Three important lapse rates

ATM 210 – Fall, 2023 – Fovell

Review: the air parcel concept and the lapse rate

Recall that a **lapse rate**, specified as °C/km or °F/mi, quantifies how temperature (T) decreases with height (z) under specified conditions. The word *lapse* implies our expectation that the temperature change is negative. If the temperature increased with height, the lapse rate would be negative instead.

Recall also that we make an air parcel by gathering together a quantity of air and pretend the air is surrounded by an invisible boundary that insulates the parcel air from its surrounding environment. The parcel boundary, however, is flexible, permitting the outside and inside pressures to be the same. If the outside pressure drops for some reason, such as owing to lifting, so too will the inside pressure, and the parcel will expand. Similarly, a sinking parcel will cause the inside pressure to rise accordingly, making the parcel contract. If the parcel is and remains subsaturated, the parcel temperature will vary according to the **dry adiabatic lapse rate (DALR)**.

The ELR and DALR

We actually have *three* lapse rates with which to contend in atmospheric sciences. The first, the **environmental lapse rate (ELR)**, expresses how T varies with z in the environment. Recall that in the "standard atmosphere" we found a temperature drop of about 140°F over 7-8 miles in the troposphere. This means the tropospheric ELR is roughly 19°F/mi or 6.5°C/km. We will often round these ELRs to 7°C/km and 20°F/mi for convenience.

Why does T drop with height z in the troposphere? For all the reasons already discussed, including the facts that air is a poor absorber of visible light and is also a poor conductor. Yet we must appreciate two important points about this oft-cited ELR of about 7°C/km:

- The ELR is **NOT FIXED** in space and time. It can vary from place to place, from time to time, and can vary with height in the troposphere itself. However, averaged from day to night, winter to summer, land to sea, and equator to pole, the mean tropospheric ELR is about 7°C/km or 20°F/mi.
- The ELR can be negative! At night, very close to the ground, air T often increases with height over a shallow depth. This is called a temperature inversion, and the ELR in this instance would be negative. Is it obvious that the stratospheric ELR is also negative?

Recall that average sea-level pressure is about 1000 mb and pressure decreases with height. A general rule of thumb is that pressure decreases roughly 100 mb per kilometer in the lower troposphere, so the pressure one kilometer above your head is $\approx$ 900 mb. (You can prove this with the hydrostatic or hypsometric equations and some reasonable assumptions.) A tropospheric

ELR of 7°C/km simply means that you expect the temperature to be 7°C cooler there than at the surface.

Now, suppose we make an insulated yet flexible air parcel from that surface air and we make it rise. We are still assuming there is absolutely no moisture in the air. As that parcel rises, the pressure outside of the parcel decreases. Because the parcel boundary is flexible, the inside pressure also goes down. This permits the parcel volume to expand. Expanding air cools, so the T inside the parcel is dropping. The rate of expansion cooling for dry air is very close to 10°C/km or 30°F/mi and we have called this the dry adiabatic lapse rate.

As the parcel rises, the T outside of the parcel is also usually dropping (that's the ELR). The crucial point here, however, is that **outside and inside temperature changes are absolutely INDEPENDENT**. The temperature outside of the parcel is dropping because the parcel is moving away from the surface, the troposphere's primary heat source. The temperature *inside* the parcel is dropping because its volume is expanding in response to the decreasing pressure. It is rare for the environmental and parcel temperatures to change at the same rate. This has very strong implications for the notion of *atmospheric stability*, an important topic we will be exploring soon.

Example. The surface T is 20°C and the ELR is 7°C/km.

1. What is the T of the environment 2 km above the surface?
2. If you make a perfectly dry air parcel composed of surface air, and lift it 2 km, what would be the parcel temperature be?
3. Compare the temperatures outside and inside the parcel.
4. Compare the pressures outside and inside the parcel.
5. Compare the density of the parcel to that of the environment.
6. Will this parcel try to rise or sink?

Example with answers. The surface T is 20°C and the ELR is 7°C/km.

1. What is the T of the environment 2 km above the surface? (Ans.: 6°C.)
2. If you make a perfectly dry air parcel composed of surface air, and lift it 2 km, what would be the parcel temperature be? (Ans.: 0°C, since it will cool at the DALR for 2 km.)
3. Compare the temperatures outside and inside the parcel. (Ans.: The parcel is colder by 6°C.)
4. Compare the pressures outside and inside the parcel. (Ans.: The key point is they are the same. For a surface pressure of 1000 mb, the pressure at that elevation is roughly 800 mb.)
5. Compare the density of the parcel to that of the environment. (Ans.: At the same pressure, colder air is more dense, so the parcel is denser than its surroundings.)

6. Will this parcel try to rise or sink? (Ans.: It will sink, because its density is larger than that in the environment.)

Question for thought. Lift a parcel dry adiabatically to several kilometers above the surface. Compare its new density to its original density. Is it larger, smaller, the same, or are you unable to tell? (I won't give you the answer unless you offer both an answer and a justification for your answer to me first.)

Adding moisture: the MALR

The DALR not only applies to absolutely dry air parcels, but also to parcels containing water vapor, so long as the relative humidity (RH) $<$ 100%. Consider what happens to a moist but initially subsaturated parcel on ascent. **At first, the parcel's vapor supply (VS) is fixed**, the reason being that nothing has yet occurred to change it. However, as the parcel expands, its vapor capacity (VC) decreases along with T, so the parcel's RH rises. Given sufficient lifting, this parcel will become saturated. This is always true: it is possible to saturate any parcel by lifting, so long as it starts with some finite amount of moisture. That doesn't mean a source of sufficient lifting will be available; that's another story.

What happens once a parcel has been lifted to saturation? Additional lifting will cause further expansion and cooling, further reducing the VC. However, now the parcel's VS has to start decreasing, to keep the parcel's RH from exceeding 100%. In other words, condensation has started to occur, and vapor is now being transferred to liquid. Condensation is a warming process, and the *latent heat released goes to warming the air within the parcel.*

As a result, the rising saturated parcel now experiences both expansion cooling AND condensation warming. *The net result is that the parcel still cools on ascent, but at a slower rate.* This new rate is called the **moist adiabatic lapse rate (MALR)**, and we're going to take it to be 5°C/km or 15°F/mi. Don't be confused by the terminology: the "dry" in the dry adiabatic actually means subsaturated, and the "moist" in moist adiabatic really means saturated.

Example. Take a parcel with initial $T = 30°\text{C}$ and VS = 8 g/kg. Use the Temperature/moisture table to help answer these questions:

1. What is the parcel's RH?
2. Lift this parcel 1 km. What is the parcel's new T?
3. What is its new VS? (Remember, VS will not change until saturation is achieved.)
4. What is the parcel's new RH?
5. Lift this parcel another 1 km. What is the parcel's new T?
6. What is its new VS?

7. What is the parcel's new RH?
8. Lift this parcel yet another 1 km. What is the parcel's new T?
9. What is its new RH?
10. What is its new VS? (Remember, VS must decrease as vapor condenses to liquid.)
11. How much of the original vapor has condensed to liquid?
12. Why did the parcel start cooling more slowly?

Example with answers.

1. What is the parcel's RH? (Ans.: VC = 28, so RH = 8/28 = 29%).
2. Lift this parcel 1 km. What is the parcel's new T? (Ans.: The parcel is subsaturated, so it cools dry adiabatically. Lifting 1 km causes 10°C of cooling, so the new T = 20°C.)
3. What is its new VS? (Ans: VS is fixed until saturation, so it is still 8 g/kg.)
4. What is the parcel's new RH? (Ans.: new VC = 15 g/kg, so new RH = 53%).
5. Lift this parcel another 1 km. What is the parcel's new T? (Ans.: The still subsaturated parcel cooled at the DALR down to T = 0°C.)
6. What is its new VS? (Ans.: VS remained fixed at 8 g/kg since the parcel was subsaturated.)
7. What is the parcel's new RH? (Ans.: New VC = 8 g/kg, so *now the parcel is saturated*).
8. Lift this parcel yet another 1 km. What is the parcel's new T? (Ans.: The now saturated parcel cools at the MALR, or 5°/km. So, the new T is 5°C.)
9. What is its new RH? (Ans,: Still 100%, as excess vapor condenses to liquid.)
10. What is its new VS? (Ans.: The parcel is saturated, so RH = 100% and VS = VC. Air at T = 5°C can only old 6 g/kg, so that's also the VS).
11. How much of the original vapor has condensed to liquid? (Ans.: The parcel started with 8 g/kg but can only hold 6 g/kg at this point. So, 2 g/kg of vapor has already condensed.)
12. Why did the parcel start cooling more slowly? (Ans,: Expansion cooling has continued as the parcel ascended, but after saturation it became partially opposed by condensation warming.)

Question for thought. Although we're going to ignore its variation, the MALR is not actually constant. Follow a rising saturated parcel. How would you expect its cooling rate to vary during its ascent: should it increase or decrease, and why? (I won't give you the answer unless you offer both an answer and a justification for your answer to me first.)

Question for thought. Consider Table 1. In this class, we're ignoring the fact that VC actually relies on pressure as well as temperature. (The pressure dependence is a lot smaller, though.) How would you expect pressure to influence VC? That is to say, suppose you had two saturated parcels with the same T but different pressures. Which parcel would you expect to have more vapor, and why? (If you get this correct, you will be transferred into the atmospheric sciences program!)

Table 1: Temperature/moisture table

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