Sounding example: parcel ascent, clouds, metastability

ATM 210 – Fall, 2023 – Fovell

The first two columns in Table 1 below list height and environmental temperatures for the troposphere and lower stratosphere for relatively realistic situation. This is called an atmospheric "sounding". In the troposphere, the ELR employed was 7°C/km. (Acronyms are defined below.) Note that temperature stops decreasing after the 12 km level; that's the tropopause.

Suppose we take a parcel of surface air, having the same temperature as the environment and a VS of 8 g/kg. The parcel is obviously subsaturated, since the VC of that air is 28 g/kg; see Table 2. Lift the parcel, one kilometer at a time, cooling at the DALR as long as the parcel remains subsaturated. Note the RH is rising during the ascent. At some point (here, when the parcel reaches 2 km above the ground), the RH reaches 100%. This is called the **lifting condensation level (LCL)**, the level at which condensation can be achieved by lifting, also known as *cloud base*. This air has been saturated by the adiabatic expansion approach.

Now that the parcel is saturated, further lifting proceeds at the smaller MALR rate. As the saturated parcel continues to cool, its VC drops. Excess VS is removed as condensation, and accumulated as liquid (LIQ) water. It is the presence of condensation warming that makes the MALR less than the dry adiabatic rate. Does this liquid remain in the rising parcel or does some or all of it fall out as rain? Either can happen, depending on our assumptions. Here, we're carrying the liquid along with the parcel.

Note that when the parcel first starts rising, it quickly becomes **colder** than its surrounding environment. This is because the DALR > ELR. The difference between parcel and environmental temperatures is quantified in the column labeled TDIF. Recalling that we presume the parcel has the same pressure as its surroundings, it follows from the IGL that the colder parcel is denser than its environment. So why was the parcel rising, even though it was more dense? We were *pushing* it – over a mountain, over a front, by forcing air to converge, etc.. However, if we stop pushing the parcel upwards at any time at which the parcel is colder, it will try to sink back down to its original height level.

Note further, however, that the MALR < ELR. Once the parcel is saturated, it starts cooling at a slower rate than its surroundings. Thus, TDIF is most negative at the LCL, the point at which the cooling rate switches over to the moist adiabatic rate. *If you can lift the parcel high enough, it might actually become warmer than the environment*. The point at which parcel and environmental temperatures become equal is called the **level of free convection (LFC)**. In this case, the LFC is at 5 km. Not all soundings have an LFC. Springtime Oklahoma soundings usually have LFCs, Los Angeles soundings rarely do.

Above the LFC, the parcel is warmer than its surroundings, and is able to rise on its own. That is to say, it *convects freely*, without having to be forced. The parcel will continue rising as long as it is warmer. *The parcel will not rise forever*, for two reasons. First, the parcel will eventually exhaust its VS; in the example, this happens as the parcel reaches the 10 km level. After this point, the cooling rate reverts to the DALR since there is no more vapor to condense. Second, even if vapor remains, the parcel will eventually reach the stratosphere. In that layer, environmental temperature increases with height. It is inevitable that the parcel will again become cooler than its surroundings. That point is called **TOC, or top of cloud**, which in the present example resides between 12 and 13 km. This is one's first guess at cloud top.

Table 1: A sounding and lifting of a surface parcel

LOC	ENV	PRCL	TDIF	VC	VS	RH	LIQ	NOTE
sfc	30	30	0	28	8	29	0	Parcel cools at DALR
1	23	20	-3	15	8	53	0	
2	16	10	-6	8	8	100	0	LCL - now use MALR
3	9	5	-4	6	6	100	2	
4	2	0	-2	4	4	100	4	
5	-5	-5	0	3	3	100	5	LFC
6	-12	-10	+2	2	2	100	6	
7	-19	-15	+4	1.5	1.5	100	6.5	
8	-26	-20	+6	1	1	100	7	
9	-33	-25	+8	0.5	0.5	100	7.5	
10	-40	-30	+10	0	0	–	8	VS = 0, back to DALR
11	-47	-40	+7	0	0	–	8	
12	-54	-50	+4	0	0	–	8	Tropopause
13	-50	-60	-10	0	0	–	8	TOC between 12-13 km

Table 2: Temperature/moisture table used for this example

Temp (°C)	-30	-25	-20	-15	-10	-5	0	5	10	15	20	25	30	35	40
VC (g/kg)	0	0.5	1	1.5	2	3	4	6	8	12	15	22	28	40	50

Definitions

- LOC = height location of parcel (km).
- DALR = dry adiabatic lapse rate (10°C/km), lapse rate for subsaturated parcels.
- MALR = moist adiabatic lapse rate (5°C/km), lapse rate for saturated parcels.
- ENV = environmental temperature profile (°C); environmental lapse rate (ELR) taken as 7°C/km in troposphere.
- PRCL = parcel temperature (°C), using DALR if subsaturated and MALR if saturated.
- TDIF = temperature difference in °C between PRCL and ENV; TDIF > 0, parcel is warmer.
- VC = vapor capacity (g/kg).
- VS = vapor supply (g/kg).
- RH = relative humidity (%).
- LIQ = liquid water content (g/kg).
- LCL = lifting condensation level (cloud base).
- LFC = level of free convection (PRCL and ENV T same; parcel starts rising on its own).
- TOC = top of cloud (where PRCL again becomes same T or colder than ENV)
- IGL = ideal gas law

Now, we recapitulate and extend with the help of Fig. 1. The thick black lines depict environmental temperature variation in the troposphere (ELR $\approx 7^{\circ}$C/km) and lower stratosphere. The path taken by a subsaturated surface air parcel (grey dot) is shown in grey. At first, the parcel cools rapidly with height, at the DALR. Note the parcel is becoming progressively colder with respect to its surroundings. Therefore, ascent must be forced, and this is called *forced convection*.

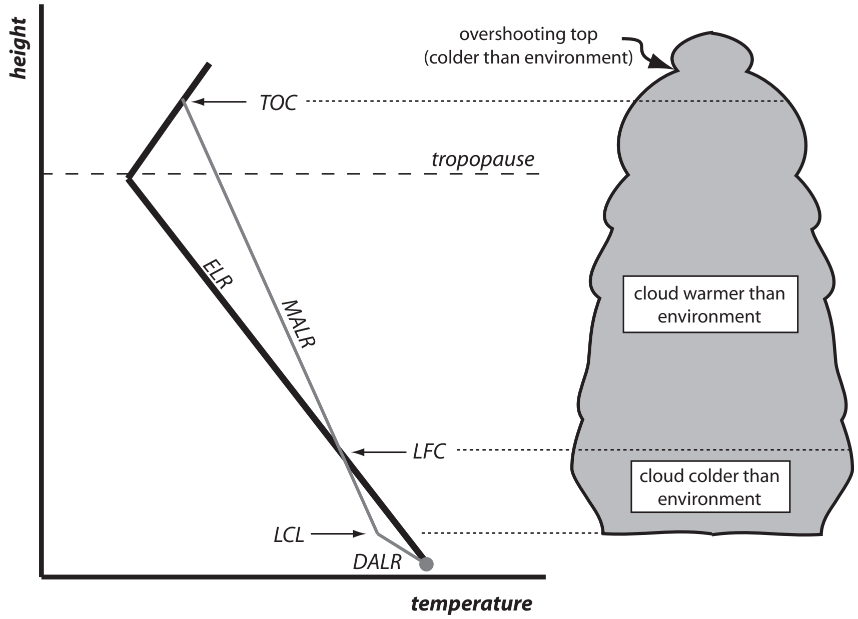

Figure 1: Temperature profile in the troposphere and lower stratosphere of a realistic environment (black lines), along with the path a surface parcel would take (grey lines).

However, saturation is achieved at the LCL (cloud base), above which further ascent is moist adiabatic. Note the parcel is still colder than its environment, but the difference between their temperatures is decreasing. Ascent still requires a push, but the push needed is becoming more gentle. At the LFC, parcel and environmental temperatures are again equal. Above the LFC, the parcel will rise on its own, and convection has become free.

The parcel will continue to rise until its temperature again becomes equal to its surrounding environment. This is the TOC, our first guess at cloud top. Many parcels never reach cloud top, and some will actually *overshoot*. The latter occurs because those parcels reach the TOC level with some considerable velocity and cannot “stop on a dime”. Thus, in very strong thunderstorms, the most quickly rising air will push the cloud top above the nominal TOC. See here, however, why the parcel will not rise far into the stratosphere. The environment is warming with height while the parcel always cools, saturated or not.

Have you ever looked at a cloud and wondered whether its colder or warmer inside than out? In the case of a deep cumulus cloud, as depicted on the right hand side of Fig. 1, the answer depends on location within the cloud. Between the LCL and the LFC, the rising parcels are colder than their surroundings, despite the release of latent heat of condensation within. Therefore, the cloud (which is made up of a set of parcels) is colder as well. Between the LFC and TOC, the cloud and its parcels are warmer. The overshooting top is colder.

When the ELR resides between the dry and moist adiabatic rates (as it often does in the troposphere), the environment is said to be **conditionally unstable**… conditioned on the presence of water vapor. A rising subsaturated parcel would become colder than its surroundings, and want to sink back from whence it came (i.e., a stable situation). A rising saturated parcel, however, would become warmer and continue rising (i.e., an unstable situation). The situation depicted in Fig. 1 is more common: air starts out subsaturated (and thus stable) but becomes unstable given sufficient lifting. This means there is *sensitivity to the degree of lift*, which is often called **metastability**.

In the following three figures, Stickman illustrates this sensitivity to the degree of lift, and the powerful implications this has for the weather. Parcels are provided with varying degrees of "kick" in an environment. In Fig. 2, the kick is small and the parcel is forced to ascend only to height "A", located beneath the LCL. We know from Fig. 1 that the parcel is colder than its surroundings at this location, so once the lift is exhausted, the parcel sinks back down to its original height. The parcel RH never reaches 100%. Weather: clear.

In Fig. 3, Stickman provides a more powerful kick to the parcel. This parcel is pushed as high as height "B", residing between the LCL and LFC. Saturation is achieved and a shallow cloud is formed, but the parcel remains colder than its environment. Therefore, once the lifting force is absent, the parcel starts descending. As it descends, the liquid water evaporates until none remains. Weather: shallow clouds (stratus, stratocumulus), drizzle or no rain.

In Fig. 4, Stickman imparts a mighty kick to the surface parcel, pushing it clear up to the LFC. Past this point, the parcel is now warmer, and thus less dense, than its surroundings, and the parcel can continue rising on its own. The parcel required an external force, provided by a front, a mountain or other form of convergence, to reach the LFC, but once it is passed, the parcel is *positively buoyant*, convecting freely and creating a deep cumulonimbus cloud. Very strong vertical motions can now develop, including strong up- and downdrafts (producing gusty "wind shear" upon striking the ground), heavy rain, hail and lightning. The parcel keeps rising until its temperature matches its surroundings at the TOC, often very near tropopause for severe storms; that's where storm clouds "flatten out" forming an anvil-like shape. Actually, the most rapidly rising parcels arrive at the TOC with an appreciable velocity, and overshoot that level by some distance. This "overshooting top" is located above the portion of the cloud with the strongest updraft, and is commonly seen in cloud photographs of deep cumulonimbi. However, above the TOC, the parcel is colder than its surroundings so it will not travel that much farther (there's no external lift). Storms cannot extend far into the very stable stratosphere.

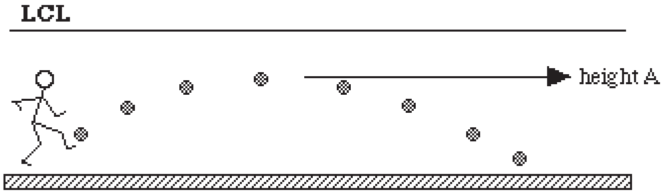

Figure 2: Stickman gives a small kick to a surface parcel.

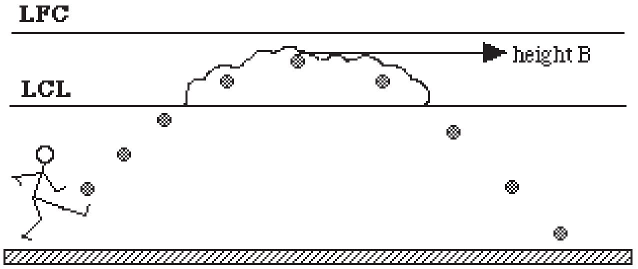

Figure 3: Stickman gives a moderate kick to a surface parcel.

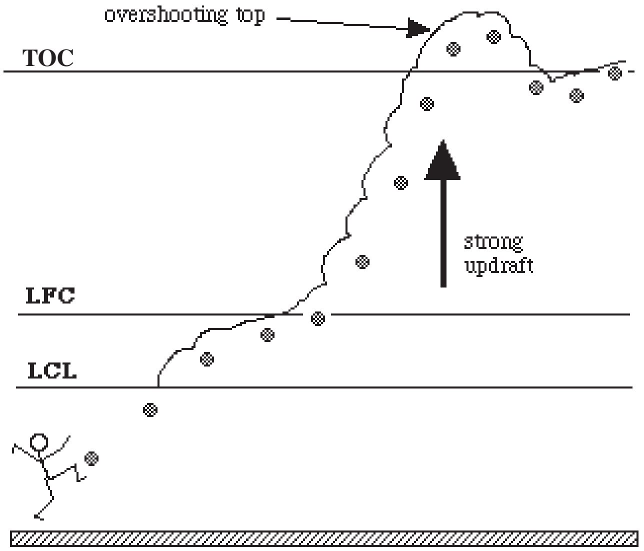

Figure 4: Stickman gives a mighty kick to a surface parcel.