Atmospheric Physics

Lecture 9

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The saturated adiabatic lapse rate

While the air in a rising parcel remains unsaturated, the derivation of the adiabatic lapse rate

$$-\left(\frac{dT}{dz}\right)_{\text{parcel}} = -\frac{R_a T}{c_p p}\left(\frac{dp}{dz}\right)_{\text{parcel}} = \frac{g}{c_p} \equiv \Gamma_a,$$

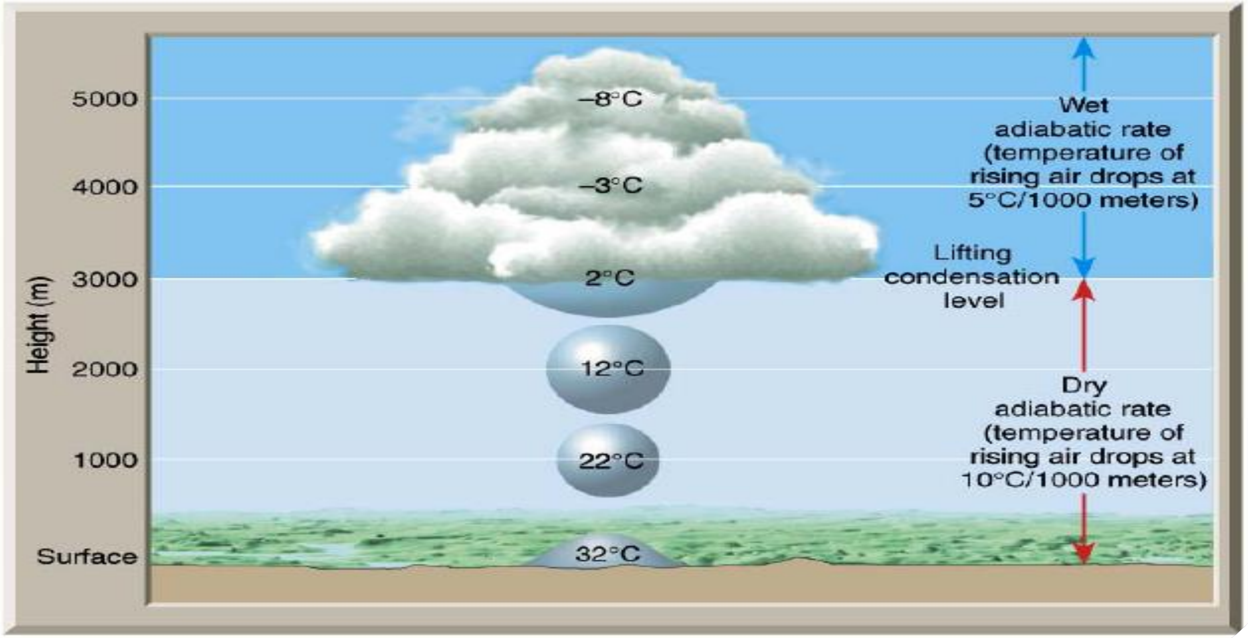
remains unchanged, apart from the use of the specific heat capacity c_p for the mixture of dry air and water vapour: this is always close to that for dry air alone (see Problem 2.6).

However, once saturation takes place, the calculation of the lapse rate following the parcel must be changed significantly, because of the latent heat released.

So the dry adiabatic vertical temperature gradient is about -9.8 K/km.

The dry adiabatic *lapse rate* (defined as $-dT/dz$) is about +9.8 K/km

Moist Adiabatic Rate



considering a saturated parcel (which is taken for convenience to be of unit mass) that rises a distance dz.

At saturation, the mixing ratio equals the saturation mixing ratio

$$\mu = \mu_s(T, p)$$

If a mass of water then $|\delta\mu_s| = -\delta\mu_s$ condenses during the rise through height δz, an amount of latent heat is given to the parcel.

$$\delta Q = L|\delta\mu_s| = -L\delta\mu_s$$

Note that $\delta\mu_s$, as is usual for a small change, is defined as an increase in μ_s; therefore $-\delta\mu$ is a decrease of μ_s.

The liquid water is assumed to fall out of the parcel and take no further part in its heat balance: this is an irreversible process and it also implies a loss of heat from the parcel.

Hence the parcel undergoes a non-adiabatic (and indeed a non adiathermal) change.

However, the amount of heat removed from the parcel by the liquid water is small compared with that remaining in the parcel, so the process is referred to as pseudo-adiabatic.

The latent heat release δQ, given by previous equation, is equal to the heat input into the parcel while it rises a distance δz and its temperature increases by δT.

We assume that this heat input occurs reversibly so

$$\delta Q = c_p\,\delta T + g\,\delta z$$

where c_p is the value for the dry air-water vapour mixture.

$$c_p\,\delta T + g\,\delta z + L\,\delta\mu_s = 0.$$

We now need to express δμ in terms of δT and δz.

$$\mu_s = \epsilon e_s/p.$$

Taking logarithms and differentiating gives

$$\frac{\delta\mu_s}{\mu_s} = \frac{\delta e_s}{e_s} - \frac{\delta p}{p}.$$

However, e_s depends only on T,so

$$\delta e_s = (de_s/dT)\,\delta T$$

moreover, from the Clausius–Clapeyron equation

$$\frac{1}{e_s}\frac{de_s}{dT} = \frac{L}{R_V T^2}$$

From the hydrostatic equation in the form $\delta p = -pg\,\delta z/(R_a T)$,

where p is the total pressure; by collecting these results we therefore get $\frac{\delta\mu_s}{\mu_s} = \frac{\delta e_s}{e_s} - \frac{\delta p}{p}$.

$$\frac{\delta\mu_s}{\mu_s} = \frac{L\,\delta T}{R_v T^2} + \frac{g\,\delta z}{R_a T}.$$

By eliminating $\delta\mu_s$ from this equations $c_p\,\delta T + g\,\delta z + L\,\delta\mu_s = 0.$ and we obtain

$$\left(c_p + \frac{L^2\mu_s}{R_v T^2}\right)\delta T + g\left(1 + \frac{L\mu_s}{R_a T}\right)\delta z = 0.$$

Letting $\delta z \to 0$, we get the saturated adiabatic lapse rate (SALR) Γ_s:

$$\Gamma_s = -\frac{dT}{dz} = \frac{g}{c_p} \frac{\left(1+\frac{L\mu_s}{R_a T}\right)}{\left(1+\frac{L^2\mu_s}{c_p R_v T^2}\right)}$$

g/c_p ➡ DALR Γ_a

$$\Gamma_s = \Gamma_a (coefficient)$$

Note that the factor g/c_p on the right-hand side of equation equals the DALR Γ_a .

For typical atmospheric values of T and μ_s it is found that $\Gamma_s \leq \Gamma_a$.

Because of the latent heat given to the air by condensation of the water vapour, the temperature drops off less rapidly with height (by about 6–9Kkm^{-1}) at the SALR than it does at the DALR (~ 9.8Kkm^{-1}

Note that Γs depends on the temperature and pressure, through its dependences on T and μ_s (T, p).

Working in terms of the pressure of the parcel, rather than its height, we may show (again using

$$g\delta z = -\frac{R_a T \delta p}{p}$$

that, following the ascending parcel,

$$\Gamma_s = -\frac{dT}{dz} \qquad \frac{dT}{dp} = \frac{\Gamma_s R_a T}{gp} = \Gamma'_s(T, p)$$

say. Curves in the T, p plane whose slopes at each point are given by this equation are called saturated adiabatics.

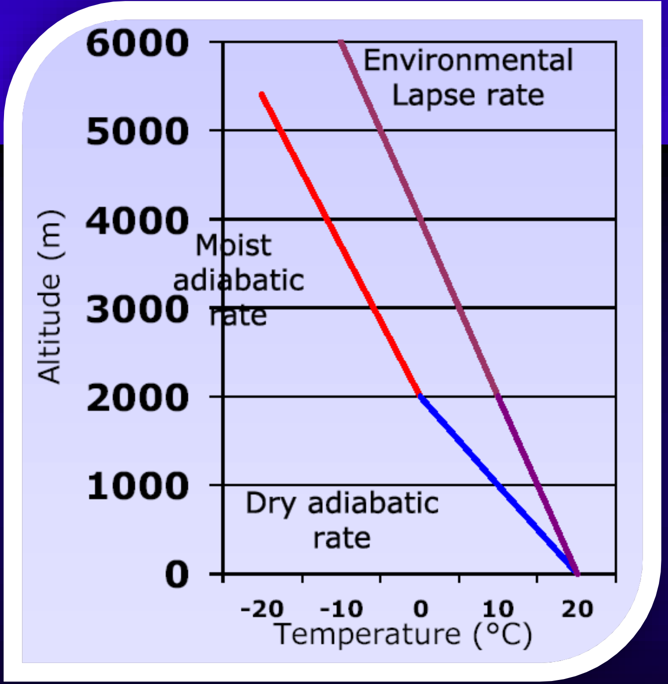
Given the expression for Γ'_s and suitable starting values of T and p, they may readily be calculated numerically.

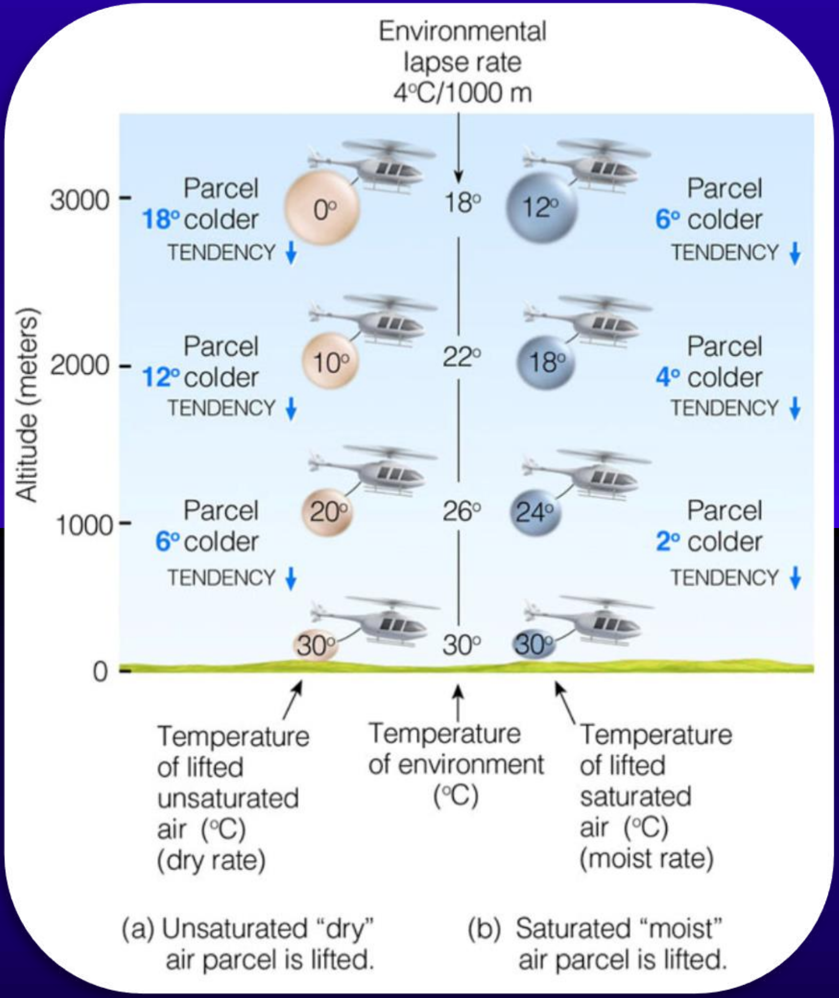
A Stable Atmosphere

stabilizing processes

nighttime surface radiational cooling;

Stable air provides ideal conditions for high pollution levels





Absolute stability

The environmental lapse rate less than the saturated adiabatic lapse rate

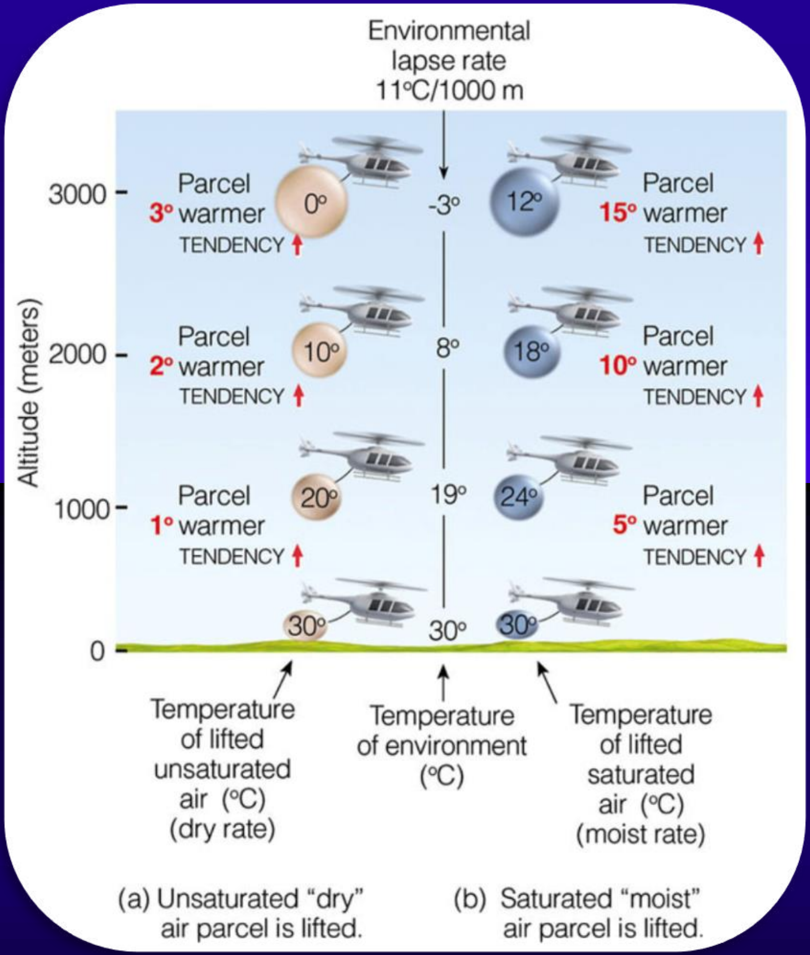
An Unstable Atmosphere

destabilizing processes
daytime solar heating of surface air;

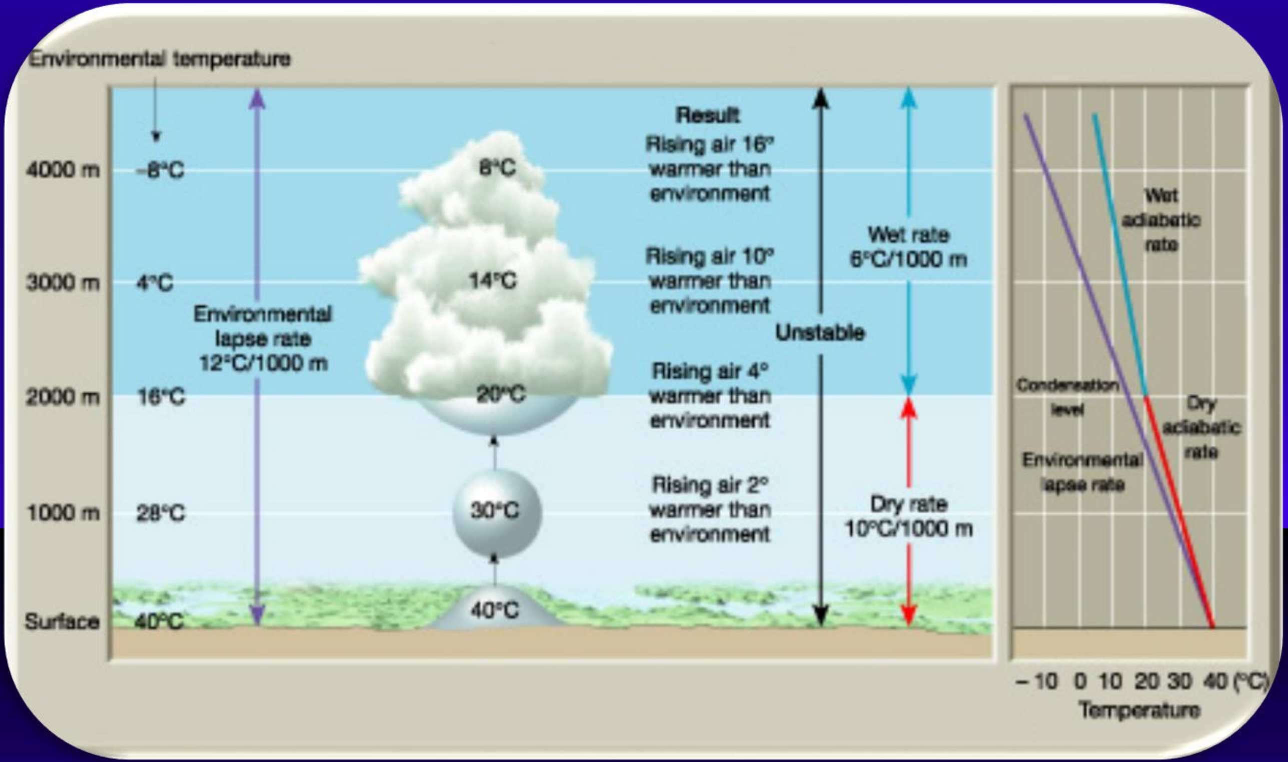
cold air advected to warm Surface

superadiabatic lapse rates (> 10 °C/km)

unstable air tends to be well-mixed



Absolute Instability



The environmental lapse rate is greater than the dry adiabatic lapse rate

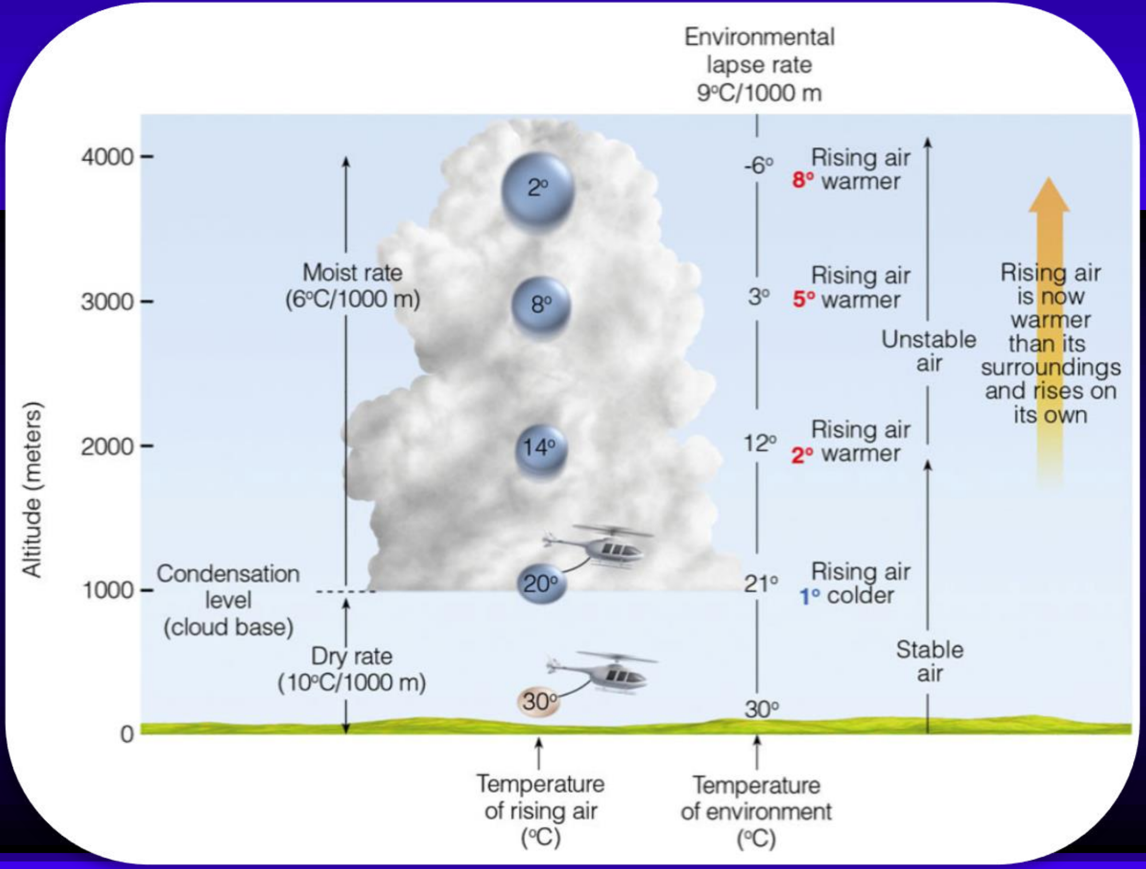
Ascending parcel always less dense than surrounding air, will always rise

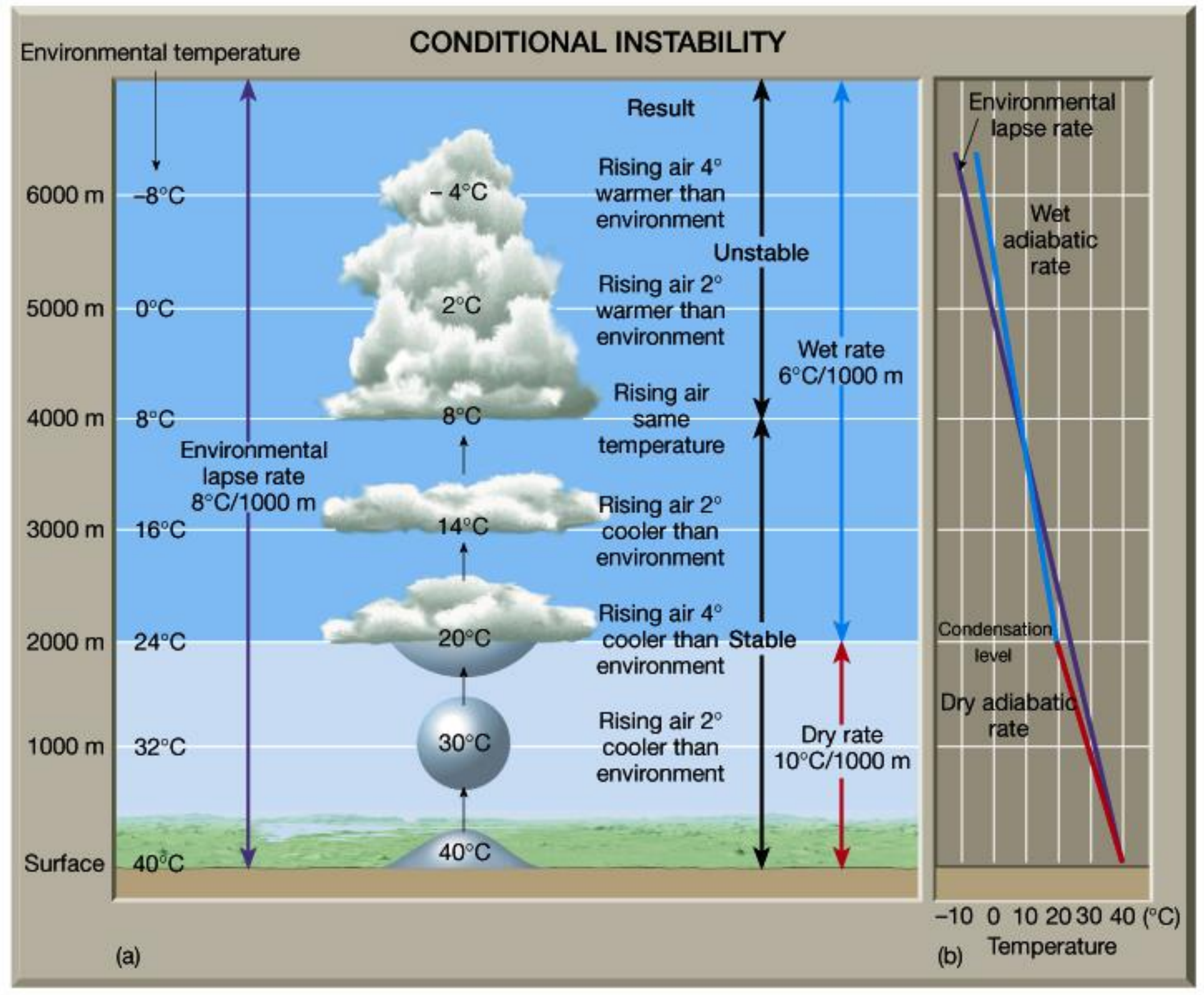

Instability Air

Conditionally Unstable Air

Conditional instability: environmental lapse rate between dry and moist lapse rates

Condensation level cloud base





Saturated parcel is unstable, unsaturated parcel is stable

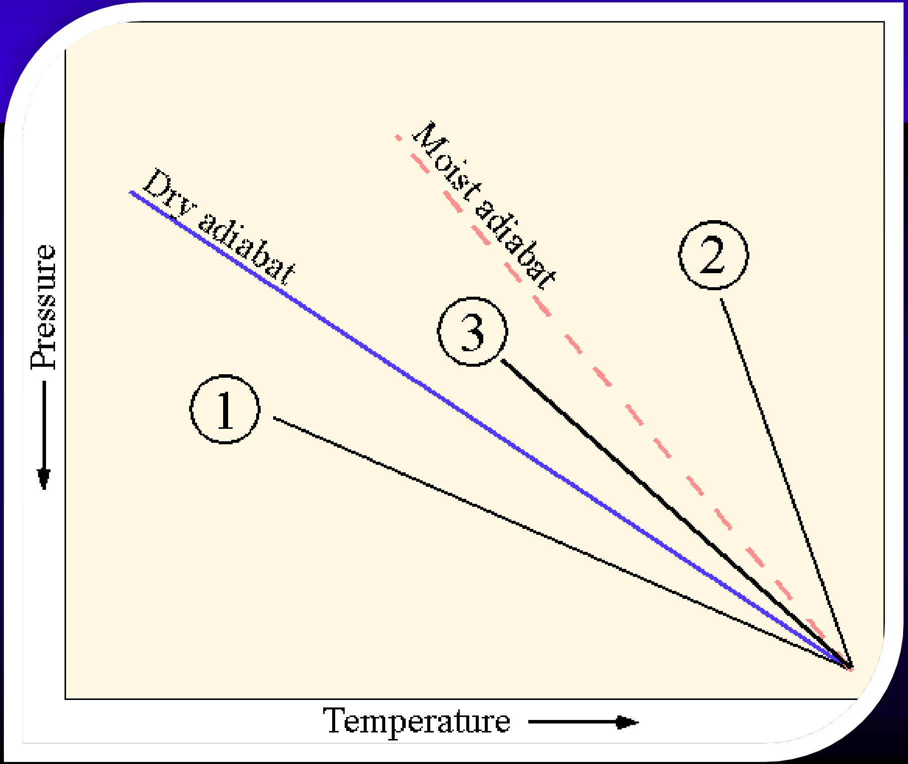
Depend on whether or not the rising air is saturated

In general

(1) is Absolutely Unstable Air

(2) is Absolutely Stable Air

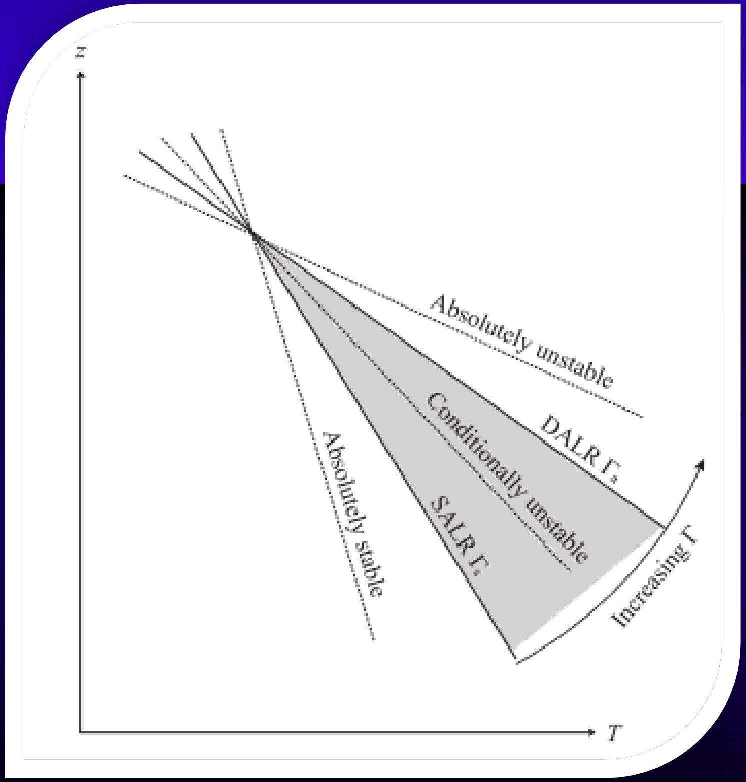
(3) is Conditionally Unstable Air.



if the actual lapse rate $\Gamma < \Gamma_s$ then the region is statically stable even if the air is saturated.

if $\Gamma > \Gamma_s$ a saturated parcel will be unstable.

if $\Gamma_s < \Gamma < \Gamma_a$ a saturated parcel is unstable but an unsaturated one is not: this situation is called conditional instability.



a graphical representation of the various cases