Understanding Cloud Formation

1. LAPSE RATE

The Earth's atmosphere is composed of several distinct layers; each layer is defined by a change of sign in the "lapse rate". The lapse rate is the change of temperature with height (Γ*). There are many ways to express "height", but the two most basic ones are geometric and pressure. Geometric coordinates use physical distance, measured in kilometers (thousands of meters) or miles, and denoted as "z". Pressure coordinates use atmospheric pressure to characterize altitude, measured in millibars**, and denoted as "p".

* The Greek letter gamma (Γ) symbolizes the change of temperature corresponding to a change in altitude. For example, if the temperature *drops* 14° Celcius over a vertical distance of 2 kilometers, Γ = -7°C/km. This is called the lapse rate.

** A millibar is a unit of pressure and is equivalent to 100 Pascals or 100 Newtons per square meter or 2.1 pounds per square foot. Standard atmospheric pressure at sea level is 1013 mb, 101300 Pa, 101300 N/m^2, or 2116 lb/ft^2.

A positive lapse rate ($\Gamma > 0$) means that temperature increases with altitude. This results in warmer air (less dense) above colder air (more dense); a stable situation.

A negative lapse rate ($\Gamma < 0$) means that temperature decreases with altitude. This results in colder air (more dense) above warmer air (less dense); an unstable situation. The more negative the lapse rate is (-9°C/km is steeper than –7°C/km), the more unstable that layer is.

The lapse rate can change locally in a short time. To change the lapse rate, alter the temperature at either the top or the bottom of the layer, or both. For example, to make the tropospheric lapse rate more negative (steeper and more unstable), increase the surface temperature and/or decrease the temperature of the air aloft.

2. THE LAYERED ATMOSPHERE

There are 5 primary and distinct atmospheric layers discussed here: the *troposphere*, *stratosphere*, *mesosphere*, *thermosphere*, and *magnetosphere*. The boundaries between each of these layers are called the *tropopause*, *stratopause*, *mesopause*, and *thermopause*, respectively. Characteristics of each layer will now be briefly outlined…

1. Troposphere
    a. Extends from 0 km to 11 km (0-7 mi) (1000-200 mb)
    b. Temperatures fall from 17°C (63°F) at the surface to –50°C (-60°F) at the tropopause
    c. the average tropopause height actually varies from 16 km (100mb) at the equator to 8 km (300mb) at the poles
    d. The average lapse rate is –6.5 °C/km (-19 °F/mi)
    e. 80% of the atmosphere's mass is in the troposphere
    f. all weather occurs in the troposphere (it has a negative lapse rate AND has moisture)
2. Stratosphere
    a. Extends from 11 km to 50 km (7-31 mi) (200-1 mb)
    b. Temperatures increase from –50°C (-60°F) at the tropopause to about 0°C (32°F) at the stratopause
3. Mesosphere
    a. Extends from 50 km to 85 km (31-53 mi) (1-0.01 mb)
    b. Temperatures decrease from 0°C (32°F) at the stratopause to about –90°C (-135°F) at the mesopause
    c. Has a negative lapse rate, but no weather occurs there because there is no moisture
4. Thermosphere
    a. Extends from 85 km to 500 km (53-310 mi)
    b. Temperature and pressure loose meaning here, there is very little atmosphere at this altitude, so very few air molecules. However, the molecules that are present are highly energetic, so in a sense, the temperature is very high (perhaps 2000°C), but the pressure is very low (less than 0.01 mb)
5. Magnetosphere
    a. Extends from 500 km (310 mi) to space
    b. Again, temperature and pressure have little meaning here
    c. Not a spherical shell, but more teardrop-shaped due to the solar wind pushing against it. This is the layer that protects the surface from the sun's highly-energetic rays and particles.

3. CONVECTION

Instability (a steep lapse rate) is naturally resolved by convection, or turbulent overturning. Convection occurs in all fluids that are heated differentially. In the case of the troposphere, the surface is heated by the sun, and the air aloft is left to cool radiatively to the overlying layers, so convection attempts to balance the temperature difference (or equivalently, the vertical density gradient; because cold air is more dense than warm air).

A "cell" of convection is characterized by a parcel of fluid that is positively buoyant (less dense than its surroundings), causing it to rise to some altitude where it is no longer positively buoyant (the parcel that was once rising cools off enough to be neutral or even temporarily negatively buoyant). In the atmosphere, this level is where the top of the cloud would be found and is called the Equilibrium Level (EL).

In the case of the atmosphere, the surface air may not be positively buoyant at first, but needs some forcing to get it there. If the parcel of air reaches the height where it can rise without external forcing, it rises freely up to the EL; the altitude at which this transition from forced convection to free convection takes place is called the Level of Free Convection (LFC).

Convection can be dynamically or thermodynamically forced. If forced *dynamically*, some external "push" is applied to the atmosphere, such as a cold front, warm front, dryline, thunderstorm outflow boundary, or any other miscellaneous surface convergence line. If forced *thermodynamically*, surface heating alone will initiate convection. If the surface air reaches its "convective temperature" (T_C), it becomes positively buoyant and will rise freely.

4. CLOUD FORMATION

The discussions of lapse rates and convection prepared the way to introduce clouds. Clouds are merely visible tracers of atmospheric convection, formed by the condensation of water vapor. Water vapor (the invisible gaseous form of H_2O) is found throughout the troposphere, but is concentrated near the surface and is very sparse at high altitudes.

A useful quantity related to water vapor concentration is the relative humidity (RH). It is related to the temperature (T) and the dewpoint (T_d). Dewpoint is a measure of the moisture content of the air… comparable to temperature, which measures the heat content of the air. Higher dewpoints indicate higher water vapor amounts. Relative humidity becomes higher as the dewpoint approaches the temperature. In a simplified sense, relative humidity increases to 100% when the dewpoint reaches the temperature.

An example of identical RH at very different temperatures is the following: if T=31°C (88°F) and T_d=22°C (72°F), then RH=60% (T, T_d, or RH can be calculated using equations not relevant to this discussion; see *http://www.mcwar.org/humid.html* for an online calculator written by the author). The same RH can be achieved for colder temperatures; consider T=7°C (45°F) and T_d=0°C (32°F), making RH=60% again. So, relative humidity is exactly that… *relative*. Dewpoint is used to express the *absolute* humidity. A dewpoint of 21°C (70°F) feels "sticky" anytime, anywhere; while a relative humidity of 60% may or may not feel "sticky".

Water vapor condenses into water droplets when the air is near or at 100% RH. Since the troposphere has a negative lapse rate, air that travels upward from the surface encounters colder air. The base of a cloud forms when the ascending air's temperature equals the dewpoint at that level. Lower cloud bases indicate that either the lower troposphere is particularly moist, or the lapse rate is particularly steep (or a combination thereof). The term for the altitude of the cloud base is the Cloud Condensation Level (CCL).

In summary, a cloud is formed by the condensation of water vapor and is merely a visible tracer of convection. It is bounded at the bottom by the Cloud Condensation Level and at the top by the Equilibrium Level. Clouds of many types (deep/shallow, narrow/broad, precipitating/non-precipitating, low-level/high-level, etc) exist because of the numerous atmospheric conditions that can exist.

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