

## The Generation of Shallow Cumulus by Solar Heating

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Clouds form when air parcels are cooled to saturation. It is, therefore, ironic that many low-level cumulus clouds are produced by solar heating. Most clouds are produced as rising air cools; a rising unsaturated parcel of air cools at the dry adiabatic lapse rate of  $10^{\circ}\text{C}$  per kilometer. The sun facilitates the lifting of air parcels to saturation by changing the environmental lapse rate<sup>1</sup> near the ground.

The temperature in an air mass ordinarily decreases with height by less than the adiabatic lapse rate, so an air parcel shoved upward becomes heavier than its environment as it cools during its ascent, and the parcel falls back to its initial level. In other words, the atmosphere is normally *stable*. As the sun heats the ground and that heat is transferred to the lowest layers of the air by conduction, the environmental lapse rate increases in a thin layer near the ground, i.e., the temperature drops more rapidly with height because the bottom of the air column is warmed. Once the decrease in temperature with height exceeds  $10^{\circ}\text{C}$  per kilometer, the shallow layer becomes unstable and air parcels are free to rise upward and mix up the air within the unstable layer.

As the sun continues to shine, more and more heat is absorbed at the surface and distributed aloft by the convective motion of the warm air parcels. The mixing produced by these buoyant air parcels modifies the environmental lapse rate throughout the convectively overturning layer, making the environmental lapse rate very close to dry adiabatic. The situation a few hours after sunrise on a clear summer day is illustrated in Figure 1, which shows a plot of temperature versus height. The temperature profile at sunrise is shown by the heavy solid line; the modification to the initial profile is shown by the heavy dashed line. Solar heating has been distributed through a layer 450 m deep and the lapse rate in this layer is  $10^{\circ}\text{C}$  per km.

Suppose the air at the surface has a dew point temperature of  $10^{\circ}\text{C}$  and neglect the dependence of dew point temperature on pressure. Then in order to form a cloud, a parcel of air from the surface must be lifted until its temperature drops to  $10^{\circ}\text{C}$ . Consider two parcels at the surface, each of which is heated  $0.5^{\circ}\text{C}$  warmer than their environment through contact with the ground. At sunrise, the  $0.5^{\circ}\text{C}$  temperature surplus will be enough to power parcel A to an elevation of about 100 m, at which point it has cooled sufficiently that it is the same temperature as its environment. The

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<sup>1</sup>The *lapse rate* is the rate at which the temperature decreases with height.

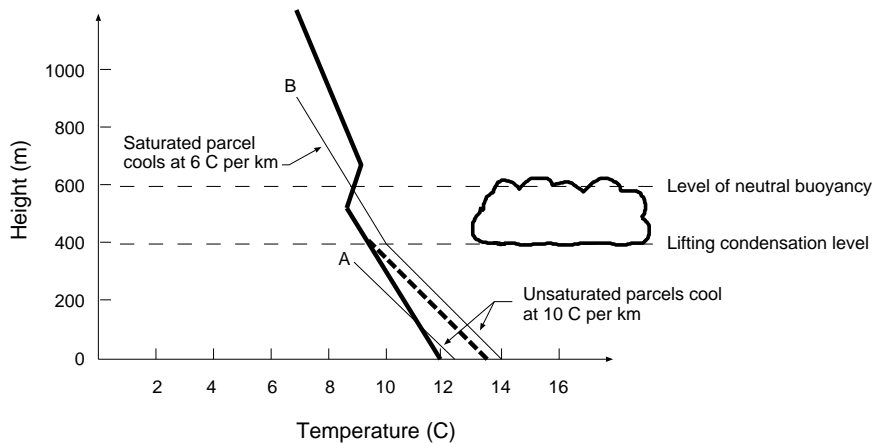


Figure 1: Change in temperature with height at sunrise (heavy line), and the modification of this temperature profile by solar heating a few hours after sunrise (heavy dashed line). The slope of the dashed line matches the dry adiabatic lapse rate. The change in temperature with height of parcels A and B are indicated by thin solid lines. Elevation of the cloud base and the average cloud top coincide with the “lifting condensation level” and the “level of neutral buoyancy.”

temperature at which parcel A ceases to be buoyant,  $11^{\circ}\text{C}$ , is not cold enough to saturate parcel A and form a cloud. (The change in temperature with height of parcel A is indicated by the thin solid line labeled “A” in Figure 1.) After a few hours of solar heating, the same  $0.5^{\circ}\text{C}$  temperature surplus is enough to keep parcel B buoyant relative to its environment up to a height of 600 m. (The change in temperature with height of this parcel is indicated by the thin solid line labeled “B”.) Parcel B cools to  $10^{\circ}\text{C}$  at a height of 400 m at which point it saturates and a cloud begins to form. The level at which saturation occurs is called the *lifting condensation level* and it coincides with the base of the clouds. After it saturates, the rising parcel cools more slowly at a moist adiabatic lapse rate of  $6^{\circ}\text{C}$  per km.

Parcel B stops rising when it is no longer warmer than its environment, which occurs when it rises to a height of 600 m. This *level of neutral buoyancy* is located in an *inversion layer*, in which the environmental temperature increases with height. Inversion layers act as lids that resist upward convective motions. The cloud tops are around the level of neutral buoyancy, but they aren’t as uniformly flat as the cloud bases because the warm parcels slightly overshoot their level of neutral buoyancy in a chaotic manner.