Terrain-Forced Flows

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Markowski and Richardson (2010): "Mesoscale Meteorology in Midlatitudes"

Jim Steenburgh, University of Utah

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

![Diagram showing concavity and convexity](image)
Whiteman (2000)\n
Topography\n
The Intermountain West

Whiteman (2000)
Topography
Topography
Topography
Angle of attack

The best lifting requires strong cross-barrier flow

Whiteman (2000)
### The Basics: Landforms associated with strong and weak surface winds

<table>
<thead>
<tr>
<th>Expect high winds at sites:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Located in gaps, passes or gorges in areas with <em>strong pressure gradients</em></td>
</tr>
<tr>
<td><em>Exposed</em> directly to strong prevailing winds (summits, high windward or leeward slopes, high plains, elevated plateaus)</td>
</tr>
<tr>
<td>Located downwind of smooth <em>fetches</em></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Expect low wind speeds at sites:</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Protected</em> from prevailing winds (low elevations in basins or deep valleys oriented perpendicular to prevailing winds)</td>
</tr>
<tr>
<td>Located upwind of mountain barriers or in intermountain basins where air masses are <em>blocked</em> by barrier</td>
</tr>
<tr>
<td>Located in areas of high <em>surface roughness</em> (forested, hilly terrain)</td>
</tr>
</tbody>
</table>
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 can form over steep cliffs or slopes on either the windward or leeward sides.
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).
Terrain Forced Flows & their basic Dynamics
Key non-dimensional parameters

1) Rossby Number $R_0$

$$R_0 = \frac{U}{fL}$$

U: cross-barrier wind speed
f: Coriolis parameter (midlatitudes $\sim10^{-4}$ s$^{-1}$)
L: Mountain barrier width

2) Non-dimensional Mountain Height $\varepsilon$
aka “inverse Froude number” (more on Froude number later)

$$\varepsilon = \frac{h_0N}{U}$$

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 ($R_o$);  \[ R_o = \frac{U}{fL} \]

$R_o << 1$

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

Mean troughs form down-wind of major mountain barriers

Wallace & Hobbs (1977)
January cyclogenesis areas and paths

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

“Lee cyclogenesis”
Rossby Number \((R_o)\); \[ R_o = \frac{U}{fL} \]

\(R_o \ll 1\)

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)
Non-Dimensional Mountain Height $\varepsilon$

“Will the air flow over the barrier?”

$\varepsilon$ 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 ($U^2/2$)

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

$\varepsilon > 1$: Inertia too weak and the flow is \textit{blocked}
  
  High stability, large mountain; weak cross-barrier flow

$\varepsilon < 1$: Inertia overcomes stability, \textit{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 $\varepsilon$

- 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)
Froude number

\[ Fr = \frac{(2\pi U)}{(N \cdot 2W)} \]

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** $\varepsilon$ and mountain aspect ratio $r$.

$N_{hm} \over u_0$ vs $r$

$r = \text{crosswise / streamwise dimensions}$

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…

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

- 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

Carney et al. (1996)
Vertically propagating and trapped lee waves can coexist!
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

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

**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.
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
Rotor flow movie, Falkland Islands

Prof. Stephen Mobbs,
University of Leeds, UK
Beran (1967)

Four factors contribute to the warmth and dryness of Chinook winds

**Compression Heating**
- +9.8°C per km of descent

**Air Mass Change**
- Cold Air

**Latent Heat Release**
- ~5°C per km of ascent when condensation occurs
- +9.8°C per km of descent

**Turbulent Mixing**
- (keeps nighttime inversion from forming)

Four Chinook mechanisms
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.
Scans within a 2-3 min time window are averaged and used in a dual doppler analysis.
Hydraulic Jumps, rotors, …
Flow Separation

Dual Doppler Winds 2013/10/19

22:38 MST

Height [km ASL]

Distance from Lidar [km]

[m s\(^{-1}\)]

0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4

0.0 1.0 2.0 3.0 4.0 5.0 6.0

2 m s\(^{-1}\)
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)
Kármán vortices in lee of New Zealand volcano

From Erick Brenstrum
Kerguelen Islands
Banner clouds
Banner Cloud, Mt. Olympus, Utah
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.
In the absence of topography and friction, the flow exhibits *geostrophic balance*. 
If flow is characterized by a low Froude number \((U/NH < 1)\), the low-level flow will be blocked and will decelerate as it approaches mountains.
As the flow decelerates, the Coriolis force weakens, and the flow is deflected toward lower pressure.
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).
The final near-barrier force balance.
Barrier Jets – Mature Force Balance

- Along-barrier antitriptic:
  Pressure gradient balances friction

- Cross-barrier geostrophic

![Diagram showing force balance with vectors for V, PG, Cor, friction, and mountain range.](image-url)
Flow splitting

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

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
Channeling

Forced Channeling

Pressure Driven Channeling
Pressure driven channeling versus forced channeling

Pressure driven channeling

Forced Channeling
Pressure driven channeling

Whiteman (2000)