

Stability and Cloud Development

This lesson deals with the mechanisms of cloud development. Cloud development is linked closely with the concept of *stability*, i.e., the propensity for a parcel of air to rise or sink. Although several factors determine whether or not clouds will form the stability of the atmosphere is far and away the single greatest indicator of cloud formation.

Air tends to cool and condense as it rises and to become warm and dry as it sinks. A parcel of air is an imaginary mass of air that doesn't exchange properties with surrounding air masses. In reality air masses do exchange properties but this often occurs very slowly, especially if the air masses are large. An *adiabatic process* is one where no heat is exchanged between an air parcel and the surrounding air. When we talk about an adiabatic process in the current context we are talking about a rising (or sinking) parcel of air that is not exchanging any heat with its surroundings. When air rises it cools at a relatively constant rate. If the air is unsaturated, this rate, called the *dry adiabatic rate*, is 10°C per 1000m (5.5 $^{\circ}\text{F}$ per 1000ft), i.e., left to its own devices a parcel of unsaturated air cools by 10°C every 1000 meters.

As air rises and cools its relative humidity increases. At some point the dew point equals the air temperature and the air becomes saturated. Further lifting results in condensation and cloud formation with an accompanying release of latent heat into the rising parcel of air (remember that condensation is a warming process). Because the heat liberated by condensation partially offsets the cooling due to expansion, the parcel now cools at a lesser rate as it rises. This rate is known as the *moist adiabatic rate*. The moist adiabatic rate applies to saturated air.

On average, the moist adiabatic rate is less than the dry adiabatic rate. The moist adiabatic rate is not constant but varies with temperature and moisture content. For cool air the moist adiabatic rate \approx dry adiabatic rate. For warmer air the moist adiabatic rate is less than the dry adiabatic rate. An average value of 6°C per 1000m (3.3°F per 1000ft) is commonly used.

Determining Stability

To determine the stability of an air parcel, one compares its temperature to the temperature of the surrounding air mass. If the air parcel's temperature is less than the temperature of the surrounding air mass, it is denser than the surrounding air and therefore has a tendency to sink. Air that has a tendency to sink is known as a *stable* air. If the air parcel's temperature is greater than the temperature of the surrounding air mass, the air parcel is less dense and tends to rise. Rising air, as we have already learned, is known as unstable.

For stable air, the *environmental lapse rate* is 4°C per 1000m (2°F per 1000ft). When the environmental lapse rate is less than the moist adiabatic rate an air parcel cools more quickly than the surrounding air mass. This is known as *absolute stability*. In this case the air parcel strongly resists lifting. If the parcel is forced to lift by mechanical means (such as orographic uplift over a mountain or uplift along a frontal boundary) it will spread out horizontally. Any clouds that form as a result will be thin and horizontal such as cirrostratus, altostratus, nimbostratus, and stratus clouds. All of these cloud types are associated with stable air.

Since the moist adiabatic rate must be less than the environmental lapse rate for stable conditions to exist, a moderate to small environmental lapse rate enhances stability in the atmosphere. Warm air aloft (caused by warm advection)

and cool air at the surface (caused by nighttime radiational cooling, cold advection, or a cold surface) result in a moderate to small environmental lapse rate.

Fog and haze form in stable atmospheric conditions because of the large scale sinking of air. This can form an inversion condition, known as a *subsidence inversion*. Subsidence inversions are often associated with large high- pressure systems. Inversions are *absolutely stable* because the air beneath the inversion is physically impeded from moving upward. This traps large numbers of particulates close to the ground that serve as fog-forming condensation nuclei.

Neutral Stability is an atmospheric condition that occurs when the environmental lapse rate is equal to the dry adiabatic rate.

Absolute instability occurs when dry adiabatic rate is less than the environmental lapse rate. In this situation, an air parcel will be warmer and less dense than the surrounding air and will rise due to buoyant forces. Clouds with extensive vertical development are indicative of absolute instability.

Conditional instability is a state of instability that depends upon whether or not the rising air is saturated. *Conditional stability* occurs when the environmental lapse rate is between the moist and dry adiabatic rates. The atmosphere is normally in a conditionally unstable state.

Many factors lead to instability. One is a steep environmental lapse rate resulting from cool air aloft (brought on by cold advection, the environmental lapse rate or both) coupled with warm air at the surface (caused by daytime solar heating, warm advection, or a warm surface). Mixing is another factor that affects instability. Mixing increases warming below and cooling higher up in the atmosphere. Another factor that enhances instability is lifting. When a layer of air is forced to rise it tends to become more unstable because the top layer cools more rapidly than

the bottom. This steepens the environmental lapse rate. This effect is enhanced even more when the lower layer of the lifted parcel is moist and the upper layer is dry. In this case, less lifting is required to steepen the environmental lapse rate. This is referred to as *convective instability* and is associated with severe storms.

Cloud Development

The lifting mechanisms associated with cloud development are:

- Surface heating and free convection
- Topography
- Convergence of surface air
- Uplift along fronts

Convection - Thermal development

As the surface of the earth heats up due to incoming solar radiation, warm bubbles of air (thermals) develop and begin to rise. When these thermals reach a height known as the *condensation level*, cumulus clouds begin to form. Cooler air surrounding the clouds sinks to replace the warm air rising from the surface. The subsidence outside of the cumulus clouds suppresses cloud formation in the area surrounding the clouds. This is why one normally sees lots of blue sky surrounding fair-weather cumulus clouds. Eventually, a growing cumulus cloud cuts off the ground from the sun's rays, reducing surface heating and convection. The cloud begins to dissipate and the process may start again. Fair weather cumulus clouds are often characterized by level bases (at the condensation level), moderate vertical development, and lots of blue sky in between.

Convective cloud formation is an adiabatic process, i.e., there is little mixing between the air parcel and the surrounding air mass. A single thermal is all that is necessary to produce a cumulus cloud. Cloud formation occurs when the relative humidity within the parcel of rising air reaches 100%. After this point, the parcel remains saturated as it rises.

Suppose that the temperature of a rising air parcel is 35°C and the dew point 27°C . At first the parcel is buoyant and rises freely. The rising air in the parcel expands and cools at the dry adiabatic rate. The dew point also drops but not as rapidly as the air temperature due to the decrease in air pressure. As the unsaturated rising air cools, the air temperature and dew point approach each other increasing the relative humidity. At some height saturation occurs followed by condensation and the formation of clouds. Above this level the air cools at the moist adiabatic rate, condensation continues, and the dew point drops with height even more rapidly than before. The temperature and dew point decrease at the moist adiabatic rate.

The rising air parcel remains warmer than the surrounding air mass and continues to rise. Eventually the air parcel has a temperature equal to the air mass temperature and spontaneous lifting ceases

Stability above the condensation level plays a major role in determining the height of cumulus clouds. The *stratosphere* is quite stable. Seldom do clouds penetrate the tropopause into the stratosphere. Vertical development of a cumulus cloud also depends upon *entrainment*. If the environment around the cloud is dry (the usual case) cloud droplets will evaporate when exposed to the drier air. Entrainment occurs when this resulting cool air mixes with the convective cloud, increasing the rate at which the rising air cools. In this case the cloud may cease

vertical development even though the lapse rate indicates conditional instability.

Topography

Orographic uplift occurs when air is forced upward over a topographic barrier. If the barrier is tall enough, the air parcel is forced upward to the *lifting condensation level* where clouds are formed and precipitation may occur. Depending on conditions, air parcels can be forced back down on the lee side of mountains (warming and drying as they sink and compress) or can continue to rise, forming cumulus clouds. In mountainous regions this often results in a *rain shadow*. When clouds form over western Oregon and Washington, for instance, they produce copious amounts of precipitation as the prevailing winds forced them up and over the western side of the Cascade Range, leaving them dry on the eastern side of the mountains. The dry areas of central Oregon and Washington are in the rain shadow of the Cascade Range.

Lenticular clouds and *standing wave clouds* are formed by topography. These clouds are associated with mountain ranges. *Rotor clouds* can form in standing wave clouds. These are very dangerous in the world of aviation due to the presence of *wind shear*.

Widespread Ascent and Clouds

Just as mountain ranges influence cloud formation by mechanical lifting, widespread convergence of air masses also forces air upward causing cloud formation. Low-pressure systems are associated with converging air. The presence of a low-pressure system is normally associated with extensive clouds and precipitation.

Frontal Lifting

The gradual lifting of stable air as a warm front passes can cause formation of stratus clouds over hundreds, even thousands of square miles. Cold fronts are much steeper and as a result, air is forced to rise more abruptly. Cold fronts are associated with instability and cumuliform clouds.

Changing Cloud Forms

Clouds often change form. A temperature change within a cloud may cause this. Clouds are good absorbers of infrared radiation. Usually the tops cool rapidly due to increased radiation and bottoms warm due to increased absorption. This leads to instability, convection, and in turn, to a change in cloud form.