Some routes to saturation

AS 101 Fall, 2003 – Fovell

Definition of terms and the Stuve diagram

The *mixing ratio* expresses the ratio of the water vapor mass to the dry air mass in an air parcel. The *saturation mixing ratio*, r_s, represents the maximum amount of water vapor the parcel can hold. This is a function of temperature and pressure. The *actual mixing ratio*, r, indicates the true water vapor content. It is a function of the dew point temperature and the pressure. The *relative humidity* is simply $\frac{r}{r_s}$.

The figure below depicts a Stuve (pseudoadiabatic) chart. The three kinds of lines/curves on this chart are:

- *dry (subsaturated) adiabats*, lines of constant potential temperature θ. For subsaturated, isolated air parcels, parcel temperature changes along this path.
- *moist (saturated) adiabats*, lines of constant equivalent potential temperature θ_e. For saturated, isolated air parcels, temperature changes along this path.
- *mixing ratio lines*, lines of constant r or r_s. These lines are used to find both actual and saturated mixing ratios.

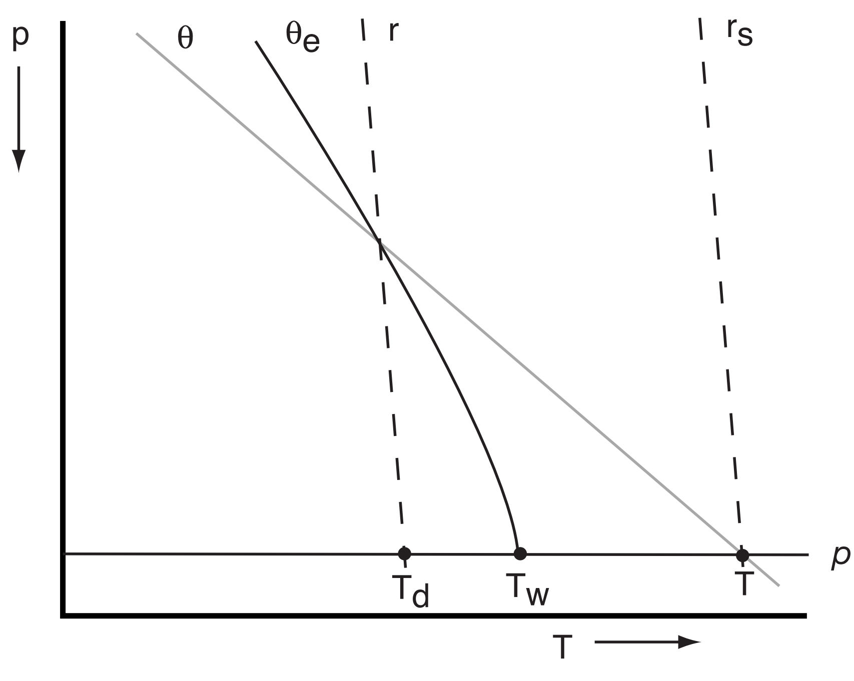

Figure 1: Stuve diagram. Please note the diagram is rather distorted.

Temperature T, pressure p and saturation mixing ratio r_s are related. If you know any two of these, the third may be obtained from the Stuve diagram. If you plot the point (T, p) on the diagram, r_s is given by the value of the mixing ratio line passing through that point. Similarly, dew point temperature T_d, pressure p and actual mixing ratio r are related. Knowing any two allows the third to be easily found. The mixing ratio line passing through the point (T_d, p) yields the actual water content, r.

The regular temperature T is sometimes called the "dry bulb" temperature. It is recorded with a standard thermometer. There is a third kind of temperature — the *wet bulb* temperature T_w. The wet bulb is obtained by affixing a moist cloth to the thermometer bulb (hence making the bulb "wet"). It can also be estimated graphically with the Stuve diagram (see below).

Three approaches to saturation

A subsaturated air parcel has a vapor capacity (r_s) that exceeds its vapor supply (r). The parcel may be brought to saturation via three distinct methods, identified here as the *dew point*, *adiabatic lifting*, and *wet bulb approaches*.

Dew point approach

In the *dew point approach*, air is isobarically cooled without changing its vapor content. Thus, r and p are fixed. As the temperature decreases, r_s declines as well, causing the relative humidity to increase. When r_s has declined to r, T has cooled to T_d (see figure below).

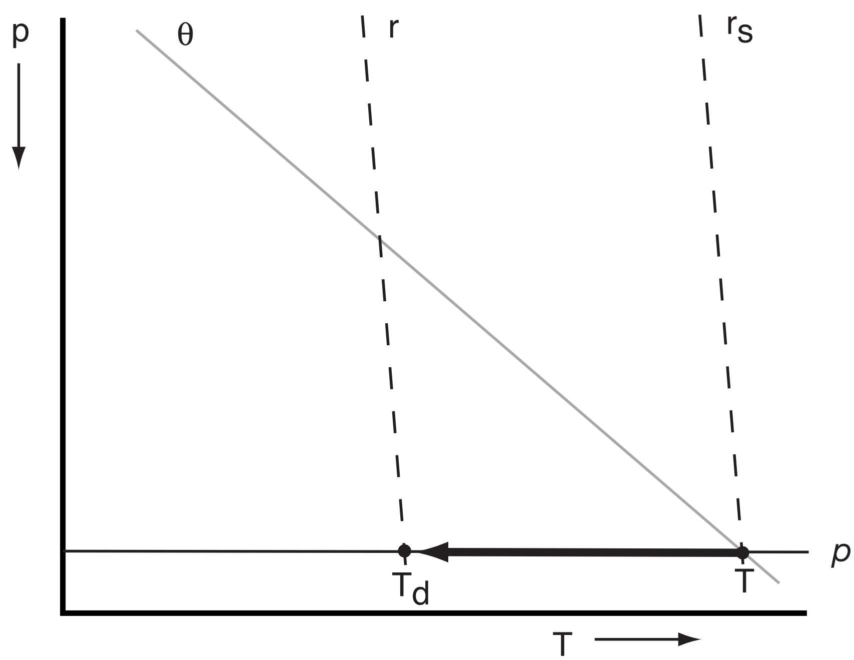

Figure 2: Dew point approach to saturation.

The dew point temperature may be defined as the temperature air must be cooled to in order to reach saturation without change in vapor content.

Adiabatic lifting approach

Air may also be saturated by expansion cooling, via *adiabatic lifting* of the parcel towards lower pressure, without change of water vapor content (r is again constant). While the parcel remains subsaturated, θ is conserved. This process can be depicted on the Stuve diagram in the following manner:

a Start at the point (T, p), and decrease the temperature along the dry adiabat intersecting this point. The temperature cools rapidly, at nearly 10°C km^{-1}. θ is conserved.

b Start at the point (T_d, p), and decrease the dew point temperature along the mixing ratio line intersecting that point. The dew point decreases very slowly with height. r is conserved.

Where the θ line from [a] intersects the r line from [b], saturation is achieved. This point is called the **LCL** (Lifting Condensation Level), the level at which condensation is achieved via lifting.

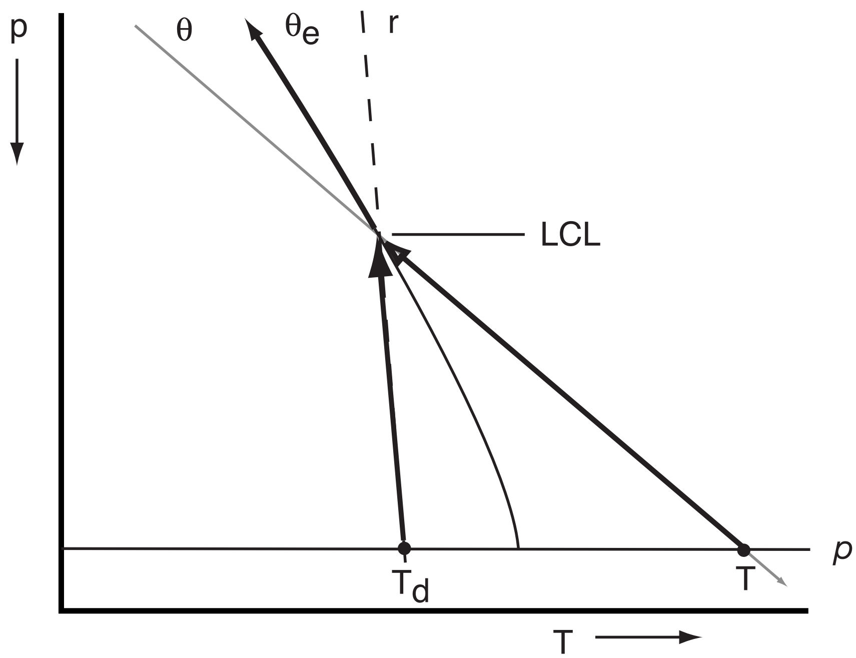

Figure 3: Adiabatic lifting approach to saturation.

Up to now, the process has been strictly adiabatic, because there is no heat source, either outside or inside of the air parcel. Once the parcel is saturated, however, further expansion cooling causes the vapor capacity r_s to become smaller than the vapor supply r. As a result, some vapor must condense.

As vapor condenses, however, heat is released to the air parcel. This is called the *latent heat of condensation*. Because there now is an (albeit internal) heat source, the process is no longer strictly adiabatic, but rather *moist (saturated) adiabatic*.

Note there are now two competing effects: **adiabatic expansion cooling** is being partially offset by **condensational warming**. As a result, a saturated parcel still cools upon lifting, but more slowly than the dry adiabatic rate that applied to subsaturated parcels. The moist adiabatic lapse rate is not a constant, and varies widely depending on the temperature and pressure (more accurately, it varies with the condensation rate, which varies with T and p).

The moist adiabatic pathway above the LCL proceeds along the moist adiabat curve. Note the path carries the parcel in between the original θ and r lines. Neither θ nor r are conserved for a moist adiabatic process. The parcel's potential temperature increases upon further lifting while its vapor supply diminishes (as vapor is lost via condensation). The conserved quantity for moist adiabatic processes is the equivalent potential temperature, θ_e.

The wet bulb approach: isobaric and net isobaric processes

Neither the dew point nor the adiabatic lifting approaches saturated air by adding water vapor to the parcel. In the *wet bulb* approach, the vapor content is increased by evaporating liquid water into the parcel at constant pressure. So, r increases during this process. However, the heat for evaporating the liquid water comes from the parcel itself; this causes the *temperature to simultaneously decrease*. As the temperature decreases, the vapor capacity r_s decreases.

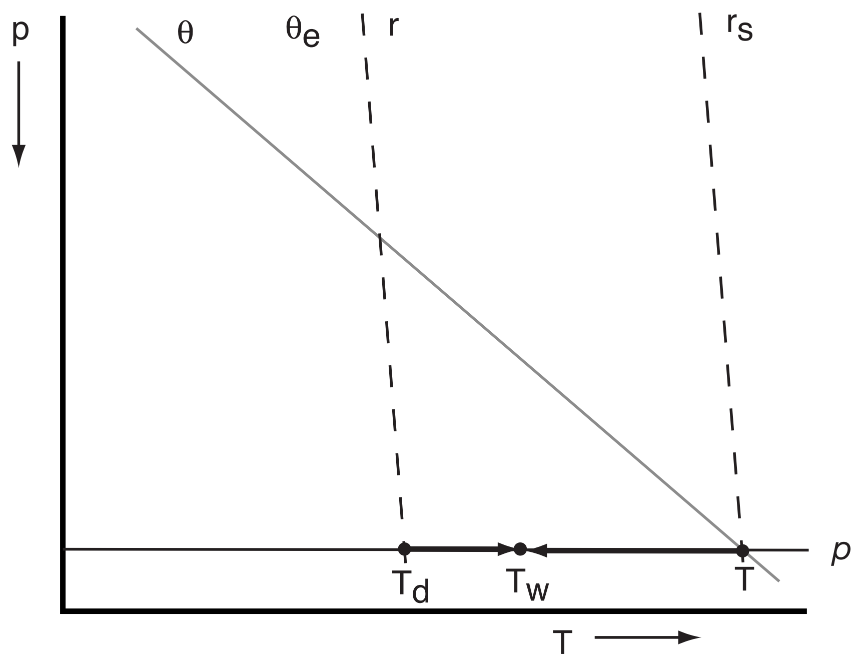

Figure 4: Wet bulb approach to saturation (isobaric path).

In the diagram below, we see we start with a subsaturated parcel with temperature T and dew point T_d. Again, at a given pressure, the dew point indicates the actual vapor content of the parcel. Thus, as vapor is added, the parcel T_d rises. Evaporation cooling, however, causes the T to decrease from its original value. The falling T and rising T_d meet at an intermediate temperature, called the wet bulb T_w. When the temperature reaches the wet bulb temperature, the air is saturated.

We can define the wet bulb as the temperature at which air will reach saturation via evaporation cooling.

Keep this in mind: Say we have a parcel with $r = 5$ g kg^{-1}, and $r_s = 9$ g kg^{-1}. Thus, it appears that we can fit another 4 g kg^{-1} into the parcel before saturation. Actually, we can't do it [without also adding some heat ourselves] because the act of forcing vapor into the parcel causes the parcel's vapor capacity to decrease. The parcel will saturate before all 4 g kg^{-1} are incorporated into the parcel. This is like trying to fill a glass of water, only to find the glass shrinks as liquid is poured into it.

The wet bulb approach as described above is a strictly isobaric process, but we can't get a parcel's T_w isobarically on the Stuve diagram. We can, however, graphically estimate the T_w by performing a *net isobaric* process on the diagram. The figure below sketches out this process.

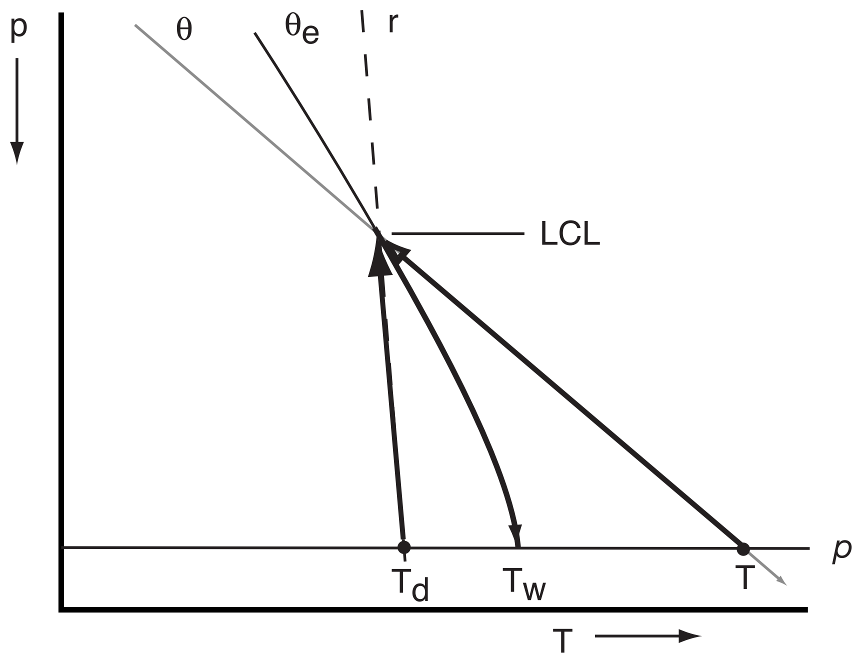

Figure 5: Wet bulb approach to saturation (net isobaric path).

Start with T and T_d at pressure p and bring the parcel to saturation dry adiabatically. From the LCL, however, return down to the original pressure level along the moist adiabat intersecting the LCL. Where the moist adiabat crosses the original pressure level, the temperature there is T_w. Note this is a net isobaric process. The wet bulb temperature found by this procedure is not identical to the value that would be found isobarically, but in practice it is a very good approximation.

What is happening as the parcel descends moist adiabatically from the LCL? At the LCL, the parcel is saturated. If we push the parcel downward towards higher pressure, however, the parcel will become subsaturated – unless we add vapor to it. (The temperature will rise due to compression, increasing r_s and decreasing the relative humidity unless we augment r.) Suppose we think of the parcel's descent from the LCL as a collection of many small steps, and at each step, we add however much vapor we need to keep the parcel saturated. By the time we reach the original pressure level, the parcel will still be saturated, owing to the addition of that extra moisture. Note the parcel reaches that pressure level with a lower temperature (the wet bulb temperature) and a higher vapor supply than it started with.