Mountain Forced Flows

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Overview

Mountain Forced Flows

Well-known weather phenomena directly related to flow over orography include

- mountain waves
- lee waves and clouds
- rotors and rotor clouds
- severe downslope windstorms
- lee vortices
- lee cyclogenesis
- frontal distortion across mountains
- cold-air damming
- track deflection of midlatitude and tropical cyclones
- coastally trapped disturbances
- orographically induced rain and flash flooding
- orographically influenced storm tracks.

A majority of these phenomena are mesocale and are induced by stably stratified flow over orography.

Mountain Wave Examples

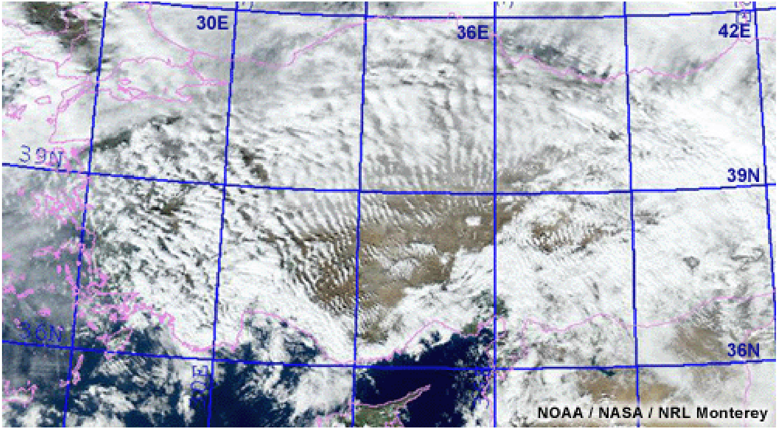


Figure: MODIS image of mountain wave clouds over Turkey. (credit: UCAR/COMET)

Mountain Wave Examples

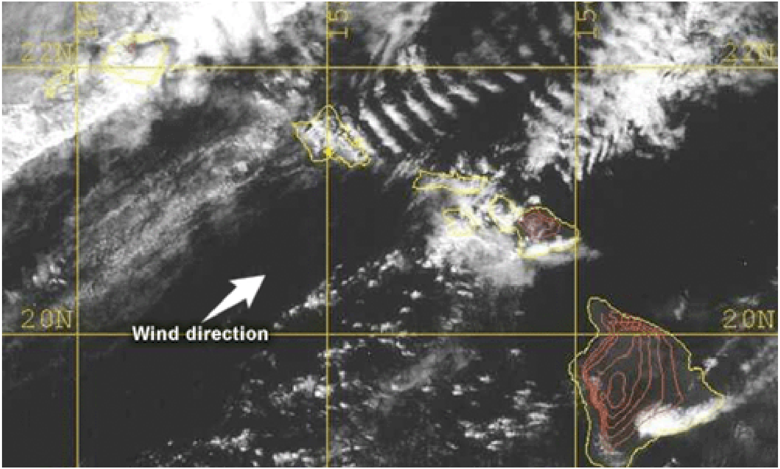


Figure: Trapped lee waves extend downwind from the Hawaiian Islands. (credit: UCAR/COMET)

Mountain Wave Examples

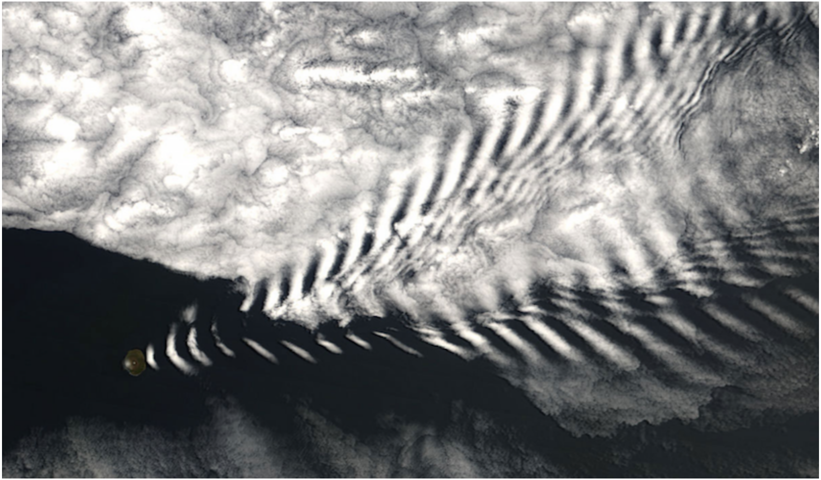


Figure: Wave clouds extend downwind from Amsterdam Island. (credit: Jeff Schmaltz/NASA)

Mountain Wave Examples

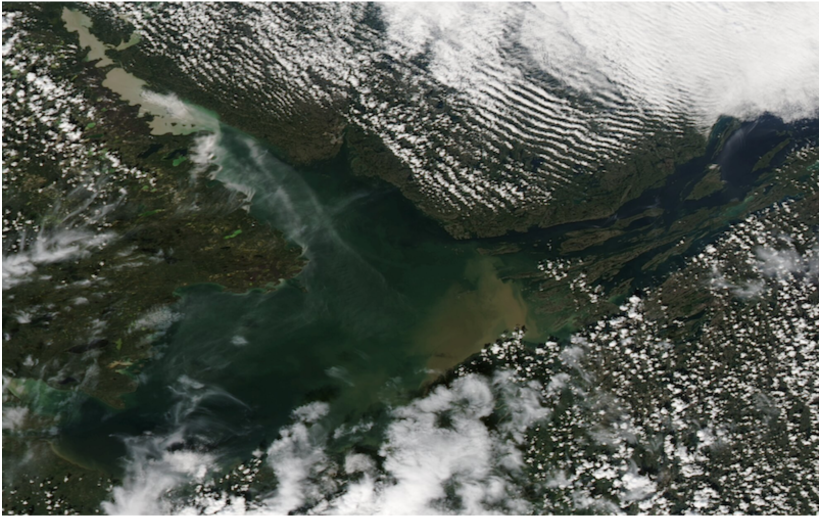
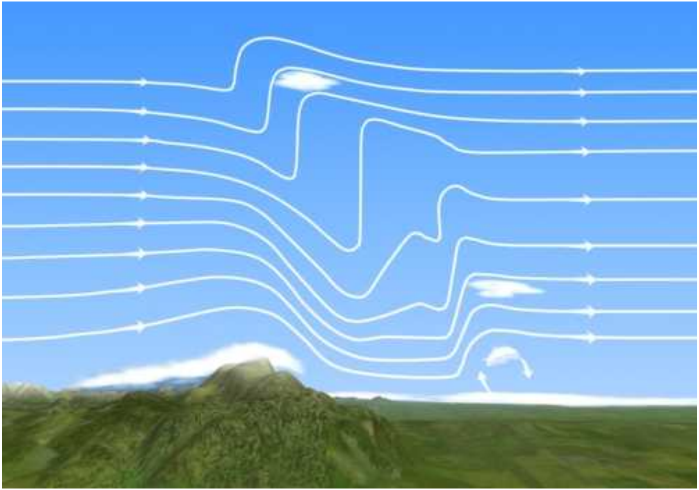


Figure: Wave clouds extend downwind over Canada's Great Slave Lake (credit: Earth Snapshot)

Typical Mountain Waves Features



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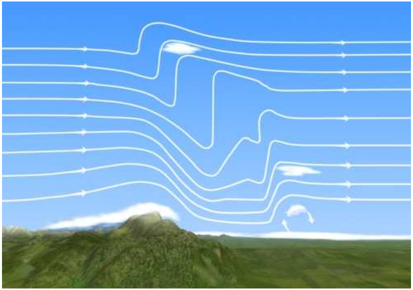
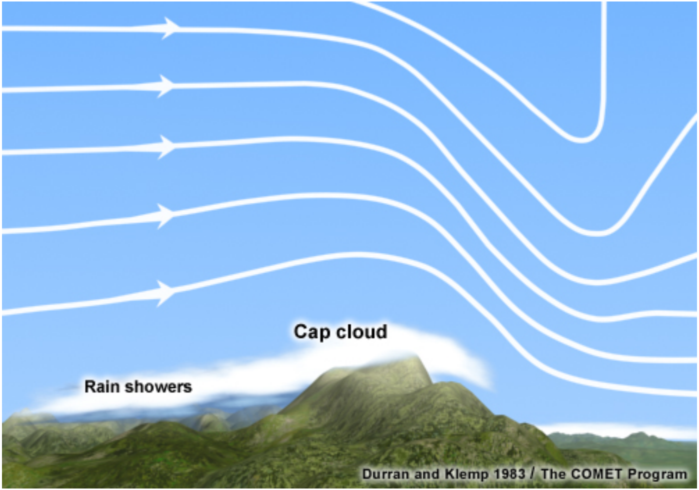
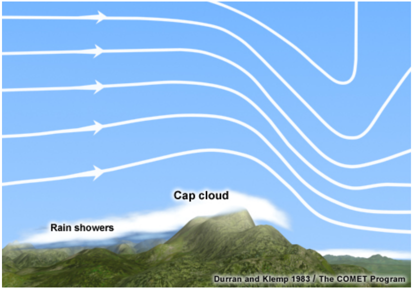


This figure shows the development of the typical features often associated with a mountain wave system. Notice the wind flow, with a strong component perpendicular to the primary ridge line. This is a typical condition for mountain wave development, as is a stable atmosphere. If air is being forced over the terrain, it will move downward along the lee slopes, then oscillate in a series of waves as it moves downstream. Sometimes these waves can propagate long distances in "lee wave trains.

Cap Clouds

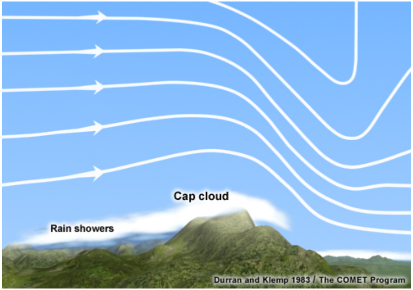

Cap cloud
Rain showers
Durran and Klemp 1983 / The COMET Program

Cap Clouds



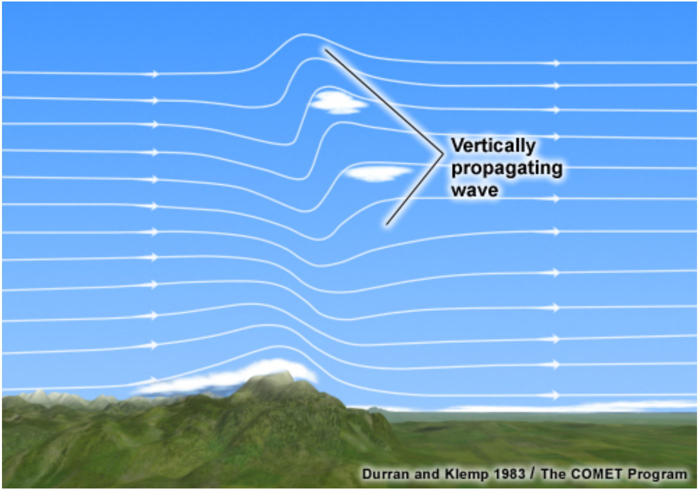
Cap clouds indicate likely wave activity downstream. They often appear along mountain ridges as air is forced up the windward side. If the flow is sufficiently humid, the moisture will condense into a cloud bank that follows mountain contours. Quite often, heavy orographic precipitation occurs on the upwind side of the barrier, particularly for barriers located near the sea. As the flow descends in the lee of the mountain ridge, the cloud evaporates. Viewed from downstream, cap clouds frequently appear as a wall of clouds hanging over the ridge top.

Cap Clouds



It is important to remember that while cap clouds indicate likely wave activity, their absence does not mean that waves are absent. Under drier conditions, waves may be present without cap clouds.

The Vertically-Propagating Wave



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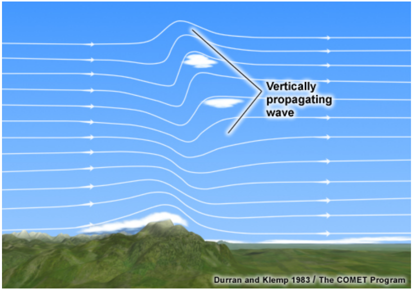
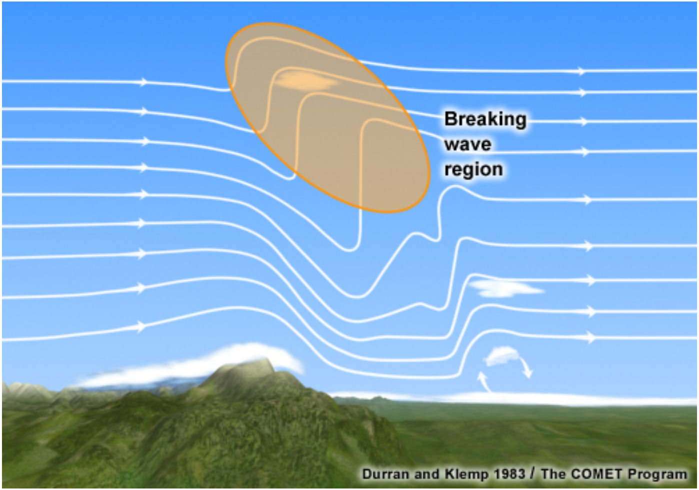
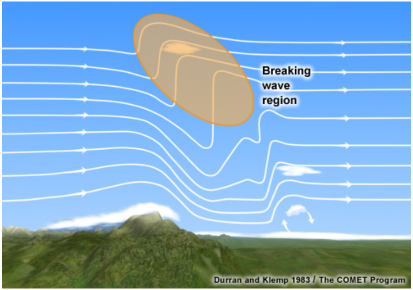


The vertically-propagating wave is often most severe within the first wavelength downwind of the mountain barrier. These waves frequently become more amplified and tilt upwind with height. Tilting, amplified waves can cause aircraft to experience turbulence at very high altitudes. Clear air turbulence often occurs near the tropopause due to vertically-propagating waves. Incredibly, these waves have been documented up to 70 km and higher.

Breaking Waves

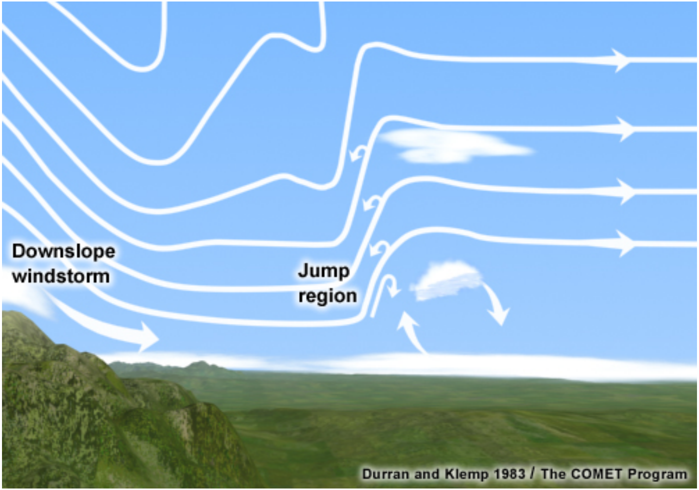


Breaking Waves

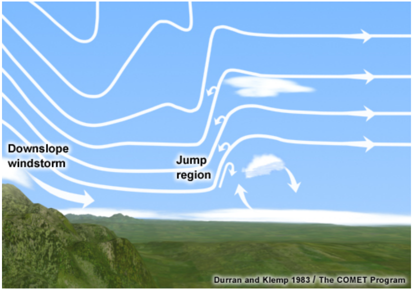


Vertically-propagating waves with sufficient amplitude may break in the troposphere or lower stratosphere. Wave-breaking can result in severe to extreme turbulence within the wave-breaking region and nearby, typically between 7 and 14 km. If a vertically-propagating wave doesn't break, an aircraft would likely experience considerable wave action, but little turbulence.

Downslope Winds

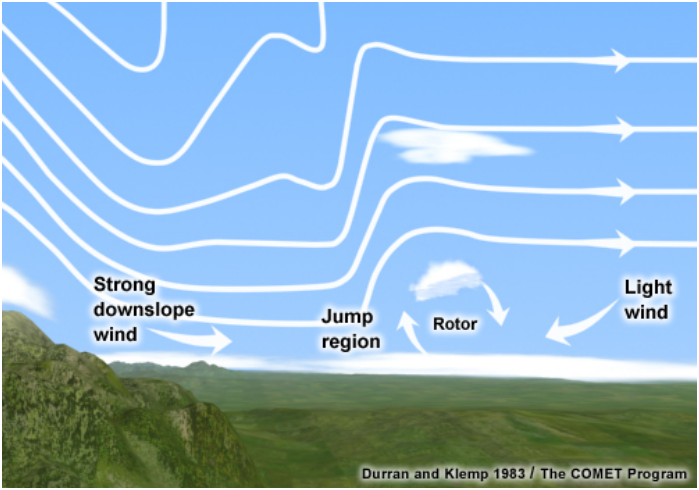


Downslope Winds

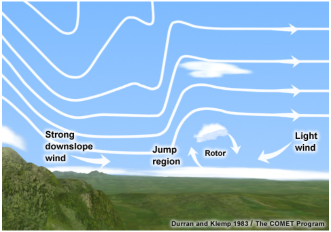


At times, strong downslope winds accompany mountain wave systems. Strong downslope wind cases are usually associated with strong cross-barrier flow, waves breaking aloft, and an inversion near the barrier top. In extreme cases, winds can exceed 100 knots. This may be double or triple the wind speed at mountaintop level. These high winds frequently lead to turbulence and wind shear at the surface, causing significant danger to aircraft and damage at the surface. Downslope windstorms often abruptly end at the "jump region," although more moderate turbulence can exist downstream. The jump region is an extremely turbulent area that can extend up to 3 km.

Rotors

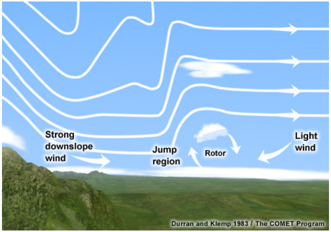

Strong
downslope
wind
Jump
region
Rotor
Light
wind
Durran and Klemp 1983 / The COMET Program

Rotors



Rotors are part of a low-level turbulent zone that often forms in association with a mountain wave system. Rotors are also called horizontal roll vortices because they form a complete rotational pattern, with the axis of rotation parallel to the ground. The low-level turbulent zone is another region of potentially significant turbulence. It exists immediately downstream of the jump region and under a wave crest. Rotor axes typically occur at altitude equal to or below mountain-top level and within 20 nautical miles of the ridge line. Smaller-scale rotations embedded within the low-level turbulent zone can cause rolling that exceeds an aircrafts ability to stay level. This occurs most frequently when development of a convective boundary layer aids powerful upward motions in the jump region.

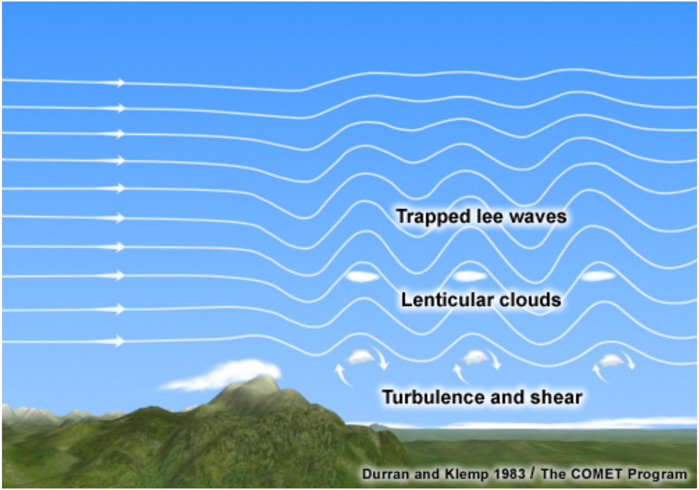
Rotors



Rotor location can often be identified if sufficient moisture is available to form an associated rotor cloud. Rotor clouds are found near the top of the rotor circulation and under higher lenticular clouds. Immediately above the rotor cloud, smooth, wavy air is likely.

The rotor cloud can look innocuous, but does contain strong turbulence and should be avoided by pilots. Eventually, we can expect operational NWP models to resolve rotors so that they can be identified in the absence of rotor clouds.

Trapped Lee Waves and Clouds



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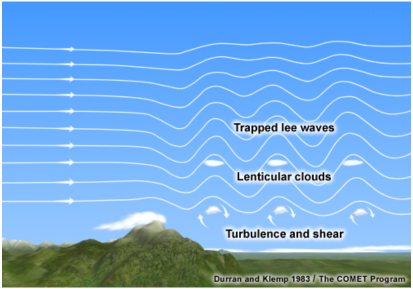
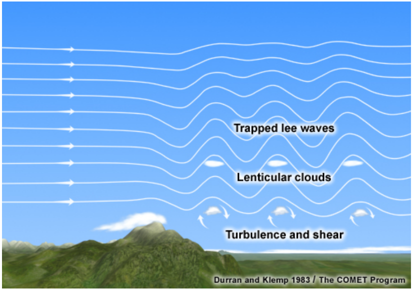


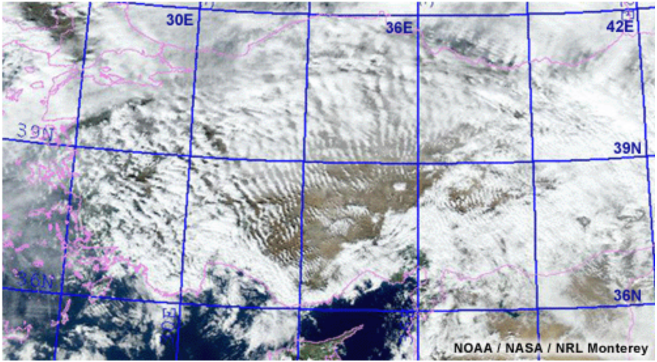
Lee waves whose energy does not propagate vertically because of strong wind shear or low stability above are said to be "trapped." Trapped lee waves are often found downstream of the rotor zone, although a weak rotor may exist under each lee wave. These waves are typically at an altitude within a few thousand feet of the mountain ridge crest and turbulence is generally restricted to altitudes below 8 km. Strong turbulence can develop between the bases of associated lenticular clouds and the ground.

Trapped Lee Waves and Clouds



Lenticular clouds form near the crests of mountain waves. As air ascends and cools, moisture condenses, forming the cloud. As that air descends in the lee of the wave crest, the cloud evaporates. Because air flows through the cloud while the cloud itself is relatively stationary, many people refer to these clouds as standing lenticulars.

Areal Extent of Mountain Waves



Mountain wave activity can occur over broad regions. This figure shows wave clouds covering most of Turkey, a region spanning about 1000 km! However, despite their occasionally broad extent, regions of strong or severe turbulence within mountain wave systems are often limited horizontally and vertically.

The End

Just kidding. Now we do math.