Lecture Seventeen

Mountain Influences on the Atmosphere

Scope: As we've seen, the Earth's surface has significant terrain features that can block, channel, lift, and steal moisture from air. In this lecture, we'll examine influences of mountains on the atmosphere; how mountains can disturb the atmosphere into which they intrude; and how sometimes mountains save their most extreme influences for their own backsides.

Outline

I. Mountains represent a disturbance to the atmosphere that is felt far and wide; the atmosphere responds to this disturbance by producing waves.

II. Mountain waves form in a stable atmosphere, so let's review some of the concepts relating to stability that we've learned in previous lectures.

- **A.** Here's a stable environment, with temperature decreasing at 6.5°C per kilometer in the troposphere and increasing in the stratosphere. If we make a subsaturated air parcel and force it to rise or sink, it cools or warms at the DALR, as long as water substance is not changing phase.
- **B.** Given that the tropospheric temperature changes less quickly with height than it does for our parcel, air displaced up or down wants to return to its starting point; we call that situation stable. This means that the stratosphere is even more stable than the troposphere.
- **C.** Let's look at a vertical cross-section of a stable atmosphere. The horizontal lines are isentropes, lines of constant entropy. The narrower the space between the isentropes, the more stable the environment.
- **D.** Forcing 2 isentropes together increases the wind speed between them. Turning the isentropes vertically decreases the stability of the environment.

III. How can mountains and mountain waves disturb the environment in a way that makes the atmosphere less stable?

A. Consider a bell-shaped mountain standing 500 meters tall.

B. Putting a mountain in the path of westerly winds creates a disturbance. Air at ground level is forced to rise up and over the mountain.

C. The resulting mountain waves are stationary relative to the ground, but they are traveling upward.

D. Where isentropes turn upward, air is rising, and when they get close to vertical, the environment is much less stable.

IV. One of the most dramatic examples of mountain-associated weather is the downslope windstorm and the hydraulic jump.

A. A hydraulic jump is a sudden change from a thin, high-velocity fluid to a thicker and slower one. We can encourage jump formation by altering environmental stability.

B. We see a profile with a temperature inversion near the surface. In general, temperature inversions can be present in conditions where vertical wind shear and direction—not just speed—are changing with height, resulting in 2 different air masses rising upward from the surface.

C. Temperature inversions can prevent mountain-induced disturbances from influencing the atmosphere higher above, trapping the disturbances in the lower troposphere.

D. We see a mountain that has had a profound influence on air passing up and over the summit. On the leeside, the air plunges suddenly downward, with high wind speeds. This is a downslope windstorm.

E. Parcel paths are also vertical about 50 kilometers farther downwind; at that point, the fast-flowing air abruptly slows down, and that's the hydraulic jump.

V. We can gain some insight into what ingredients go into downslope windstorms by looking at a simple system, similar to a river flowing over a rock on a riverbed.

A. If we place an obstacle in a free-flowing river, the oncoming flow will slow down as it rises up and over the obstacle, which will make the fluid thicker. Once it passes the obstacle, the flow speed will pick up again and return to its original velocity farther downstream. We call this supercritical flow.

B. If the initial oncoming flow is somewhat slower, however, the result is subcritical flow. Here, the flow speeds up over the obstacle and the fluid thins, but again, it recovers its initial velocity downstream.

C. To create a downslope windstorm, a hybrid of these 2 situations is required, 1 that starts out subcritical and becomes supercritical. The flow will increase uphill and downhill.

D. This flow can be characterized by a ratio called the Froude number. The numerator here is the flow speed, U, and the denominator is $\sqrt{gD}$, where g is 10 m/s/s and D is fluid depth. When the Froude number is greater than 1, we are in a supercritical state.

VI. We've seen a situation in which downslope windstorms could occur, owing to a trapping mechanism. Another way to trap disturbances is with vertical wind shear.

A. The phenomenon called lee waves is created when mountain waves are trapped by decreasing stability or the presence of vertical wind shear. Instead of being able to propagate above the mountain, the waves extend down the lee of the mountain.

B. If the relative humidity is sufficiently high when the air is rising, the vertical motions can lead to clouds, which then disappear when the air starts sinking again. These are the lenticular clouds we saw earlier.

VII. Mountains make troughs, but they also make extratropical cyclones.

A. Consider westerly flow passing over a formidable topographic barrier. If the process involved is dry adiabatic, the mass between the 2 isentropes is fixed.

B. Picture a cylinder of air between the 2 curves approaching the mountain. The cylinder has spin. Subsidence on the leeside can cause the cylinder to be stretched vertically, increasing its spin and creating low pressure in the lee of the mountain.

C. These effects result in leeside cyclogenesis, the formation of new cyclones.

Suggested Reading:

Durran, "Mountain Waves and Downslope Winds."

Questions to Consider:

1. Consider supercritical flow approaching an obstacle. What happens to its Froude number as the air ascends to the obstacle's crest? Can you provoke a down slope windstorm in this fashion?
2. The forecast calls for mid-level warm advection above a mountain range. What is the consequence of this for the vertical propagation of mountain waves?

Lecture Eighteen

Thunderstorms, Squall Lines, and Radar

Scope: In this lecture, we will examine the squall line thunderstorm, especially common in the warm season. Such storms often appear at or near cold fronts associated with extratropical cyclones. We'll use some of our wind and moisture concepts, including wind shear; spin; positive buoyancy; and LCL, LFC, and CAPE.

Outline

I. Radar uses radiation at the shorter end of the electromagnetic spectrum.

- **A.** NEXRAD (next-generation radar) is an example of a pulse radar. It has 2 alternating phases of operation: the transmission phase (the pulse), followed by listening.
- **B.** Waves scatter off radar targets, and the returned energy is referred to as backscatter. The time it takes for the energy to return tells us how far away the echo is.
- **C.** Typical weather or precipitation radar uses a 10-centimeter wavelength, which requires large dish-shaped antennae.
- **D.** Radar "sees" what's called radar reflectivity. A certain amount of signal—returned energy—could indicate a small number of large particles or a large number of small particles, but radar can't tell the difference. Reflectivity is measured in decibels (dBZ).
- **E.** In precipitation mode, radars execute a series of circular scans at 9 different elevation angles.

II. A squall line is a continuous or broken line of thunderstorms with adjacent areas of precipitation.

- **A.** Squall lines are long-lived, unsteady, and multicellular, and they have evaporationally produced subcloud cold pools as their principal propagation mechanism.
- **B.** We see a schematic depicting a squall line in maturity. The leading part is the convective region, with the most intense rain and strongest winds.
- **C.** Behind the convective region is the trailing stratiform region, an extended zone of lighter rain.

III. Before we look at the vertical structure and air flow through a squall line storm, let's consider 2 important points.

A. In our depiction, the winds are westerly and increase in magnitude with height. Westerly vertical wind shear exists because it's colder to the north, and this westerly shear tries to make the air spin in a clockwise fashion. This spin represents horizontal vorticity.

B. If we change the frame of reference, the squall line is moving east faster than the lower tropospheric winds can blow in that direction, but we still have westerly vertical wind shear.

IV. Let's look at a vertical cross-section across a squall line thunderstorm.

A. A mature squall line cloud is usually over 100 kilometers across and the depth of the entire troposphere. Below the leading edge is the subcloud cold pool. The leading edge of the cold pool is called the gust front because the winds gust and pick up as it passes by.

B. Often, these storms are oriented north/south, and they propagate eastward in the mid-latitude westerly winds. However, the storms also tend to move faster than the westerlies, so that the storm relative flow is largest at low levels, where all the moisture is.

C. We have a low-level inflow that is colliding with the cold pool's gust front and being lifted to saturation and positive buoyancy, thereby creating the storm's front-to-rear flow.

D. Beneath the front-to-rear flow is the rear inflow current. The rear inflow descends toward the surface as it moves forward because of precipitation that evaporates before it hits the ground.

E. The evaporation of precipitation in this air makes the rear inflow air cold and negatively buoyant. Sometimes this descending rear inflow can bring extremely strong winds to the surface.

F. The freezing level is just about the narrow bright band in the stratiform region.

V. The thunderstorm life cycle consists of 3 stages: the cumulus stage, the mature stage, and the dissipating stage.

A. In the cumulus stage, air has been lifted to its LCL, then to its LFC, and CAPE is being converted into kinetic energy, driving the air upward ever more strongly. Condensation at this time is mainly in the small cloud droplets, which are being lofted by the winds.

B. The rising air creates divergence above the rapidly growing cloud, pushing mass out of the column and causing the surface pressure to drop. That induces flow into the cloud from below, feeding more moisture into the cloud, but the droplets aren't falling yet.

C. When the drops get large enough to fall, the cloud has reached the mature stage. The mature cell has rising and sinking motions. Some of the downward motion is caused by water loading.

D. In the dissipating stage, the cloud has reached maximum height. Ice has appeared, but there is little upward motion remaining.

E. A squall line represents a collection of such cells, each at different stages of the life cycle.

VI. Let's zoom in on the convective region of our squall line.

A. The depiction we see represents a family of cells, spanning the life stages of a single cell storm from right to left.

B. Focusing on the storm's inflow, we noted that the storm was vertically sheared, resulting in horizontal vorticity. By itself, the shear circulation is trying to make the cloud lean to the right with height in the downshear direction.

C. Why isn't the storm leaning downshear? Notice that the circulation around the cold pool also has spin. This negative buoyancy also produces a circulation, which from our point of view, is opposite to the shear's induced circulation. Here, the cold pool circulation is the stronger of the 2, so the flow tilts upshear.

D. A third circulation causes such storms to be unsteady and multicellular.

VII. Let's look at squall lines in a derecho.

A. Squall lines that have a strongly bowed appearance on radar are called bow echoes. Behind these echoes, the rear inflow current has descended to the ground, pushing the gust front from behind.

B. This bow echo is a visual manifestation of windstorms called derechos, the key to which is straight-line winds.

C. We see a representative sounding from the warm sector of a squall line, taken prior to its passage. A surface parcel has been lifted to its LCL, then to its LFC. Once it reaches that point, CAPE comes into play, resulting in tremendous positive buoyancy.

Suggested Reading:

Browning et al., "Structure of an Evolving Hailstorm."

Byers and Braham Jr., "Thunderstorm Structure and Circulation."

Fovell and Ogura, "Numerical Simulation of a Midlatitude Squall Line in Two Dimensions."

Fovell and Tan, "The Temporal Behavior of Numerically Simulated Multicell-type Storms."

Houze Jr., "Mesoscale Convective Systems."

Rotunno, Klemp, and Weisman, "A Theory for Strong Long-Lived Squall Lines."

Questions to Consider:

1. Radars operate by issuing pulses of microwave radiation, typically at 10 centimeter wavelengths for "precipitation radars" like NEXRAD designed to detect large particles, among other targets. A website claims that if you understand how microwave ovens work, you understand radar. It says that the microwave energy is absorbed and re-emitted by the targets, and the radar then detects the re-emitted microwave energy. Is this true?
2. A strong, negatively buoyant and moist downdraft emerges from beneath the base of a severe thunderstorm. What kind of environmental temperature lapse rate beneath the cloud is most conducive to preserving the strength of this downdraft as it approaches the ground?

Lecture Nineteen
Supercells, Tornadoes, and Dry Lines

Scope: In the last lecture, we learned about weather radar and examined squall lines, a form of organized precipitating system. Squall lines are a type of mesoscale convective system (MCS). These storms are responsible for a large fraction of warm season precipitation in the American Midwest. In this lecture, we will see new uses for radar and another type of MCS, the supercell thunderstorm.

Outline

I. Squall lines and other kinds of storms, such as supercells, can form on or near cold fronts and along other barriers, such as the front range of the Rocky Mountains or a pseudo–cold front called the dryline.

A. The dryline is a boundary characterized by a substantial difference in moisture content. Generally, the dryline is the meeting place between hot, moist mT air and hot, dry cT air.

B. A map of a dryline shows a dew point drop from 68°F on 1 side to 29°F on the other. Typically, there's a larger temperature contrast across drylines at night.

C. Earlier, this dryline was farther to the west and caused a line of storms to be initiated, some of which were supercell storms.

D. Supercells are a form of organized convection. They're rotating storms and form in environments with substantial vertical shear.

II. The key ingredient for supercells is large amounts of vertical wind shear, along with CAPE. Shear makes the difference between the ordinary multicellular thunderstorm and the rotating supercell, because spin creates low pressure.

A. In this case, the spin is in a vertical plane, which is useless to the supercell unless it's tilted.

B. Consider a vortex tube inserted in a flow of westerly wind shear. Part of the tube might be pushed up by a thunderstorm, tilting its rotation to a horizontal plane. This creates 2 counter-rotating vortices.

C. The vortices that are lifted create low pressure on the north and south flanks of the original updraft, but this is not yet a supercell.

D. New storms seem to split off from the flanks of the original updraft; these are the rotating supercell storms.

E. A sounding taken to the east of a group of supercells reveals CAPE at 6200 joules and almost no convective inhibition.

III. Once the cells split, they tend to move away from each other.

A. Ordinary convective cells tend to move with the mean wind, but split supercells tend to move either to the left (left movers) or to the right (right movers) of the mean winds.

B. The right mover has counterclockwise rotation. In the center, the spin creates low pressure, which keeps the air rising.

C. The updraft is still lifting vortex tubes, so counter-rotations are still being induced on its flanks, just as in the ordinary cell. But now, the updraft is part of a rotating supercell, and the storm tends to move toward the flank that is producing the same sense of rotation.

D. Shear also creates pressure perturbations: low pressure on the downshear side, which is to the right in this case, and high pressure on the upshear side. This also makes the storm tend to move to the east because the pressure is dropping in that direction.

IV. Many times, the left mover fails to form or dies quickly.

A. A hodograph is a plot showing how winds change as a function of height.

B. Clockwise directional shear enhances the right mover and suppresses the left mover.

C. The shear vector was originally westerly and didn't favor either of the split storms. But with the addition of directional shear, low pressure was created on the downshear side in a position to help the updraft of the right mover.

V. Sometimes, the right mover radar echo takes on a distinctive hook shape. This is evidence of strong horizontal rotation, such as might be concentrated into a tornado.

A. Frontal boundaries surrounding a basic hook echo shape represent places where evaporatively cool air is colliding with the warm, moist environmental air that's feeding the supercell.

B. Nearby is the main storm updraft, which is being fed by unstable air from the mesocyclone's warm sector. The downdraft air is spreading and pushing the cold and warm fronts around.

VI. NEXRAD can also see winds, in addition to radar echoes, as long as they're directed at or away from the radar's line of sight.

A. This ability uses the Doppler effect, which we know from the changing pitch of a car horn as it approaches or recedes from us.

B. A radar image of a tornado shows strong winds directed both away from and toward the radar. Filling in the gap that the radar doesn't see, we deduce strong counterclockwise rotation.

VII. A map of tornado reports over a 7-year period shows a southwest-to-northeast motion for many of the tracks.

A. The parent storms of the tornadoes are commonly right-moving supercells, moving to the right of north or northeast-bound mT flow coming up from the Gulf.

B. Tornadoes are classified using the Fujita scale, which consists of 6 categories based on wind speeds: F0 through F5.

VIII. We'll close with a few tornado facts.

A. Tornadoes can last from seconds to roughly an hour. Their color comes from condensation and the debris picked up by the vortex.

B. The fastest winds ever recorded were over 300 miles per hour. That vortex probably had a pressure drop of 100 millibars.

C. The wall cloud is a distinctive feature of the supercell and a possible precursor of a tornado.

Suggested Reading:

Lemon and Doswell III, "Severe Thunderstorm Evolution and Mesocyclone Structure as Related to Tornadogenesis."

Rotunno and Klemp, "The Influence of the Shear-Induced Pressure Gradient on Thunderstorm Motion."

Weisman and Klemp, "The Dependence of Numerically Simulated Convective Storms on Vertical Wind Shear and Buoyancy."

Questions to Consider:

1. Consider a dry line, in which the air on the drier side is slightly hotter. Does the moisture difference across the line serve to increase or decrease the density difference? Hint: Adding moisture to air increases the gas constant.

2. The vast majority of tornadoes—sometimes also called cyclones—in the American Midwest are observed to rotate counterclockwise. This is for the same reason that large-scale cyclones do. True or false?