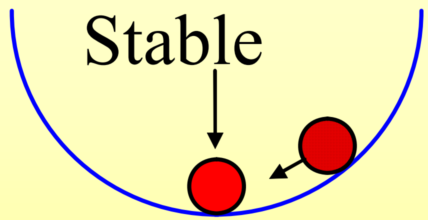
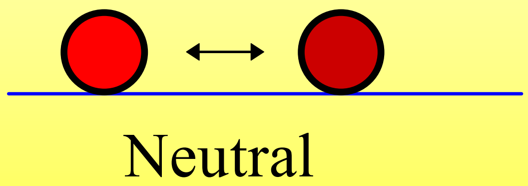
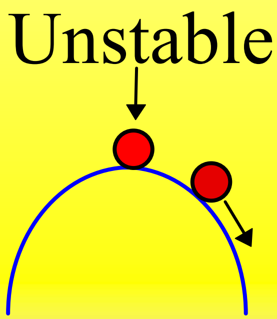
Atmospheric Stability & Cloud Development

- **Stable situations**
  - a small change is resisted and the system returns to its previous state



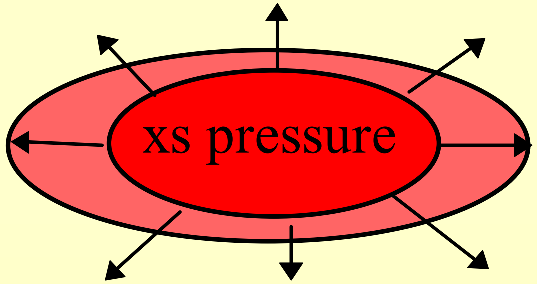
- **Neutral situations**
  - a small change is neither resisted nor enlarged



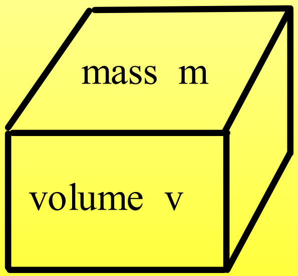


- **Unstable situations**
  - a small change initiates a bigger change, and hence a bigger still, and hence …..

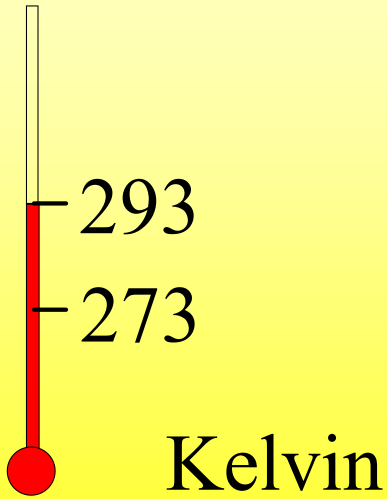
The Players



- **Pressure** - we've met before, as force per unit area. If a parcel of air has greater pressure inside it than its surroundings, it will expand
- **Density** determined by **1/Volume**



$$\text{Density} = \frac{\text{mass}}{\text{volume}} = \frac{m}{v}\ \text{kg m}^{-3}$$

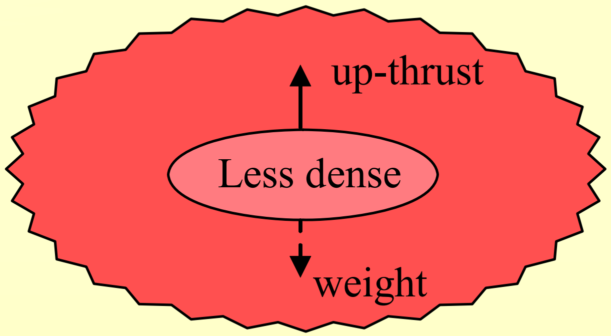


- **Temperature** – measured by radiosonde
- **Moisture content**

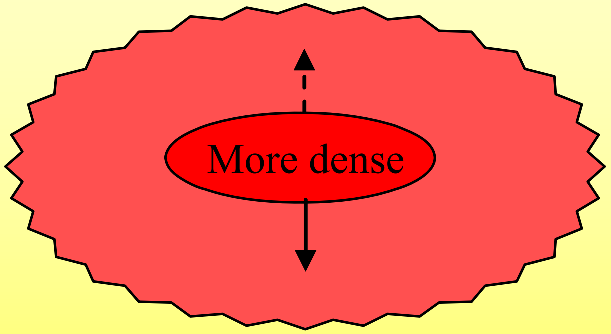
$$\text{Relative humidity} = \frac{\text{actual vapour pressure}}{\text{saturation vapour pressure}} \times 100\%$$

Floating in air

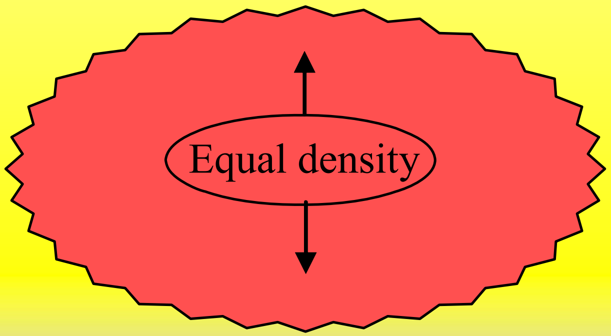
- There are two forces on an object in a fluid: weight ↓; up-thrust ↑
  - weight < up-thrust: object rises
  - weight > up-thrust: object sinks
- weight ∝ density of object, ρ_{object}
- up-thrust ∝ density of fluid, ρ_{fluid}
  - density object < density of fluid: object rises
  - density object > density of fluid: object sinks



Rising parcel



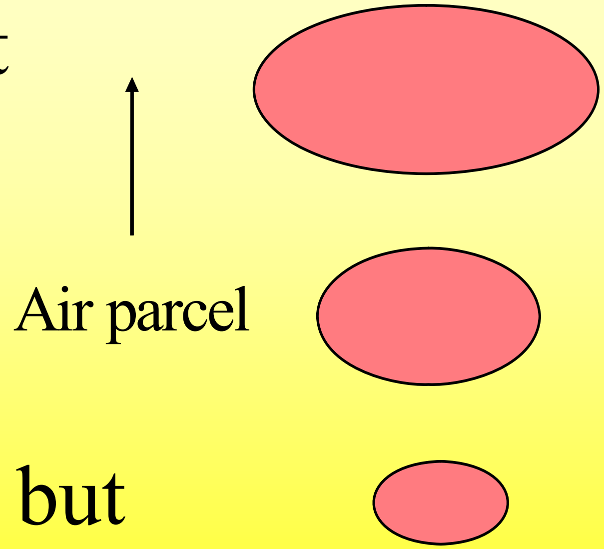
Sinking parcel



Static parcel

Rising & Falling

- The atmosphere is a fluid whose density and pressure generally decreases with height
- The fluid has irregularities in it
- An air parcel will rise if it is less dense than its surroundings
- It then rises into less dense air, but the density inside the packet also falls
- If it stops rising, it is **stable**; if it keeps rising, it is **unstable**



Density Depends on Temperature

- Pressure **P**, volume **V**, and temperature **T**, of a parcel of gas are linked by a relationship
  - for an *ideal gas* (the simplest model of a gas)

$$\boxed{PV = nRT}$$

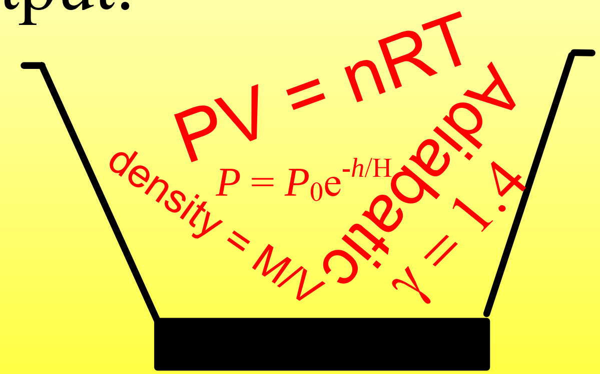
  - R is 'the gas constant', per mole, and *n* the no. of moles
- If two parcels of gas are at the same pressure, then the **warmer gas has the lesser density**
  - this follows because the gas law above can be written [p 212/220/194]

$$\boxed{P \propto \text{density} \times T}$$

Adiabatic Changes in a Parcel of Gas

- When a parcel of gas expands on rising, how much the volume changes depends on **how the expansion takes place**
  - **adiabatic**:- no heat input or output:

$$\boxed{PV^{\gamma} = \text{constant}}$$

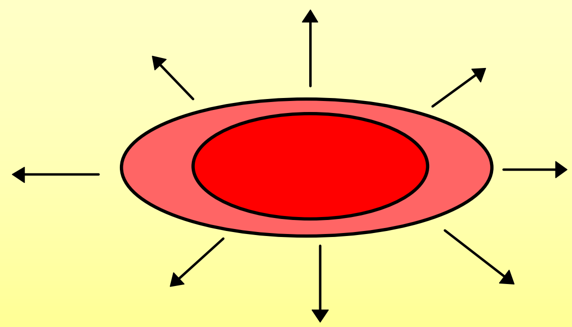


- γ is about 1.4 for air

- This relationship, along with the gas law and the pressure variation with height determines how temperature changes with height (next slide)

Adiabatic Lapse Rates

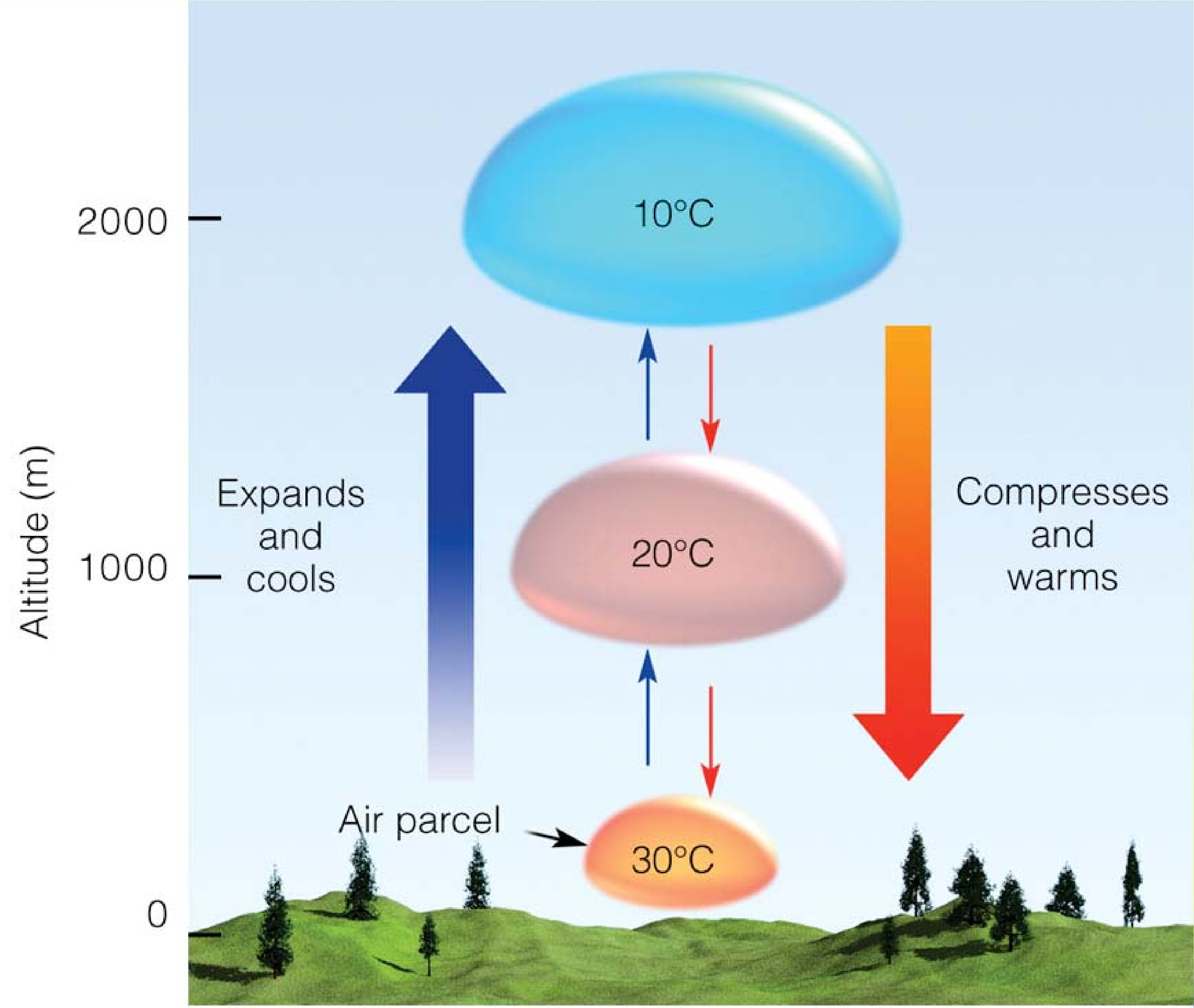
- As a parcel of air expands without heat input from its surroundings, its pressure and temperature drop and its volume increases



Adiabatic expansion

- Meteorologists concentrate on the temperature drop
  - the temperature drop with changing height is called **the lapse rate**
  - for adiabatic change of dry air, the **dry adiabatic lapse rate** is 10°C per 1000 m [p. 160/167/140]
  - the **moist adiabatic lapse** rate is less (~6°C per 1000 m)
    - why?

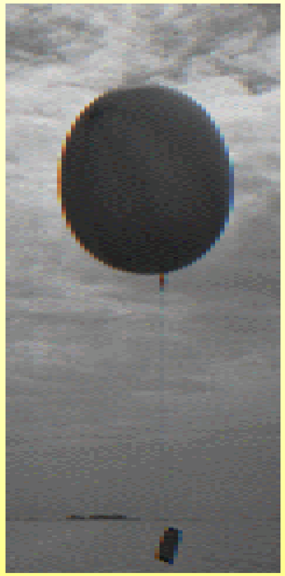
In summary

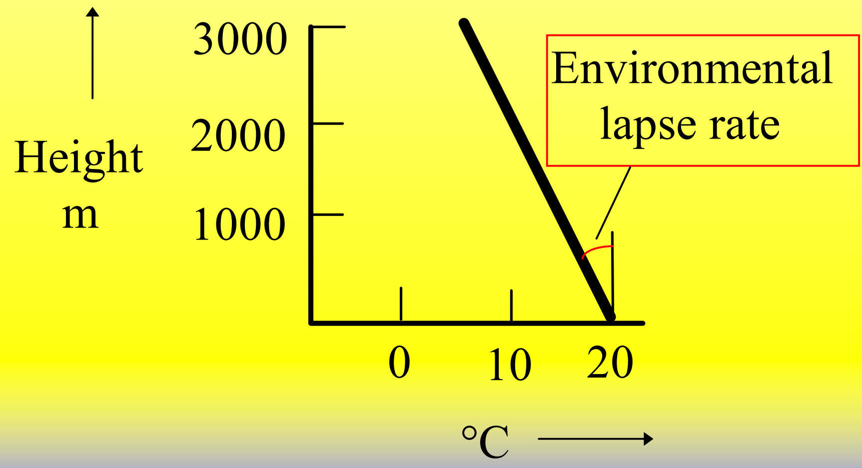


Altitude (m)
2000
1000
0
10°C
20°C
30°C
Expands and cools
Compresses and warms
Air parcel

Atmospheric Temperature Profile

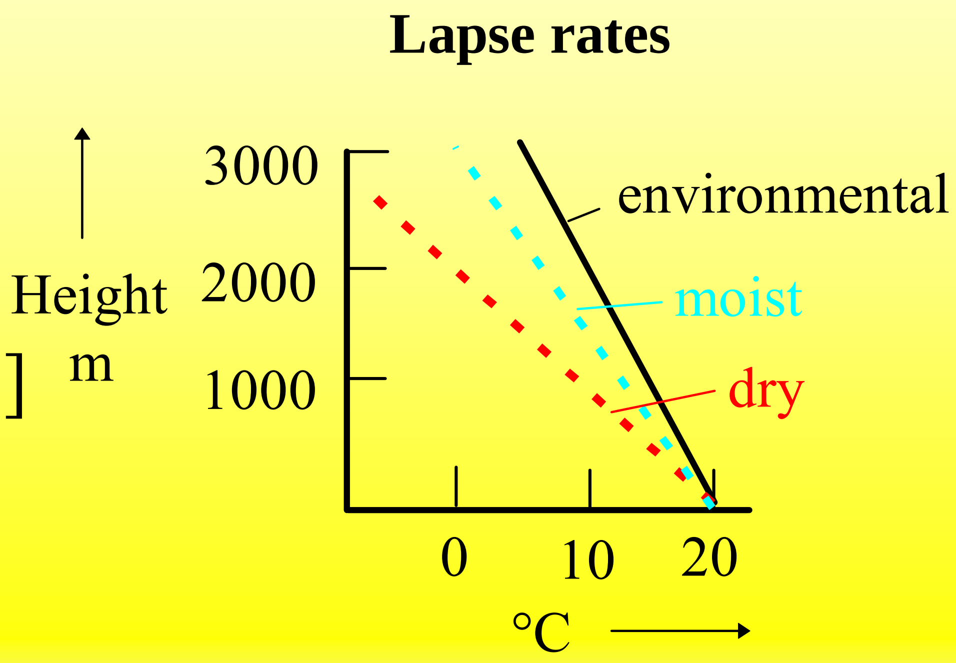
- The profile of temperature change with height in the atmosphere depends on the history of the air
  - this profile can be measured by a balloon borne thermometer
  - the result is called the **environmental lapse rate**
  - lapse rate is measured in °C per 1000 m
    - e.g. 5°C per 1000 m in the diagram





Stable Air

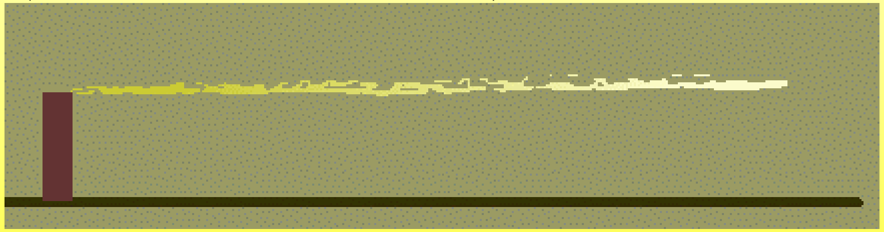
- The stability of air is determined by comparing the environmental lapse rate to the dry and moist adiabatic lapse rates
  - **absolutely stable**
    air has a lapse rate less than both moist and dry lapse rates [p 162/168/141]
  - smaller lapse rate means a steeper line
  - **temperature inversion** means increasing temperature with height



Stable Conditions

- Formed by cooling of lower air layers
  - by radiation at night
  - by air moving in over cold ground
  - influx of cold air (**cold advection**)

  - fanning:



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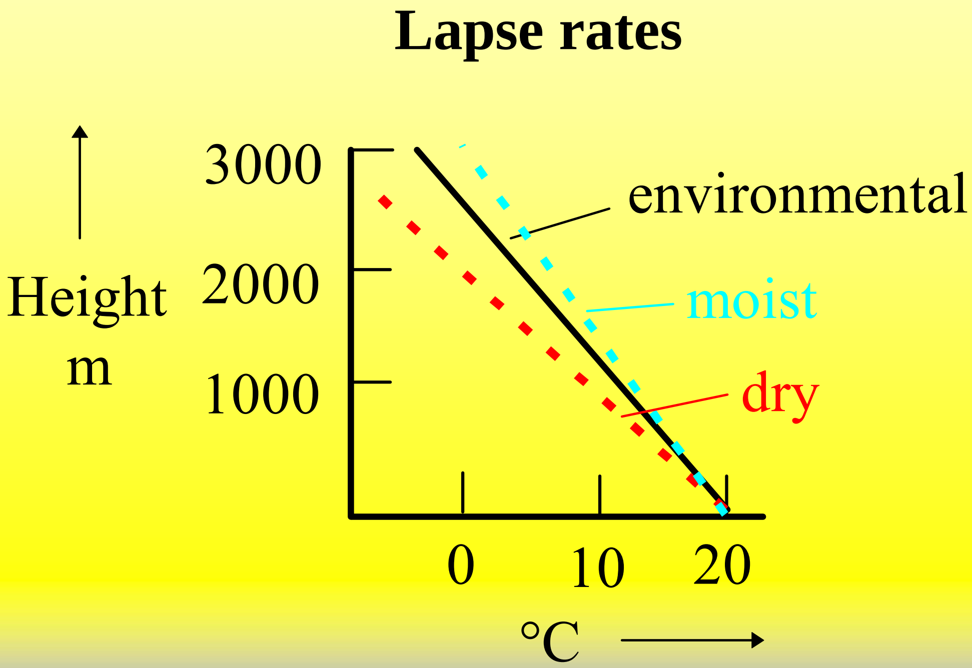
Conditional Instability

- Environmental lapse rate is between the dry and moist lapse rates [p. 165/171/145 + fig. 7.7/6.8]
- Here **dry** air is **stable**; **saturated** air is **unstable**
  - average lapse rate in troposphere is 6.5°C per 1000 m
  - normal state of the atmosphere is conditionally unstable



Unstable Conditions

- Formed by warming of lower air layers
  - by radiation during the day
  - by air moving over warm ground
  - by influx of warm air (**warm advection**)
    - enhanced effect if moist air near ground and dry air aloft is lifted (*convective instability*)

Instability encouraged

- Lifting encourages instability
- See the lecture notes for the numbers behind this figure

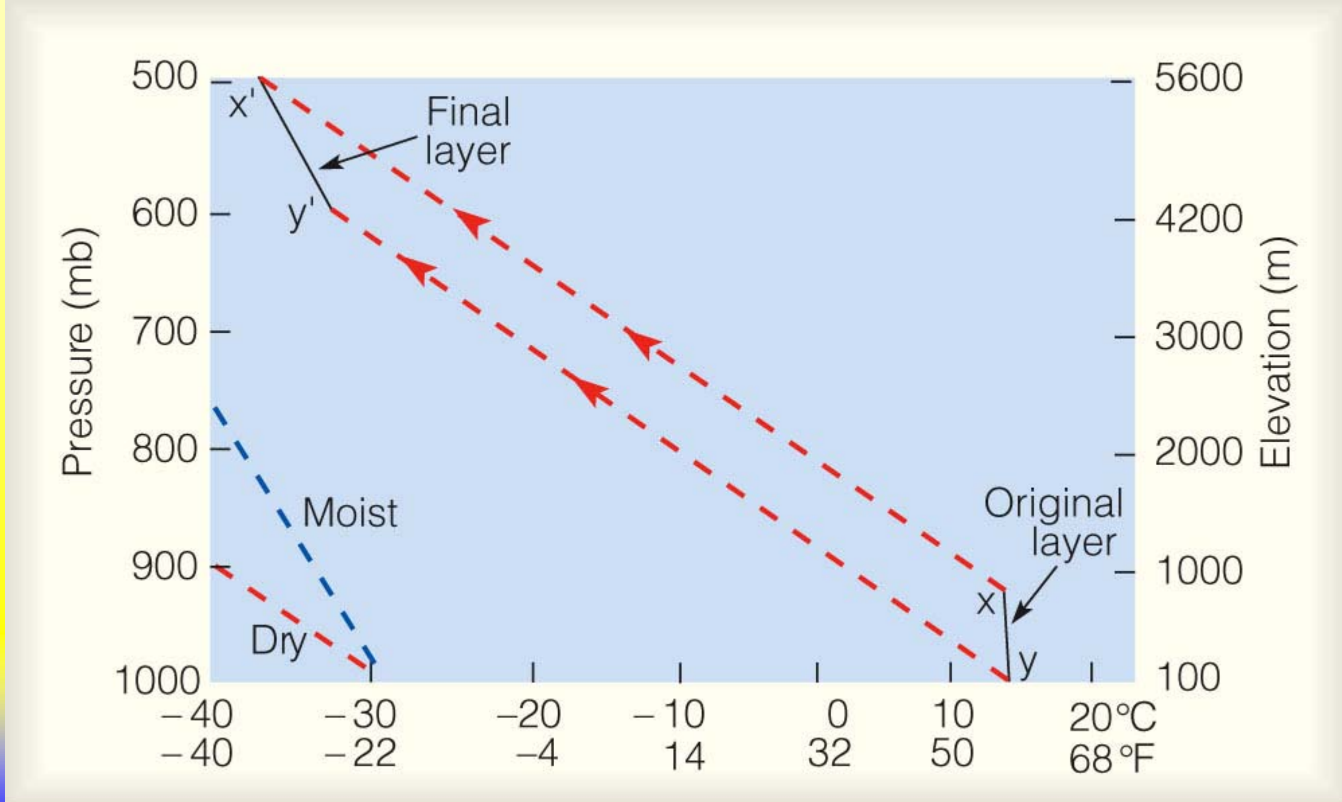
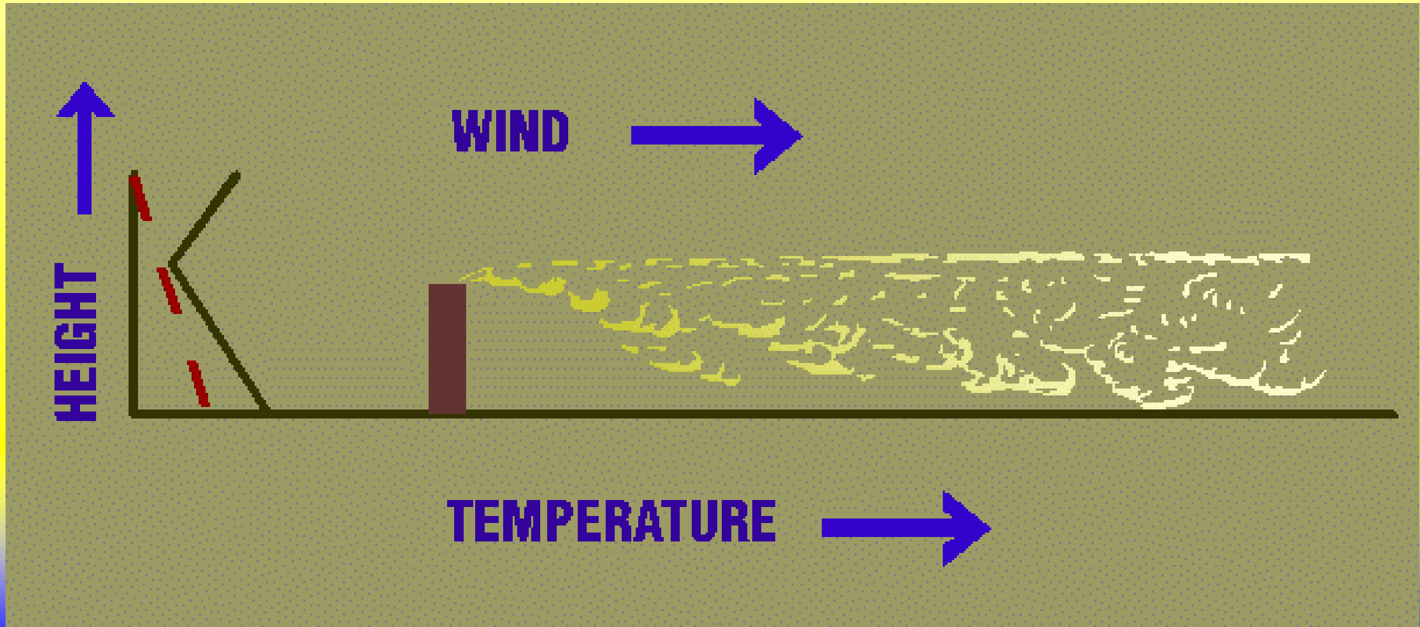


Diagram courtesy:
Thomson Higher Education

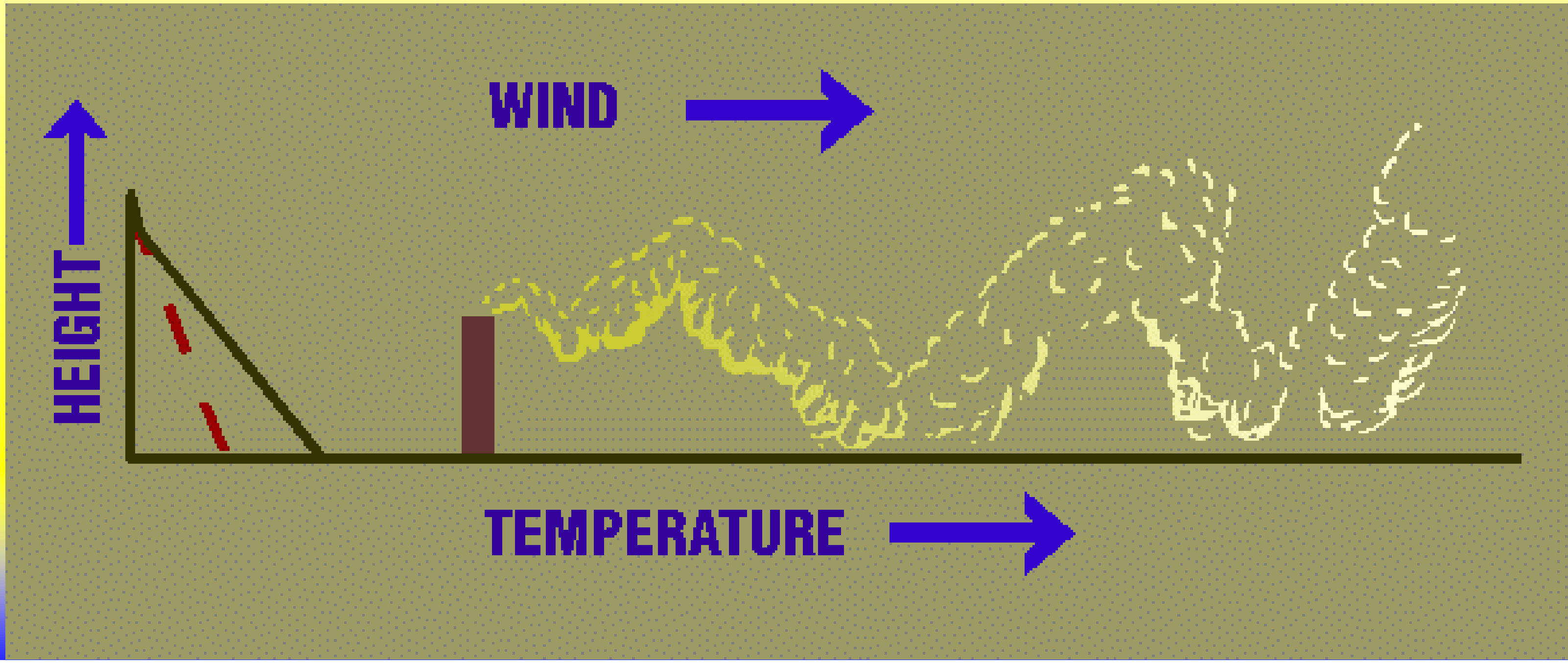
Fumigation

- With warming near ground level, downward mixing takes place, confining the smoke emissions to a narrow layer [p 459/479/506]
  - unstable near ground, stable higher up
  - tall chimneys are best



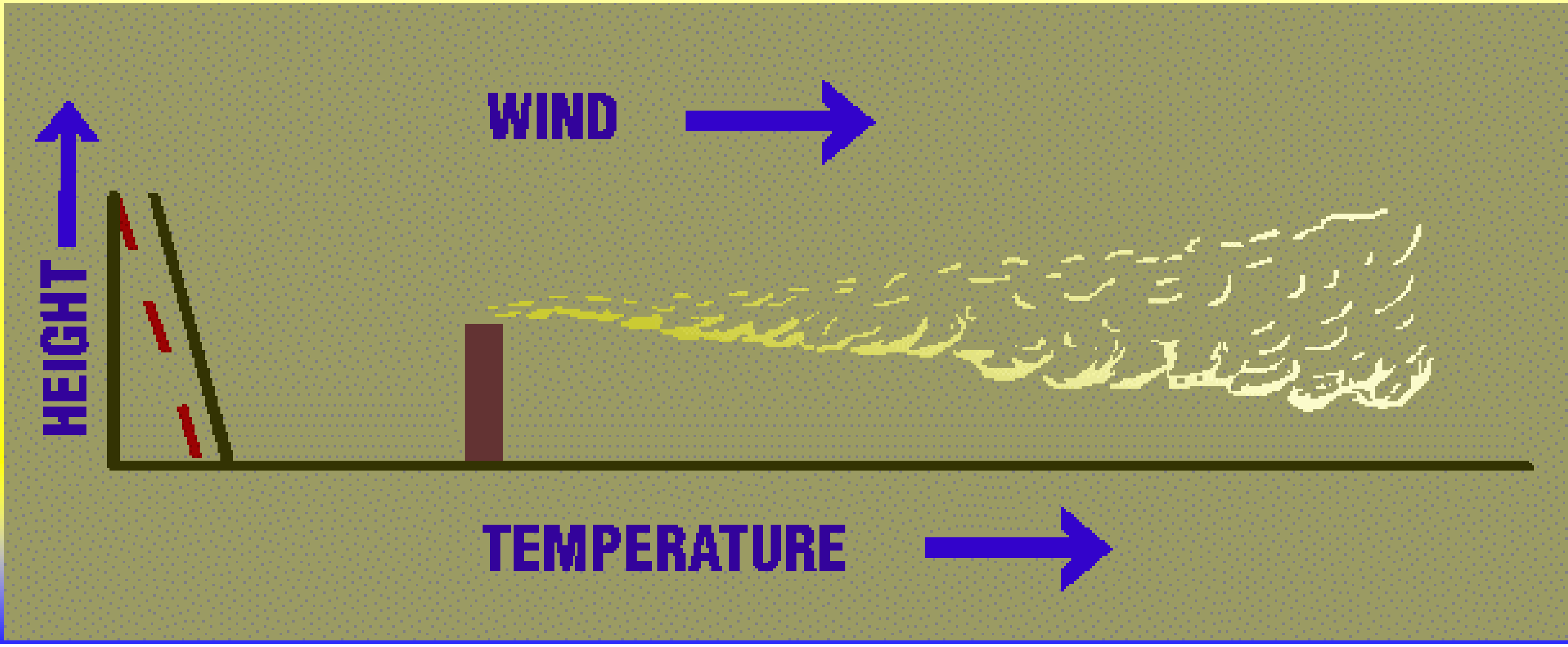
Looping

- In **unstable conditions**, the plume rises and falls as light winds take it away. If this happens without too much dispersion of pollutants, the plume follows a looping path



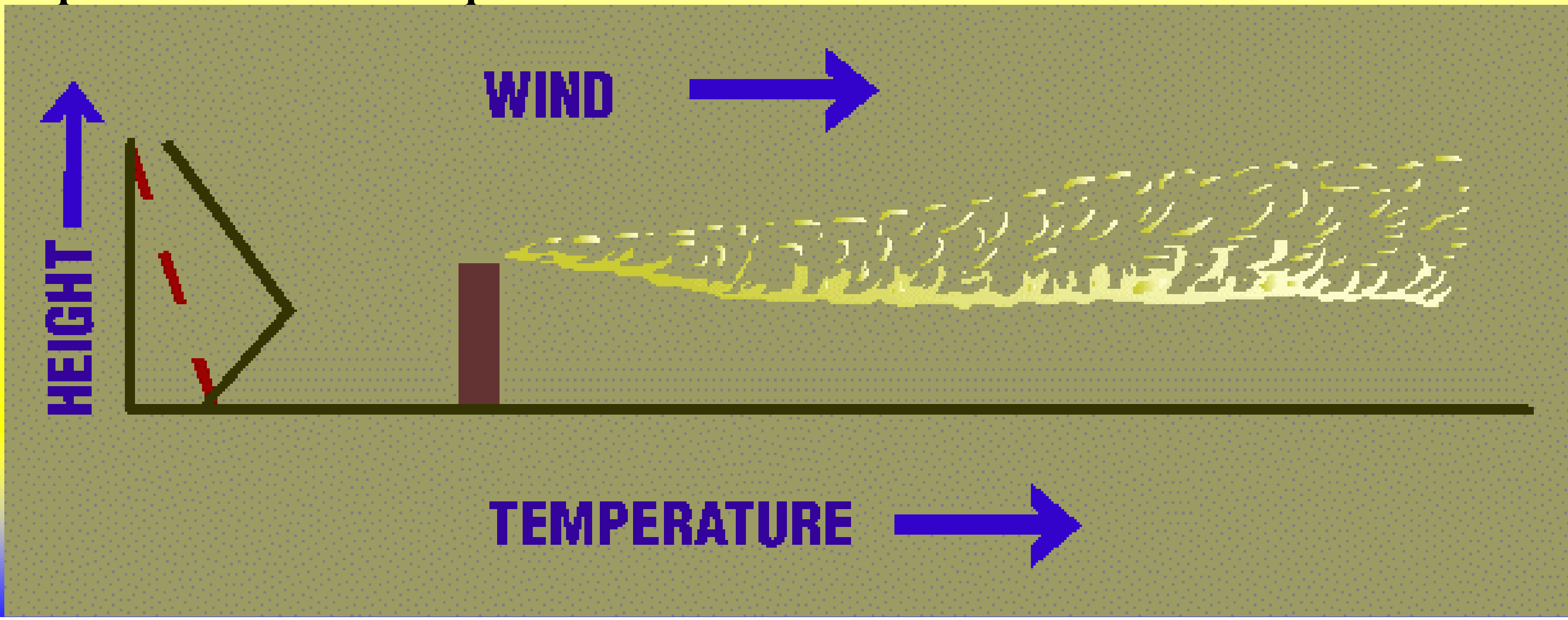
Coning

- In neutral conditions, the environmental lapse rate equals the dry adiabatic lapse rate and the plume spreads up and down about equally without turbulence



Lofting

- Stable air near the ground and unstable air aloft gives no downward mixing and the best conditions for sending plumes upwards [fig. 17.3/ chpt. 18 fig. 4, p. 459/220/506]
  - with a good exit velocity and high temperature of pollutants the plume will rise faster than shown



Lofting

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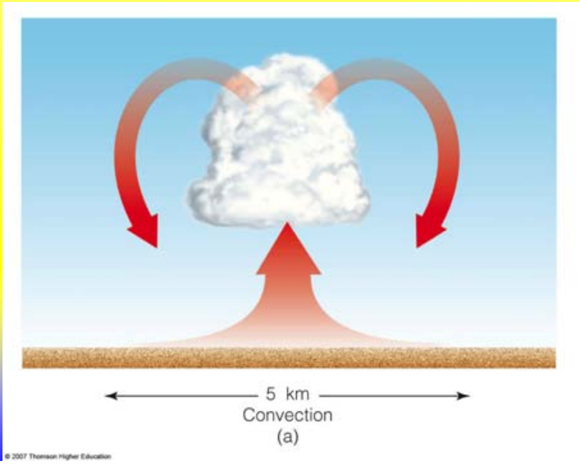
- Lofting over an Australian mining town

Cloud Development

- 4 main processes leading to cloud formation [fig 7.13/6.15]
  - convection → cumulus
  - topographic lifting → mountain cloud
  - convergence
  - uplift along weather fronts
- We shall look only at cumulus cloud formation

Cumulus (Cu) Formation

- The cumulus cloud is part of a convective cell
  - local heating induces instability in the air (fig. 7.14/6.16)
  - the cloud base is at the height where air reaches its dew point



Harbour entrance, Aberdeen

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Dew Point Revisited

- For every rise of 1000 m in height, pressure falls by 10%
  - when water vapour pressure falls by 10% , the dew point falls by 2°C
- Hence for every 1000 m rise in height, dew point falls by 2°C [p. 172/177/153]

Cloud Base Height

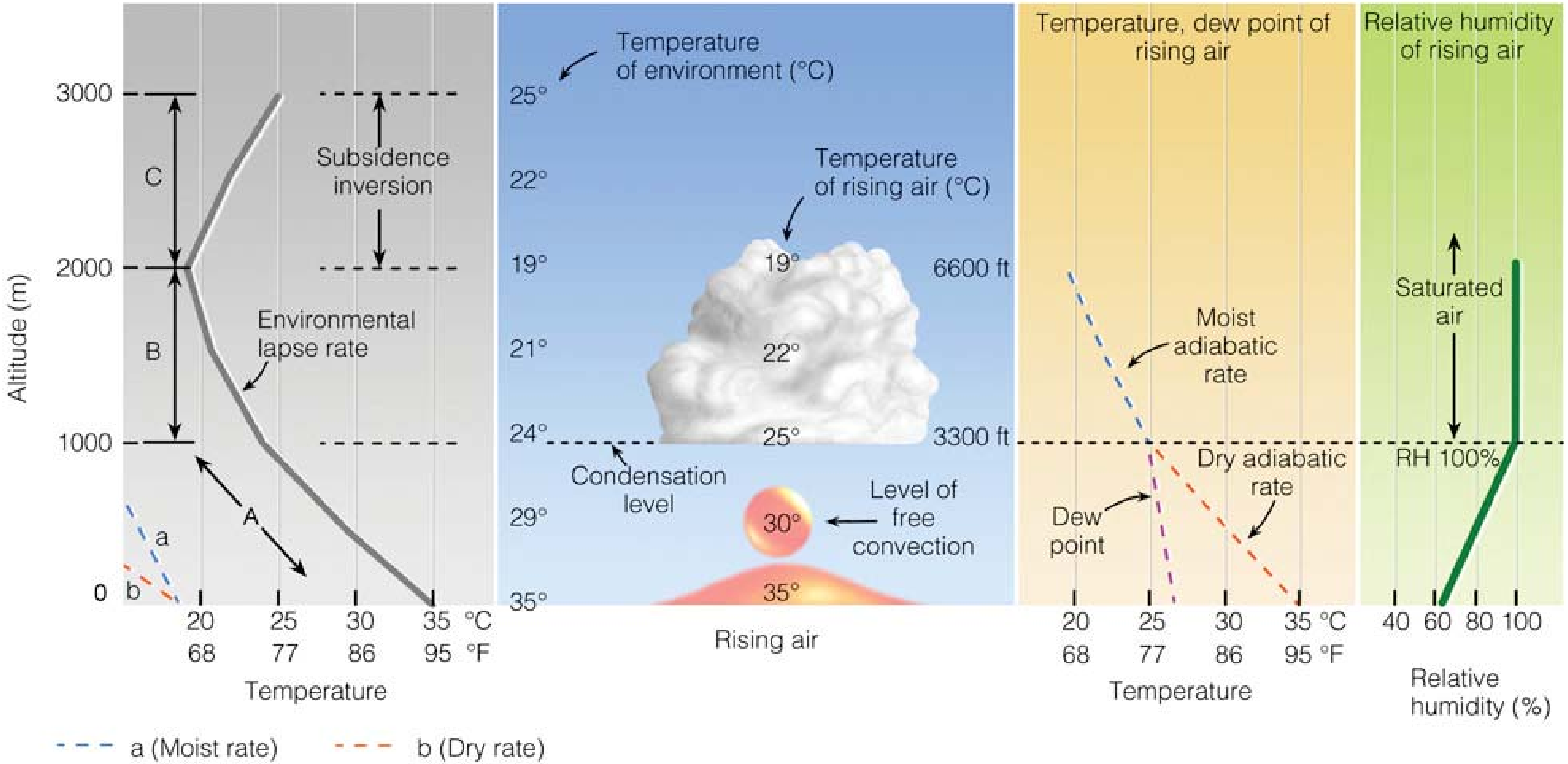
- The lapse rate for 'dry' air is 10°C per 1000 m
- The dew point decreases at 2°C per 1000 m
- Hence the air temp and dew point approach each other at 8°C per 1000 m, or 1°C per 125 m
- **Rule**: T is ground level temp; T_d ground level dew point; H_{metre} height of cloud base, then

$$\boxed{H_{metre} = 125(T - T_d)}$$

  - e.g. $T = 22$°C ; $T_d = 16$°C , then

    $H_{metre} = 125 \text{ x } (22 - 16) = 750$ m

Graphic summary of condensation



Cumulus  Clouds

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- Fig 7.16/6.18 [previous slide] is a graphic summary
  - rising air in the cloud remains saturated
  - the cloud height is controlled by a stable layer on top (which may be the tropopause)
  - outside the cloud, air sinks, warms and creates a cloud-free space
  - as a layer of air rises and stretches, its lapse rate tends to increase, making it more unstable and liable to rise further. See the earlier slide on this topic

Alto- and Cirro-cumulus Formation

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- A uniform layer of cloud gets heated from below by the Earth and loses heat from the top to space (p176/182/156)
- This increases the lapse rate across the cloud and can make the air unstable
- Convection cells result
  - convective instability further increases the vertical extent as lifting begins, since drier air at the top cools faster than moist air at the bottom