Sull'Atlantico un minimo barometrico avanzava in direzione orientale incontro a un massimo incombente sulla Russia, e non mostrava per il momento alcuna tendenza a schivarlo spostandosi verso nord. Le isoterme e le isotere si comportavano a dovere. La temperatura dell'aria era in rapporto normale con la temperatura media annua, con la temperatura del mese più caldo come con quella del mese più freddo, e con l'oscillazione mensile aperiodica. Il sorgere e il tramontare del sole e della luna, le fasi della luna, di Venere, dell'anello di Saturno e molti altri importanti fenomeni si succedevano conforme alle previsioni degli annuari astronomici. Il vapore acqueo nell'aria aveva la tensione massima, e l'umidità atmosferica era scarsa. Insomma, con una frase che quantunque un po' antiquata riassume benissimo i fatti: era una bella giornata d'agosto dell'anno 1913.

Robert Musil - Mondadori, 2013

Clouds
Part 1

- Textbooks and web sites references for this lecture:
- Joseph M. Moran e Michael D. Morgan, Meteorology, The Atmosphere and the Science of Weather, Mc Millan College Publishing Company, 1994, ISBN 0-02-383341-6 (§ 7)
- https://www.eoas.ubc.ca/books/Practical_Meteorology/
- http://www.atmos.washington.edu/Atlas/
- http://cloudappreciationsociety.org/gallery/#p=1&i=0

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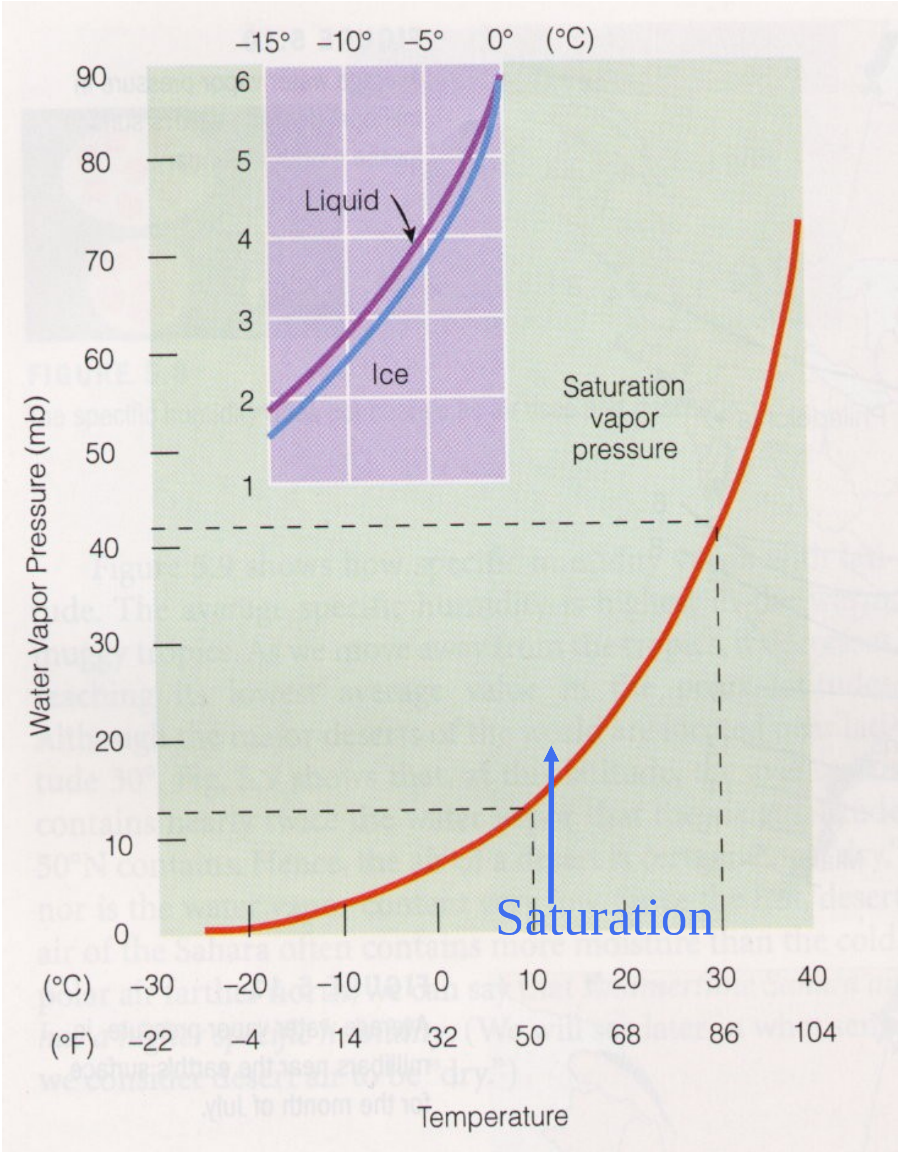
Water vapor, Dew, Frost, Fog and Clouds

Condensation

- Condensation is the phase transformation of water vapor to liquid water
- Water does not easily condense without a surface present
  - Vegetation, soil, buildings provide surface for dew and frost formation
  - Particles act as sites for cloud and fog drop formation

$$\frac{dE_s}{dT} = \frac{LE_s}{R_v T^2}$$



Why is stability important?

- Vertical motions in the atmosphere are a critical part of energy transport and strongly influence the hydrologic cycle
- Without vertical motion, there would be no precipitation, no mixing of pollutants away from ground level - weather as we know it would simply not exist.
- There are two types of vertical motion:
  - **forced motion** such as forcing air up over a hill, over colder air, or from horizontal convergence
  - **buoyant motion** in which the air rises because it is less dense than its surroundings - **stability** is especially important here

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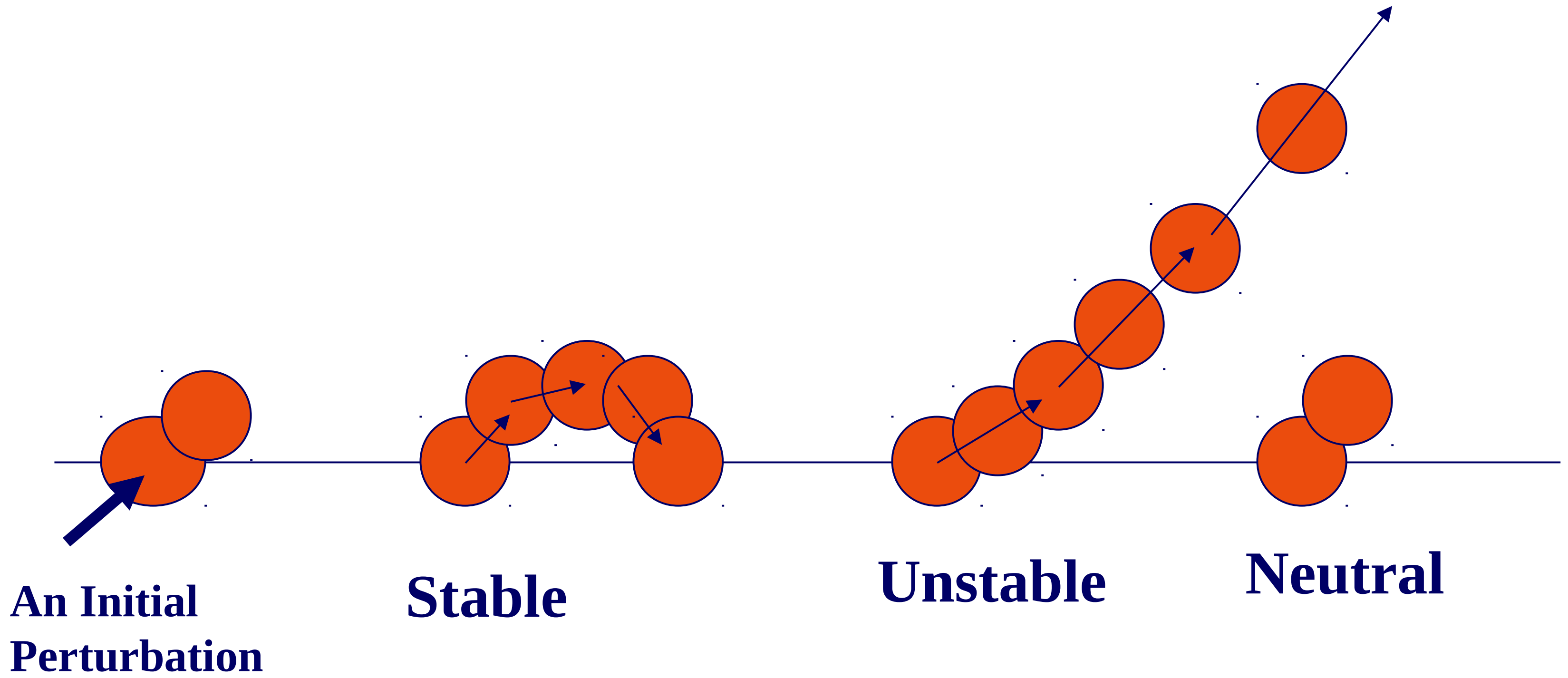
Atmospheric Stability

- Adiabatic Processes
  - Parcel of air expands and cools, or compresses and warms, *with no interchange of heat with the surrounding environment*
  - An adiabatic process is reversible
- If the parcel doesn't saturate, cooling or warming occurs at ***dry adiabatic lapse rate;*** Constant in our atmosphere: **10 °C / km**
- If the parcel does saturate…
  - Condensation (RH = 100%), Latent Heat released; Latent Heating offsets some of the cooling
  - Cooling at slower rate: ***moist adiabatic lapse rate***; Not constant, varies with temperature and moisture; Average value **~ 6 °C / km**
  - Not reversible (heat added, moisture probably removed)
    - » *Pseudo-adiabatic process*

Stability in the atmosphere



If an air parcel is displaced from its original height it can:

- Return to its original height - Stable
- Keep right on moving because it is buoyant - Unstable
- Stay at the place to which it was displaced - Neutral

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Buoyancy

- An air parcel rises in the atmosphere when it's density is less than its surroundings
- Let ρ_{env} be the density of the environment. From the Equation of State/Ideal Gas Law

  $\rho_{env} = P/RT_{env}$

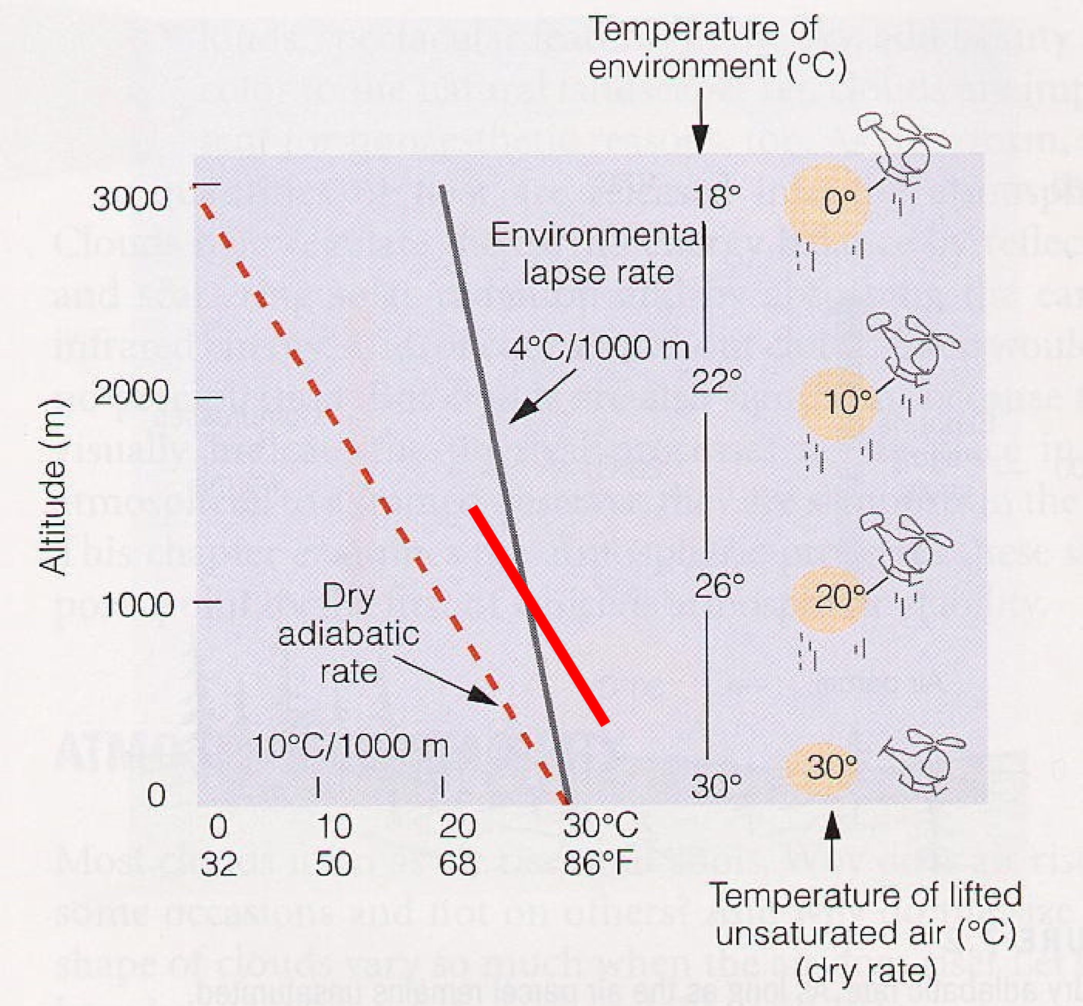
- Let ρ_{parcel} be the density of an air parcel. Then

  $\rho_{parcel} = P/RT_{parcel}$

- Since both the parcel and the environment at the same height are at the same pressure
  - When $T_{parcel} < T_{env}$ $\rho_{parcel} > \rho_{env}$
  - When $T_{parcel} > T_{env}$ $\rho_{parcel} < \rho_{env}$

Stability and the dry adiabatic lapse rate

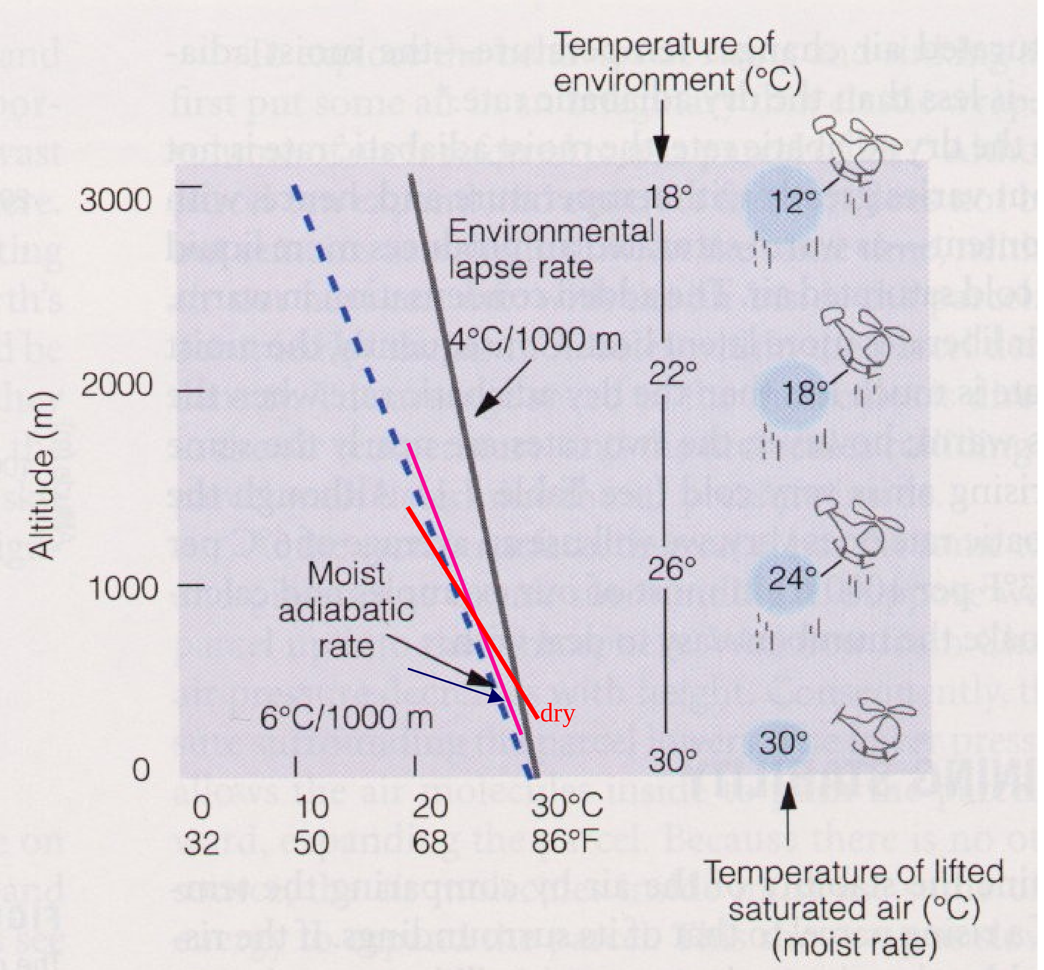
- Atmospheric stability depends on the environmental lapse rate
  - A rising unsaturated air parcel cools according to the dry adiabatic lapse rate
  - If this air parcel is
    - » warmer than surrounding air it is less dense and buoyancy accelerates the parcel upward
    - » Colder than surrounding air it is more dense and buoyancy forces oppose the rising motion



(a) Lifted, unsaturated air at each level is colder and heavier than the air around it. If given the chance, the parcel would return to its original position

Stability and the moist adiabatic lapse rate

- Atmospheric stability depends on the environmental lapse rate
  - A rising saturated air parcel cools according to the moist adiabatic lapse rate
  - When the environmental lapse rate is smaller than the moist adiabatic lapse rate, the atmosphere is termed *absolutely stable*
    - » Recall that the dry adiabatic lapse rate is larger than the moist
  - What types of clouds do you expect to form if saturated air is forced to rise in an absolutely stable atmosphere?



(b) Lifted, saturated air at each position is colder and heavier than the air surrounding it. If released, the parcel would return to its original position.

What conditions contribute to a stable atmosphere?

- Radiative cooling of surface at night
- Advection of cold air near the surface
- Air moving over a cold surface (e.g., snow)
- Adiabatic compression due to subsidence (sinking)

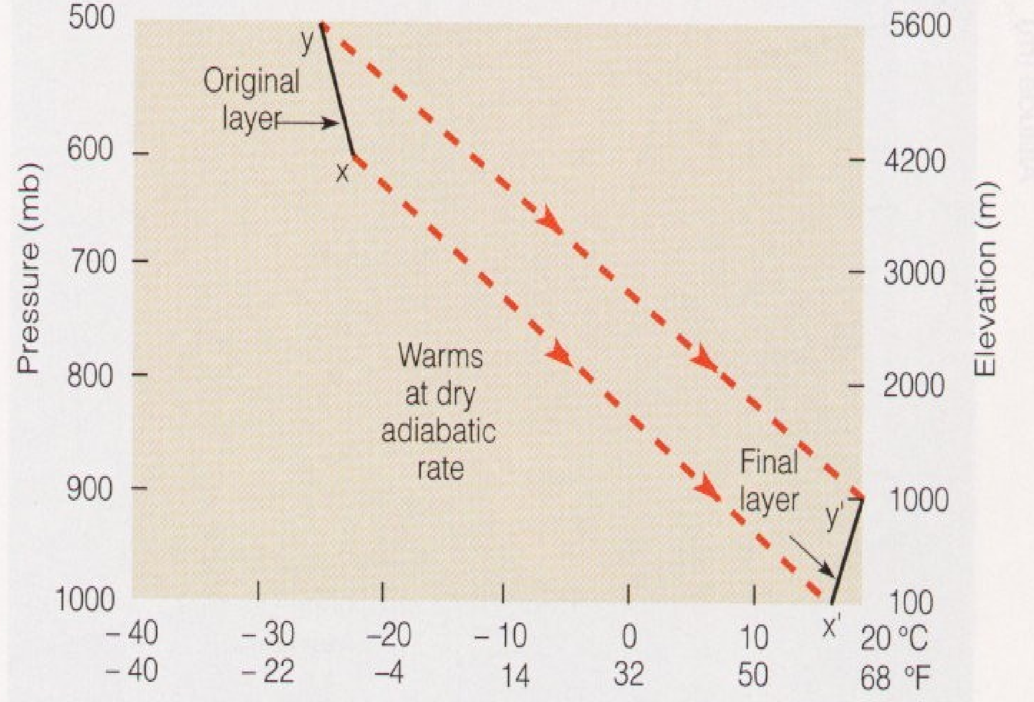
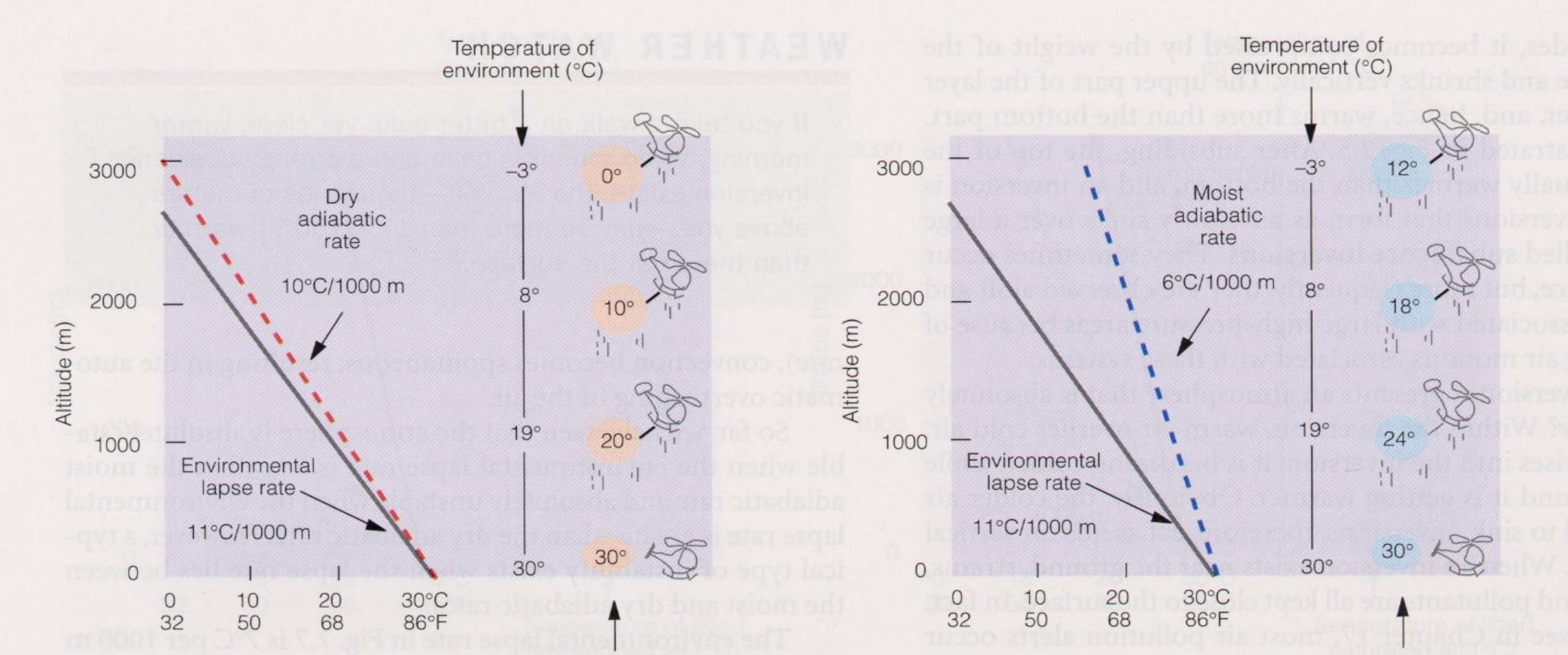


FIGURE 7.5
The layer x–y is initially 1400 m thick. If the entire layer slowly subsides, it shrinks in the more-dense air near the surface. As a result of the shrinking, the top of the layer warms more than the bottom, and the entire layer (x'–y') becomes more stable.

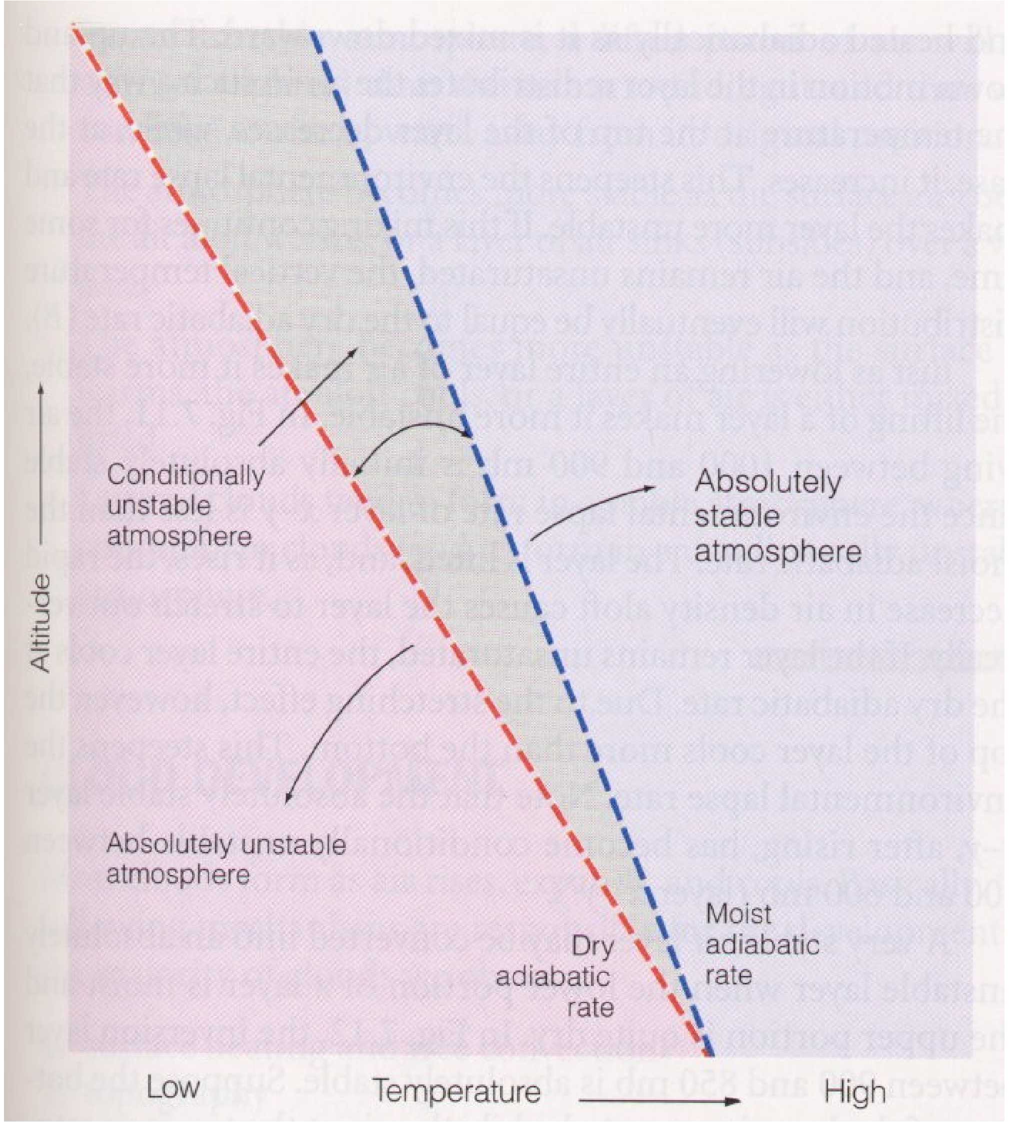
Absolute instability



- The atmosphere is absolutely unstable if the environmental lapse rate exceeds the moist and dry adiabatic lapse rates
- This situation is not long-lived
  - Usually results from surface heating and is confined to a shallow layer near the surface
  - Vertical mixing can eliminate it

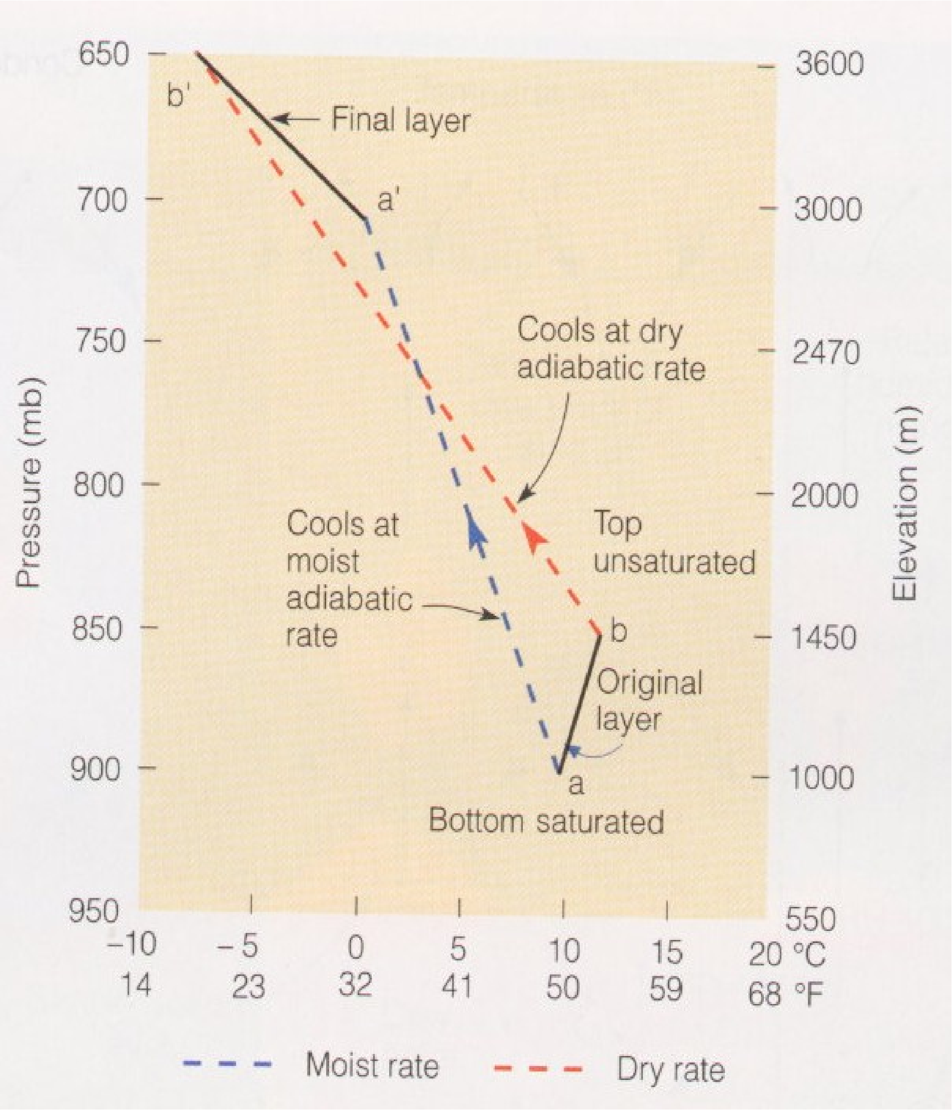
Conditionally unstable air

- What if the environmental lapse rate falls between the moist and dry adiabatic lapse rates?
  - The atmosphere is unstable for saturated air parcels but stable for unsaturated air parcels
  - This situation is termed *conditionally unstable*
- This is the typical situation in the atmosphere



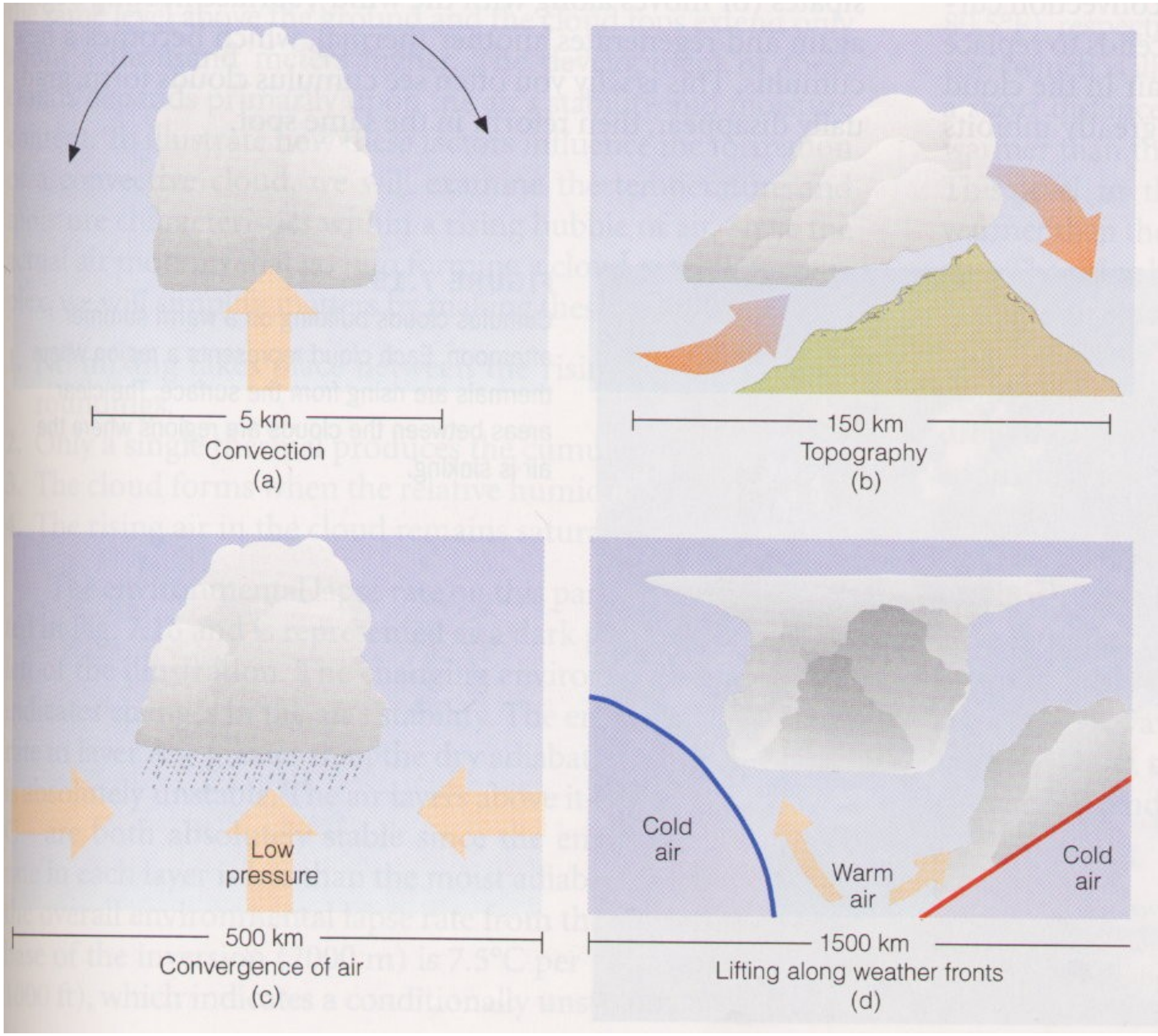
What conditions enhance atmospheric instability?

- Cooling of air aloft
  - Cold advection aloft
  - Radiative cooling of air/clouds aloft
- Warming of surface air
  - Solar heating of ground
  - Warm advection near surface
  - Air moving over a warm surface (e.g., a warm body of water)
    - » Contributes to lake effect snow
- Lifting of an air layer and associated vertical "stretching"
  - Especially if bottom of layer is moist and top is dry



Cloud development

- Clouds form as air rises, expands and cools
- Most clouds form by
  - Surface heating and free convection
  - Lifting of air over topography
  - Widespread air lifting due to surface convergence
  - Lifting along weather fronts



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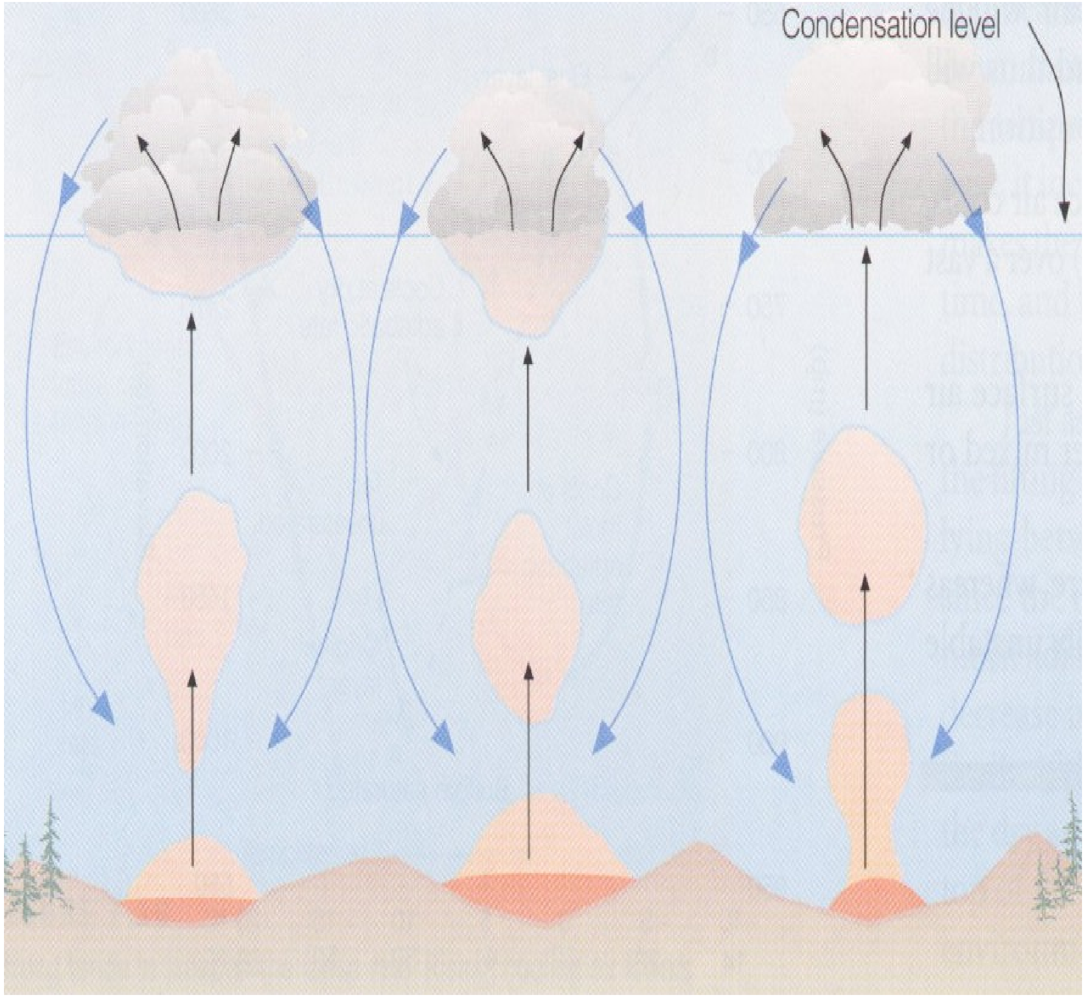
Fair weather cumulus cloud development

- Air rises due to surface heating
- RH rises as rising parcel cools
- Cloud forms at RH ~ 100%
- Rising is strongly suppressed at base of subsidence inversion produced from sinking motion associated with high pressure system
- Sinking air is found between cloud elements
  - Why?



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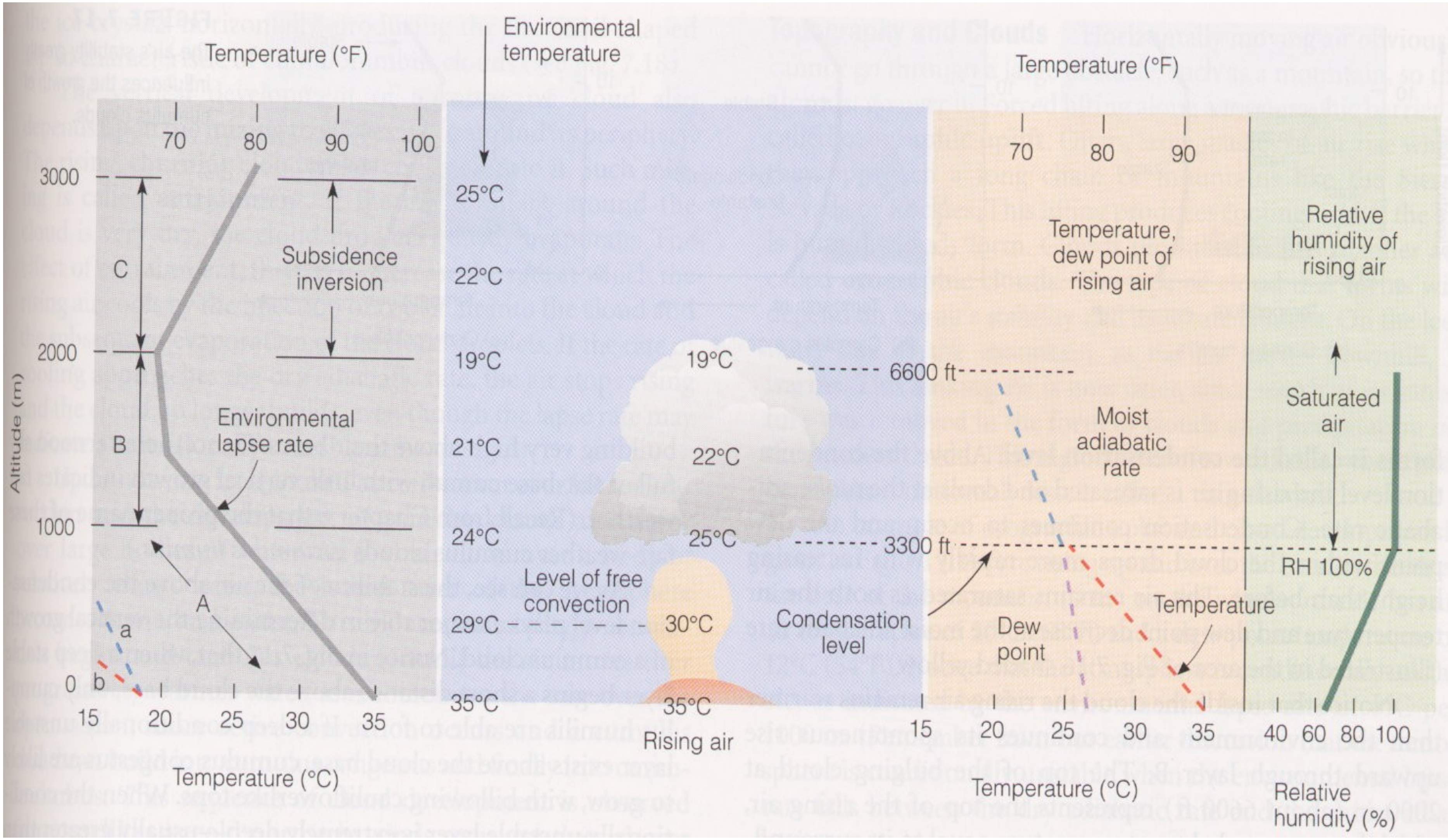
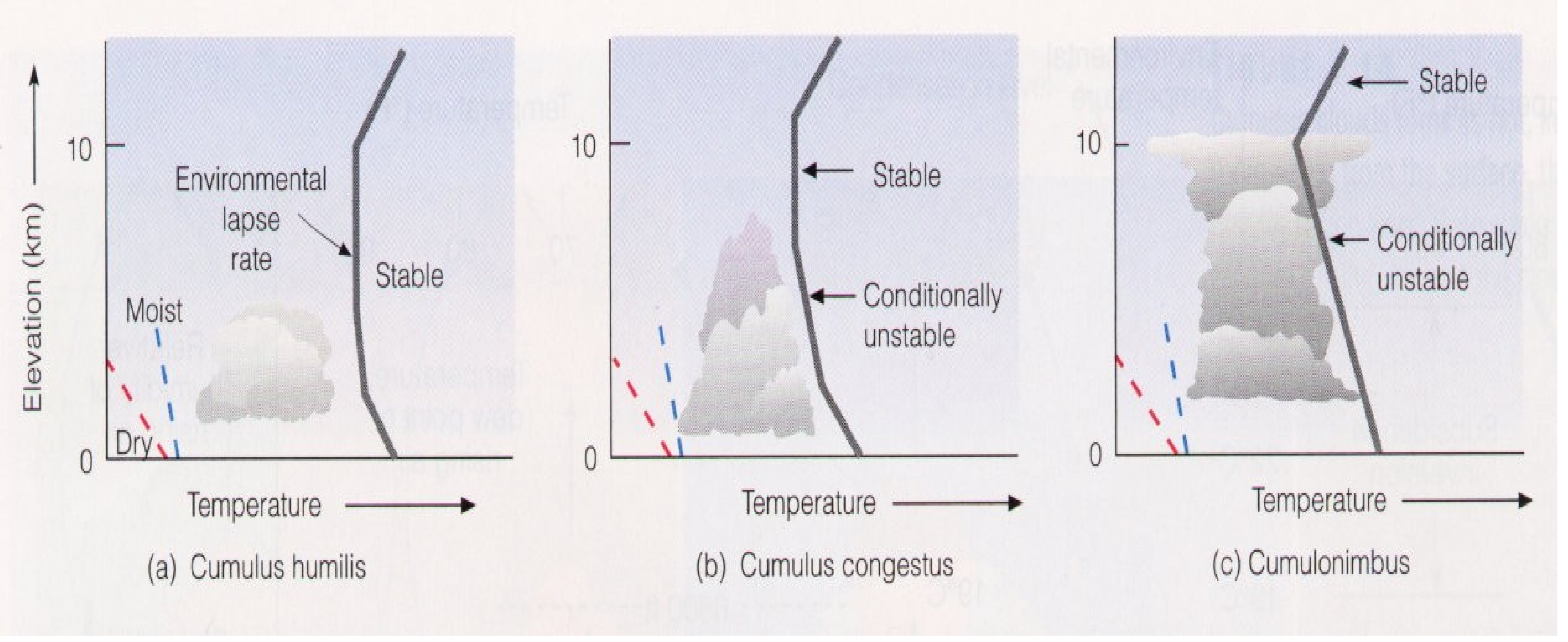
Fair weather cumulus cloud development scheme



What conditions support taller cumulus development ?

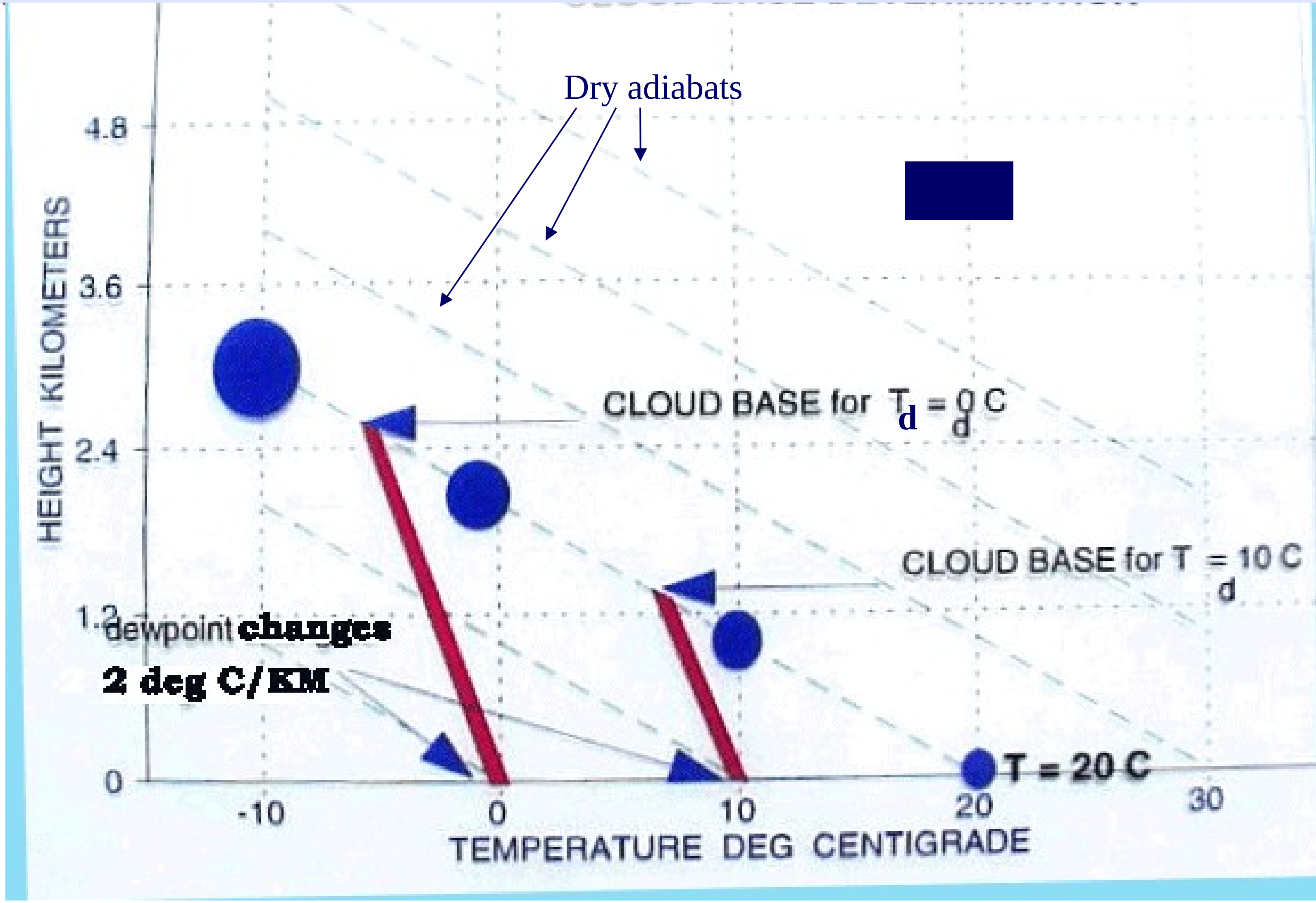
- A less stable atmospheric profile permits greater vertical motion



Rule of thumb for determining Convective Cloud Bases

- Dry air parcels cool at the dry adiabatic rate (about 10 ^{o}C/km
- Dew point decreases at a rate of ~ 2 ^{o}C/km
- This means that the dew point approaches the air parcel temperature at a rate of about 8^{o}C/km
- If the dew point depression were 4^{o}C at the surface, a cloud base would appear at a height of 500 meters
  - Cloud base occurs when dew point = temp (100% RH)
- Each one degree difference between the surface temperature and the dew point will produce an increase in the elevation of cloud base of 125 meters

Rule of thumb for determining Convective Cloud Bases

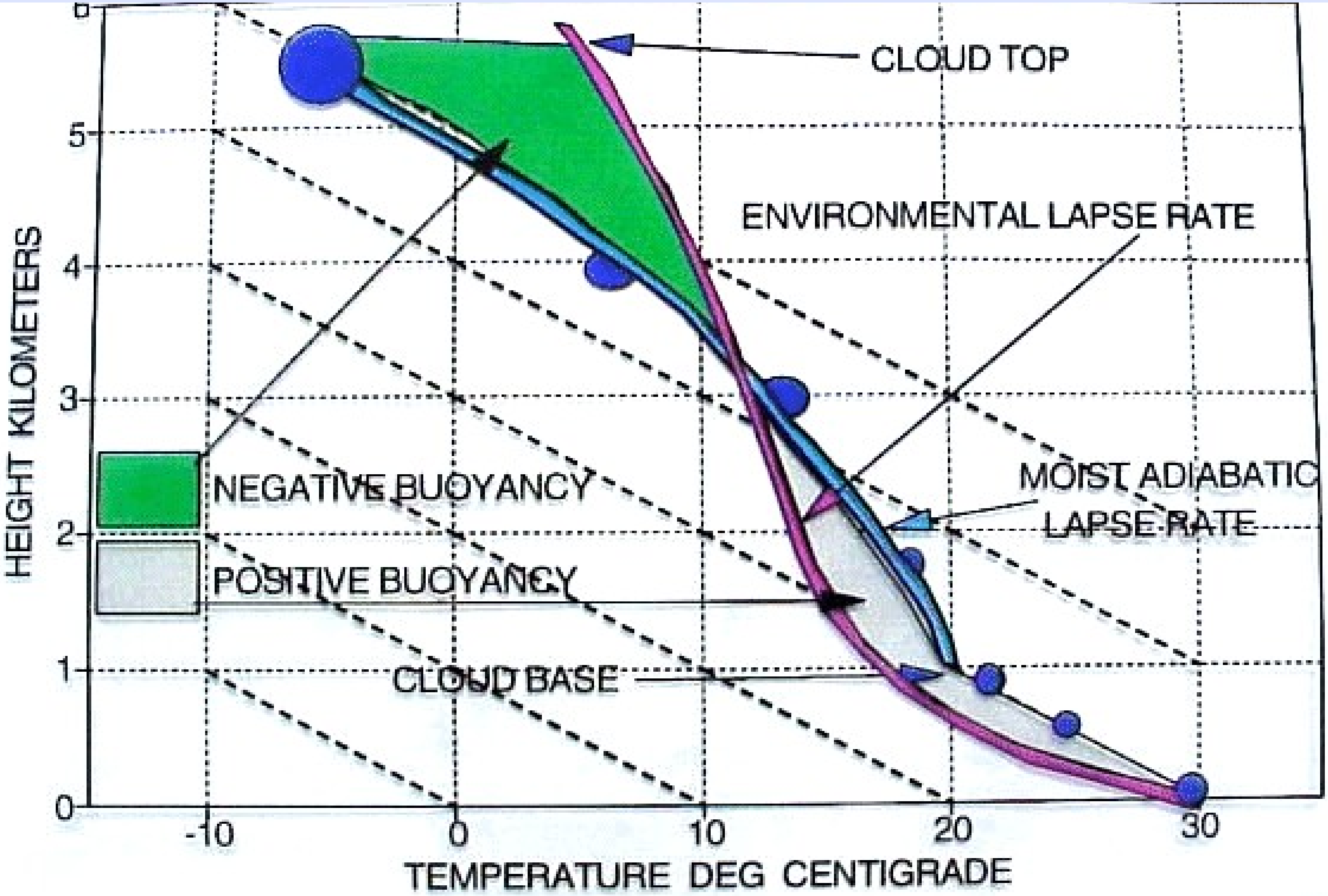


Drier air produces higher cloud bases; moist air produces lower cloud bases

Rule of thumb for determining convective cloud top

- **Cloud top will be defined by the upper boundary to air parcel rise**
- **The area between the dry/moist adiabatic lapse rate, showing an air parcel's temperature during ascent, and the environmental lapse rate, can be divided into two parts**
  - A positive acceleration part where the parcel is warmer than the environment
  - A negative acceleration part where the parcel is colder than the environment
- **The approximate cloud top height will be that altitude where the negative acceleration area becomes nominally equal to the positive acceleration area**

Rule of thumb for determining convective cloud top



Changing cloud forms

- Differential heating/cooling of top and bottom of a continuous cloud layer can cause it to break up into smaller cloud elements
  - Cloud top absorbs solar radiation but cools more quickly by radiative cooling
  - Bottom of cloud warms by net absorption of IR radiation from below
  - The result is that the layer within the cloud becomes less stable and convection may ensue

Dew

- Surfaces cool strongly at night by radiative cooling
  - Strongest on clear, calm nights
- The *dew point* is the temperature at which the air is saturated with water vapor
- If a surface cools below the dew point, water condenses on the surface and dew drops are formed

Frost

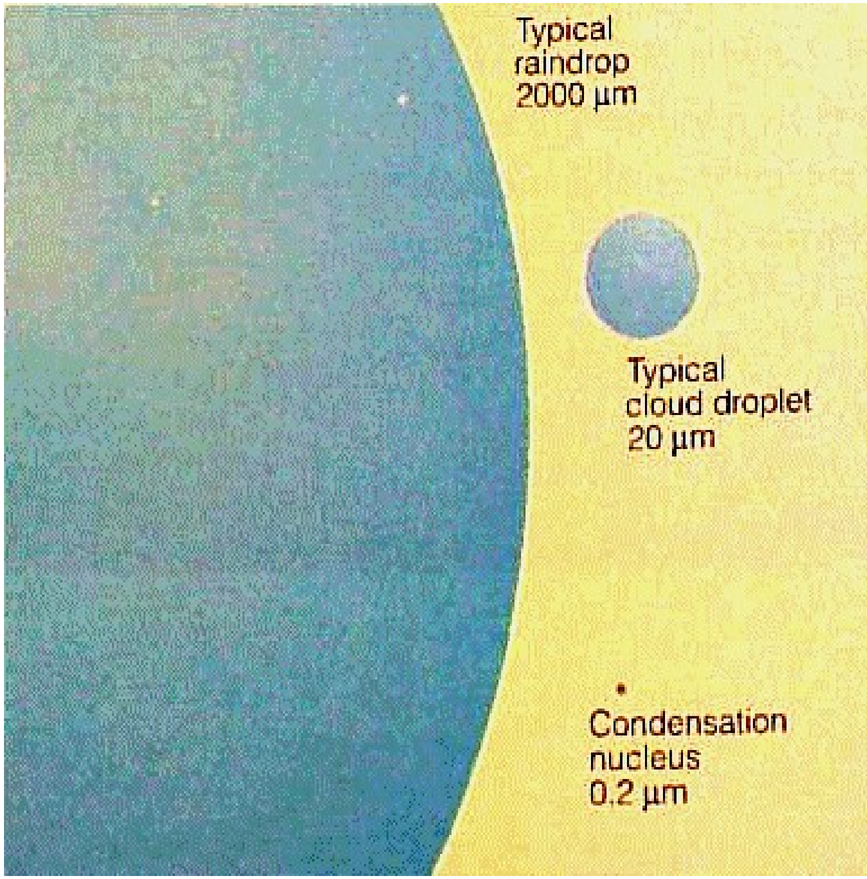
- If the temperature is below freezing, the dew point is called the frost point
- If the surface temperature falls below the frost point water vapor is deposited directly as ice crystals
  - *deposition*
- The resulting crystals are known as frost, hoarfrost, or white frost

Other fenomenon of condensation at the ground

- ***Hoarfrost (Galaverna):*** Formed by solidification of drop of fog (they are always present in liquid shape also with temperatures under 0°C) on objects with temperature inferior to 0°C (because the water is good conductor of heat), generally in the presence of fog all the objects to its inside have the same temperature, for which galaverna cover all surfaces: trees, houses, etc
- ***Glaze (vetrone):*** Formed in the presence of drizzle for solidification on the ground (if it is at a temperature inferior to 0°C) or in case of fog and wind (the last case is rare one in Padana plain but it is frequent in the zones subject to advective fog or in mountain)

Cloud and fog drop formation

- If the air temperature cools below the dew point (RH > 100%), water vapor will tend to condense and form cloud/fog drops
- Drop formation occurs on particles known as cloud condensation nuclei (CCN)
- The most effective CCN are water soluble.
- Without particles clouds would not form in the atmosphere
  - RH of several hundred percent required for pure water drop formation



Effects of cloud condensation nuclei

Results of cumulus clouds grown in marine and continental air

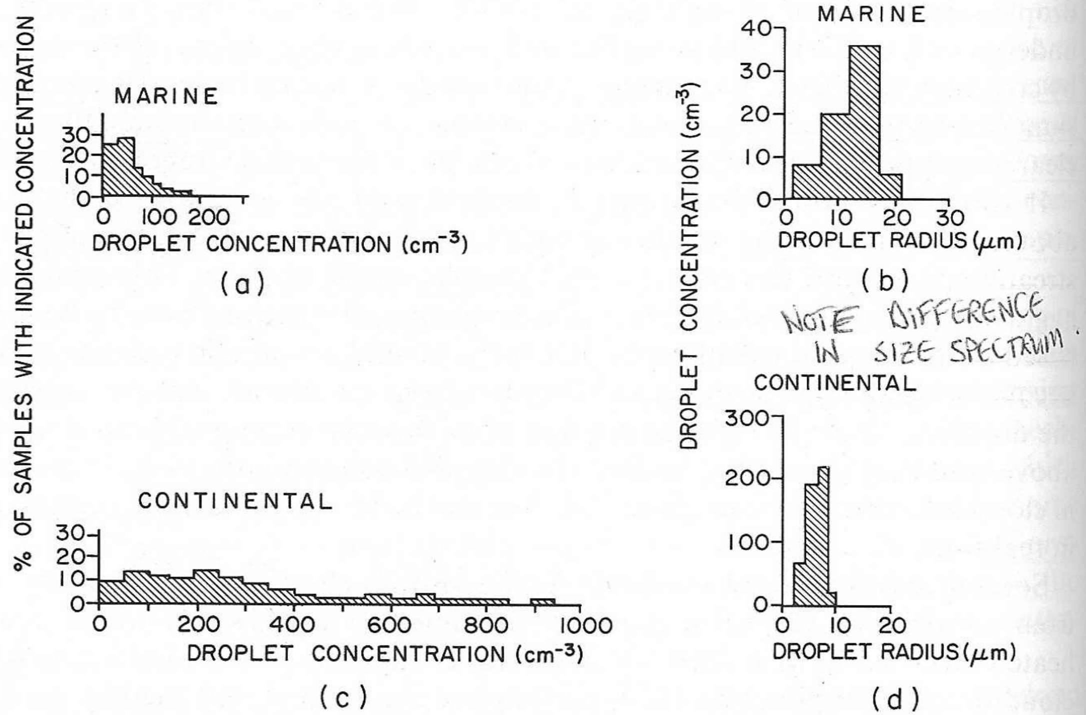


Fig. 4.15 (a) Percentage of marine cumulus clouds with indicated droplet concentrations. (b) Droplet size distributions in a marine cumulus cloud. (c) Percentage of continental cumulus clouds with indicated droplet concentrations. (d) Droplet size distributions in a continental cumulus cloud. Note change in ordinate from (b). [From *Tellus* **10**, 258–259 (1958).]

Cloud liquid water content, drop sizes, and droplets concentration

environment	cloud-type	r	r'	N	L
continental	stratus	4.7	7.3	250	0.28
	cumulus (clean)	4.8	5.8	400	0.26
	cumulus (polluted)	3.5	4	1300	0.3
	cumulonimbus (growing)*	6-8	7-10	~500	1-3
	cumulonimbus (dissipating)*	7-8	9-10	~300	1.0-1.5
	fog	8.1	10.7	15	0.06
maritime	stratus	6.7	11.3	80	0.3
	(strato) cumulus	10.4	12.7	65	0.44
continental or maritime	Cirrus (-25 °C)	-	92	0.11	0.03
	Cirrus (-50 °C)	-	57	0.02	0.002

E. Linacre and B. Geerts, 1999

r (r') = median (effective) radius [microns]

N = # of droplets [# cm^{-3}]

L = liquid water content [g $cm^{-3]}$

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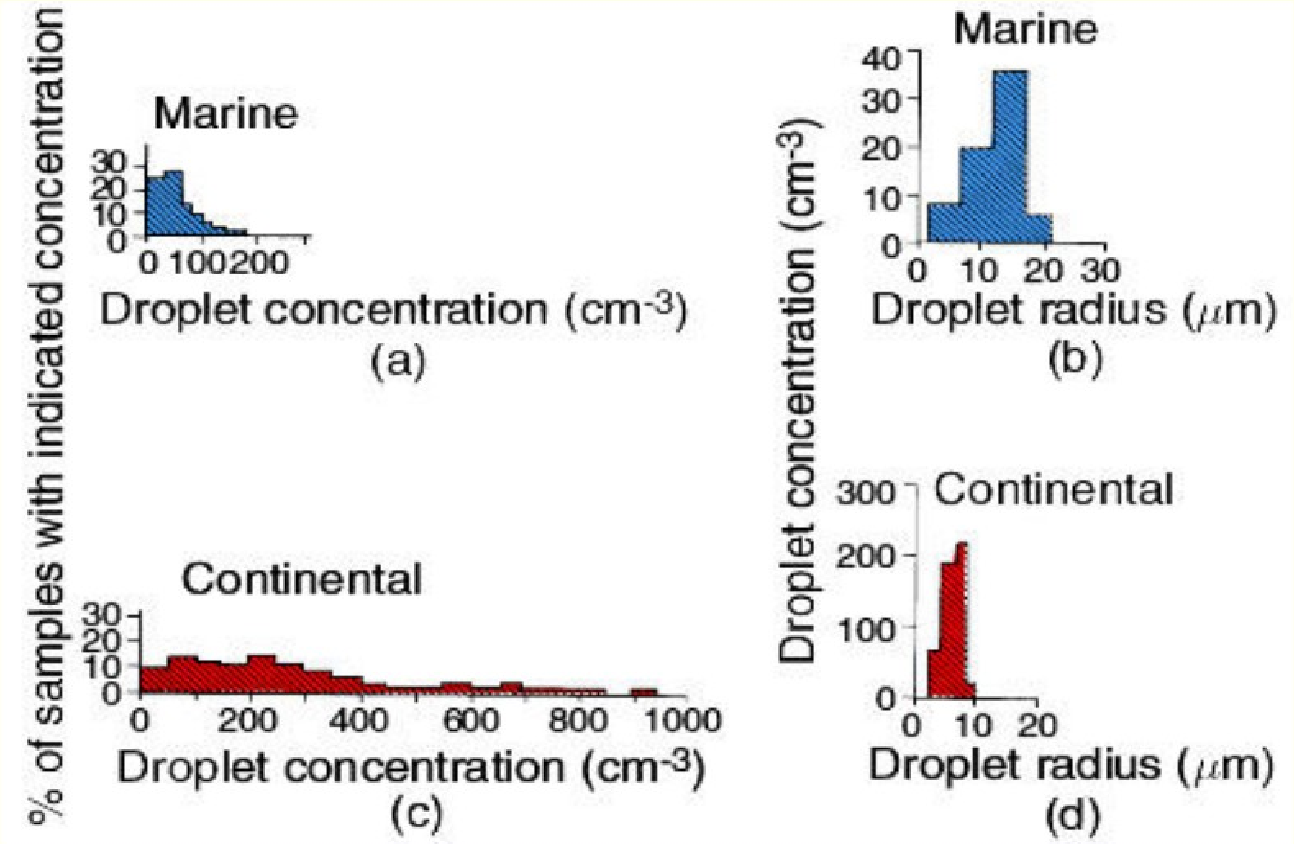
Cloud liquid water content, drop sizes, and droplets concentration



(a) Percentage of marine cumulus clouds with indicated droplet concentrations. (b) Droplet size spectrum in a marine cumulus cloud. (c) Percentage of continental cumulus clouds with indicated droplet concentrations. (d) Droplet size spectrum in a continental cumulus cloud.

Fogs

- Fogs are clouds in contact with the ground
- The cooling of the land (for emission of infrared thermal radiation) → cooling of the low atmospheric layers → decrease of the saturate vapor tension $E_s(T)$ → RH increase → reachment of the dew point $e=E_s(T_d)$ → in case of ulterior temperature decrease there is condensation → formation of dew, frost (hearfrost) or fog
- Such phenomena are common in winter inside of windows; dew on the cold bottles in summer; dew on mirror after the shower in the bathroom

- Several types of fogs commonly form
  - Radiation fog
  - Advection fog
  - Upslope fog
  - Evaporation (mixing) fog

Radiation Fog

- Surface radiation and conduction of heat away from the overlying air cool air temperatures near the ground
- A layer of air near the ground becomes saturated and fog forms
- Fog deepens as radiative cooling from the fog top continues overnight
- Solar heating warms the ground and causes the fog to “burn off” from the ground up
- What type of meteorological conditions would favor radiation fog?

Advection Fog

- Warm air moves (is *advected*) over cold surface
- Cold surface cools warm air
- If saturation is reached, fog forms
- Common on west coast of U.S.
  - Warm moist air from Pacific is advected over upwelling cold coastal waters
  - As foggy air moves ashore, solar heating warms the ground and overlying surface
    - » Fog evaporates near ground
  - Coastal advection fogs are key moisture sources for California Redwoods

Frederic Larson / The Chronicle

Other Fog Types

- Evaporation (mixing) fog
  - Mixing of warm, moist air with colder air produces saturated air parcel
  - Examples
    - » Exhale on a cold day
    - » Evaporation of water from relatively warm, wet surface and mixing with colder air above.
    - » (Smokestack plume, contrails)

- Upslope fog
  - Moist air flows up along sloped plain, hill or mountain
  - Expansion of rising air causes cooling and RH increases

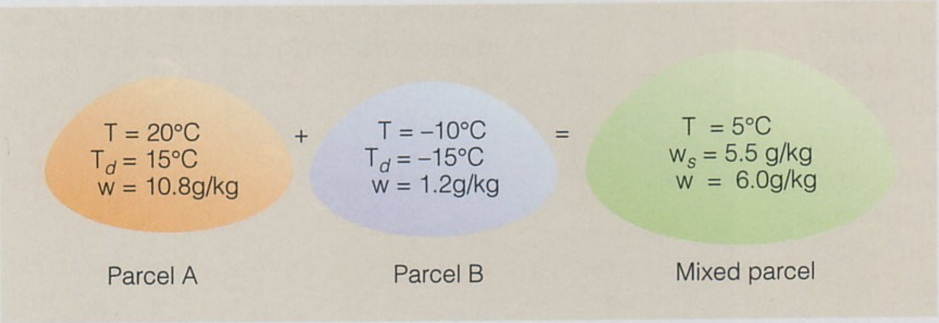


FIGURE 2
The mixing of two unsaturated air parcels can produce fog. Notice in the saturated mixed parcel that the actual mixing ratio (*w*) is too high. As the mixed parcel cools below its saturation point, water vapor would condense onto nuclei, producing liquid droplets. This would keep the actual mixing ratio close to the saturation mixing ratio, and the relative humidity of the mixed parcel would remain close to 100 percent.

Fogs and visibility

- Light scattering by fog drops (geometric scatterers) degrades visibility, leading to
  - Traffic fatalities
  - Airport accidents and closures
- Remedies
  - Fog monitoring and warning (optical sensors)
  - Fog dispersal (expensive and of limited utility)

FIGURE 3
Helicopters hovering above an area of shallow fog (diagram a) can produce a clear area (photograph b) by mixing the drier air into the foggy air below.

Clouds

- Clouds just don't happen - there's always a reason
- A particular cloud's shape and location depend on (and can therefore tell us about): the movement of the air; amount of water vapor in air; stability (flat clouds = stable air while puffy clouds = unstable air)
- Clouds result when air becomes saturated away from the ground
- They can
  - be thick or thin, large or small
  - contain water drops and/or ice crystals
  - form high or low in the troposphere
  - even form in the stratosphere (important for the ozone hole!)
- Clouds impact the environment in many ways
  - Radiative balance, water cycle, pollutant processing, earth-atmosphere charge balance, etc….

Cloud Classification

- In 1803, **Luke Howard** devised the basic system of cloud classification, still used today
- Based on Latin names
- **Two parts to a cloud's name**:
  - **Shape** (example: cirrus, stratus, cumulus)
  - **Height** (cloud base & vertical extent)
  - also important is the appearance of the cloud
- Shapes
  - Cirrus = curly and wispy
  - Stratus = layered or stratified
  - Cumulus = lumpy or piled up
- Heights
  - Cirro = high level (bases above 7 Km)
  - Alto = mid level (bases 2-7 Km)
  - Nimbo = producing precipitation
  - Cumulo = vertically extended

Classification of clouds using *latin* names

- Based on their **form**:

  cirrus, i.e. fibrous (*cirrus*=hair) as formed by ice

  layered, i.e. most developed horizontally than vertically, also disposed in many vertical layers, associated with small verical velocities (≅ 30 m/s or more)

  cumuliform i.e. puffy, covering small areas, associated with large vertical velocities (≅ 30 m/s or more)

- Based on the **heigth of their basis**:

  high (7-18 Km), with T < -25 °C formed completely by ice

  medium (2-7 Km), with (-25 < T < 0) °C composed by supercooled water sometimes mixed with ice

  low (0-4 Km), with T > -5 °C composed by water droplets

  vertically developed (0-3 Km), they begin at the LCL

- Subclassified on the basis of their **somatic characteristics**:

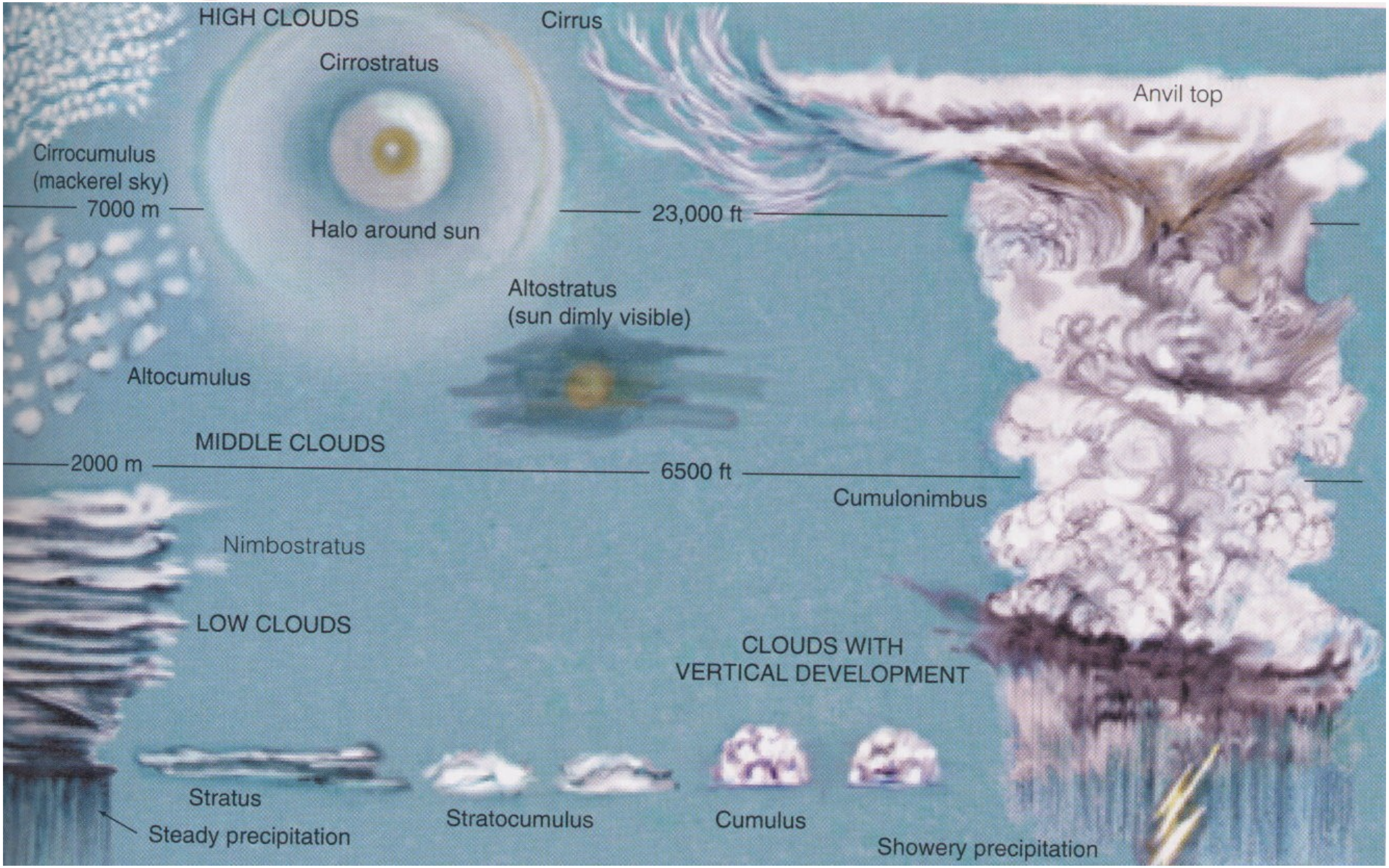
  castellanus developed with tower shape
  congestus crammed in piles

  fractus indented
  humilis vertically not much developed

  lenticularis shaped like a lens
  mammatus with roundish protrusions

  uncinus shaped like a hook

Cloud type summary



High Clouds

- High clouds
  - White in day; red/orange/yellow at sunrise and sunset
  - Made of ice crystals
  - Cirrus
    - » Thin and wispy
    - » Move west to east
    - » Indicate fair weather
  - Cirrocumulus
    - » Less common than cirrus
    - » Small, rounded white puffs individually or in long rows (fish scales; mackerel sky)
  - Cirrostratus
    - » Thin and sheetlike
    - » Sun and moon clearly visible through them
    - » Halo common
    - » Often precede precipitation

- Cirrus = high altitude wispy clouds
- Quite thin and often have a hairlike or filament type of appearance.
- Made up of ice particles
- The curled up ends (called mares' tales) as depicted in the following picture are very common features.

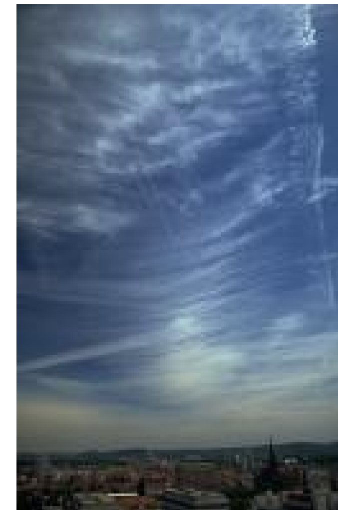
High Clouds: cirrus

Cirrus (Ci) transparent filamentous in the form of silk string, delicate, so-called “a tail of horse”; filaments are due to strong wind which disperse crystal ice; they do not form shadows










Cirrus

Cirrus

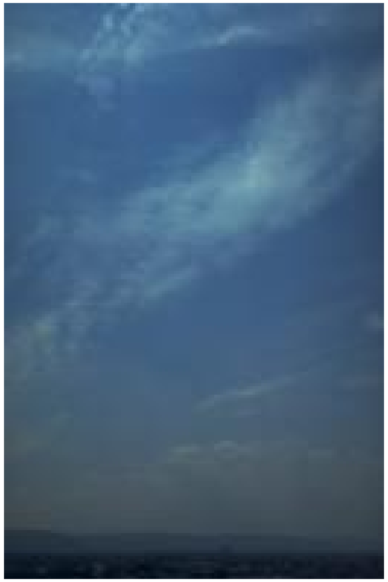
Cirrus Display at Dawn

Cirrus

Cirrus with virga

Cirrocumulus

- Cirrocumulus (Cc) small roundish white globes disposed in wave-like way, rarely cover all the sky; they do not prevent the shadows



Cirrocumulus

- High cumulus clouds
- Can see individual “puffy” features

Cirrocumulus

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Cirrocumulus

Cirrocumulus at Sunset

Cirrostratus

Cirrostratus (Cs) nearly transparent, leaves to pass (more or less) the sun, formed in a white thin veil (or sheet) which covers partially or totally the sky; it does not prevent the shadows




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Cirrostratus

- High-level stratus clouds
- Not as thin as cirrus and less defined than cumulus

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Cirrostratus

Cirrostratus with Halo

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Contrails

- Contrail is short for “condensation trails”
- Formed from vapor contained in the exhaust of a jet engine when it condenses in cold air aloft