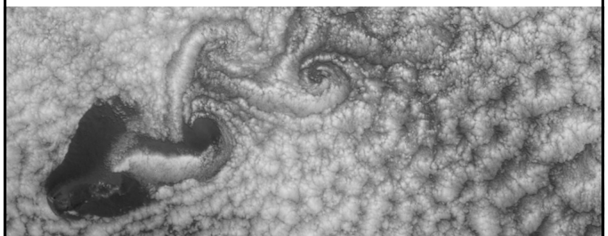
Dynamically Driven Flows



Atmos 6250: Mountain Meteorology
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Reading


Chapter 3
Dynamically-Driven Winds

Jackson, P. L., G. Mayr, and S. Vosper, 2013: Dynamically-driven winds. *Mountain Weather Research and Forecasting: Recent Progress and Current Challenges*. T. Chow, S. de Wekker, and B. Snyder, Eds., Springer, 121–218.

Discussion

- How and why is the behavior of the flow different over areas of complex terrain?
- What mechanisms drive this differing behavior?

Types of Mountain Winds

- *Dynamically driven flows* produced by the interaction of the large-scale flow with topography
- *Thermally driven flows* (a.k.a. diurnal mountain winds) produced by horizontal contrasts in heating and cooling that arise from topographic and land-surface contrasts
- Frequently combined to some extent

Types of Mountain Winds

- *Dynamically driven flows* produced by the interaction of the large-scale flow with topography

This Lecture

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Discussion

- What options does air have when it approaches a mountain barrier?
- What characteristics of the incident flow and the topography are likely to determine the outcome?

Dynamically Driven Flows

- As air approaches a barrier it can flow
  - *Over* the barrier
    - Mountain waves and downslope winds
  - *Tthrough* gaps or valleys that dissect the barrier
    - Gap flows
  - *Around* the barrier
    - Ridges: Barrier jets, damming
    - Isolated obstacles: Flow splitting; leeward convergence, vortices, and wakes
- Outcome determined by
  - Strength and stability of the incident flow
  - Shape and size of the topography
- All three can occur simultaneously within a given region

Source: Jackson et al. (2013)

Basic Dynamics of Dynamically Forced Flows

Photo: http://www.pa.op.dlr.de/ostiv/Projects/mwavproj.htm

Key Parameters: Rossby Number (R_o)

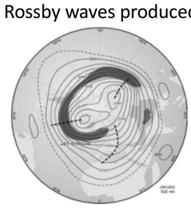
$R_o = U/fL$

U = Cross-barrier wind speed
f = Coriolis parameter
L = Mountain barrier width

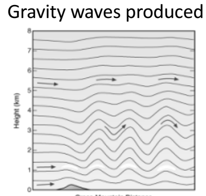
Key Parameters: Rossby Number (R_o)

$R_o = U/fL$

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



$\underline{R_o >> 1}$
Coriolis effects negligible
Buoyancy force dominates
Parcels displaced vertically
Gravity waves produced



Images: Whiteman (2000)

Key Parameters: Rossby Number (R_o)

$R_o = U/fL$ This Lecture

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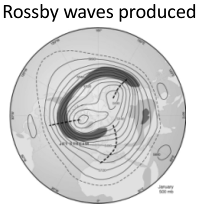

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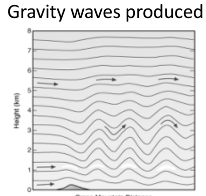


Images: Whiteman (2000)

Key Parameters: Non-Dimensional Mountain Height ($\hat{H}$)

$\hat{H} = NH/U$

$N = [(g/\theta_o)(d\theta_o/dz)]^{1/2}$ = Brunt–Väisälä Frequency
H = Mountain Height
U = Cross Barrier Wind Speed

$\hat{H}^{-1} = U/NH$ is sometimes referred to as the Froude Number

Key Parameters: Non-Dimensional Mountain Height ($\hat{H}$)

$\hat{H} = NH/U$

Will the air flow over the barrier?

Basically the ratio of the energy required to get over barrier ($N^2H^2/2$) to the kinetic energy of incoming flow ($U^2/2$)

$\hat{H} = [(N^2H^2/2)/(U^2/2)]^{1/2} = NH/U$

$\hat{H} > 1$: Inertia too weak and the flow is blocked

$\hat{H} < 1$: Inertia overcomes stability, flow surmounts barrier

Key Parameters: Non-Dimensional Mountain Height ($\hat{H}$)

$\hat{H} = NH/U$

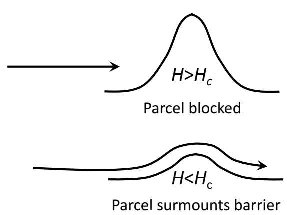
Blocking ($\hat{H} > 1$) favored by	*Flow over ($\hat{H} < 1$) favored by*
High stability	Low stability
Large mountain	Small mountain
Weak cross-barrier flow	Strong cross-barrier flow

The critical mountain height, H_c, is where $\hat{H} = 1$ and the flow transitions from blocked to unblocked

Settting $\hat{H} = 1$ and replacing H with H_c yields
$H_c = U/N$

Key Parameters: Critical Mountain Height (H_c)

- $H_c = U/N$
- H > H_c: Flow is blocked
- H < H_c: Flow surmounts barrier



Which is Most Likely to Result in a Transition from Blocking to Flow Over?

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

Which is Most Likely to Result in a Transition from Blocking to Flow Over?

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

Limitations of $\hat{H}$ and H_c

- 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

Reinecke and Durran (2008)

Mountain Waves

Lenticular clouds over Mt. Hotaka, Hida Mountains, Nagano Prefecture, Japan by Alpsdake (Wikipedia Commons CC BY-SA 3.0

Mountain Waves

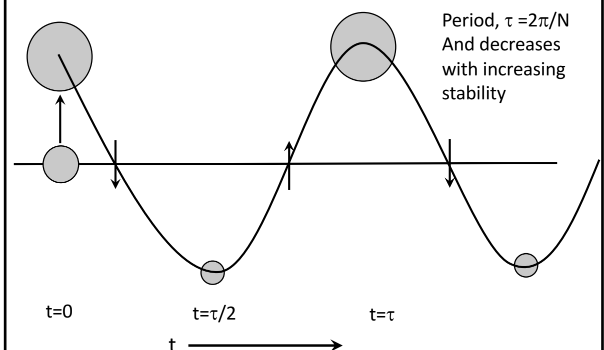
- Generic term for all gravity waves forced during flow over mountains
- <u>*Gravity wave*</u> – A wave produced by buoyancy forces when the atmosphere is stably stratified (i.e., $N > 0$)

Mountain Waves

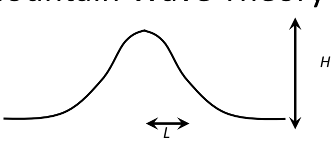
- *External gravity waves* – Occur in fluids with an upper boundary or internal density discontinuity (e.g., ocean waves) and propagate mainly in the horizontal plane
- *Internal gravity waves* – Occur in continuously stratified fluids (e.g., the atmosphere) and can propagate in the horizontal and vertical planes
- Shallow water thinking can only take you so far

The Buoyancy Oscillation

Period, $\tau = 2\pi/N$
And decreases with increasing stability



Mountain Wave Theory



- Based on linear theory
- We will assume a bell-shaped ridge where $h(x) = H/2$ at $x = \pm L$ (other terrain configurations can be used)

$$h(x) = H\frac{L^2}{L^2 + x^2}$$

- We will also assume uniform U and N

Key Parameters: Internal Froude Number (F_L)

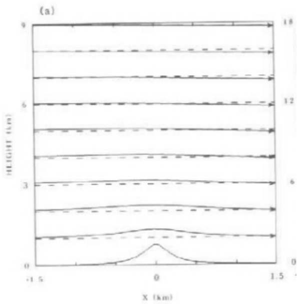
$$F_L = U/NL$$

Ratio of the natural "frequency" of flow over the mountain, U/L, to the buoyancy frequency, N

<u>$F_L > 1$ ($L<U/N$)</u> "Narrow Mountain"	<u>$F_L < 1$ ($L>U/N$)</u> "Wide Mountain"
Flow moves so rapidly over mountain it can't reach pressure equilibrium with surroundings	Flow is able to adjust
Buoyancy oscillations negated	Buoyancy oscillations can occur
Evanescent waves generated	Vertically propagating waves generated

Evanescent Waves

- "Narrow Mountain"
- Pattern is symmetric about mountain
- Wave decays exponentially with height

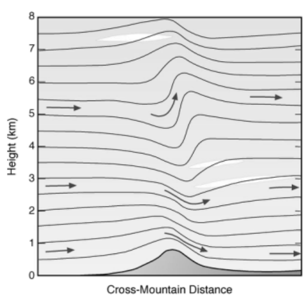


Durran (1986)

Likely Evanescent Waves

Vertically Propagating Waves

- "Wide Mountain"
- Waves propagate vertically
- Wave crests confined to over terrain
- Trough/ridge lines tilt upstream with height
- Vertical tilt results in possible lee cloud formation



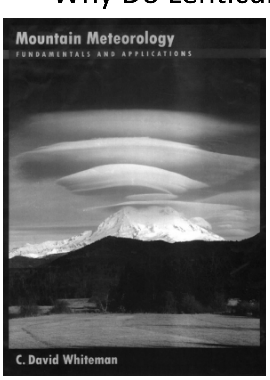
Durran (1986), Whiteman (2000)

Vertically Propagating Waves

Only one wave crest

http://www.atmos.washington.edu/~durrand/

Why Do Lenticulars Form in Layers?



"Vertically layered RH pertubations as small as ±0.25% can produce lenticular clouds with a layered structure"
- Hills and Durran (2014, QJRMS)

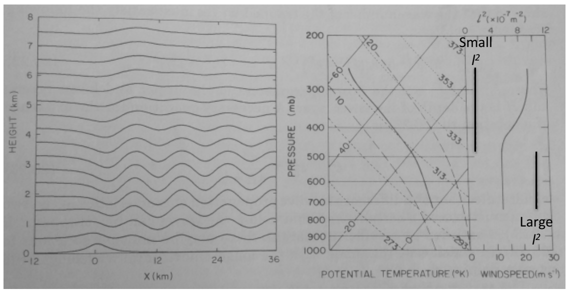
Trapped Lee Waves

- Previous discussion assumes uniform *U* and *N*
- Situations where the *Scorer Parameter*, *l*, decreases with height can produce in trapped lee waves

$$l^2 = \frac{N^2}{U^2} - \frac{1}{U}\frac{d^2U}{dz^2}$$

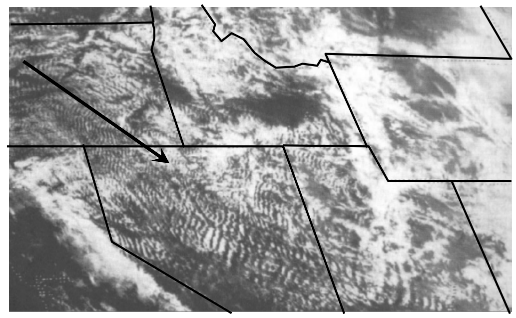
- First term usually dominates
- Possible culprits
  - Decreasing N with height
  - Increasing U with height
  - Rapid change in vertical shear such as beneath a strong jet (2nd term

Trapped Lee Waves



Durran (1986)

Trapped Lee Waves



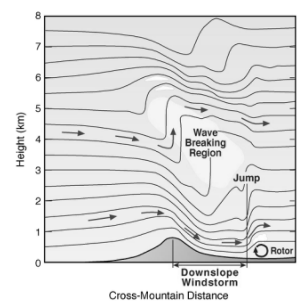
Durran (1986)

Linear Theory Strengths and Weaknesses

- Strengths (predictions confirmed by observations)
  - Gravity wave penetration to great heights above barrier
  - Upstream phase tilt
  - Upward energy propagation
  - Trapped waves
- Weaknesses
  - Assumes small vertical parcel displacements
    - Valid only for small (H < 500–1000 m) mountains with gradual slopes
  - Can't account for high-amplitude mountain waves that produce downslope winds, wave breaking, and rotors
  - Solutions sensitive to upper-boundary condition

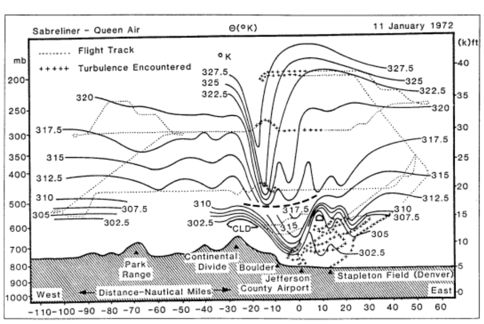
High Amplitude Mountain Waves

- Associated with
  - Downslope winds
  - Hydraulic jumps
  - Rotors
  - Wave breaking/CAT



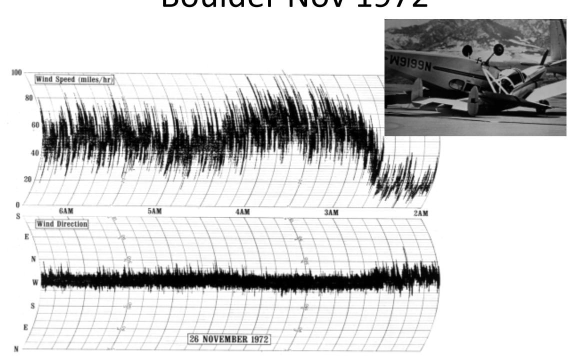
Whiteman (2000)

Boulder Jan 1972



Klemp and Lilly (1975)

Boulder Nov 1972



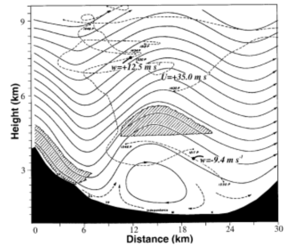
Meteogram: Whiteman, Photo: Boulder Daily Camera

Sierra Wave Photo

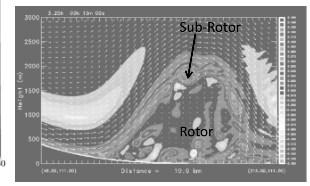
View is toward south from 11 km height. Airflow is from right to left. The cloud mass on the right is plunging down the lee slope of the Sierra Nevada; the near-vertical ascending cloud wall of the mountain wave is on the left. The turbulent lower part of the cloud wall is a "rotor"; the smooth upper 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).

Photo: Joachim Kuettner and Hal Klieforth, 1952

Rotor Simulation



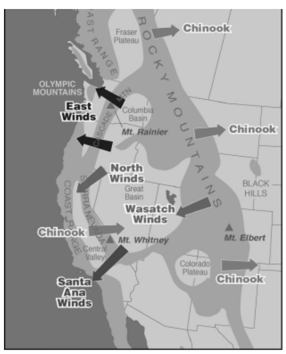
Streamlines from glider measurements (from Doyle and Durran 2002, after Holmboe and Klieforth 1957)



Simulation from Jim Doyle, NRL (Color Horizontal Vorticity)

Downslope Windstorms of the Western US

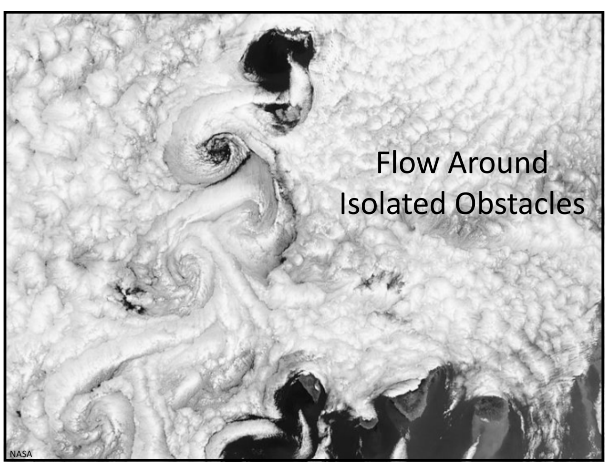
- Chinook (Alberta, Montana, Colorado)
- Canyon winds (Utah)
- Santa Ana (California)
- Cascade Bora (Washington)
- Chinook: Descending warm air replaces cold airmass
- Bora: Source airmass sufficiently cold that downslope winds are relatively cold despite compressional warming



Whiteman 2000

Mountain Wave Summary

- Broad spectrum of waves produced by mountains
  - Topographic Rossby waves (low Rossby number)
  - Inertio-gravity waves (Rossby number ~1)
  - Gravity waves (a.k.a. mountain waves; high Rossby number)
    - Evanescent waves ("narrow mountain", *L<U/N*)
    - Vertically propagating waves ("wide mountain", *L>U/N)*
    - Trapped lee waves (Scorer parameter decreasing with height)
    - High amplitude mountain waves (forthcoming talk by Horel)



NASA

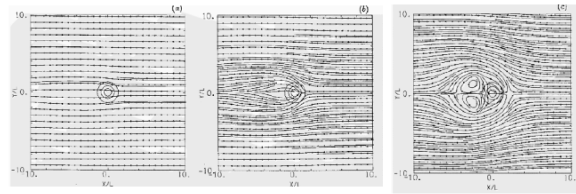
Introduction

- Isolated obstacle – A barrier with comparable length and width scales
- We will focus on mesoscale barriers, rather than small-scale objects like buildings and towers
- Examples
  - Hawaiian Islands
  - Guadalupe Island
  - Olympic Mountains
  - Mt. Rainier

Discussion

- What factors are likely to contribute to flow splitting around an isolated barrier and the formation of lee side vortices?

Low Froude Number Flow



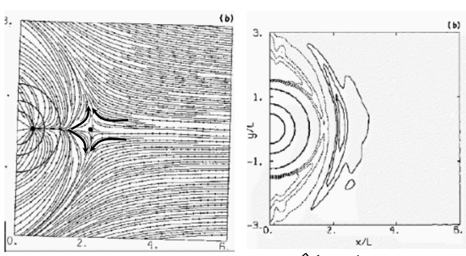
Fr=2.2 Fr=0.66 Fr=.22

Froude Number = $\hat{H}^{-1} = U/NH$

Characteristics of low Froude Number flow around isolated obstacle
Windward flow splitting and reversal
Leeward convergence, counter rotating vortices, and flow reversal

Smolarkiewicz and Rotunno (1989)

Windward Flow Reversal



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Characteristics of low Froude Number flow around isolated obstacle
Windward flow splitting and reversal
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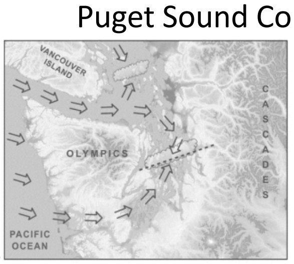
Smolarkiewicz and Rotunno (1990)

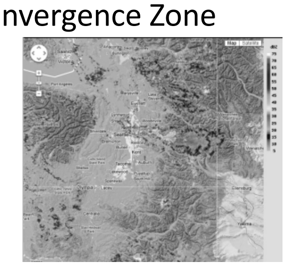
Example: Hawaiian Cloud Bands

- Form as easterly trade winds interact with Hawaii
- Narrow cloud band located over or windward of the island

Smolarkiewicz et al. (1988)

Example: Puget Sound Convergence Zone

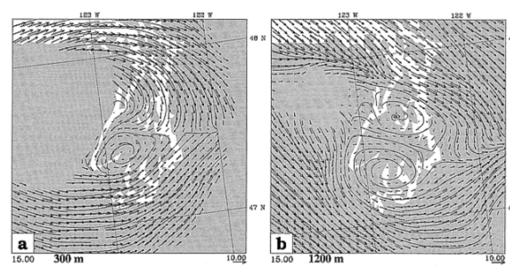




Flow around Olympic Mountains generates leeside convergence, clouds, and precipitation

Mass (2008), http://charliesweatherforecasts.blogspot.com/2013_04_01_archive.html

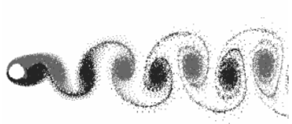
Example: Puget Sound Convergence Zone



Olympics deflect low Froude number flow (Fr=0.4) into two branches
Leeside convergence and counter-rotating vortices
Blocking by Cacscades also contributes to convergence

Chien and Mass (1997)

Vortex Shedding



Oscillatory shedding of vortices
from the generating obstacle

Known as a *von Kármán vortex street or sheet*

Banner Clouds

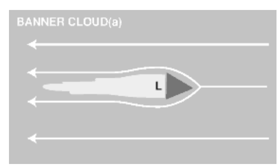
Form downstream of steep, sharp-edged peaks (e.g., Matterhorn)

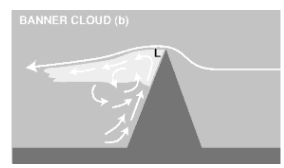
Zacharie Grossen, Wikipedia

Discussion

- How do you think banner clouds form?

Banner Clouds

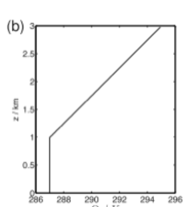




Acceleration along streamline near mountain top produces:
Low pressure immediately to lee (Bernoulli)
Leeside rotor and upslope flow
Banner cloud if air near saturation

http://science-edu.larc.nasa.gov/SCOOL/banner.html

Banner Cloud Simulations



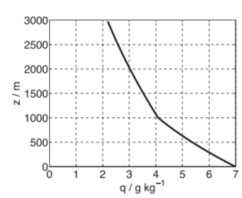
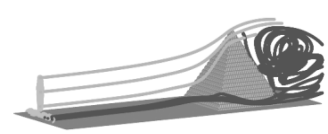


FIG. 2. Profile of specific humidity (g kg^{-1}) at the inflow boundary.

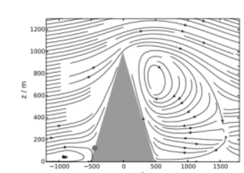
Neutral stratification to mountain top then stably stratified
Specific humidity decreases with height (i.e., PBL not well mixed, which
modeling and observations suggest is essential for banner cloud formation)

Voight and Wirth (2013), Schappert and Wirth (2015)

Banner Cloud Simulations



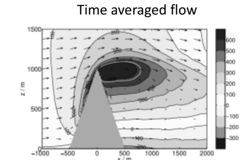
Selected trajectories



Time averaged flow

If atmosphere was well mixed, none of these would reach saturation

Existence of higher q near ground allows for banner cloud to form as near surface trajectories reach LCL below mountain top in lee



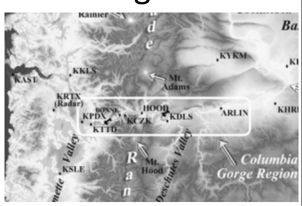
Time averaged vertical displacement (m)

Schappert and Wirth (2015)

Gap Winds

- Gap winds – Wind that are accelerated by an along-gap pressure gradient (Walter and Overland 1981)
- Examples:
  - Shelikof Strait, AK
  - Columbia Gorge, WA
  - Strait of Juan de Fuca, WA & BC
  - Straight of Gibraltar
  - Vestfjoden, Norway
  - Cook Strait, NZ

Columbia River Gorge



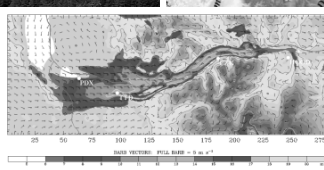
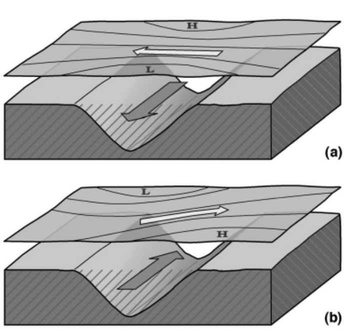


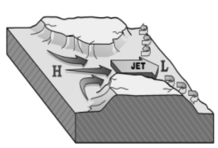
Photo: Kelvin Kay, Wikipedia; Sharp and Mass 2002; Sharp and Mass 2004

Columbia River Gorge

http://www.surfertoday.com/kiteboarding/5649-hood-river-gets-the-cabrinha-race-series

Pressure Driven Channeling





Other Factors:

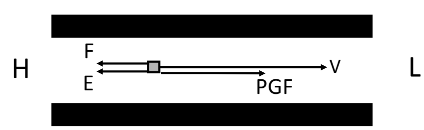
Diurnal modulation of cross-barrier pressure gradient

Marine or Arctic inversion (limits momentum mixing)

Bends and constrictions

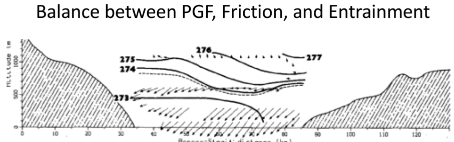
Whiteman (2000)

Force Balance in Long & Wide Gaps



Along-Gap Direction

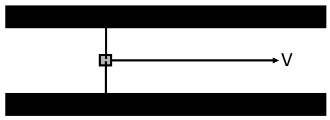
Balance between PGF, Friction, and Entrainment



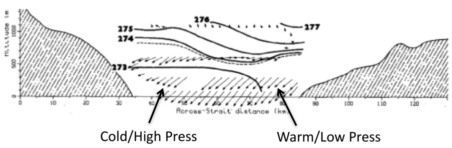
Flow below inversion much weaker than aloft

Lackmann and Overland (1989)

Force Balance in Long & Wide Gaps



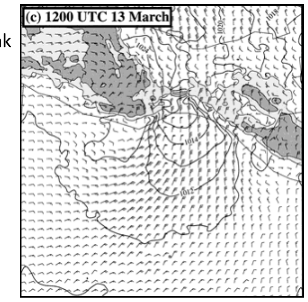
Cross-Gap Direction
Approximate geostrophic balance



Lackmann and Overland (1989)

Gap Outflow over Gulf of Tehuantepec

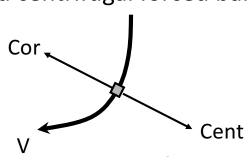
- Unique in that winds move into a region with very weak large-scale forcing
- Strongest winds directly in lee of Chivela Pass
- Counter-rotating eddies flank outlfow jet
- Outflow jet turns anticyclonically



Steenburgh et al. (1998)

Inertial Balance?

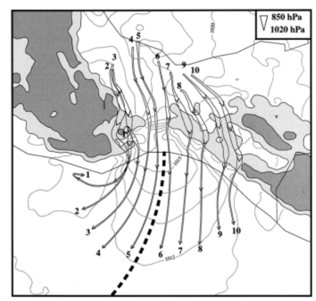
- Parcel deflected to right by Coriolis (Northern Hemisphere)
- Coriolis and centrifugal forced balance



- Radius of curvature given by $R=-V/f$ (minus sign indicates anticyclonic curvature)

Inertial Balance?

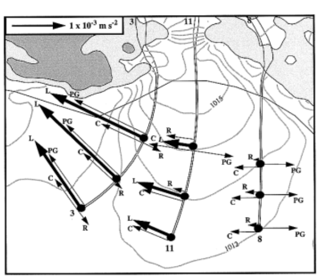
- Trajectories along axis of outflow jet follow inertial path (dashed)
- Trajectories to right of jet core (relative to flow) have stronger curvature
- Trajectories to left have weaker or cyclonic curvature



Steenburgh et al. (1998)

Inertial Balance?

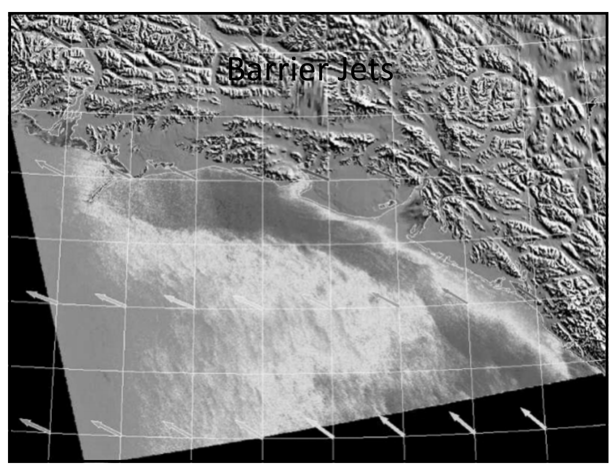
- Trajectories along axis of outflow jet deflected rightward by Coriolis and are inertially balanced
- Fanning of winds caused by cross-trajectory pressure gradient



C = Coriolis acceleration
R = Total acceleration

Steenburgh et al. (1998)

Barrier Jets



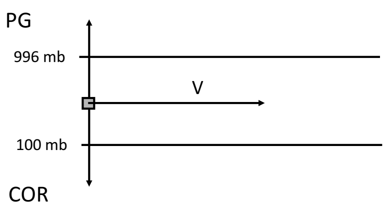
Barrier Jets

- Mesoscale, along-barrier winds that develop adjacent to steep terrain in the extratropics
- Associated with low-level blocking, although other factors can contribute
- Impacts: Cold-air damming, moisture transport, orographic precipitation, hazardous winds

Discussion

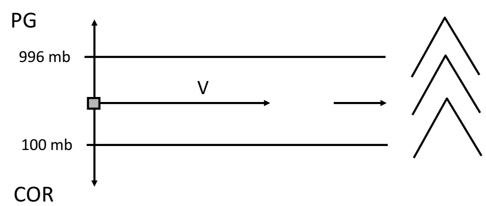
- As flow approaches a mountain barrier, what factors are likely to lead to along-barrier flow and the formation of a barrier jet?

Basic Dynamics



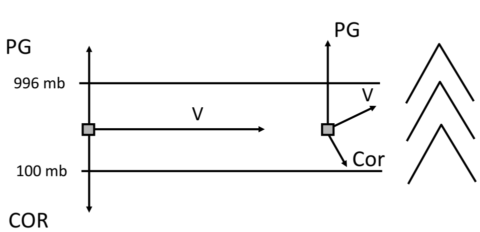
In the absence of topography and friction, the flow exhibits geostrophic balance

Basic Dynamics



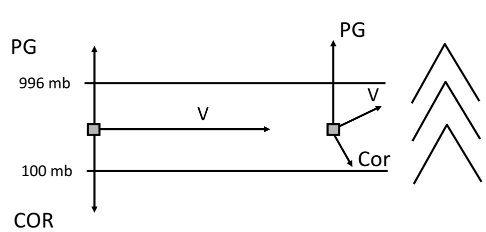
If flow is characterized by a low Froude number (U/NH < 1), the the low-level flow will be blocked and decelerate as it approaches mountains

Basic Dynamics



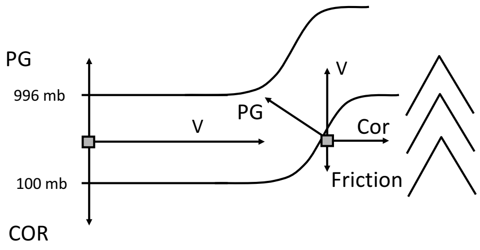
As the flow decelerates, the Coriolis force weakens, and the flow is deflected toward lower pressure

Basic Dynamics



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

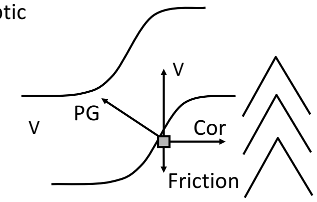
Basic Dynamics



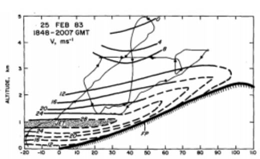
The final near-barrier force balance

Mature Force Balance

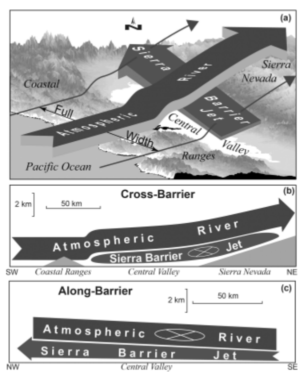
- Along-barrier antitriptic
  - Pressure gradient balances friction
- Cross-barrier geostrophic



Sierra Barrier Jet

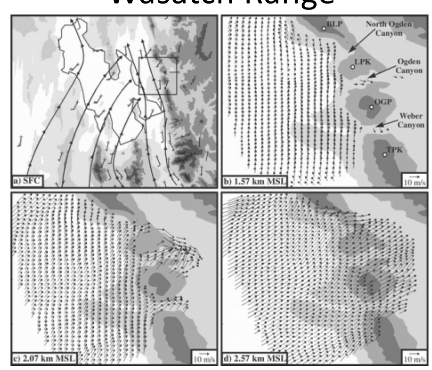


Old School (Marwitz 1987)



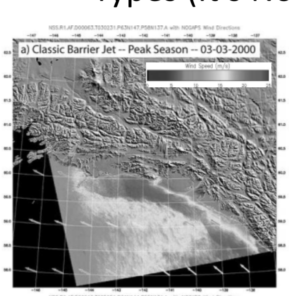
New School (Kingsmill et al. 2013)

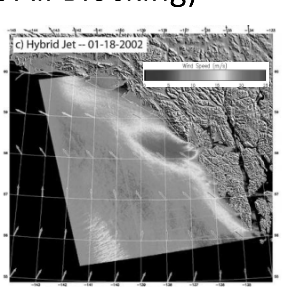
Wasatch Range



Cox et al. (2005)

Types (It's Not All Blocking)



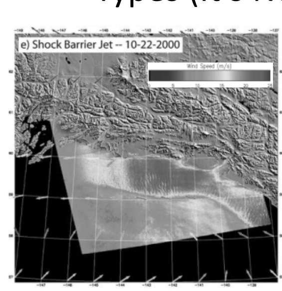


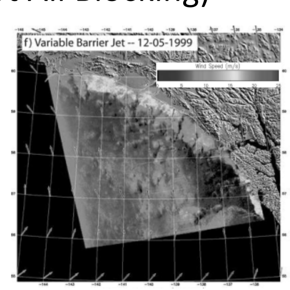
Classic – Produced by blocking as upstream flow impinges on barrier

Hybrid – Gap outflow turns terrain parallel merges with terrain parallel synoptic flow

Loescher et al. (2006)

Types (It's Not All Blocking)





Shock – Classic barrier jet with sharp boundary on synoptic upwind side

Variable – Terrain parallel flow is segmented

Loescher et al. (2006)

Summary

- Wide range of dynamically forced flows in complex terrain
- Controlled by characteristics of incident flow and shape of terrain
- Key phenomena
  - Mountain waves and downslope winds
  - Flow splitting, vortices, von Kármán vortex street
  - Gap flow
  - Blocking, barrier jets

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