Mountain Forced Flows

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Overview

Trapped Lee Waves Behind a 3D Mountain

We used two-dimensional mountain wave theories helped explain some important flow phenomena:

- upward propagating mountains waves
- lee waves
- wave overturning and breaking
- severe downslope winds

In reality most of the mountains are three-dimensional and complex in form.

Trapped Lee Waves Behind a 3D Mountain

As in the two-dimensional mountain wave problem, a rapid decrease of the Scorer parameter with height leads to the formation of trapped lee waves.

The formation of three-dimensional trapped lee waves is similar to that of *Kelvin ship waves* over the water surface.

Let's look at an example of the cloud streets associated with three-dimensional trapped lee waves produced by flow past a mountainous island.

You'll notice that the wave pattern is generally contained within a wedge with the apex at the mountain.

Trapped Lee Waves Behind a 3D Mountain

Figure: Satellite imagery showing three-dimensional trapped lee waves induced by the Sandwich Islands in southern Atlantic Ocean on November 23, 2009. The wave pattern is similar to that of the ship waves. (credit: NASA)

Trapped Lee Waves Behind a 3D Mountain

The three-dimensional trapped lee waves are composed by *transverse waves* and *diverging waves*.

The transverse waves lie approximately perpendicular to the flow direction, and are formed by waves attempting to propagate against the basic flow but that have been advected to the lee.

The formation mechanism of transverse waves is the same as that of the two-dimensional trapped lee waves.

Trapped Lee Waves Behind a 3D Mountain

Unlike the transverse waves, the diverging waves attempt to propagate laterally away from the mountain and have been advected to the lee.

The diverging waves have crests that meet the incoming flow at a rather shallow angle.

The significant disturbance is confined within a wedge angle of $\sim 19^\circ$ with the x-axis.

Trapped Lee Waves Behind a 3D Mountain

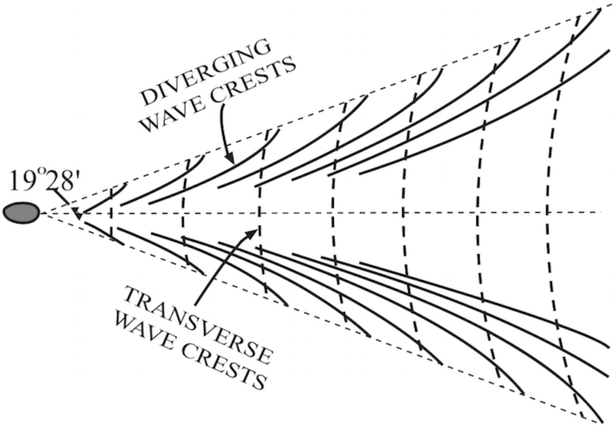


Figure: Schematic of transverse (bold-dashed) and diverging (solid) phase lines for a classical deep water ship wave. (Adapted after Sharman and Wurtele 1983)

Blocking of the Wind by Terrain

Throughout Section 2.1 we considered various atmospheric phenomena that arise due to air flowing over mountains.

In this section we will investigate phenomena that result from the blocking of wind by terrain.

Over or Around?

Consider an air parcel approaching a mountain.

Will it go over or around the mountain?

What factors determine the parcel's path?

Over or Around?

The air parcel's path depends on several factors:

- the height of the parcel relative to the height of the mountain
- the slope and dimensions (height/width) of the mountain
- the static stability
- the strength of the upstream horizontal winds directed at the mountain

Over or Around?

Some general scenarios when a parcel is most likely to go around rather than over a mountain include

- there is increased stratification
- the speed of an approaching parcel decreases
- the distance that must be climbed by a parcel increases

Over or Around?

It seems like the easy way to assess blocking potential is to compare the kinetic energy of an approaching parcel to the work that must be done to overcome stratification and lift the parcel over the barrier.

This method, however, neglects pressure perturbations, which we previously saw were very important to flow over a mountain - especially for downslope wind events

Over or Around?

Consider a streamline in steady flow that passes over a barrier.

Far upstream ($x = -\infty$), the streamline is located at height z_0.

Near the barrier, the streamline is displaced upward some distance δ, such that its new height is $z_0 + \delta$.

Here, we assume that parcel motions are dry adiabatic, meaning that $\theta = \theta_0$ along a streamline.

Over or Around?

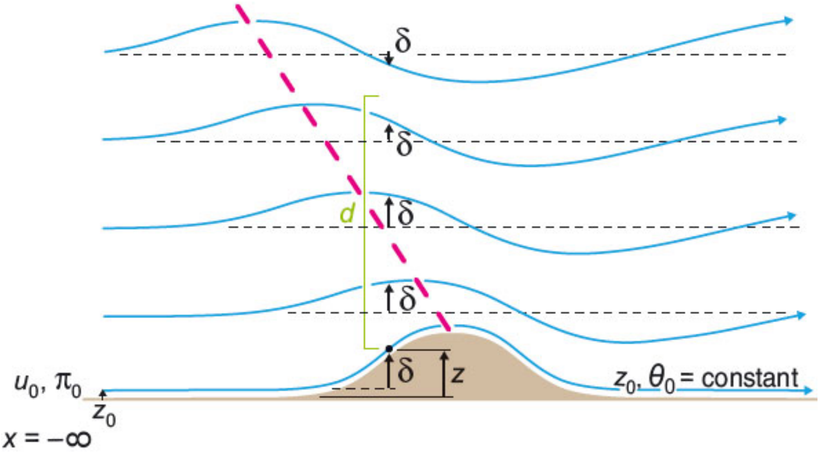


Figure: A schematic illustration of streamlines (blue; coincident with isentropes for inviscid, dry adiabatic motion), passing over a mountain, along which the Bernoulli equation applies. [From Markowski and Richardson]

Math Break!

"PARDON ME SIR – COULD YOU PLEASE EXPLAIN STEP 3?"

Cold-Air Damming

In the eastern USA, northerly surges of cold air down the east side of the Appalachian Mountains are commonly observed in winter on the south side of a surface anticyclone.

Here, winds having an easterly geostrophic wind component are directed from offshore toward the mountains and are blocked and deflected southward by the mountains

This type of orographically trapped cold-air surge is locally referred to as *cold-air damming*.

Cold-Air Damming

In most cold-air damming cases, the lower atmosphere satisfies

$$h_m > \frac{u}{N} \rightarrow \mathrm{F_{rm}} < 1 \ , \tag{1}$$

where u is the barrier-normal wind component and N is the vertically (over the depth of the barrier) averaged Brunt-Väisälä frequency. If the flow is blocked over a significant depth, $\mathrm{F_{rm}}$ is significantly less than one.

Cold-Air Damming

The obvious takeaway from Eq. (1) is that these trapped surges are favored in strongly stable environments.

Upwind clouds, especially those that precipitate into a dry boundary layer, further act to enhance the potential for damming.

In some instances, this evaporation of precipitation is enough to overcome a marginal Froude number by increasing static stability.

We call these scenarios *diabatic damming* cases.

Cold-Air Damming

Consider a low-level air parcel approaching a north-south mountain barrier from the east.

Winds are deflected southward, resulting in a large southward ageostrophic wind component east of the barrier.

A ridge of high pressure builds southward as a hydrostatic consequence of the trapped cold air.

Cold-Air Damming

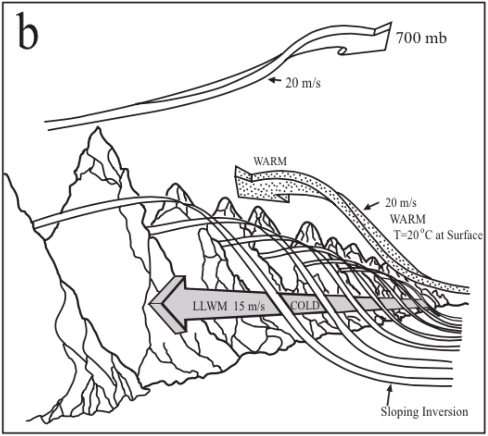


Figure: Conceptual model of a mature cold-air damming event. LLWM stands for low-level wind maximum. (Adapted after Bell and Bosart 1988)

Cold-Air Damming

The width of this pressure ridge is approximated by the *Rossby radius of deformation*,

$$L_R = \frac{Nh}{f} \ , \tag{2}$$

where f is the Coriolis parameter, h is the scale height of the flow that is perturbed by the terrain, and N is some representative static stability over h.

Cold-Air Damming

When $\mathrm{F_{rm}} < 1$, an appropriate scale height is $h = h_I = u/N$, where h_I is known as the *inertial height scale*.

In this case, the previous equation becomes

$$L_R = \frac{u}{f} = L_{Rm}\mathrm{F_{rm}} \ , \tag{3}$$

where $L_{Rm} = Nh_m/f$ is the so-called *mountain Rossby radius*.

Cold-Air Damming

Consider the case when a layer of warm air subsides over the cold air, separated by a strong inversion.

Here, the system approaches a two-layer system. In this case,

$$L_R = \frac{\sqrt{g' H}}{f} \ , \tag{4}$$

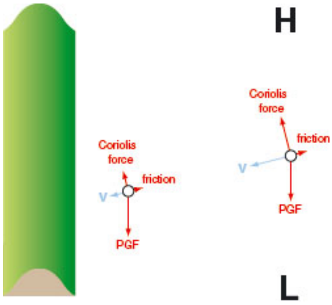
where $g' = g\Delta\theta/\overline{\theta}$ is reduced gravity, H is the depth of the cold layer, $\overline{\theta}$ is the mean potential temperature of the cold layer, and $\Delta\theta$ is the potential temperature gradient across the inversion.

Cold-Air Damming

In terms of deflection, again consider an air parcel approaching a north-south mountain barrier from the east.

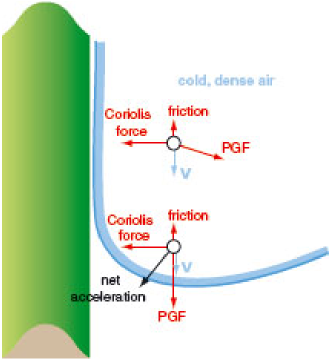
An example of this setup is an episode of cold-air damming east of the Appalachian Mountains when an anticyclone is positioned to the north of the parcel.

Cold-Air Damming



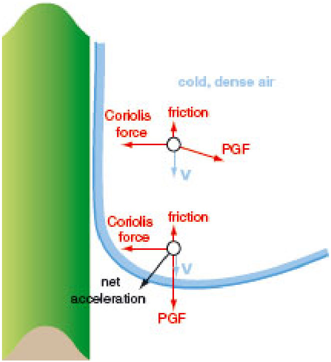
- Far upstream the parcel experiences no net acceleration owing to a balance among the pressure gradient, Coriolis, and friction forces
- The parcel decelerates once it begins ascending
- This deceleration is associated with a weakening of the northward-directed Coriolis force, resulting in a southward deflection by the large-scale pressure gradient force

Cold-Air Damming



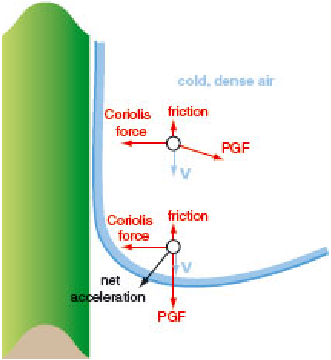
- Once air has been diverted southward, the Coriolis force keeps the cold air trapped against the mountains
- Farther upstream within the cold-air mass (where northerly winds are approximately steady and blowing roughly along the elevation contours) the pressure gradient force is directed downslope and is in approximate balance with the upslope-pointing Coriolis force and friction forces.

Cold-Air Damming



- If the pressure gradient force is the same near the mountain range as it is a large distance from the mountains, then the upstream balance among the pressure gradient, Coriolis, and friction forces cannot be maintained as higher terrain is encountered.
- The parcel experiences a net acceleration in the direction of the pressure gradient force.

Cold-Air Damming



- In many cold-air surge cases, the deflection of air by the terrain produces a barrier jet on the upslope side of the barrier.
- Barrier jets can attain wind speeds of 15-30 ms^{-1} and are usually centered at an altitude roughly half the height of the mountain crest.

Cold-Air Damming

The approximate scale of the velocity increase in the direction parallel to the coast or mountain range is

$$\Delta v \approx \frac{N^2 h_l^2}{f L_{Rm}} = \frac{u^2}{f L_{Rm}} \ , \tag{5}$$

where v is the barrier-parallel wind component. The strongest barrier jets are therefore observed when there is a strong mountain-normal wind (u) and small mountain Rossby radius L_{Rm}, and thus small N and h_m, but not so small (nor u so large) that $\mathrm{F_{rm}} > 1$.

Lee Vortices

Counter-rotating vortices are commonly observed in the lee of an isolated terrain obstacle when the flow is strongly stratified and forced to pass around the obstacle.

On some occasions a single pair of oppositely signed vertical vorticity extrema is observed in the wake of the obstacle.

Lee Vortices

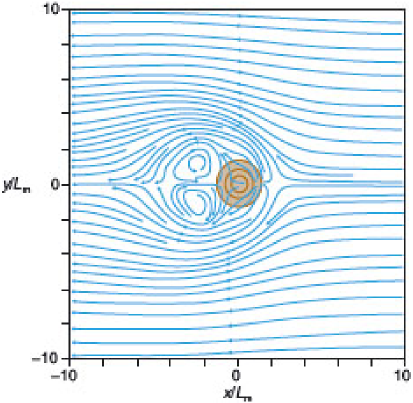


Figure: Example of a pair of counter-rotating vortices in the wake of an isolated mountain peak in a numerical simulation. [From Markowski and Richardson]

Lee Vortices

When the wake flow in which the lee vortices are embedded becomes unstable, the vortices tend to shed downstream and form a *von Kármán vortex street*

A von Kármán vortex street is a repeating pattern of alternate and swirling vortices along the center line of the wake flow, and is named after the fluid dynamicist, Theodore von Kármán.

This process is also known as vortex shedding.

Lee Vortices

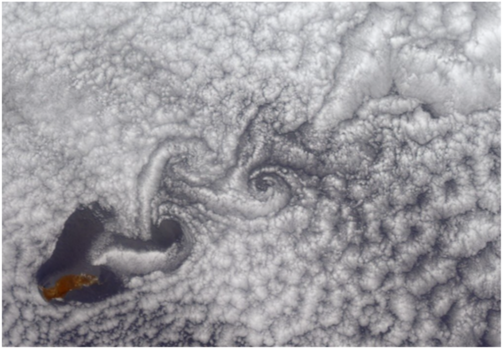


Figure: A von Kármán vortex street that formed to the lee of the Guadalupe Island, off the coast of Mexicos Baja Peninsula, revealed by MISR images from June 11, 2000 detected by NASA satellite Terra. (credit: Visible Earth, NASA)

Lee Vortices

You might assume that all wake vortices form as a result of the separation of a viscous boundary layer from an obstacle.

However, numerical simulations have shown that frictional forces are not necessary.

This variety of wake vortices, at least in numerical simulations, is confined to a range of $\mathrm{F_{rm}}$ between 0.1 and 0.5. This is fairly typical of cases in which wake vortices are observed in the real atmosphere.

In the case of wake vortices that form as a result of a purely inviscid mechanism, baroclinic vorticity generation is key!

Lee Vortices

For $\mathrm{F_{rm}}$ outside of the range of 0.1-0.5, wake vortices are not observed to form as a result of purely inviscid processes, at least not in numerical simulations.

When wake vortices are observed outside of this range of $\mathrm{F_{rm}}$, it is likely that the separation of the viscous boundary layer from the obstacle has played the dominant role in their formation

Gap Flows

When a low-level wind passes through a gap in a mountain barrier or a channel between two mountain ranges, it can significantly strengthen due to the acceleration associated with the along-gap pressure gradient force.

The significant pressure gradient is often established by:

- the geostrophically balanced pressure gradient associated with the synoptic-scale flow
- the low-level temperature differences in the air masses on each side of the mountains.

Gap Flows

Gap flows occurring in the atmosphere are also known as

- mountain-gap winds
- jet-effect winds
- canyon winds

Gap flows perhaps most often occur in conjunction with cold-air surges, when significant cross-barrier temperature differences and cross-barrier winds may both be present.

Gap Flows

Gap flows are found in many different places in the world. Examples include:

- the Columbia River Gorge and the Strait of Juan de Fuca in the northwestern United States
- the Rhine Valley of the Alps
- the Sierra Nevada in Independence, California
- the lee side of the Rockies in Boulder, Colorado

Gap Flows

1700 UTC 9 December 1995

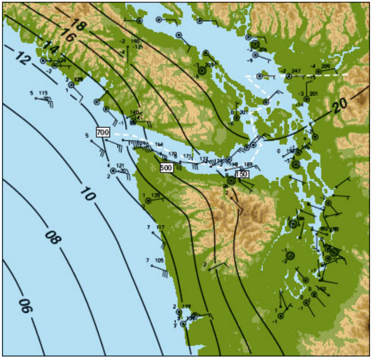


Figure: Surface analysis from 1700 UTC 9 Dec 1995 during a gap flow event in the Strait of Juan de Fuca. The contour interval for sea level pressure is 2mb. [From Markowski and Richardson]

Gap Flows

Based on $\mathrm{F_{rm}}$, three gap-flow regimes can be identified:

- *linear regime* (large $\mathrm{F_{rm}}$): insignificant enhancement of the gap flow;
- *mountain wave regime* (mid-range $\mathrm{F_{rm}}$): large increases in the mass flux and wind speed within the exit region due to downward transport of mountain wave momentum above the lee slopes, and where the highest wind occurs near the exit region of the gap
- *upstream-blocking regime* (small $\mathrm{F_{rm}}$): the largest increase in the along-gap mass flux occurs in the entrance region due to lateral convergence

Gap Flows

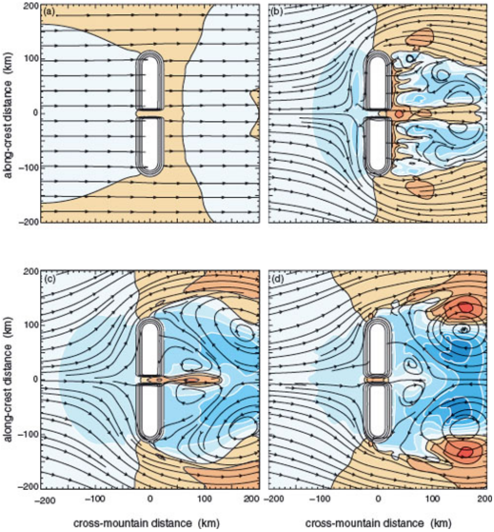


Figure: Simulation of westerly winds encountering a ridge with a gap when the $\mathrm{F_{rm}}$ is equal to (a) 4.0, (b) 0.7, (c) 0.4, and (d) 0.2.

Gap Flows

Gap flows are also influenced by frictional effects, which imply that:

- the flow is much slower
- the flow accelerates through the gap and upper part of the mountain slope
- the gap jet extends far downstream
- the slope flow separates, but not the gap flow
- the highest winds occur along the gap

Next Class

Coming soon ....

- Finish up mountain forced flows (orographic precip)
- Perhaps start on boundary layer if there is time
- Homework 1 distributed


That's all Folks!