Cloud Physics and Modeling

Course on “atmospheric aerosols and clouds with
introduction to process oriented modeling”,
Sao Paulo University

Vaughan.Phillips@nateko.lu.se

Plan

- 1st lecture (L3, 18 March): microphysics of hydrometeors
- 2nd lecture (L4, 18 March): dynamics of clouds and moisture
- 3rd – 6th lectures (L5-8, 19-20 March): introduction to cloud modeling

- Exercises in MATLAB (18-20 March, afternoons):
  - simulate drop growth
  - create parcel model of cloud

FURTHER READING

Highly recommended:

- Rogers, R. R., and M. K. Yau, 1991: *A short course in cloud physics*. Pergamon Press
- Bluestein’s textbook

Optional extra reading:

- Houze, R. A., 1993: *Cloud dynamics.* Academic Press
- Houghton, H. G., 1985: *Physical Meteorology*. MIT Press
- Wallace, J. M., and P. V. Hobbs, 1977: *Atmospheric science - an introductory survey.*
- Barry, R. G., and R. J. Chorley, 1987: *Atmosphere, Weather and Climate.* Routledge

Cloud Microphysics and Properties. Part I: Cloud-particles and Precipitation

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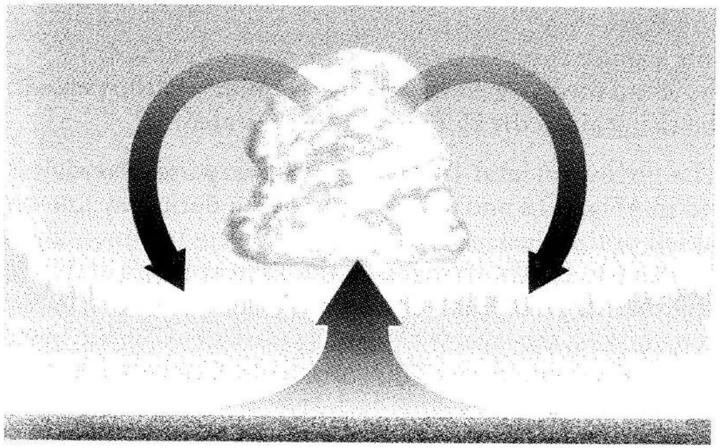
Outline

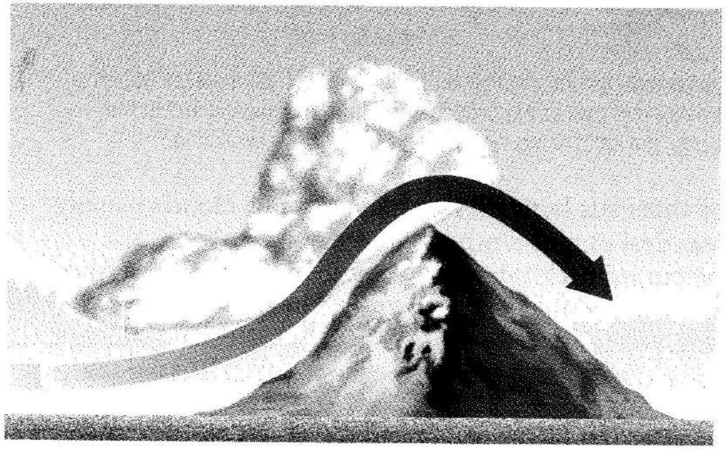
- Introduction to Clouds
- Nucleation and Growth of Hydrometeors
- Basic Cloud-types
- Types of Precipitation
- Classification of Precipitation Systems
- Aerosol-cloud interactions and cloud-radiation feedbacks
- Summary

INTRODUCTION TO CLOUDS

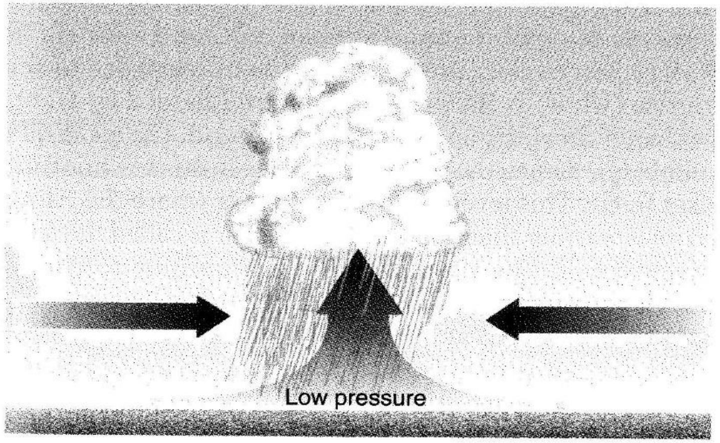
Usually, clouds form when air ascends to saturation



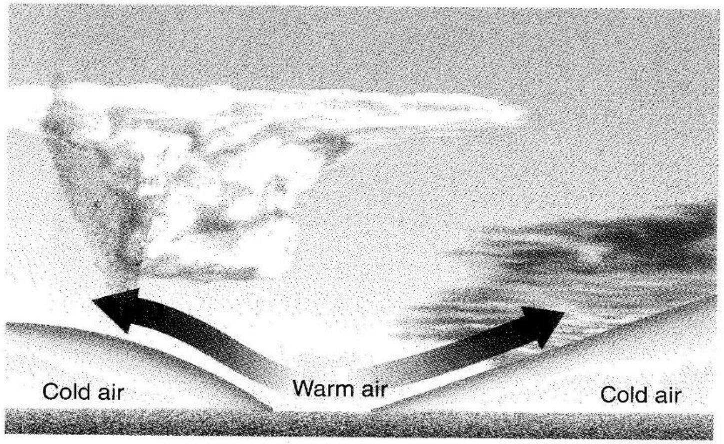
5 km
Convection
(a)



150 km
Lifting along topography
(b)



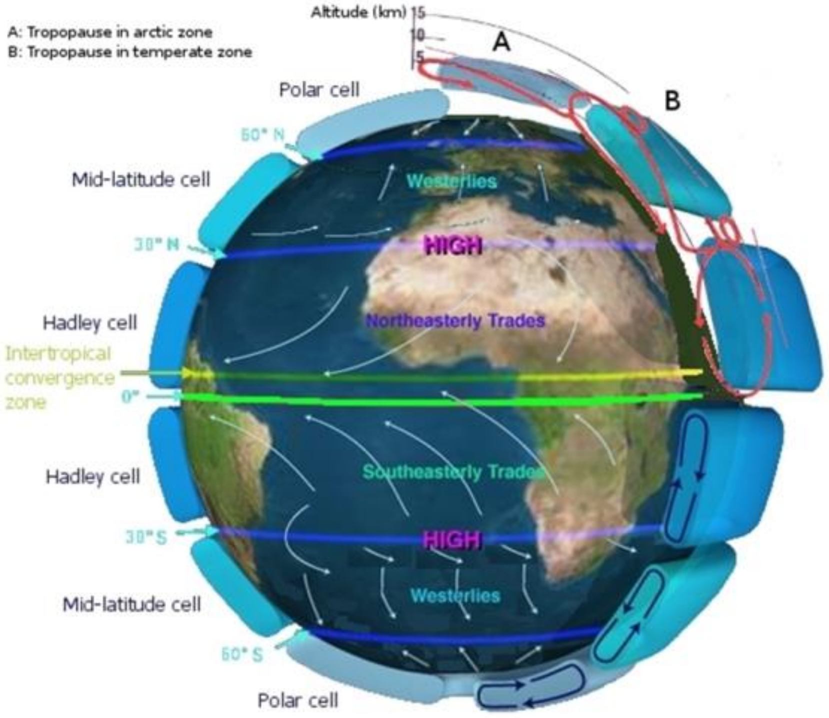
500 km
Convergence of air
(c)

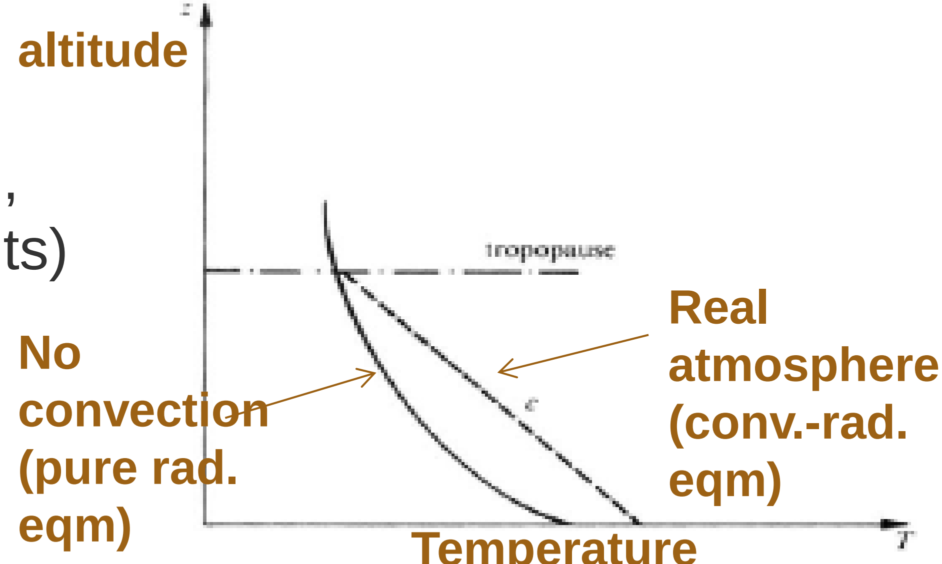


1500 km
Lifting along weather fronts
(d)

Role of convection

- Much ascent of tropical (e.g. ITCZ) and mid-latitude cells of global circulation is in convective clouds
  - These cells transport heat from excess to deficit regions, and vertically too
  - Outflow affects radiation
- Deep convective clouds mix boundary layer air – with moisture, aerosols, and gases (e.g. pollutants) – up into the free-troposphere
- Can cause severe weather
  - Hail damage, lightning, floods

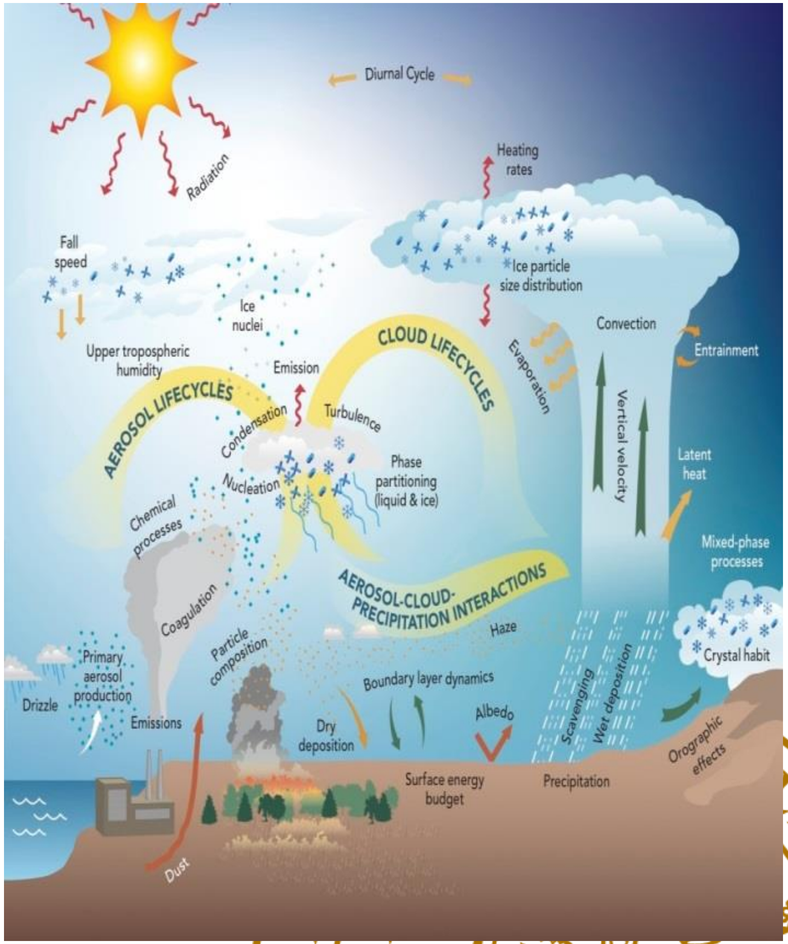




Houghton (1985)

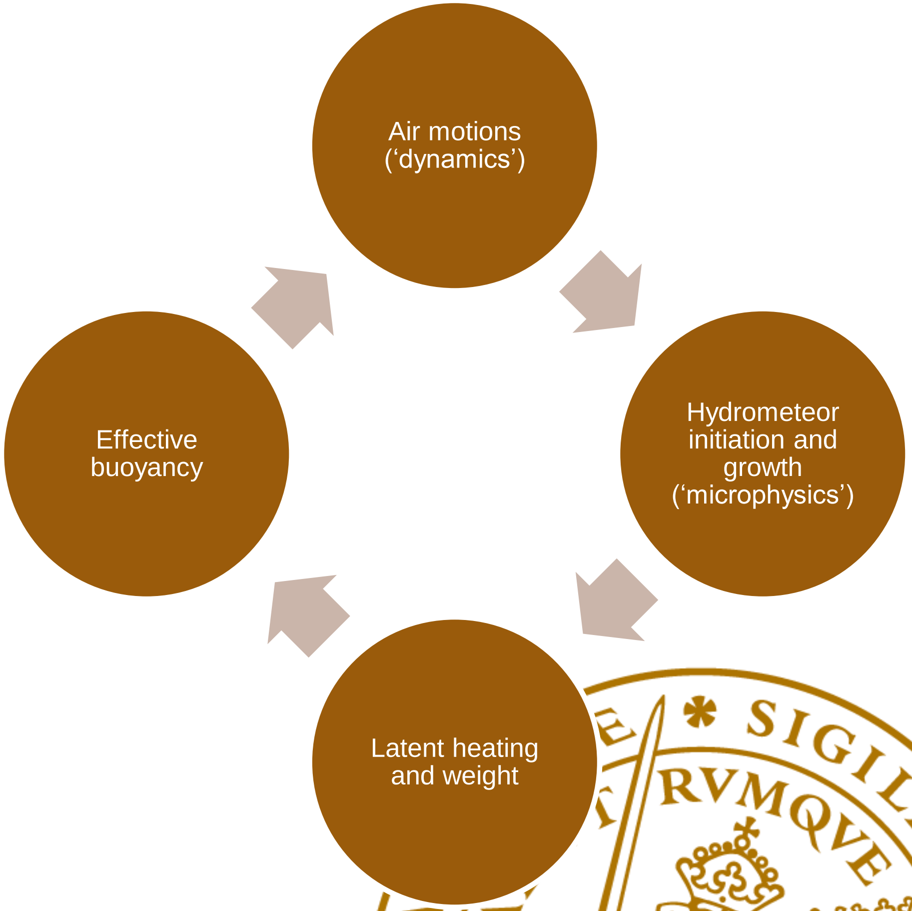
Chemistry in Deep Convection

- Clouds provide environment for aqueous-phase chemical reactions
- Aerosol particles modified in clouds
  - Aqueous-phase reactions with gases dissolved in droplets
  - Coalescence of droplets brings dissolved material of many aerosols together
    - Chemically different aerosol may react
    - On evaporation of droplet, a single aerosol particle is formed, containing material from all contributing droplets
    - Outflow from deep convection is source of smallest aerosols aloft



Microphysics-dynamics coupling

- Concentration, sizes and phase of hydrometeors are governed by:
  - air motions in-cloud
  - and aerosol conditions
    - E.g. Precipitation from riming, accretion, coalescence, aggregation … depend on updraft speed and entrainment
- **Release of latent heat** from phase changes in formation of cloud and precipitation, and weight, modify the buoyancy and vertical air motions
  - Complex feedbacks between microphysics and dynamics



Air motions ('dynamics')

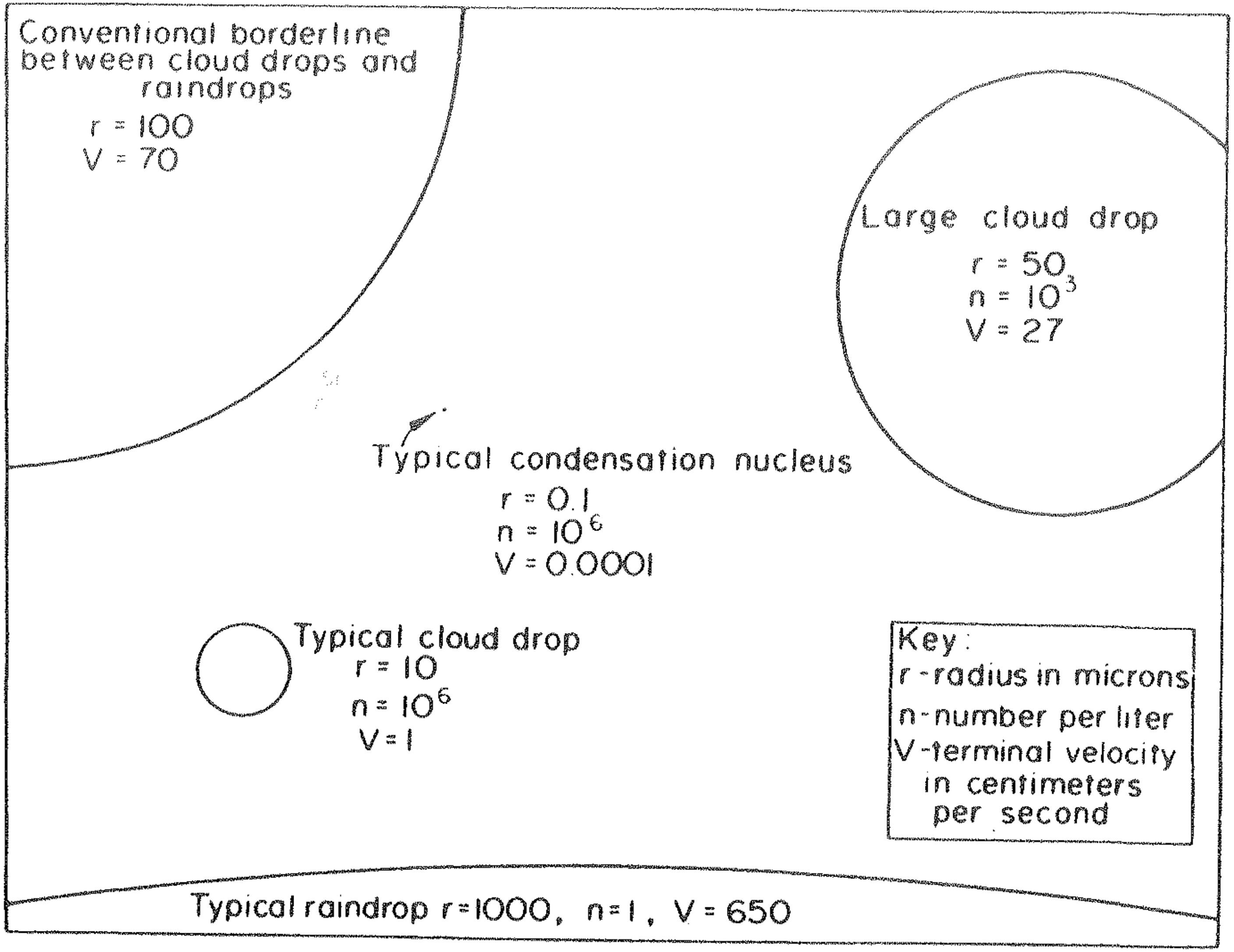
Hydrometeor initiation and growth ('microphysics')

Latent heating and weight

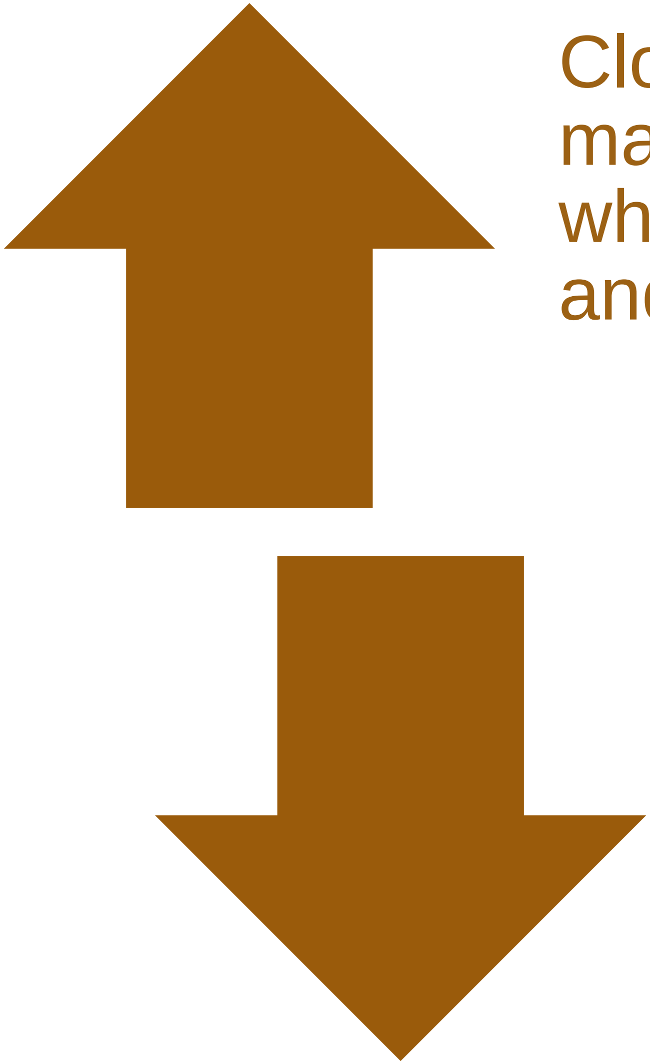
Effective buoyancy

NUCLEATION AND GROWTH OF HYDROMETEORS

Types of particle in atmosphere



Two general types of hydrometeor related to clouds



Clouds consist of many **cloud-particles,** which are < ~0.1 mm and suspended in air

Precipitation is > ~0.1 mm and falls out of clouds towards Earth’s surface

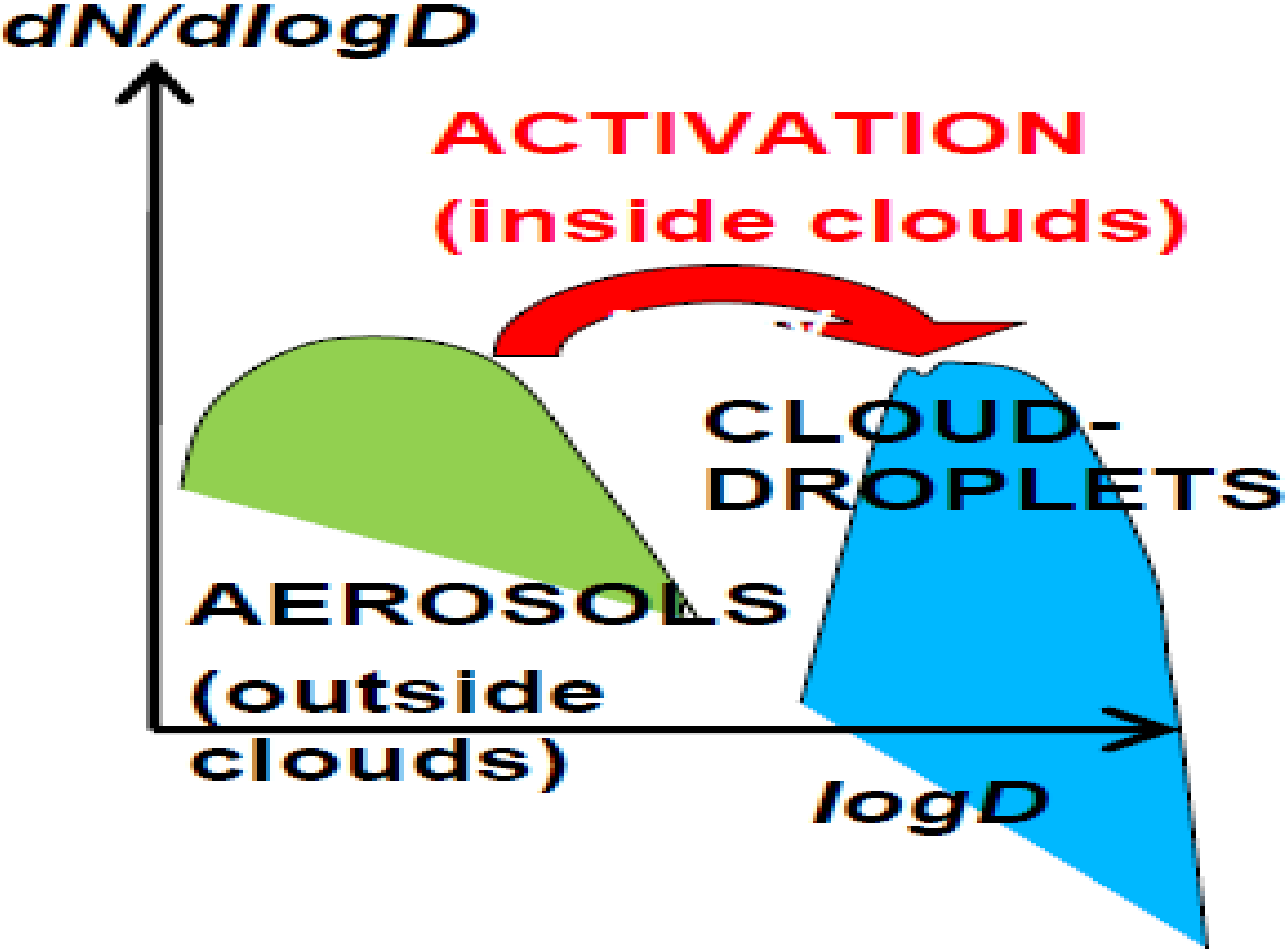
- Only generated by clouds that are deep enough

- Cloud-droplets and ice crystals are cloud-particles

- Each cloud-droplet forms on a cloud-**condensation nucleus (CCN) aerosol**; growth then occurs by condensation
  - CCN aerosols are abundant everywhere
  - Number of cloud-droplets governed by (ascent-dependent) supersaturation of vapour
  - Aerosols consist of foreign material (e.g. dissolved in water) and are usually sub-micron (mostly 1 nm – 1 μm)

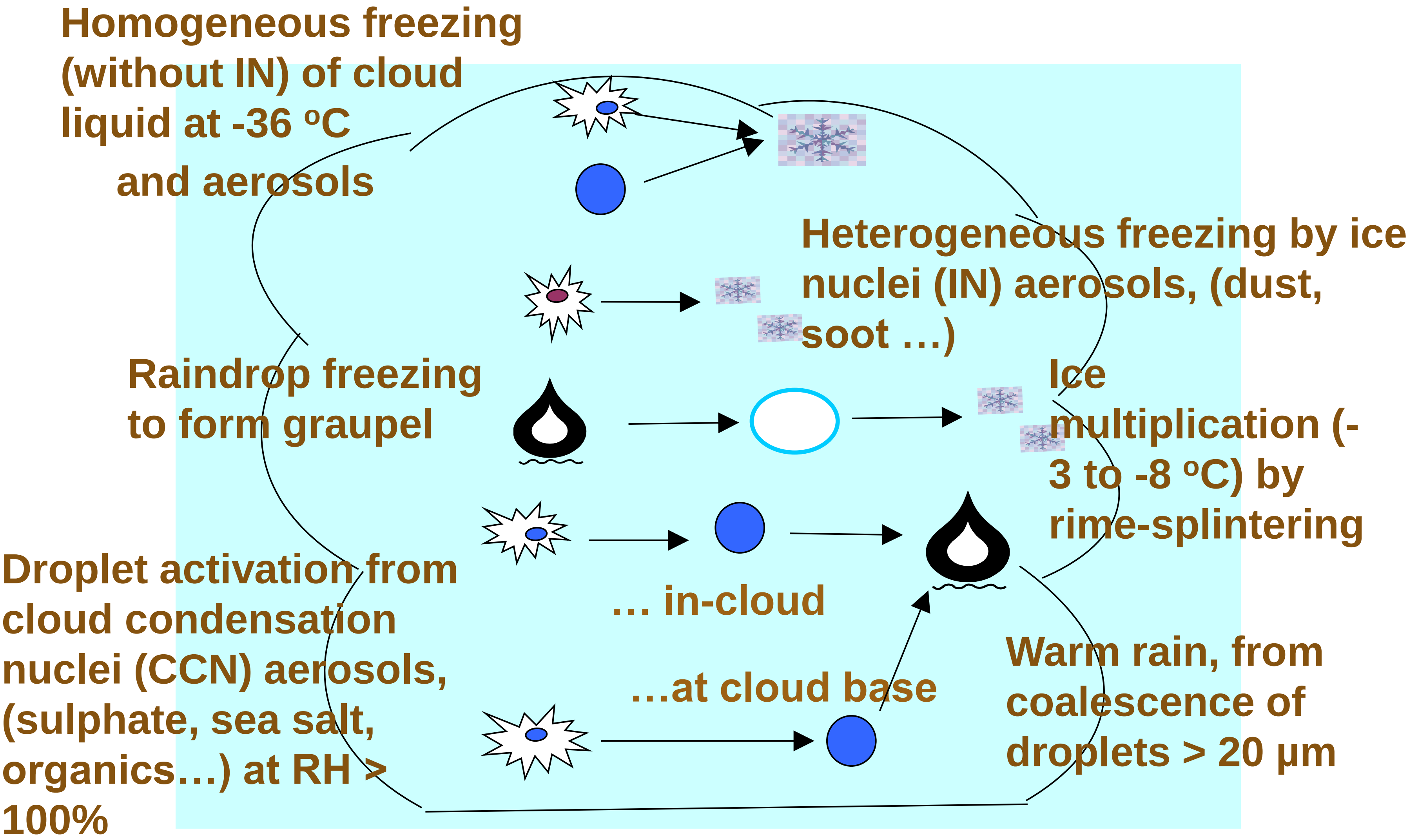
- **Cloud droplets** are 1 to 100 μm in diameter and grow only by condensation initially
  - Condensation/evaporation growth can occur within a few 10s of seconds when smallest, but is slower at larger sizes

- **Raindrops** are 0.1 to 5 mm in diameter, growth from vapour would take hours – longer than lifetime of convective clouds.



dN/dlogD
ACTIVATION
(inside clouds)
CLOUD-
DROPLETS
AEROSOLS
(outside
clouds)
logD

Cloud microphysics - overview



Homogeneous freezing (without IN) of cloud liquid at -36 ^{o}C

and aerosols

Heterogeneous freezing by ice nuclei (IN) aerosols, (dust, soot …)

Raindrop freezing to form graupel

Ice multiplication (-3 to -8 ^{o}C) by rime-splintering

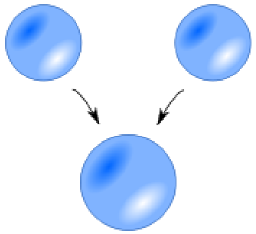
Droplet activation from cloud condensation nuclei (CCN) aerosols, (sulphate, sea salt, organics…) at RH > 100%

… in-cloud

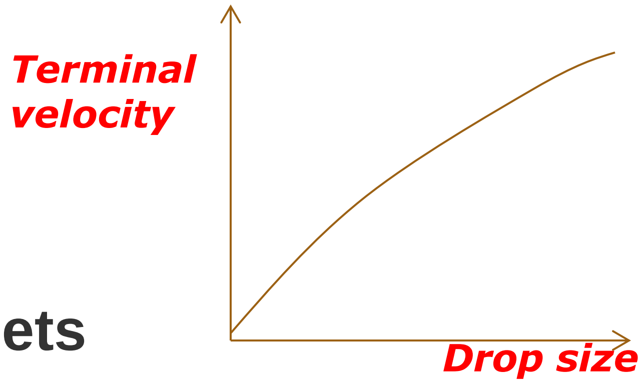
…at cloud base

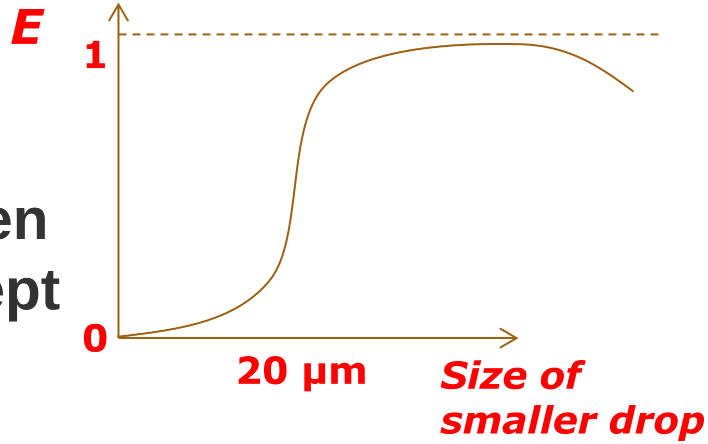
Warm rain, from coalescence of droplets > 20 µm

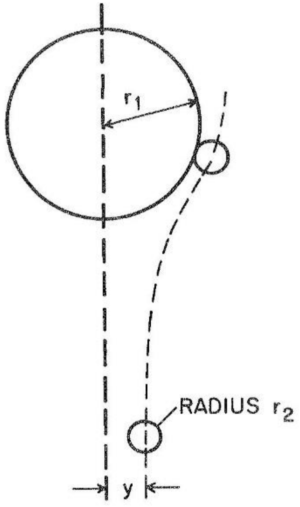
Coalescence of cloud-droplets



- Cloud = very many cloud-droplets (1-100 µm) suspended in air
- Collision efficiency, *E*
  - *E* = Probability of collision, given that smaller drop is in path swept out by larger one
  - *E* ≈ 0 for smallest cloud-droplets, as smaller drop follows airflow around larger drop
    - smaller drops fall slower (drag)
- Rain (> 0.1 mm) only if mean size of cloud-droplets is > 20 µm near cloud-top







BASIC CLOUD-TYPES

General Types of Clouds

- 3 broad types:
  - **Convective (or ‘cumuliform’) clouds: fast ascent**
    - cells of buoyant convection, occupying any depth of troposphere,
    - due to anomalies in parcel temperature.
  - **Stratiform clouds: weak ascent**
    - widespread layers of statically stable air in lower or mid-troposphere
  - **Cirriform clouds: weak ascent**
    - widespread layers of ice-cloud in upper troposphere

General Types of Clouds

General types	Ascent	Time-scale	Width, *L*, and depth, *H*	In-cloud temperatures	Level of cloud-base	Precipitation rate at surface, if deep	Phase of condensate
convective	> 1 m/s in updraft, due to buoyancy force	< 1 hr	L ~ H	Any	Usually low, sometimes middle	> 25 mm/hr	Liquid below 0 °C level, mixed-phase or ice-only above
stratiform	< 1 m/s	Many hrs	L >> H	> -32 °C	Low or middle	< 25 mm/hr	
cirriform	< 1 m/s			< -32 °C	High	~ 0	Ice-only

More Detailed Classification of Clouds

High Level: (*cirro-*)

- Cloud base colder than about -30 degC (higher than 6 km usually)
- Are all forms of cirrus (ice clouds)

Medium (or ‘middle’) Level: (*alto-*)

- Cloud base above boundary layer 2000-6000m

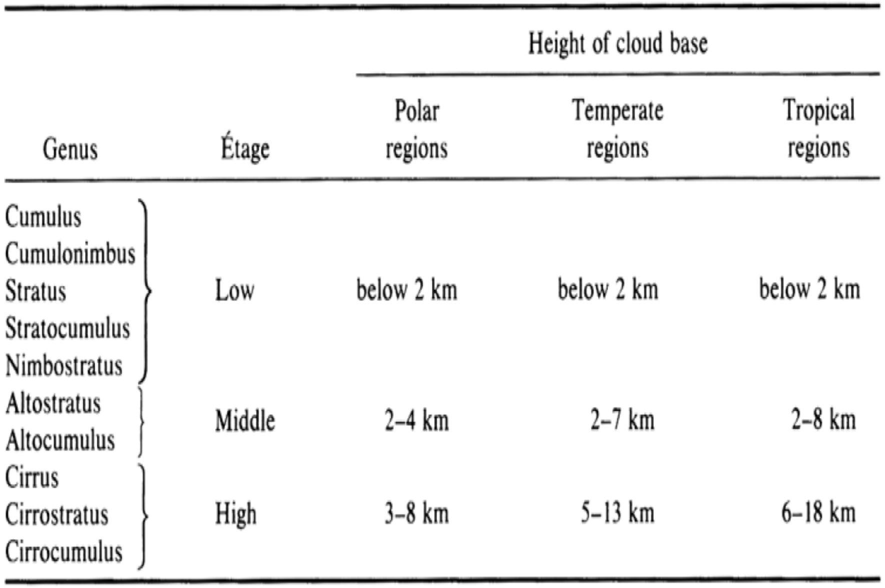
Low level:

- Cloud base below 2000m (within boundary layer)
- Most convective clouds, globally, are low

Most Detailed Classification of Clouds

Latin basis for naming clouds:

- **Cirrus** : fibrous or hair-like
- **Cumulus** : a heap or pile (vertically developed)
- **Stratus** : a horizontal sheet or layer
- **Nimbus** : rain-bearing

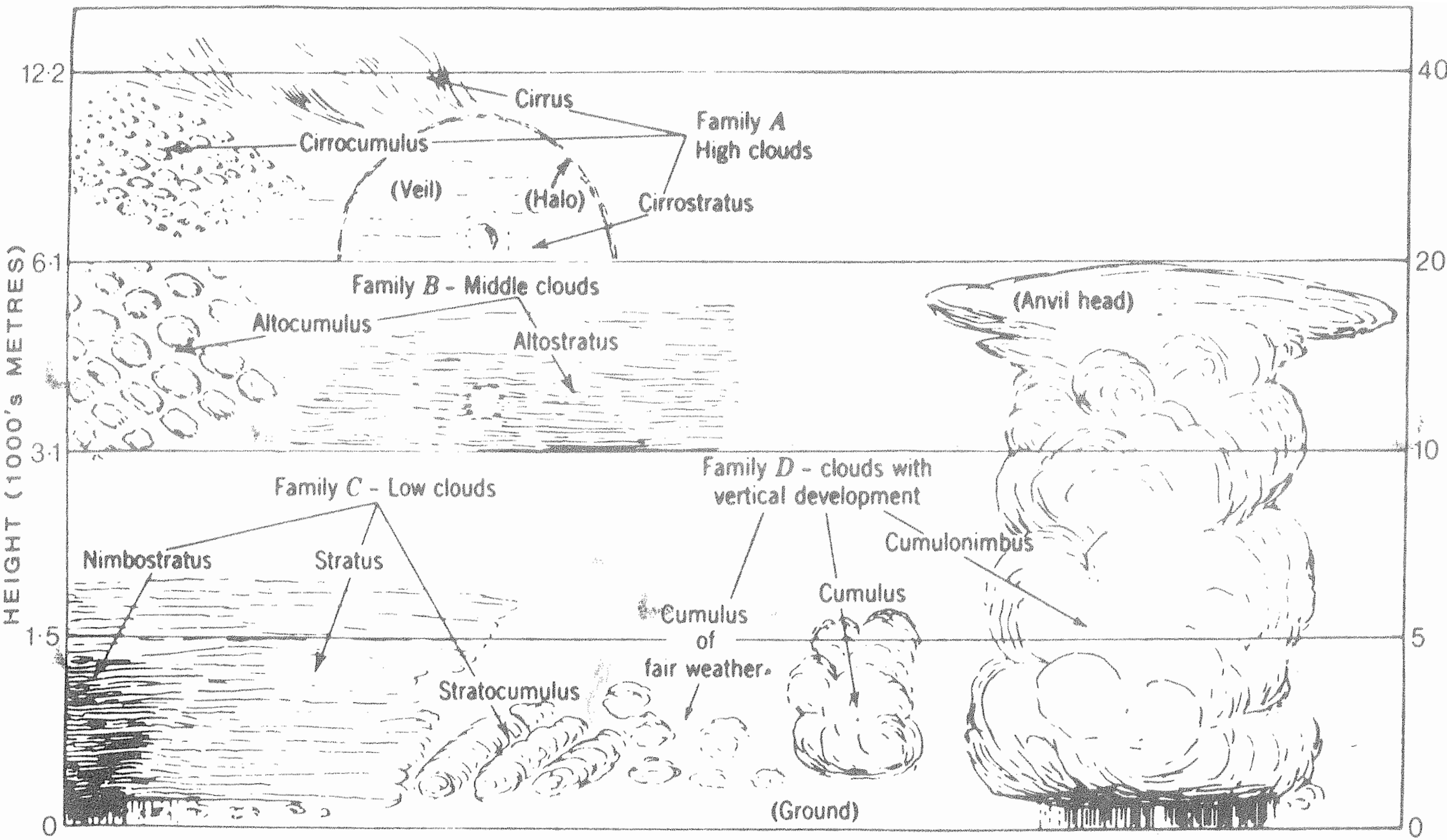


		Height of cloud base		
Genus	Étage	Polar regions	Temperate regions	Tropical regions
Cumulus	Low	below 2 km	below 2 km	below 2 km
Cumulonimbus				
Stratus				
Stratocumulus				
Nimbostratus				
Altostratus	Middle	2–4 km	2–7 km	2–8 km
Altocumulus				
Cirrus	High	3–8 km	5–13 km	6–18 km
Cirrostratus				
Cirrocumulus				

Prefix **Alto** ➡ medium level

Terms combining these as prefixes (cirro- strato- cumulo-, nimbo-) and suffixes proposed by L. Howard, 1803.

http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/cld/cldtyp/home.rxml



according to height and form

Low-level convective clouds

- develop vertically,
  - rising towers that have a ‘cauliflower’-like appearance.
  - up- (warm) and down- (cool) drafts form cell of convection

- with wide range of sizes:
  - many are too shallow for rain, never deeper/wider than 1 km.
  - a few become deeper with rapidly fluctuating bulbous towers, growing to a depth of several km. Such *cumulus congestus* clouds often extend into the middle levels.
  - a *cumulonimbus* (a ‘deep cumulus cloud’ or ‘cumulus tower’) is a dense, heavy, deep cloud that extends into the high levels and produces heavy rain.

Low-level convective (‘*cumulus*’ or ‘*cumuliform*’) clouds

- Cumulonimbus clouds are the deepest of convective clouds and their upper portion has an anvil, typically just below tropopause:
  - Anvil is cirrus-like, with a fibrous and striated appearance due to ice
  - Anvil outflow creates a vast cirriform plume with a flat top spreading out from the updraft core due to environmental shear

- Base of a cumulonimbus cloud is dark, while top is glaciated.
- A cumulonimbus cloud is the end result of explosive vertical growth of a *cumulus congestus* cloud.

Low-Level Convective Clouds

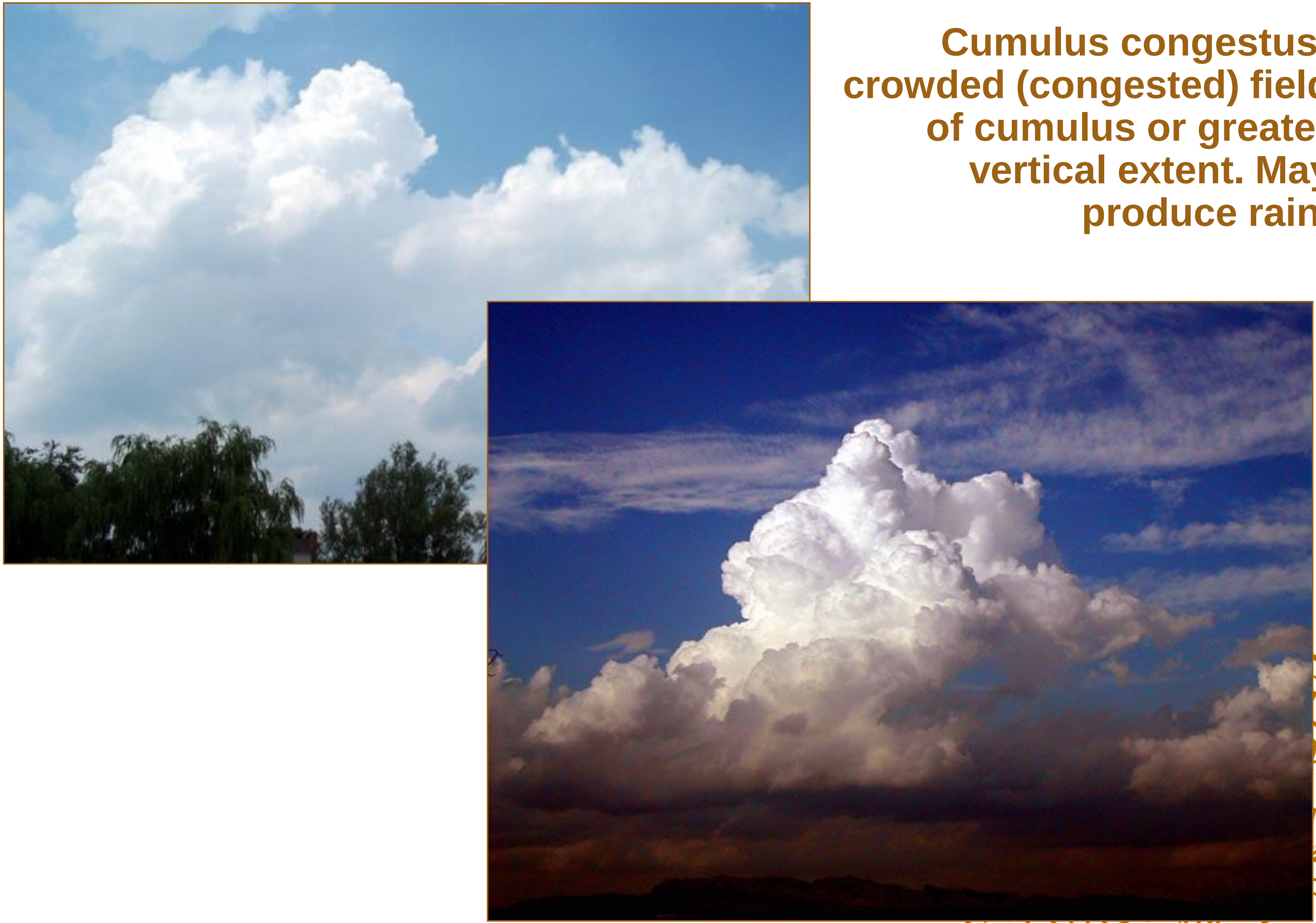
Cumulus (Cu): Brilliant white to grey, dense detached clouds. Forms clumped or heaped (cauliflower-like) shapes, usually with sharp outlines and flat base. Field of Cu often have bases all at same (lifting condensation) level.

Cumulus humilis (Cu hum): small cumulus, of limited vertical extent, may have a flattened appearance. Also called fair-weather cumulus. Too shallow to precipitate usually.

© 2003 Roger Edwards

Cumulus mediocris : cumulus, of moderate vertical extent. Either non-precipitating or very weakly precipitating.

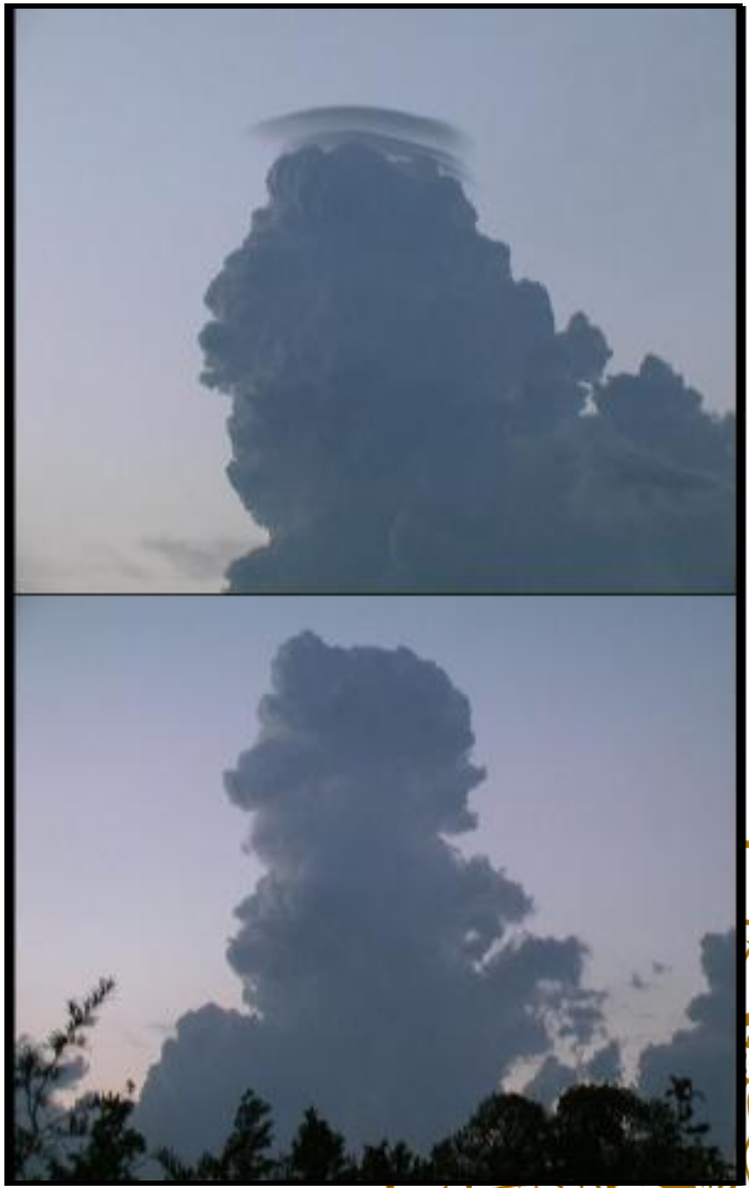
Cumulus congestus: crowded (congested) field of cumulus or greater vertical extent. May produce rain.



Congestus over Benin, 17 August 2006

(c) 1999 Dave Crowley www.stormguy.com
Tulsa Ok June 1999

Pileus : cap clouds that form above large cumulus as the upward motion of the convective cloud distorts the layer of air above (pileus is latin for skull-cap)



Pileus over Benin, 17 Aug 2006

Cumulonimbus (Cb) : huge towering cloud, dark base and white sides. Associated with heavy rain, thunderstorms, and hail. Frequently has an anvil shaped top.

More Cb

mammatus : smooth, rounded shapes sometimes formed on the underside of cumulonimbus; they result from downdrafts within the cloud.

Arcus cloud (over Lincolnshire). This cloud appears at the head of the "cold pool" of low level air which is produced by the rainfall in a cumulonimbus storm. It indicates the location of the "gust front".

Arcus cloud (over Benin, August 2006). This cloud appears at the head of the "cold pool" of low level air which is produced by the rainfall in a cumulonimbus storm. It indicates the location of the "gust front". Here we can see rainfall behind the gust front.

Stratiform Clouds

Nimbostratus (Ns) : The deepest of stratiform clouds. Dark grey, featureless, thick layer of cloud, causing prolonged precipitation. Commonly forms in frontal systems. It can co-exist alongside convective clouds in mesoscale cloud systems.

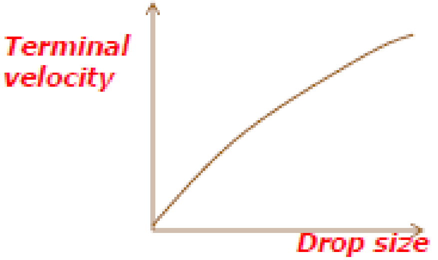
TYPES OF PRECIPITATION

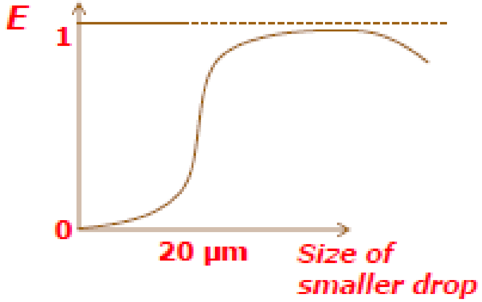
Definitions

Precipitation type	Typical size (mm)	Bulk density (kg/m^3)	Fall-speed (m/s, mean sea level)	Main source of mass	Typical cloud-type generating precipitation at ground
rain	0.1-5 mm	1000	0.3-13	coalescence	any deep cloud with warm enough base
snow	0.3 mm – few cm	~10-100	~0.1-1	aggregation of ice crystals (or vapour diffusion)	Stratiform
graupel	0.3 – 5 mm	~100-700	~0.1-5	Riming	Convection (cloud-liquid is abundant)
hail	> 5 mm	~700-920	~5-40	Riming	vigorous deep convection

Recap: warm-rain process

- **Coalescence** is how cloud-droplets form rain
  - Drops (radius *r*, mass m_r) fall faster (v_t) if larger, and may collide with smaller, slower drops
  - Probability of collision, if one droplet is in volume swept out by other, is *'collision efficiency' (E)*,
    - E increases with *r*
- Only droplets > 20 µm have significant *E*
  - Clouds must be deep enough to form rain, with a warm cloud-base, as droplets grow during ascent
    - *LWC and r* = functions of height above base
  - Extra aerosols increase critical depth of cloud for rain formation
  - *E* is boosted by turbulence in convection
    - extra particles enter swept-out volume

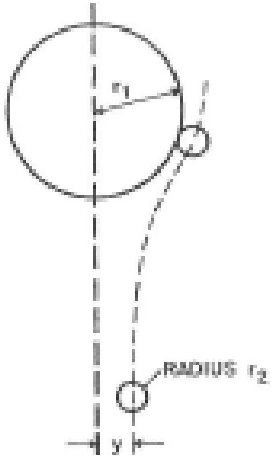




Growth of raindrop (r, m_r)

$$\frac{Dm_r}{Dt} \approx E\,\pi\,r^2\,v_t\,\boxed{LWC}$$

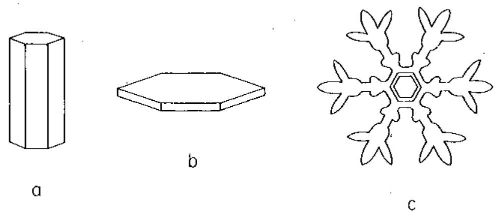
kg/m³ of cloud-liquid

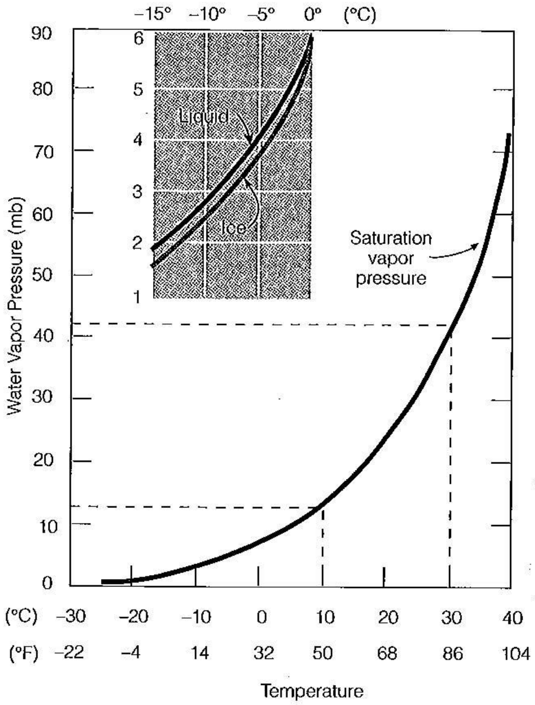


Ice-crystal process

- If droplets are too small to coalesce and cloud is sub-zero, then ice phase can produce precipitation

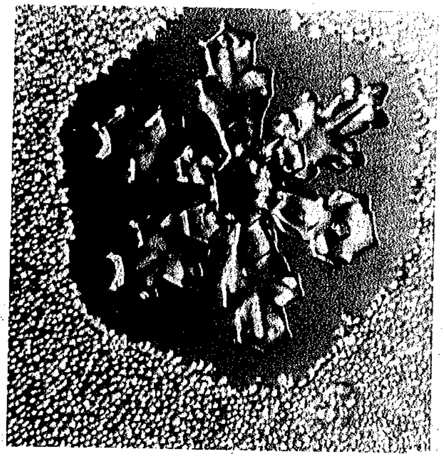
- Ice nucleus (IN) aerosols are solid (e.g insoluble) and much rarer than CCN:
  - without IN, ice will not form spontaneously unless the temperature is colder than about -40° C
  - IN nucleate ice if colder than 0 ^{o}C and with supersaturation relative to ice (e.g. in mixed phase clouds)
  - just a few ice crystals can grow very fast in mixed-phase clouds, "stealing" available water, and falling out of the cloud as they grow large.

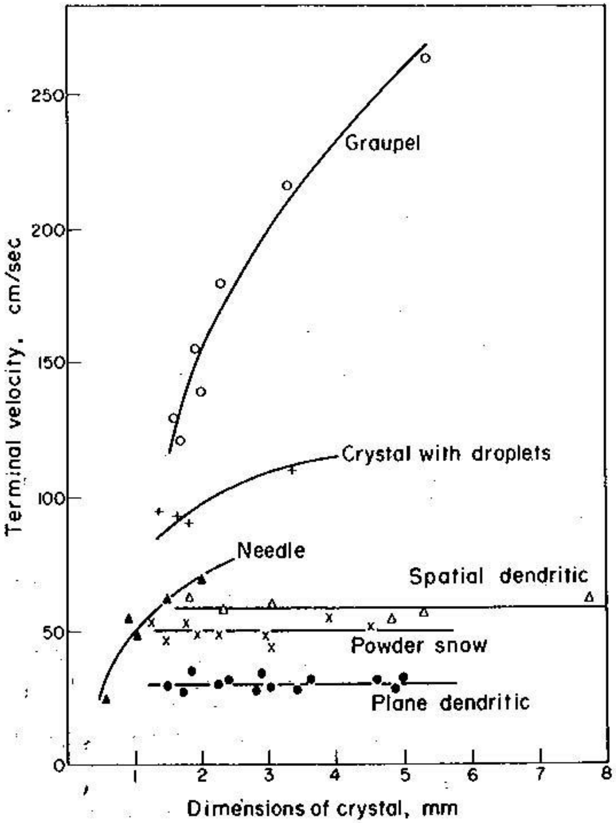




Ice-crystal process (cont.)

- Ice crystals in mixed-phase cloud grow to form snow by vapour growth and aggregation of ice crystals
  - Saturation vapour pressure over ice is less than that over water ⇒ ice crystals grow at expense of water droplets
  - If snow particle touches ice crystal it may stick (‘ice-ice aggregation’)
  - If cloud-liquid is abundant, snow particle (e.g. snowflakes = clumps of crystals) falls past cloud-droplets, collecting them and causing them to freeze onto it
    - ‘*Riming*’ (dense) growth of graupel or hail
  - Graupel or rimed snow falls from cloud, melting before reaching surface as rain

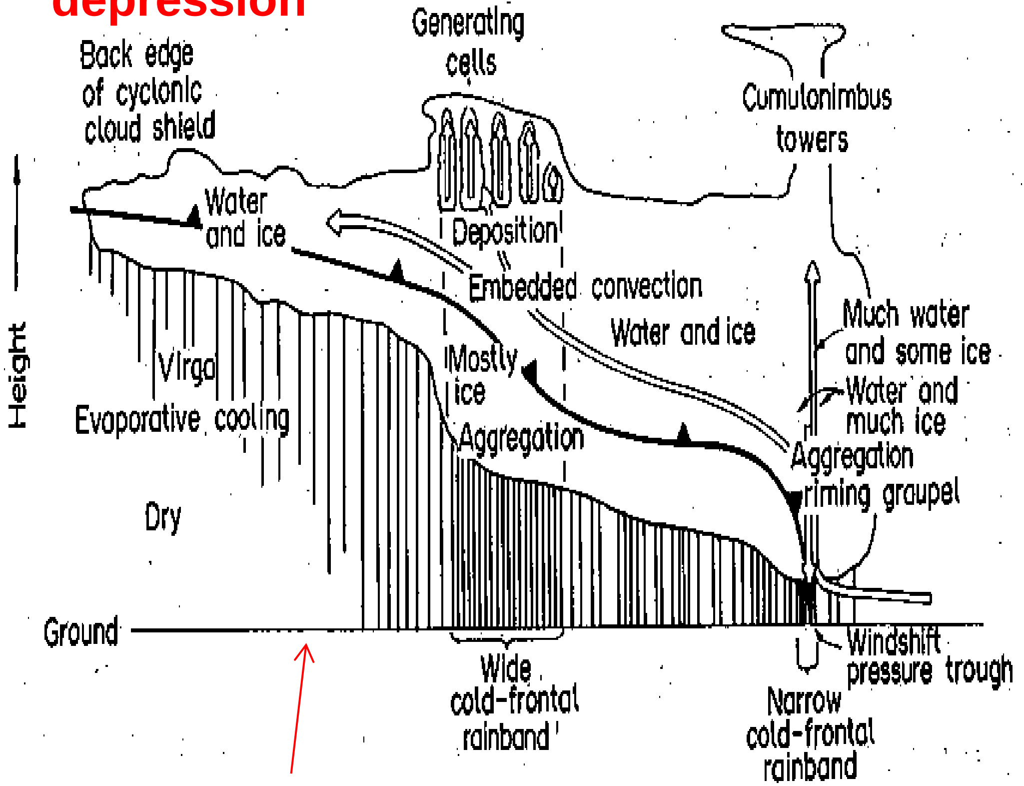




CLASSIFICATION OF PRECIPITATION SYSTEMS

- **Convective precipitation**
  - Narrow, short-lived
  - Intense at surface, P > 25 mm/hr
  - From convective clouds
    - |w| > 1 m/s,
    - turbulent, nonhydrostatic
- **Stratiform precipitation**
  - Widespread, long-lived
  - Weak, P < 25 mm/hr
  - From stratiform clouds
    - |w| < 1 m/s,
    - Hydrostatic, laminar

Example: cold front of mid-latitude depression



Both convective and stratiform types co-exist

Total water m. r. = mass of liquid + vapour per kg of air

$$\boldsymbol{S = \frac{Dq_T}{Dt} = \frac{D(q_v+q_L)}{Dt} \approx \frac{D(q_s+q_L)}{Dt} = \frac{Dq_L}{Dt} + w\,\frac{\partial q_s}{\partial z} \Rightarrow}$$
$$\boldsymbol{condensation\ rate, C = -w\,\frac{\partial q_s}{\partial z} \Rightarrow P \propto \int_{cb}^{ct} \rho C\, dz \propto \overline{w}}$$

Column of saturated ascent ($q_v \approx q_s$) **with mean,** $\overline{w}$

- **Intensity of precipitation increases with cloud depth and with ascent rate**

- Convective clouds have faster ascent than stratiform clouds

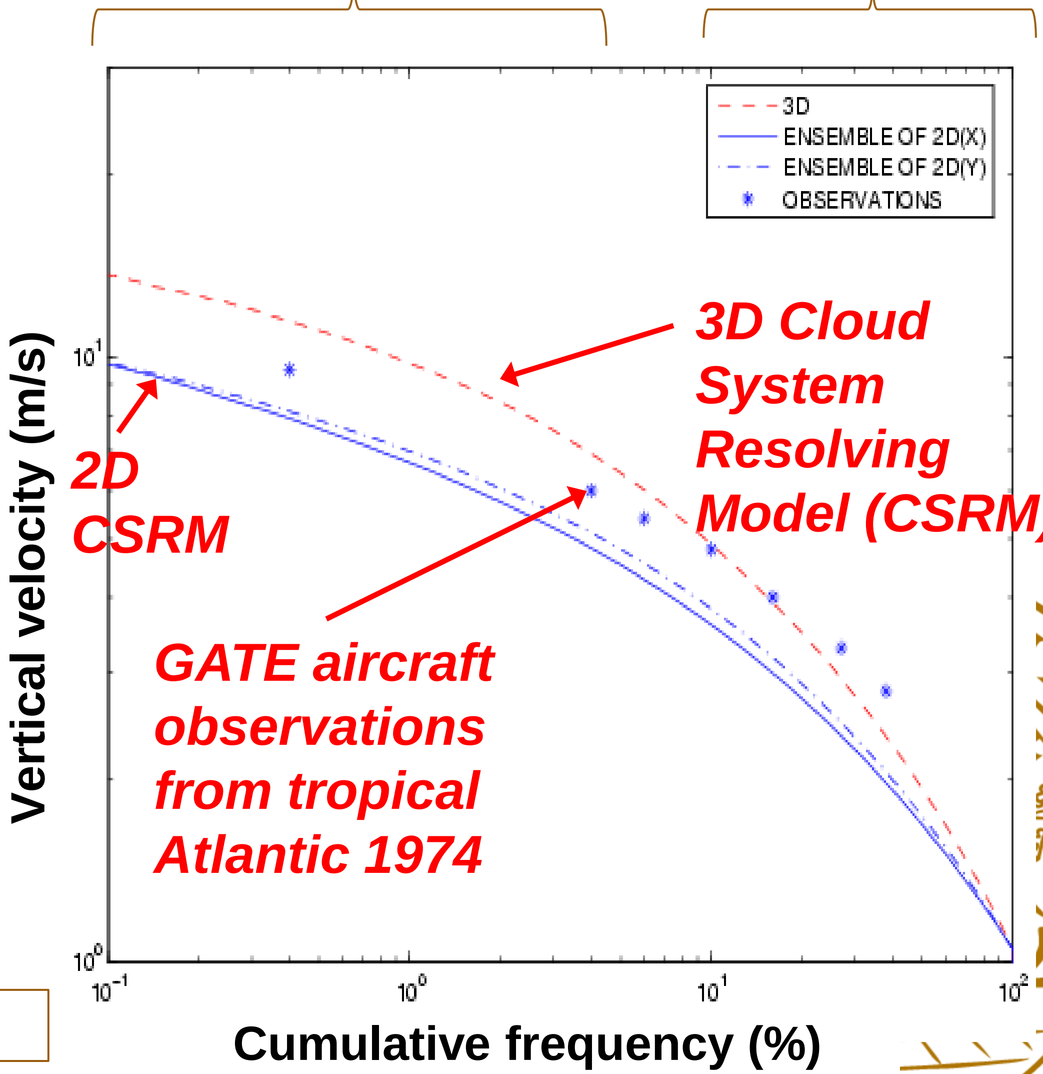
  ⇒ condensation faster

  ⇒ precipitation more intense

- Stronger ascent is rarer than weaker ascent
  - Convective precipitation is more short-lived

Phillips and Donner (2006, QJRMS)

Example: mesoscale systems of deep convection over tropical Atlantic



Faster ascent: rarer and narrower

Weaker ascent: more widespread

3D Cloud System Resolving Model (CSRM)

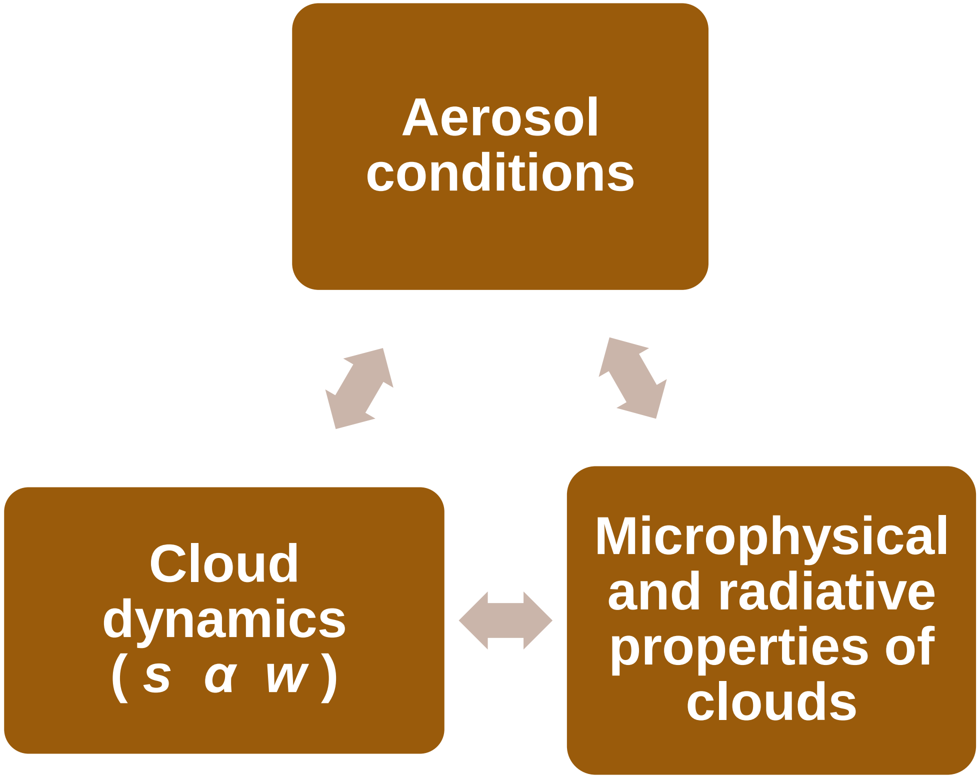
2D CSRM

GATE aircraft observations from tropical Atlantic 1974

AEROSOL-CLOUD INTERACTIONS AND CLOUD-RADIATION FEEDBACKS

Aerosols and clouds

- Soluble aerosols (‘CCN’) can form cloud-droplets
- Cloud-particles (> 1 µm) are aerosols (< 1 µm usually) made bigger by condensation
- Supersaturation, *s*, and ascent, *w*,
  - numbers of cloud-particles initiated by aerosols
- More numerous cloud-particles must be smaller
  - collision efficiency, albedo


Aerosol conditions

Cloud dynamics (s α w)

Microphysical and radiative properties of clouds

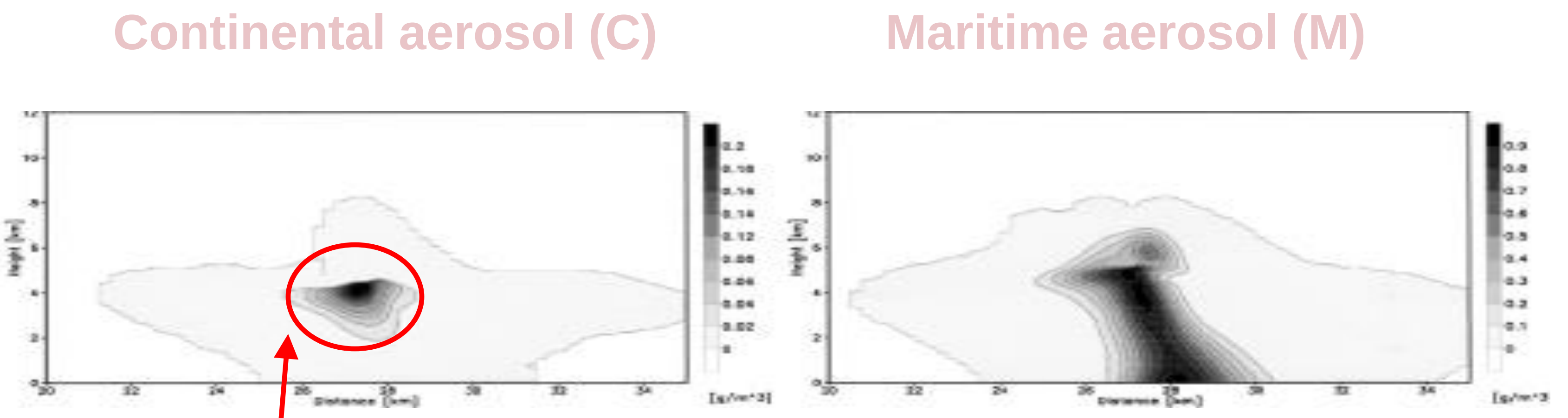
Clean air (few aerosols)


Few cloud-droplets

Polluted air (many aerosols)


Many cloud-drople

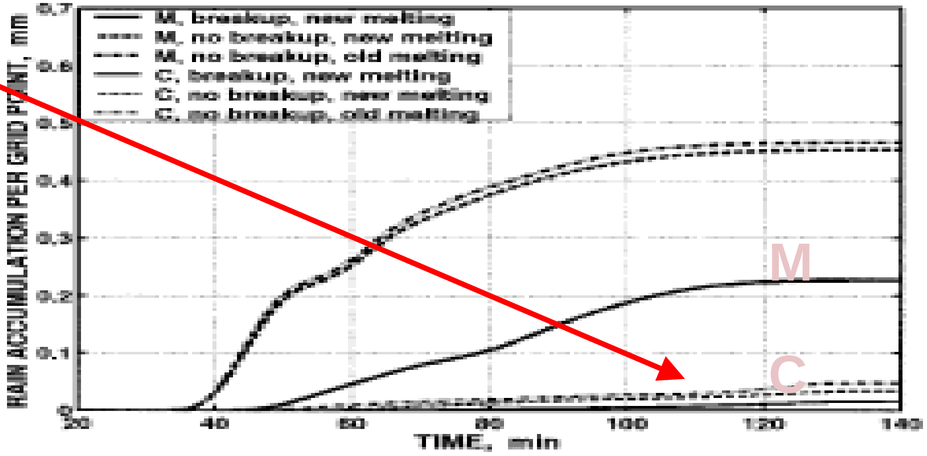
Impact from CCN aerosols on rain production in Texan clouds in spectral cloud model



Continental aerosol (C)

Maritime aerosol (M)

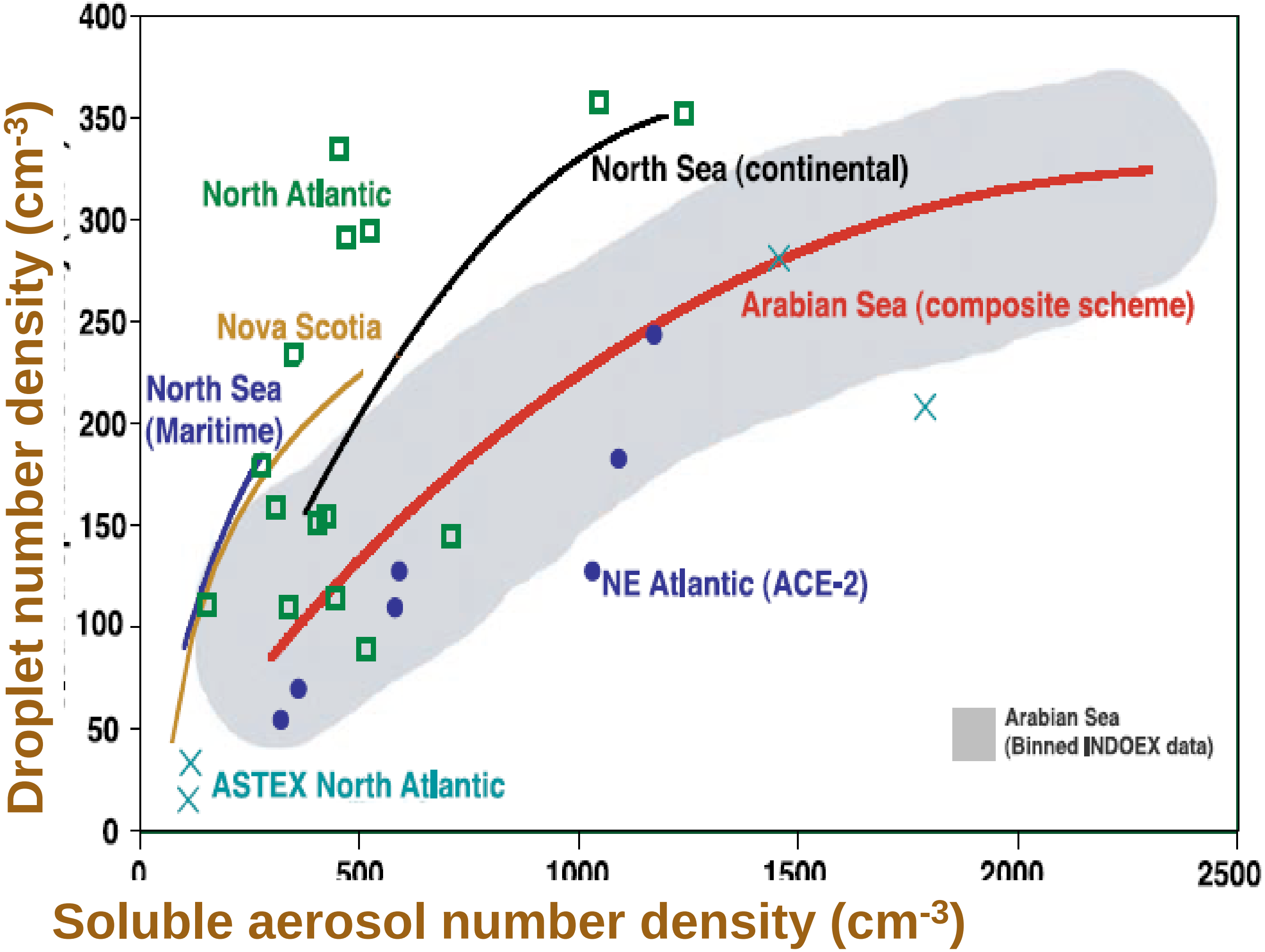
rain formation delayed by more numerous and smaller cloud-droplets

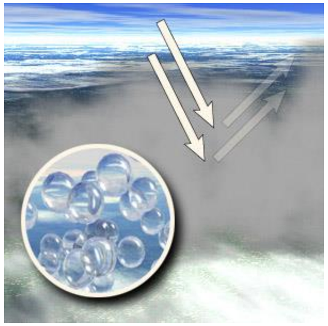


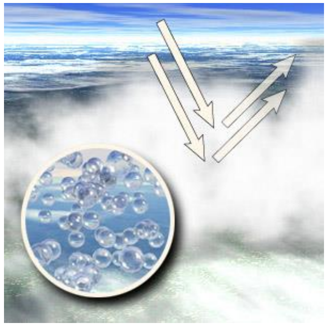
Khain et al. (2004)

Aerosol pollution alters clouds, causing a forcing (Q) of climate change

Aerosols from pollution boost the concentrations and reduce the mean sizes of cloud-particles:



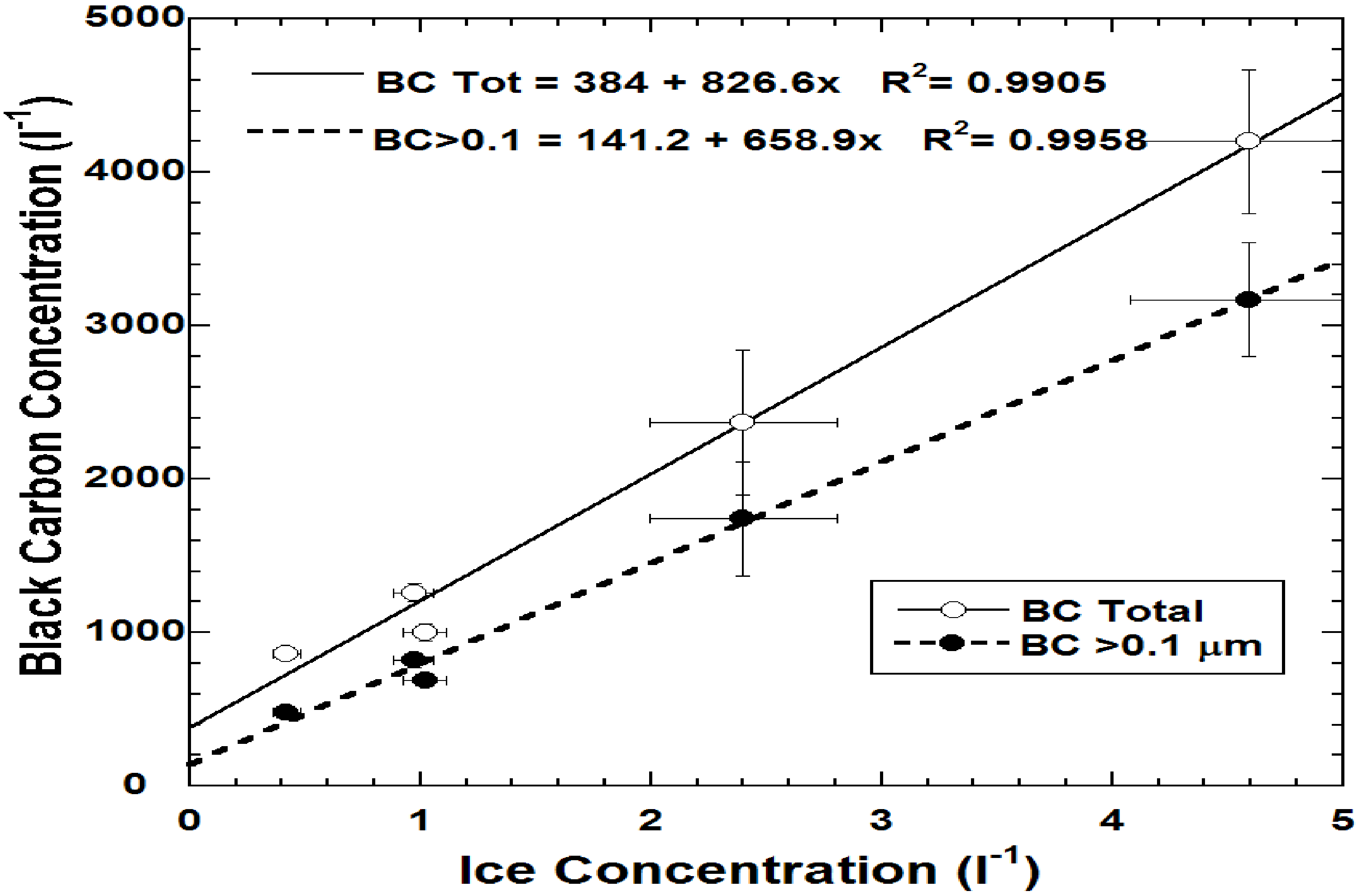




Ramanathan *et al.* (2001)

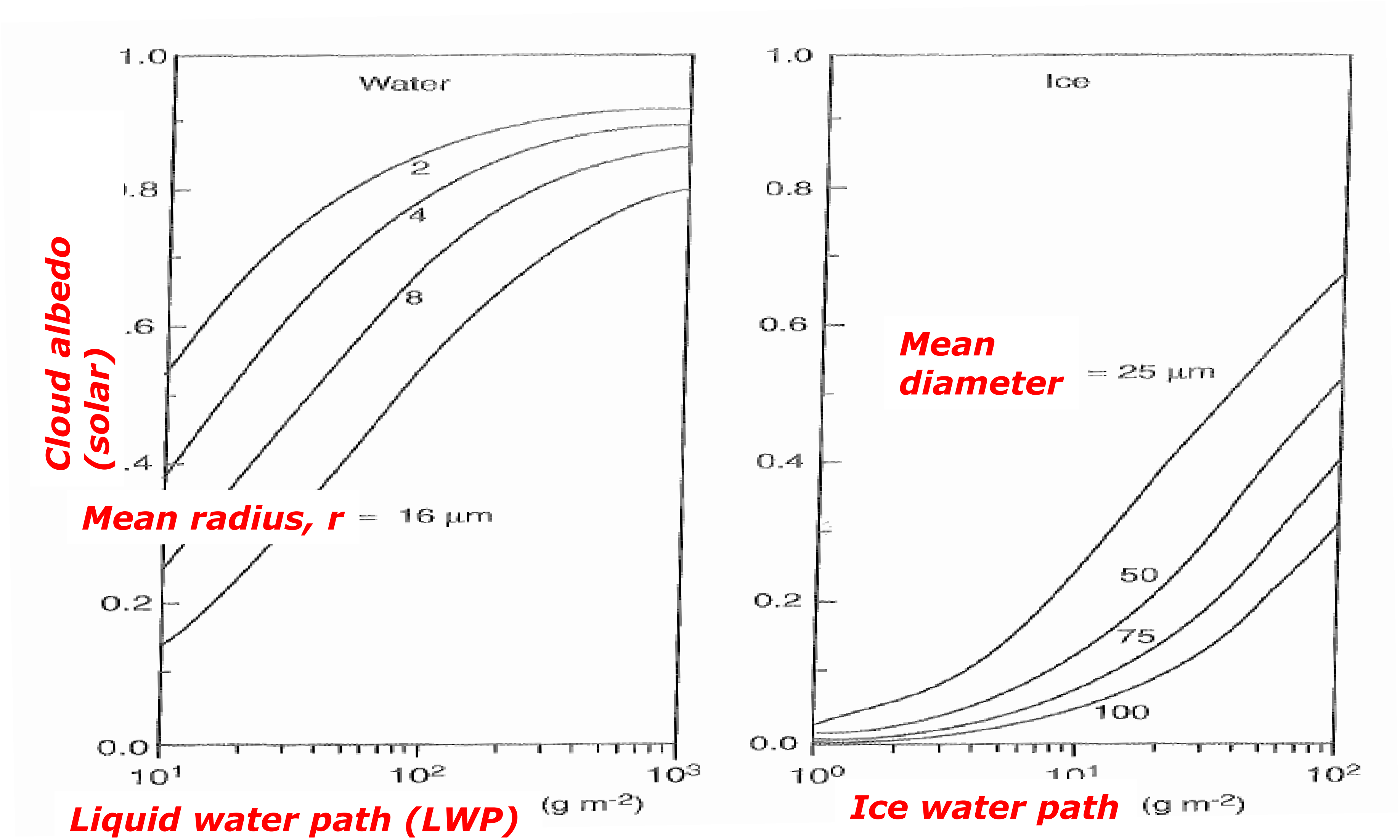
Aerosols from pollution alter the concentrations and mean sizes of ice particles:

Ice in Layer-clouds Expt (ICE-L)



Twohy et al. (2010, JAS)

Albedo = solar flux reflected / incident



Cloud albedo (solar)

Mean radius, r

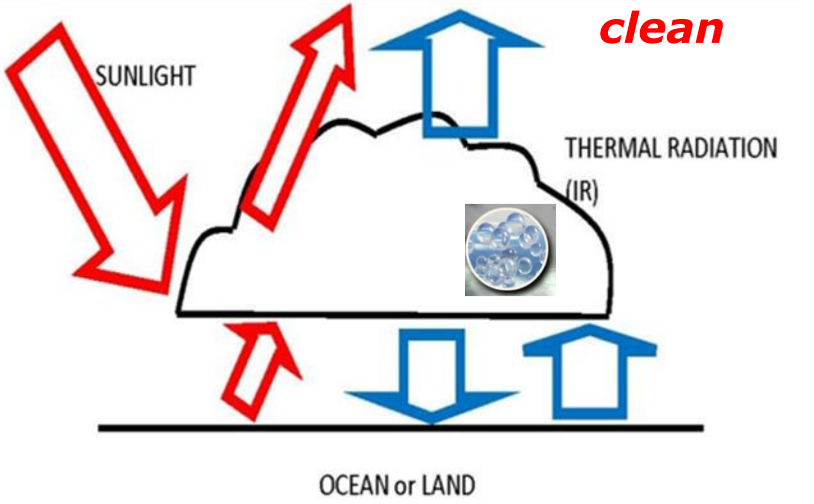
Liquid water path (LWP)

Mean diameter

Ice water path

Effects from aerosol pollution

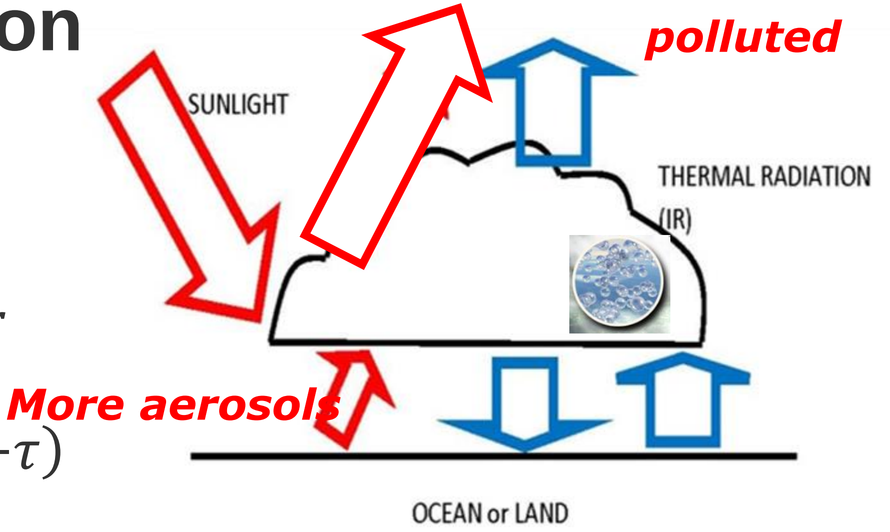
- ‘Cloud-albedo indirect effect’
  - Optical depth: $\tau \propto LWP/r$
  - Cloud albedo $= 1 - \exp(-\tau)$



Effects from aerosol pollution

» ‘Cloud-albedo indirect effect’

- Optical depth: $\tau \propto LWP/r$
- Cloud albedo $= 1 - \exp(-\tau)$
- Clouds are more reflective
  (Charlson et al. 1992)



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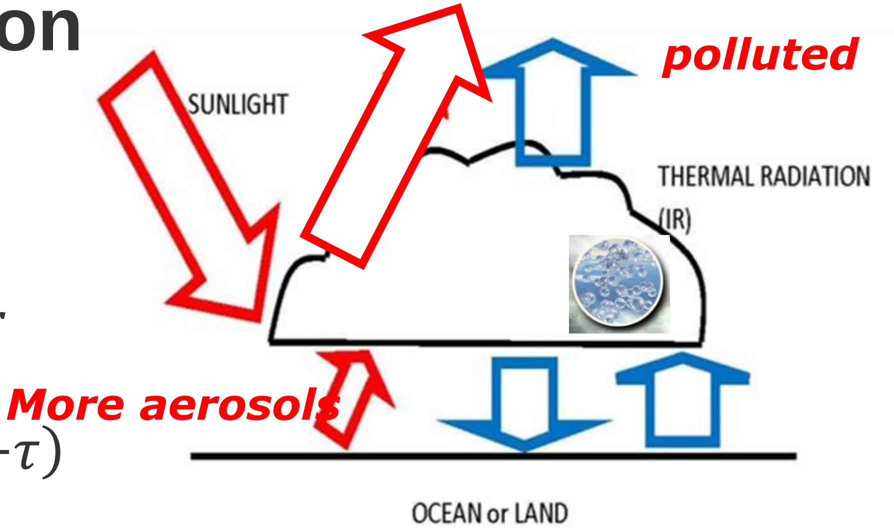
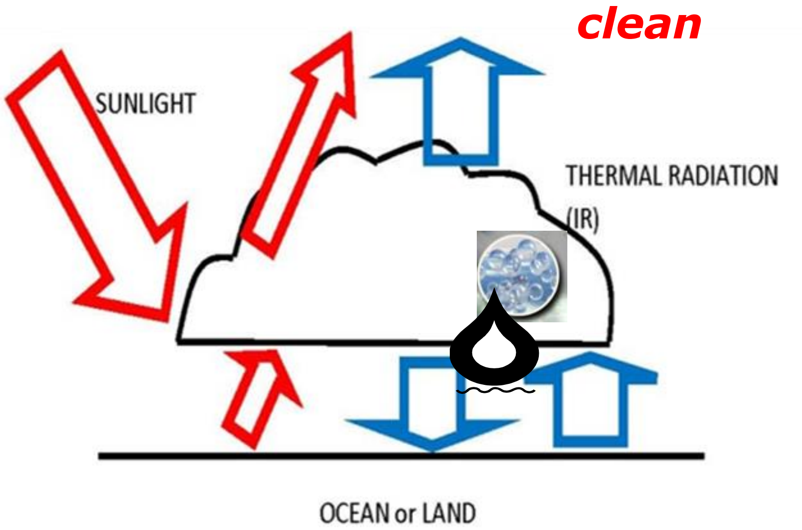
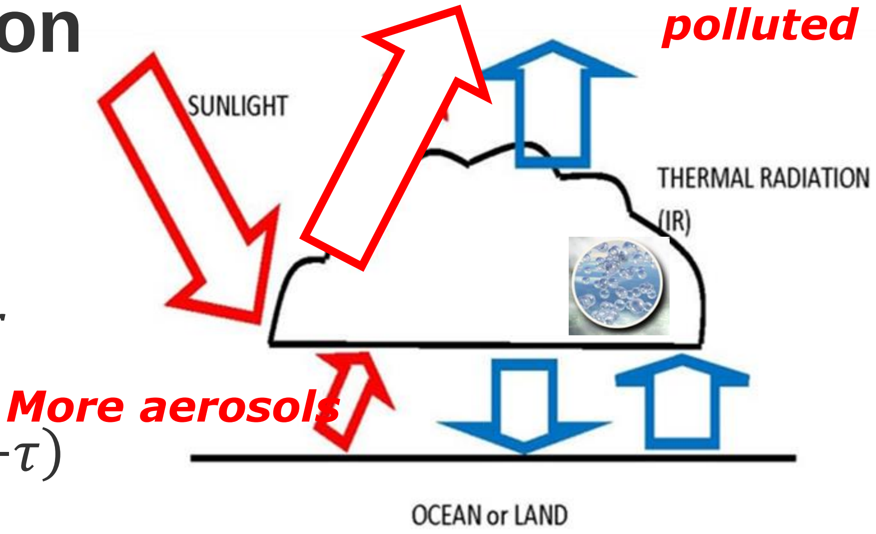


- ‘Cloud-lifetime indirect effect’



Effects from aerosol pollution



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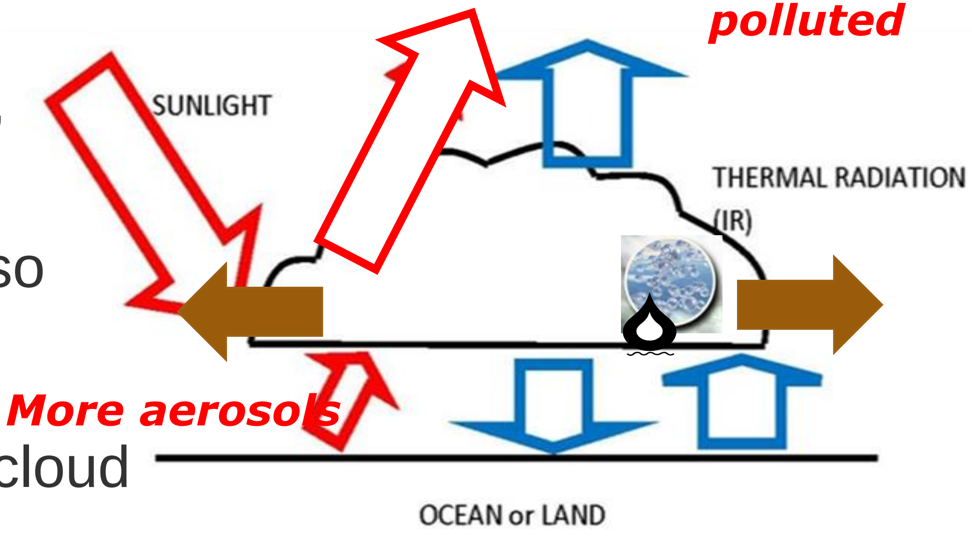
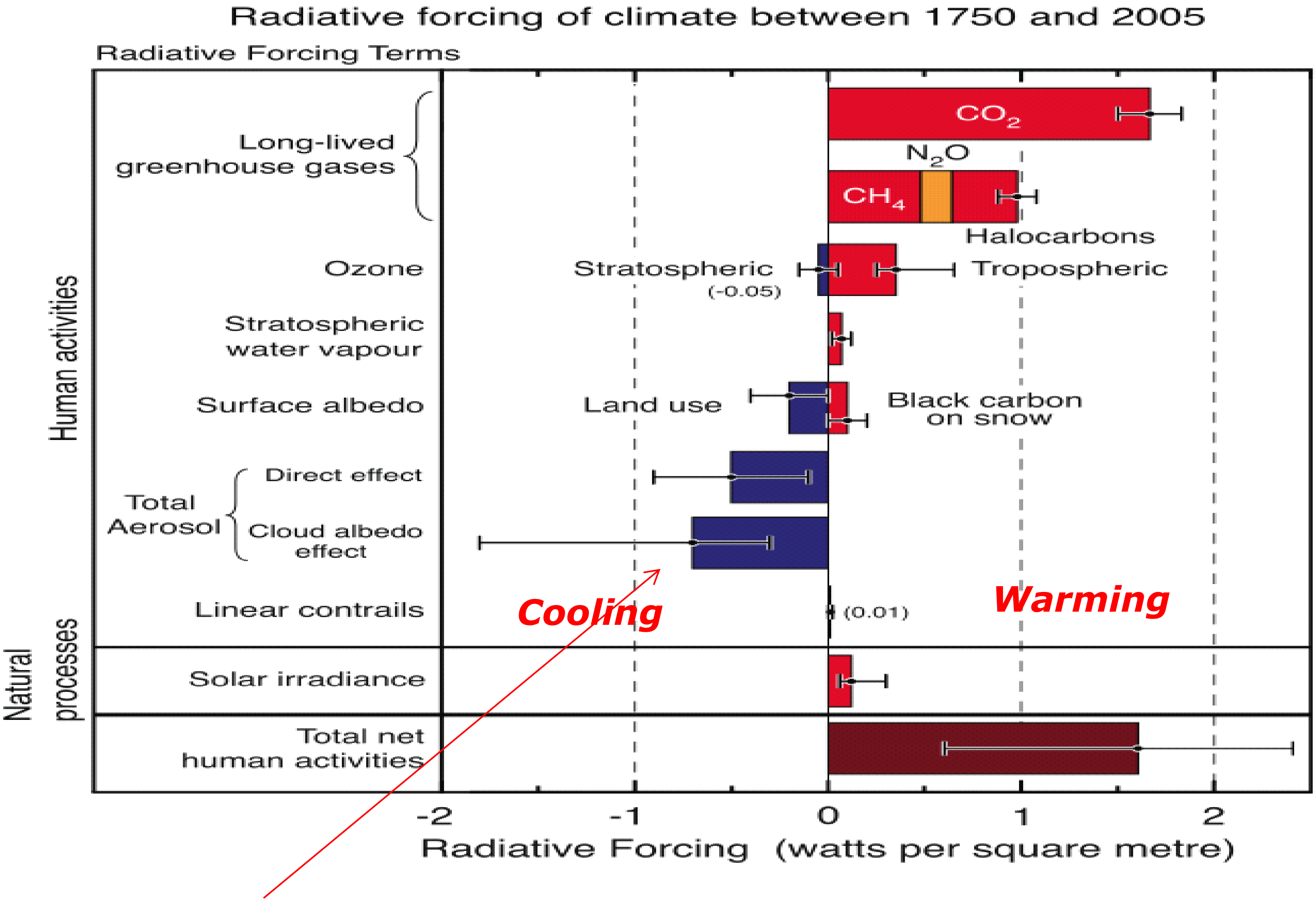


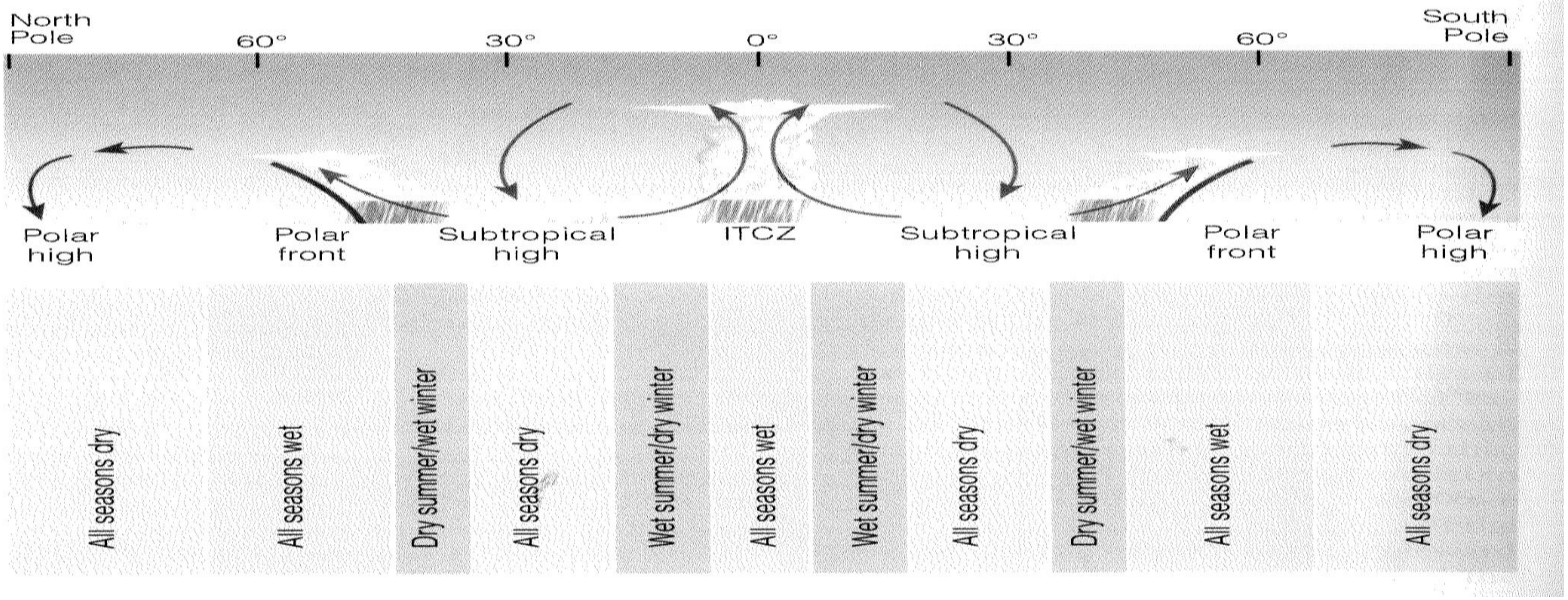
- ‘Cloud-lifetime indirect effect’
  - Cloud-particles smaller, so less rain
  - clouds live longer, more cloud cover, more reflection of sunlight

Current knowledge of indirect effects on climate from aerosol pollution via clouds



Aerosol indirect effects (via clouds) act to cool the global climate.

In warm clouds, extra droplets from aerosol pollution may have offset up to about half of global warming from past emissions of GHGs



- Large-scale ascent, surface heating and vertical profiles of temperature and humidity all govern extent of clouds

- *Net radiation, Q,* entering TOA is the driver of climate change

  - Instantaneous change in *Q* due to external impact (e.g. pollution) = Q_0, radiative forcing

  - *Q* changes during climate change, altering these factors and clouds

- Some models/observations: more convective cloud in warmer world, with more cirrus and less stratiform cloud

Quantifying the climate feedbacks

- *Climate feedback parameter:* $Y = -dQ/dT_s = \sum Y_i$, sum from all feedback processes

- Convention:
  - $Y_i < 0$ is +ve feedback; $Y_i > 0$ is -ve feedback

- Climate must have a net negative feedback: $Y > 0$
  - But individual feedback processes can be any sign

- **Challenge:** Y is uncertain for the present-day climate, largely due to cloud-radiation feedbacks
  - Eqm warming, $\Delta T_{s,eq}$, is uncertain too, since: $\boxed{\Delta T_{s,eq} = \Delta Q_0 / Y}$

Climate modeling

- Climate may be simulated by detailed climate models solving eqns numerically for heat, motion & mass of 3D atmosphere

- Detailed climate models simulate black-body (‘BB’), water vapour (‘WV’), lapse rate (‘LR’), snow/ice albedo (‘ICE’), cloud-cover (‘Ac’) and cloud-property (‘LWP’) feedbacks

- Some typical estimates from models:

Cloud feedback

$$Y = Y_{BB} + Y_{WV} + Y_{LR} + Y_{ICE} + Y_{Ac} + Y_{LWP}$$

$$= 3.5 - 1.5 + 0.6 - 0.7 + (-1 \rightarrow 0.5)\ \mathrm{W/m^2/K}$$

$$= 0.9 \rightarrow 2.4\ \mathrm{W/m^2/K}$$

Cloud feedback is +ve or –ve (?)

- Most of uncertainty in Y is from cloud feedbacks, e.g. 2x CO2:

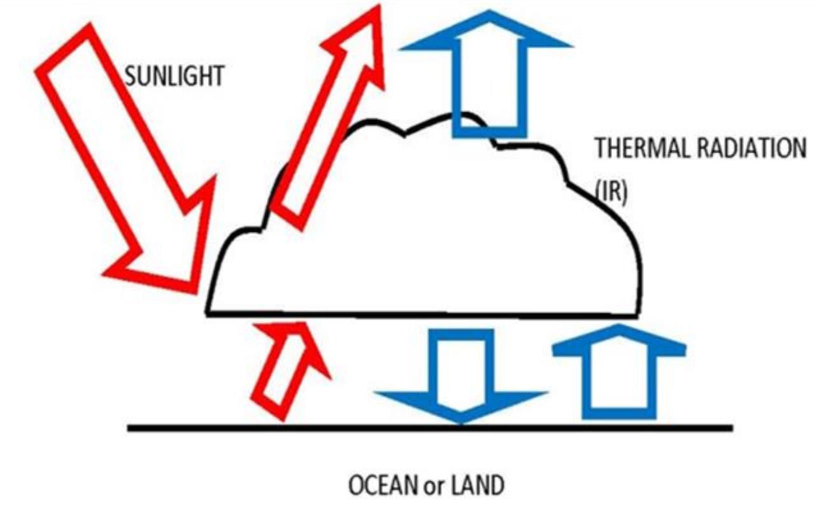
$$\Delta T_{s,eq} = 4 / Y = 2 \rightarrow 4\ K$$

Clouds alter fluxes of radiation, contributing to climate feedbacks (Y)

Cloud-radiation feedback

Present

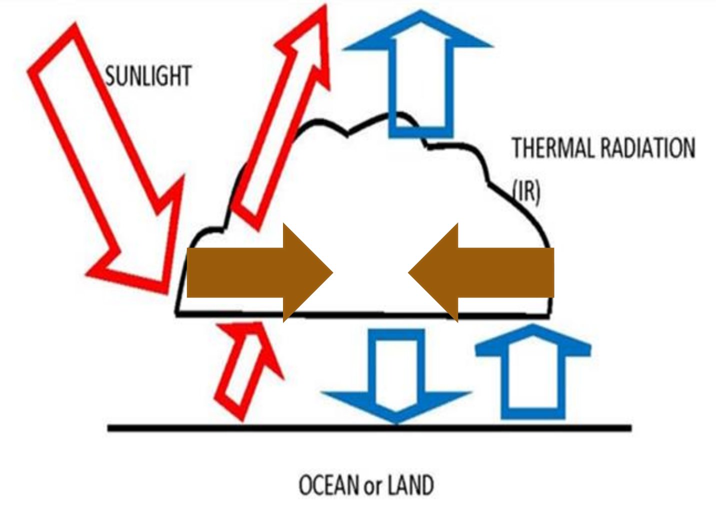
- Ascent, temperature and vapour content of troposphere change during global warming
- Cloud cover can change during global warming



Cloud-radiation feedback

Warmer world

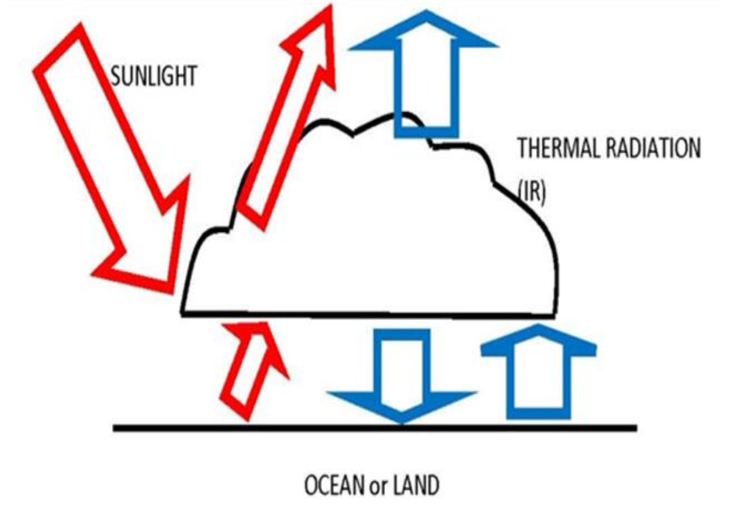
- Ascent, temperature and vapour content of troposphere change during global warming
- Cloud cover can change during global warming



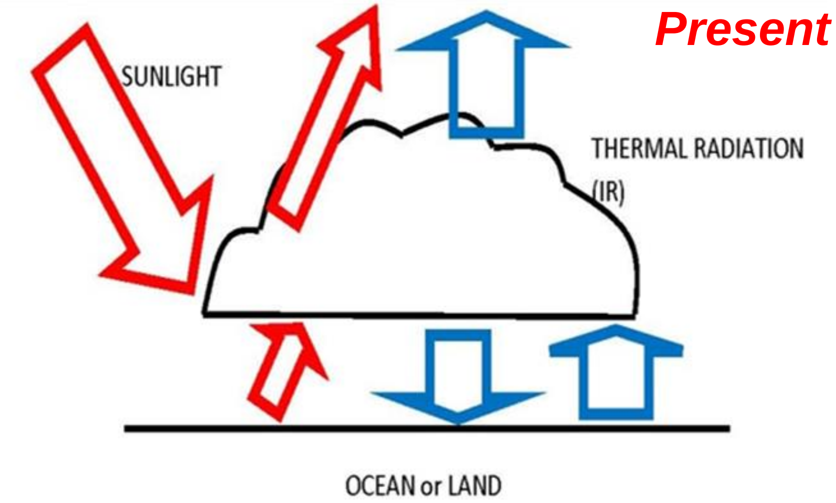
Cloud-radiation feedback

- Ascent, temperature and vapour content of troposphere change during global warming
- Cloud cover can change during global warming
- Cloud properties (optical thickness) can change too
  - mass of cloud-liquid in column (unit area)changes

Warmer world



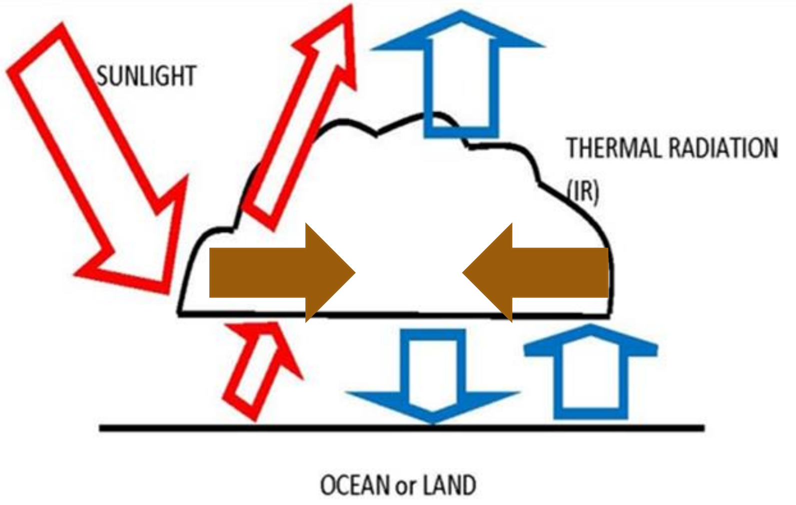
Present

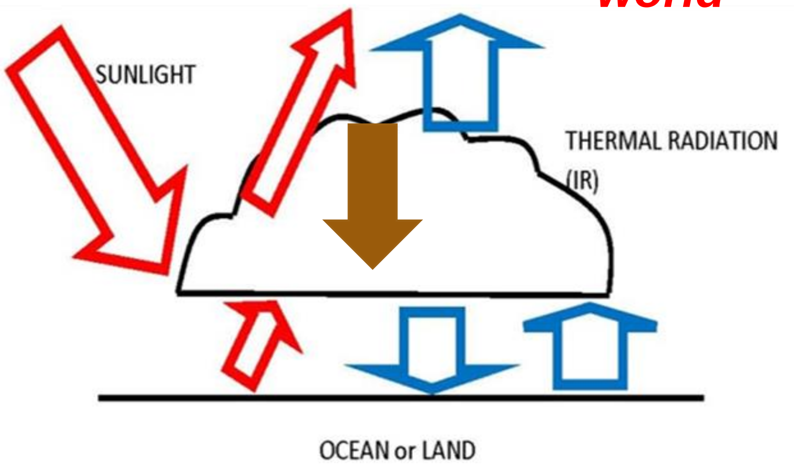


Cloud-radiation feedback

- Ascent, temperature and vapour content of troposphere change during global warming
- Cloud cover can change during global warming
- Cloud properties (optical thickness) can change too
  - mass of cloud-liquid in column (unit area)changes
- If reflection of sunlight to space decreases, this amplifies warming of climate

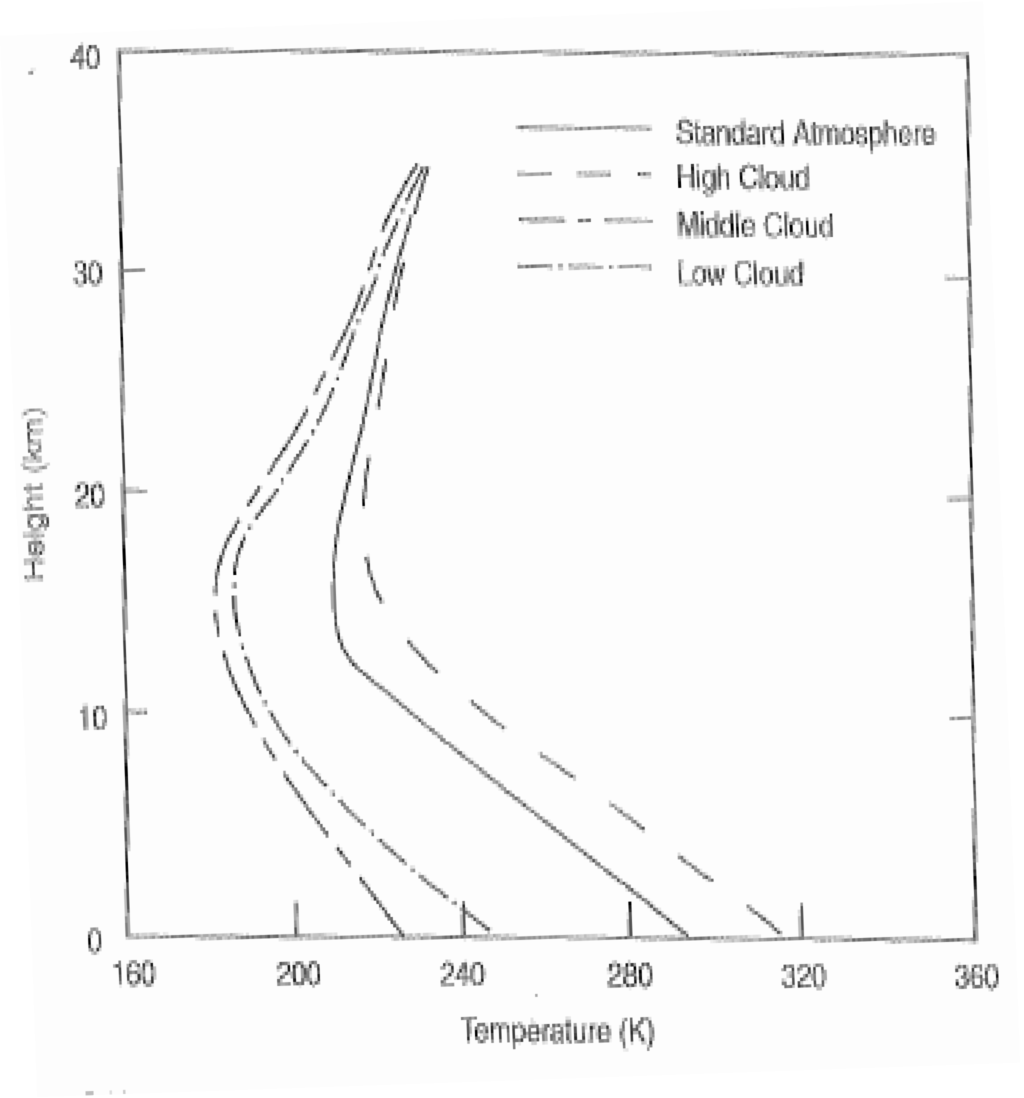
- Cloud-rad. Feedback is **+ve**





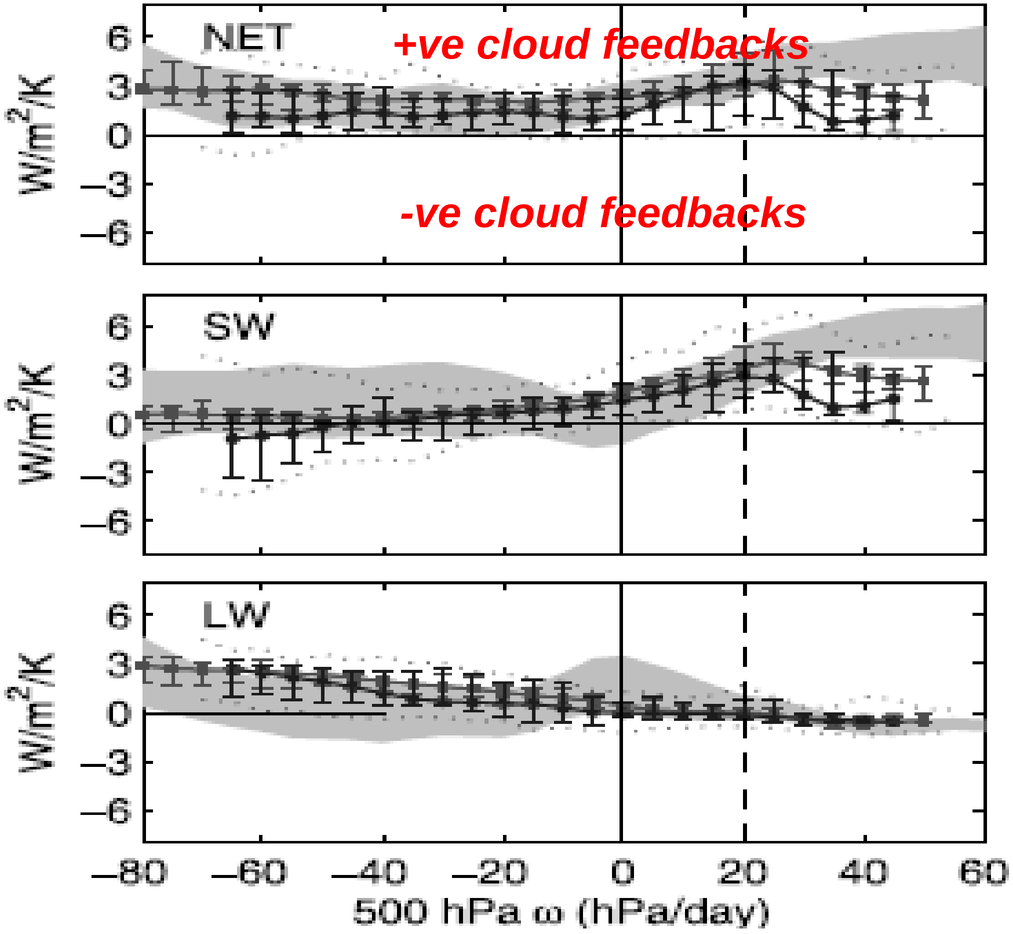
- Solar (SW) cooling by low, middle clouds
  - albedo (SW) ~ 0.8,
  - emissivity (LW) ~ 1
- Longwave (LW) warming by high cloud
  - albedo (SW) ~0.1,
  - emissivity, ε (LW) ~0.5
  - cold temperature (T_{cld})
  - flux to space = $\varepsilon \sigma T_{cld}^4$
- Some climate models: more cirrus and less stratiform cloud in warmer world would warm the surface both in LW and SW

Impact on average temperature profile from imposing 100% cloud cover globally (Liou and Ou 1983)



Observations of past 20th century warming in sub-tropics

- Subtropical stratocumulus cloud-decks in BL observed by satellite
- Less cloud cover when warmer
    - *CRF* = ‘cloud radiative forcing’ = difference between Q with and without clouds (hypothetical)
    - *Cloud feedbacks:* $Y_{ac}+Y_{LWP}$ = - $\Delta CRF/ \Delta T_s$
- Hypothesis: more convection in BL, less stratiform cover



$\Delta CRF/\Delta T_s$

+ve cloud feedbacks

-ve cloud feedbacks

Free-tropospheric descent

Bony and DuFresne (2005)

SUMMARY

Summary

- Aerosols consist of foreign material and initiate cloud-particles
- Cloud-particles grow to become precipitation (> 0.1 mm) by:
  - Coalescence (‘warn rain process’), forming rain directly
  - Ice-crystal process, forming snow that may melt to form rain (or snow might rime to form graupel that melts)
- Only certain clouds (e.g. deep or glaciated) can precipitate
- Variety of types of cloud-particle and precipitation, especially for ice
- Convective and stratiform clouds can co-exist in same system
  - Stronger ascent (convective) is rarer, more short-lived than weak ascent
- Clouds are usually caused by ascent, which brings air to saturation
  - Ascent determines the intensity and longevity of precipitation

Questions ?

- Just ask
- Email: Vaughan.Phillips@nateko.lu.se