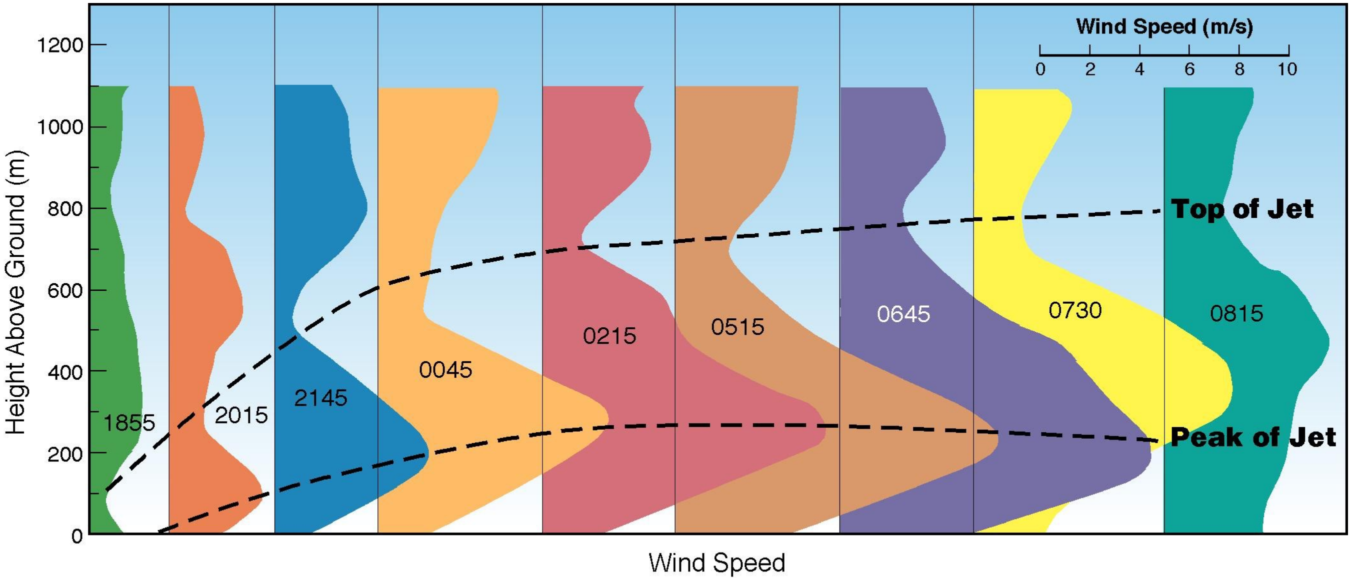
Markowski and Richardson (2010)

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)

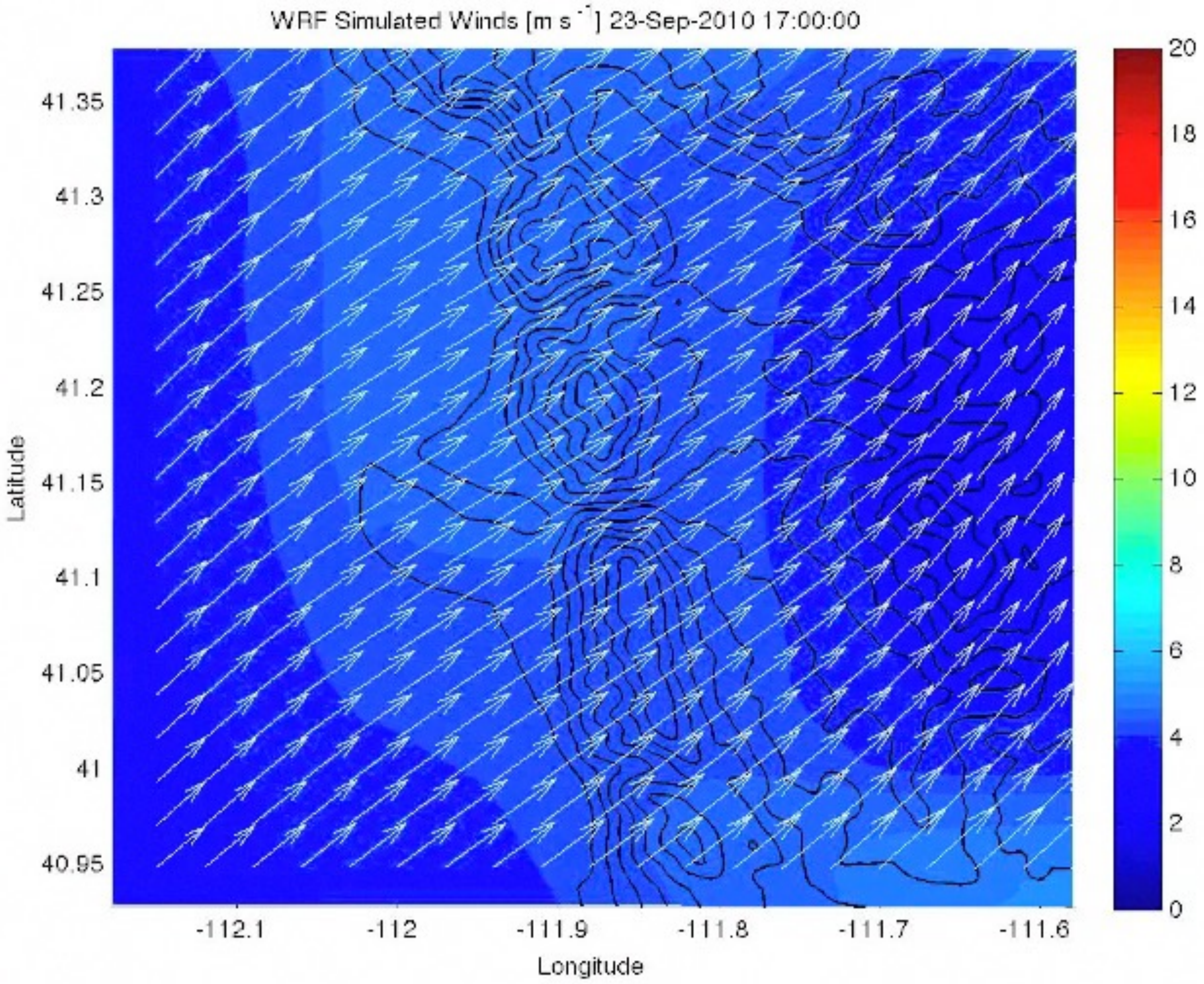
Valley exit jet



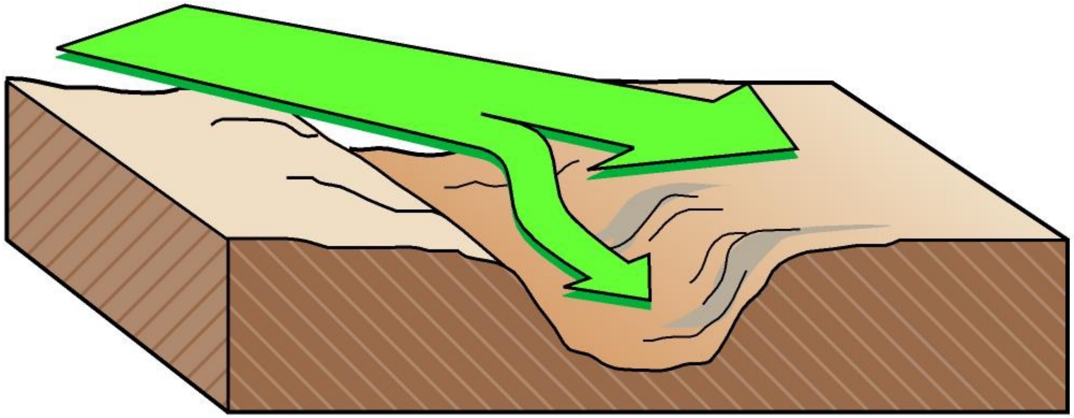
adapted from
Pamperin &
Stilke (1985)



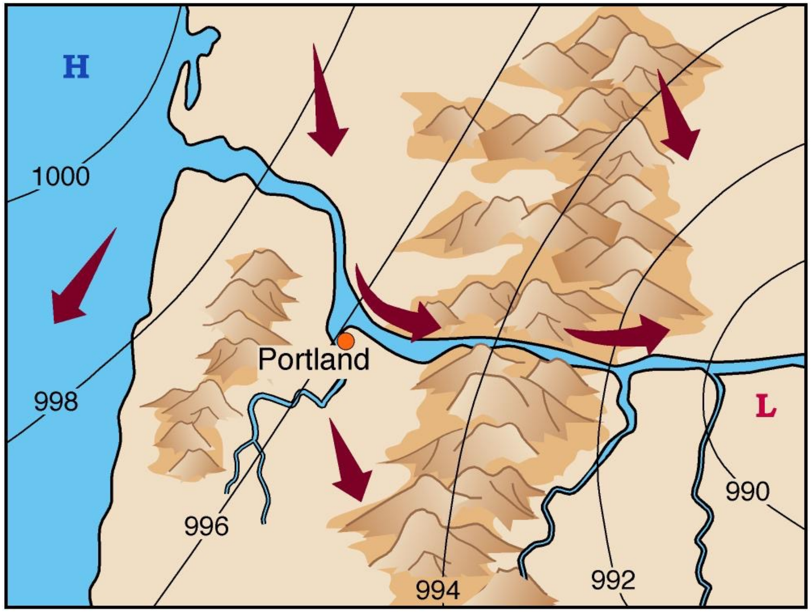
Weber Canyon, UT


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

Channeling

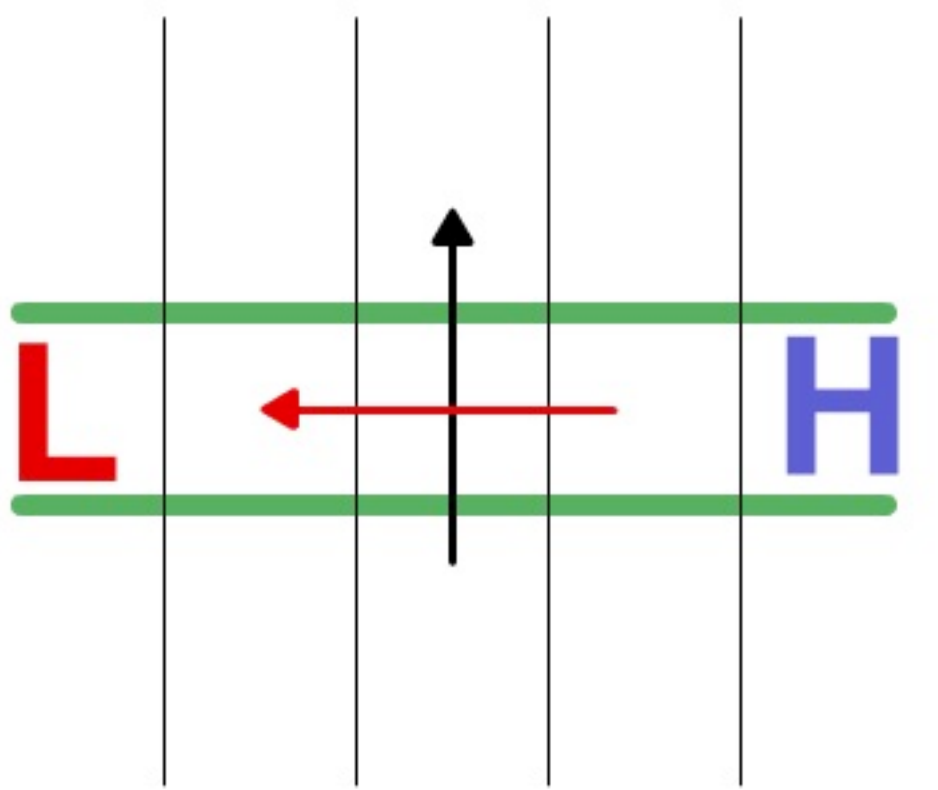


Forced Channeling

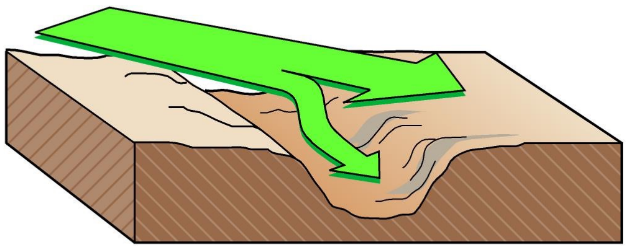


Pressure Driven Channeling

Pressure driven channeling versus forced channeling

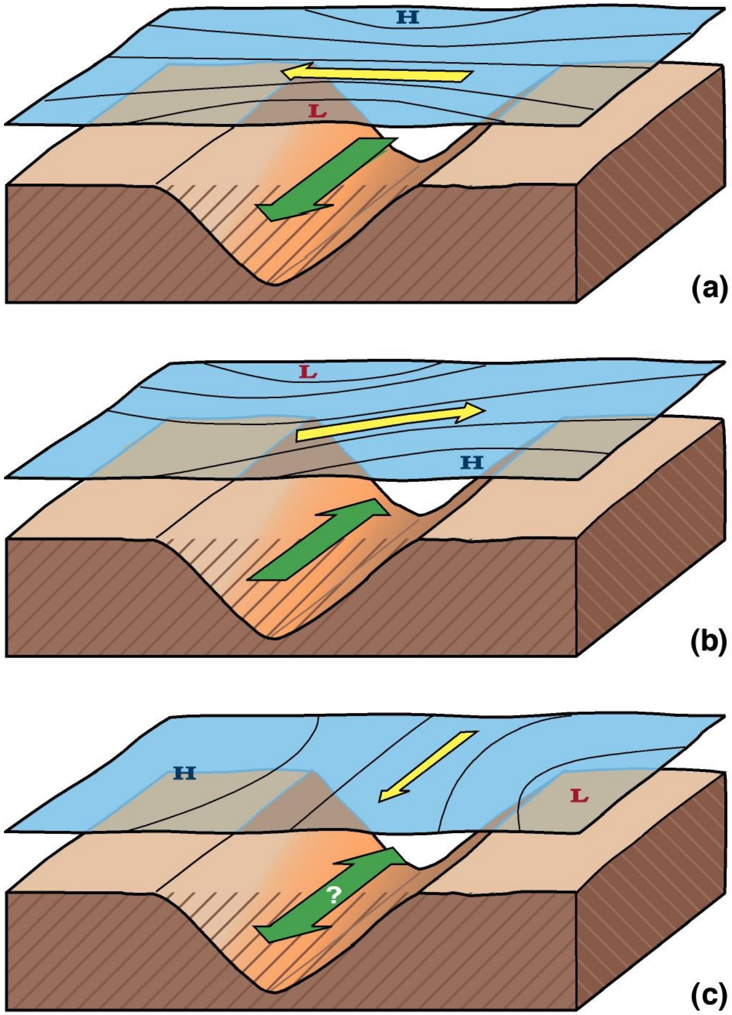


Pressure driven channeling



Forced Channeling

Pressure driven channeling



Whiteman (2000)

The End

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