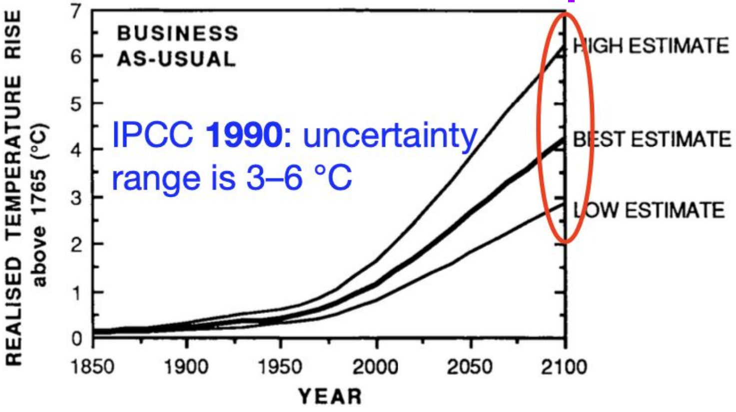
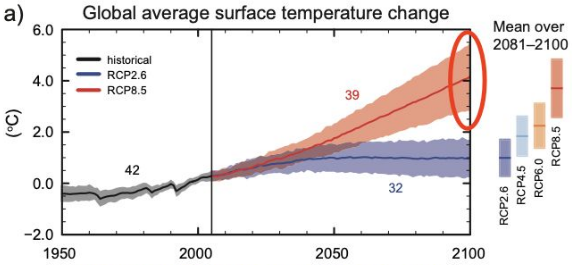
Cloud feedbacks & climate prediction uncertainty

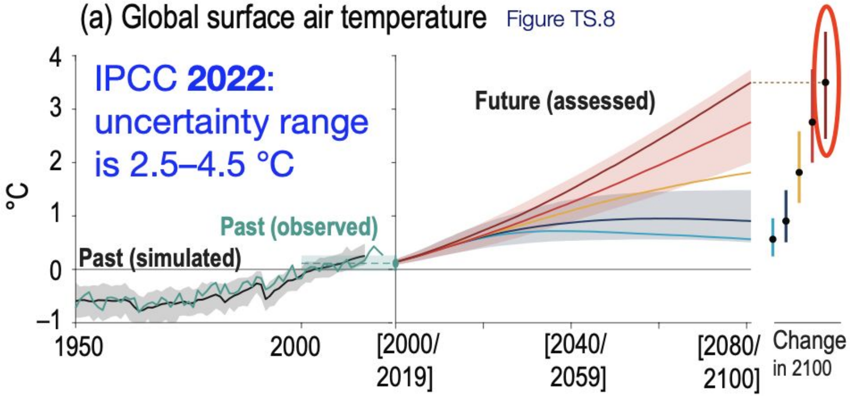
Resources:
- Global warming science: chapter 7
- Global physical climatology: chapters 3 and 10

Climate prediction uncertainty





IPCC **2013**: uncertainty range is 3–5.5 °C

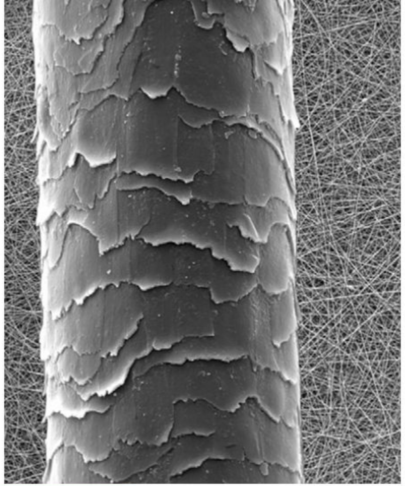


Why aren't we making progress??

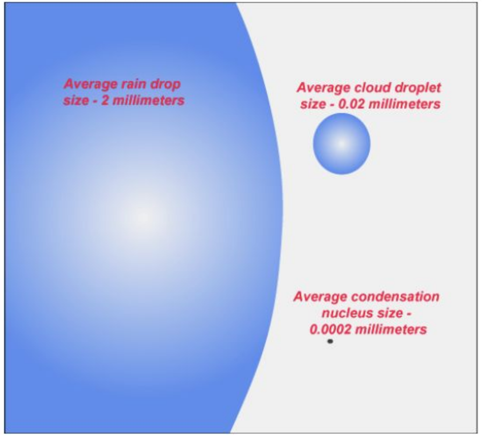
What are Clouds?

- **Clouds are aggregates of water droplets and ice particles** in the Earth's atmosphere.
- Cloud droplets range from 1–100 μm in diameter, much smaller than raindrops (500 μm+ diameter).
- Typical cloud droplets are considerably smaller than the thickness of human hair.
- The typical distance between droplets in a cloud is ~1 mm.

https://www.researchgate.net/figure/Scanning-electron-microscope-SEM-image-A-1000-of-a-human-hair-on-the-left-and-a_fig2_316750591



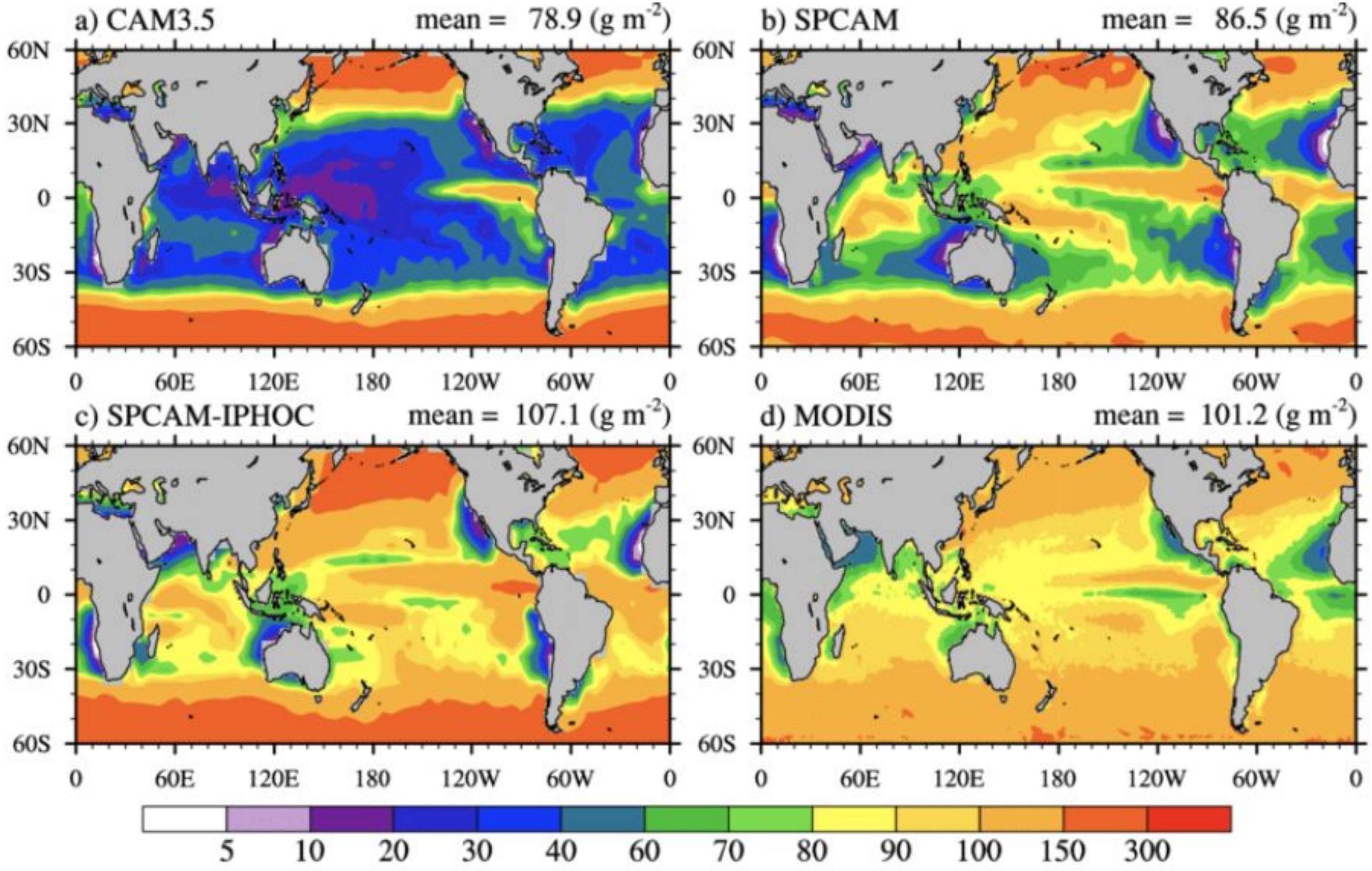
http://earth.wiki.huji.ac.il/images/Drop_cloud_size.gif



Top: Human hair, ~100 μm diameter, **Bottom:** Typical Cloud Drop, ~20 μm diameter. Same length scale in images.

Orders of magnitude

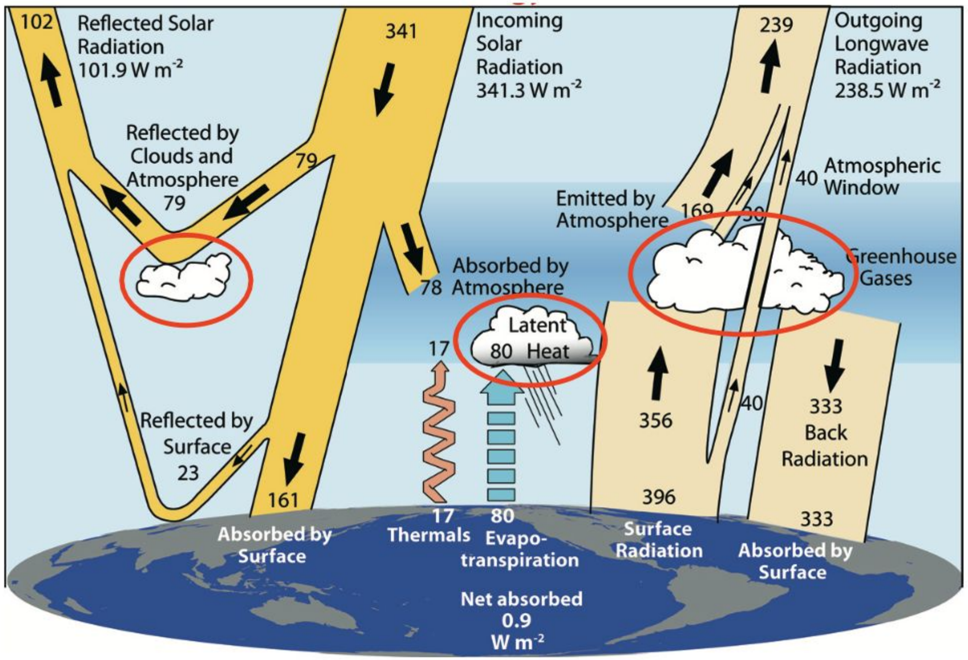
- Most of the water in the atmosphere is in water vapor form
- The global content of water vapor would cover the Earth's surface with a 25mm layer of liquid water
- Cloud water would form a layer of only 0.08mm thickness (300x thinner than that for water vapor)
- Despite the small amount of cloud water, clouds have dominant radiative effects
- Considerable model disagreement on the future spatial distribution of clouds leads to uncertainties



Mean “Liquid Water Path” (total weight of liquid water in 1m^2 air column) of several climate models vs MODIS satellite observations. There are large differences in spatial distribution.

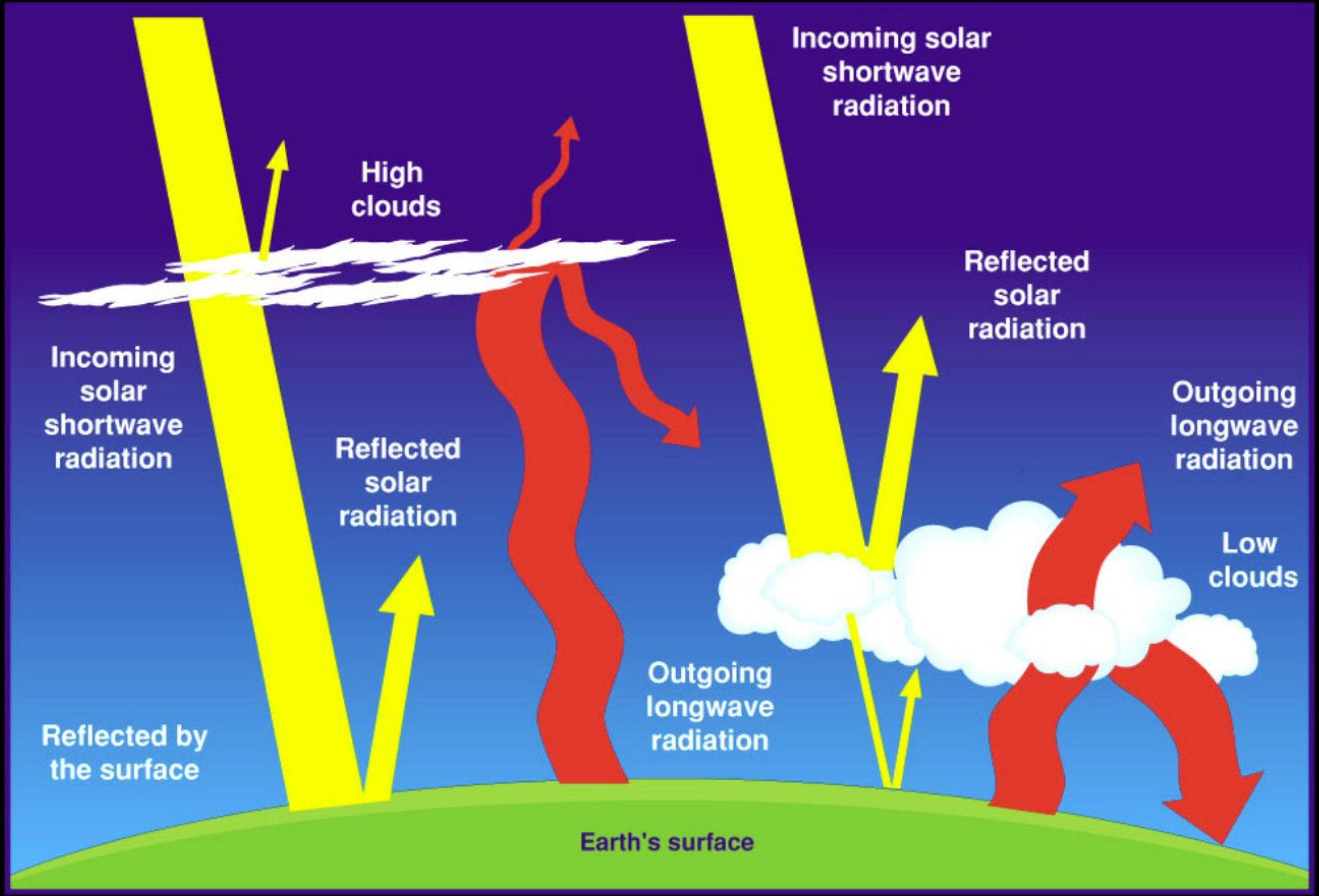
Clouds, radiation and energy balance

- Clouds are characterized by two competing radiative effects.
- On the one hand, they cool the Earth by shading the surface from shortwave solar radiation.
- On the other, they warm the Earth by blocking the emission of longwave radiation to space.



(Trenberth et al., 2009).

Cloud Effects On Earth's Radiation

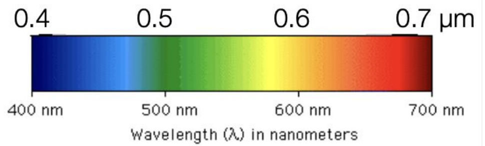


Cloud LW emissivity vs SW albedo

- Cloud droplet diameter: 1–100 μm
- Clouds behave essentially as black bodies in the infrared spectrum (**LW, 5–30 μm**) because water efficiently absorbs LW radiation via its molecular vibration/rotation energy levels.
- Cloud droplets of size > 0.5 μm, equal or larger than **visible SW** wavelengths (**0.4–0.7 μm**) "Mie-scatter" visible SW, in all directions, including forward, with **no wavelength dependence**. Clouds don't absorb SW, as water is transparent to it.
- *For a given amount of cloud water*, smaller cloud droplets (as long as $r/\lambda \gtrsim 1$) will yield more SW scattering cross-section. ➡ Small droplets scatter more efficiently!
- Rayleigh Scattering: by molecules, smaller than wavelengths. Wavelength dependence is $1/\lambda^4$: blue scattered more efficiently than red.

Schematic of SW Cloud Scattering

"Mie-scattering" Gustav Mie (1868–1957)



Cloud Radiative Forcing

$$\mathrm{CRF}_{LW} = LW_{\text{with clouds}} - LW_{\text{without clouds}}$$

- Units: W/m^2
- Typically evaluated at the surface or at the top of the atmosphere
- LW without clouds is calculated using a radiation model, yet the uncertainty is not large.
- Similarly, for SW CRF:

$$\mathrm{CRF}_{SW} = SW_{\text{with clouds}} - SW_{\text{without clouds}}$$

The sum of longwave and shortwave radiative forcing is the "net cloud radiative forcing."

Shortwave Cloud Radiative Forcing

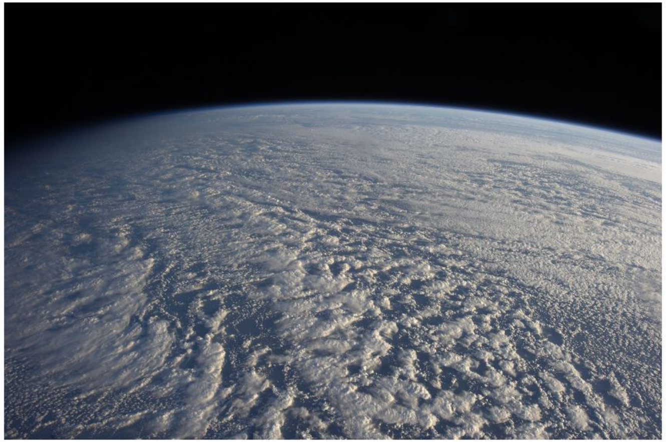
- Clouds absorb very little shortwave radiation. They either reflect or transmit/scatter.
- **Low stratocumulus** clouds have high albedo but a weak LW CRF.
- Wispy, high ice clouds, such as **cirrus**: have a low SW albedo but a large LW CRF.
- Reduction in insolation due to cloud albedo = "shortwave cloud radiative forcing."
- Clouds roughly double Earth's global albedo, from 0.15 to around 0.3.
- Globally, clouds reduce the absorbed SW radiation by about 47 W/m^2

Stratocumulus: low (lowest 2 km) clouds; high SW albedo, small LW CRF composed of water; have a net cooling effect.

cirrus: high (>6 km) clouds; low SW albedo, large LW emissivity, composed of ice; have a net warming effect.

Longwave Cloud Radiative Forcing

- Clouds effectively absorb LW radiation rather than reflect it.
- **Emissivity:** effectiveness at emitting/absorbing radiation relative to a black body.
- Clouds LW emissivity ≈ 1, absorb nearly all upwelling LW and reemit down & up.
- Reduction in outgoing LW due to clouds: "LW Cloud Radiative Forcing."
- Globally, clouds reduce outgoing long-wave emission by 26 W/m^2.
- **Globally, cloud LW+SW CRF cool climate by about $47 - 26 = 21$ W/m^2.**

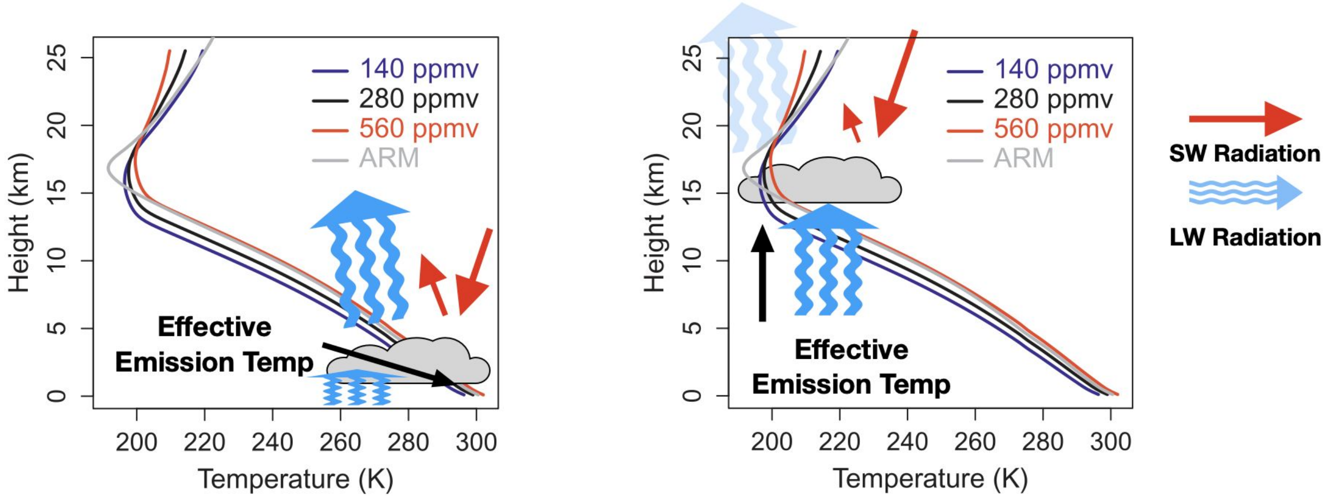


Stratocumulus: low (lowest 2 km) clouds; high SW albedo, small LW CRF composed of water; have a net cooling effect.

cirrus: high (>6 km) clouds; low SW albedo, large LW emissivity, composed of ice; have a net warming effect.

CRF summary: high cloud warming vs low cloud cooling

- SW CRF (albedo) is controlled by cloud particle size and cloud water or ice content ⇒ **Low clouds**, with high water content and many small droplets, **have a high albedo.**
- **Low clouds** radiate at a temperature close to the surface temperature, radiate upward most of the heat emitted by the surface, and thus **have little LW CRF**.
- Because it takes little water for a cloud to behave as a black body, LW CRF is primarily a function of cloud height. **High clouds**, radiate at a very low temperature and **have a strong longwave warming CRF**.

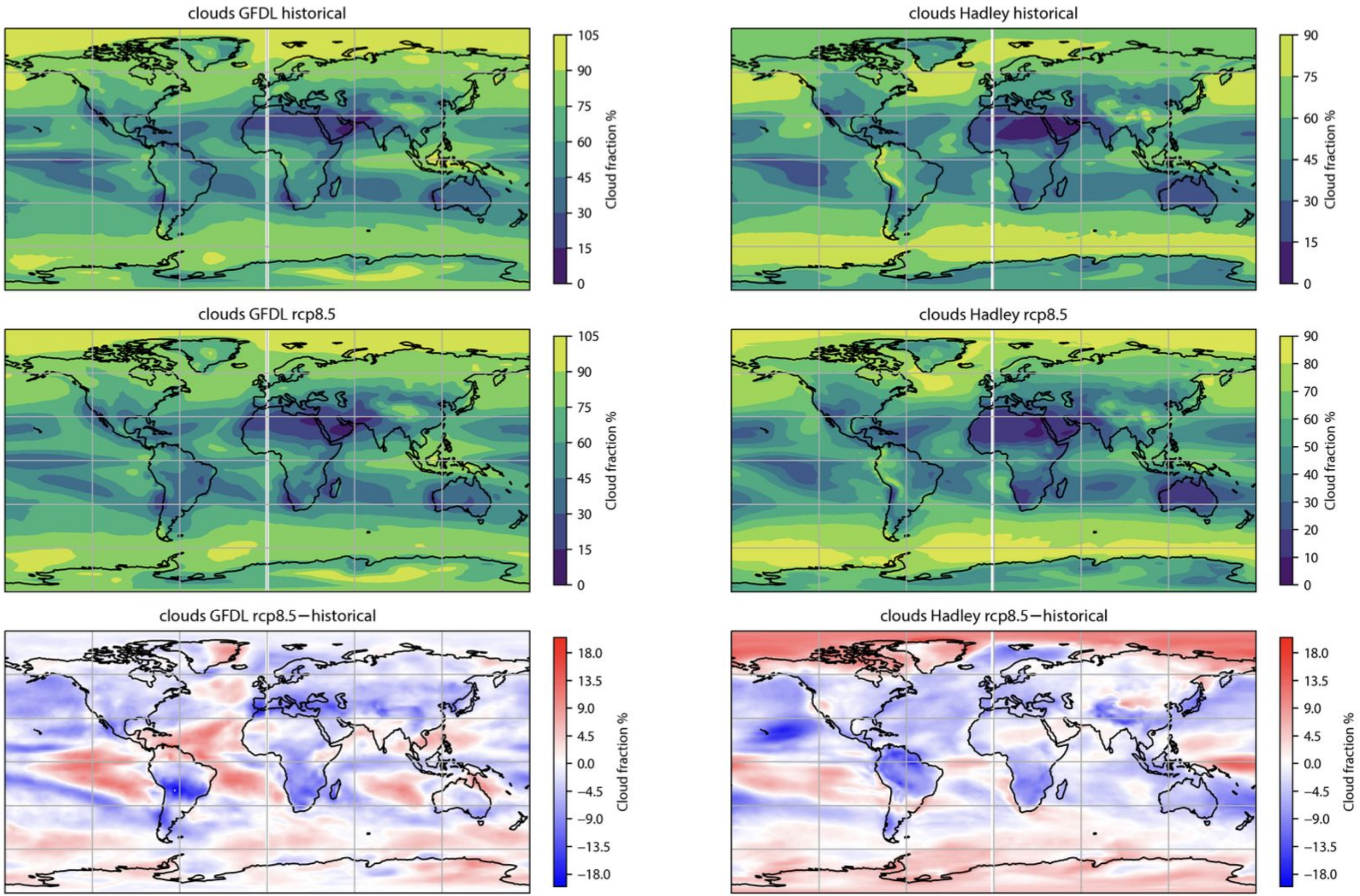


Temperature profiles from numerical simulations (Romps 2011)

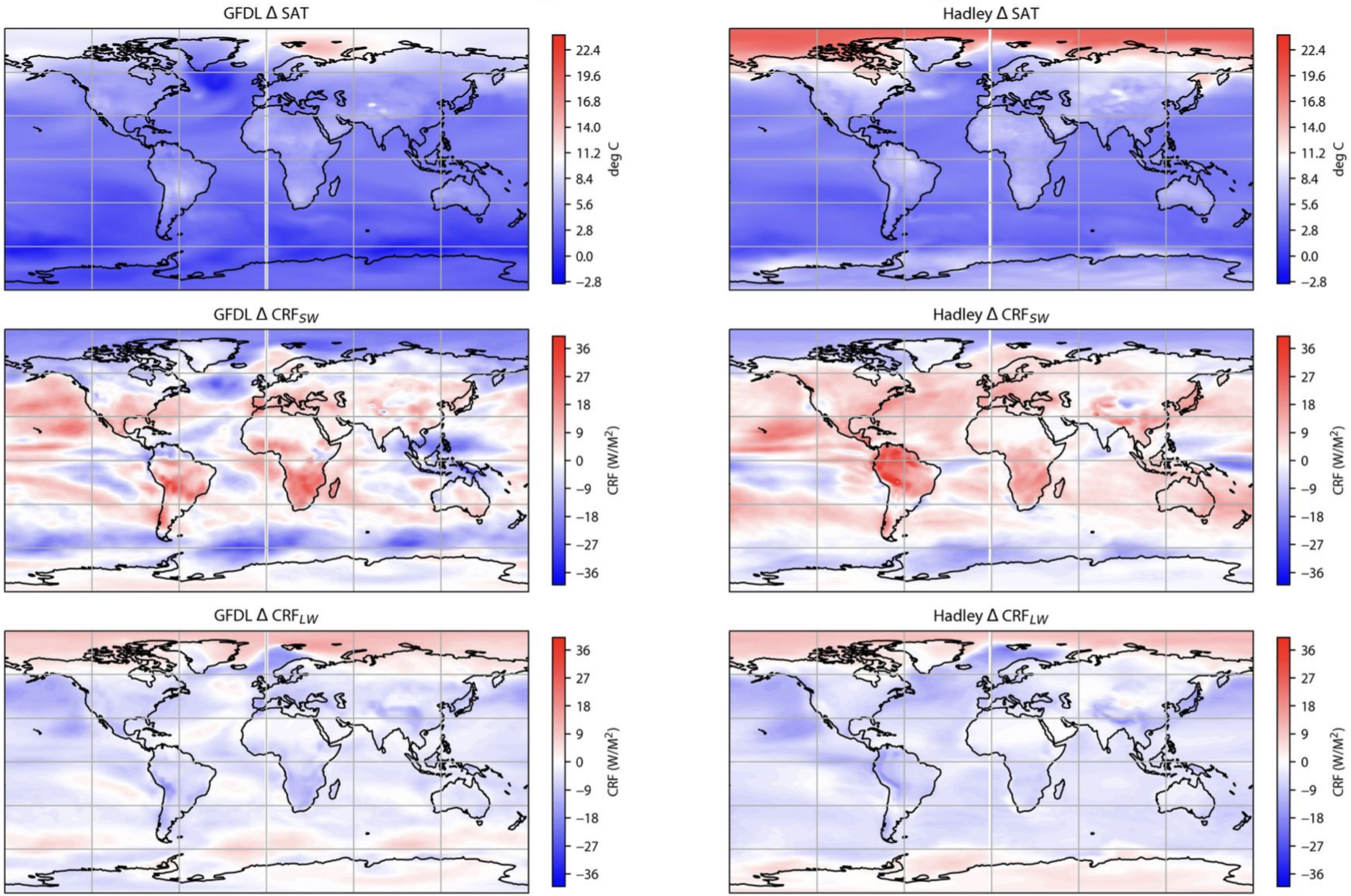
Low Clouds: Small LW CRF, large albedo, Net cooling effect

High Clouds: emit at cold temperatures, strong net LW warming effect.

Clouds radiative forcing and climate sensitivity in climate models



Clouds radiative forcing and climate sensitivity in climate models



Longwave vs Shortwave Cloud Radiative Forcing

The sum of longwave and shortwave radiative forcing is the “net cloud radiative forcing” (CRF).

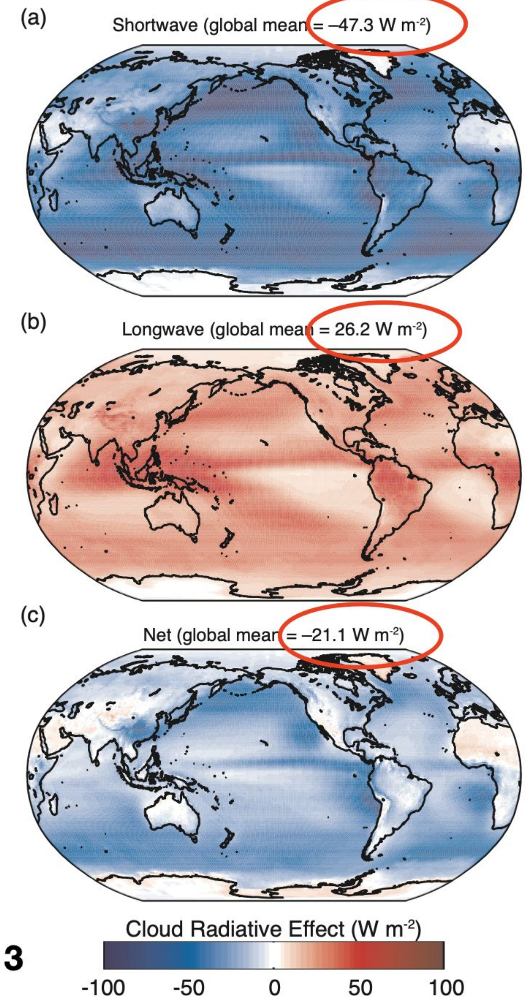


Figure 7.7 | Distribution of annual-mean top of the atmosphere (a) shortwave, (b) longwave, (c) net cloud radiative effects averaged over the period 2001–2011 from the Clouds and the Earth’s Radiant Energy System (CERES) Energy Balanced and Filled (EBAF) Ed2.6r data set (Loeb et al., 2009) and (d) precipitation rate (1981–2000 average from the GPCP version 2.2 data set; Adler et al., 2003).

IPCC AR5, 2013

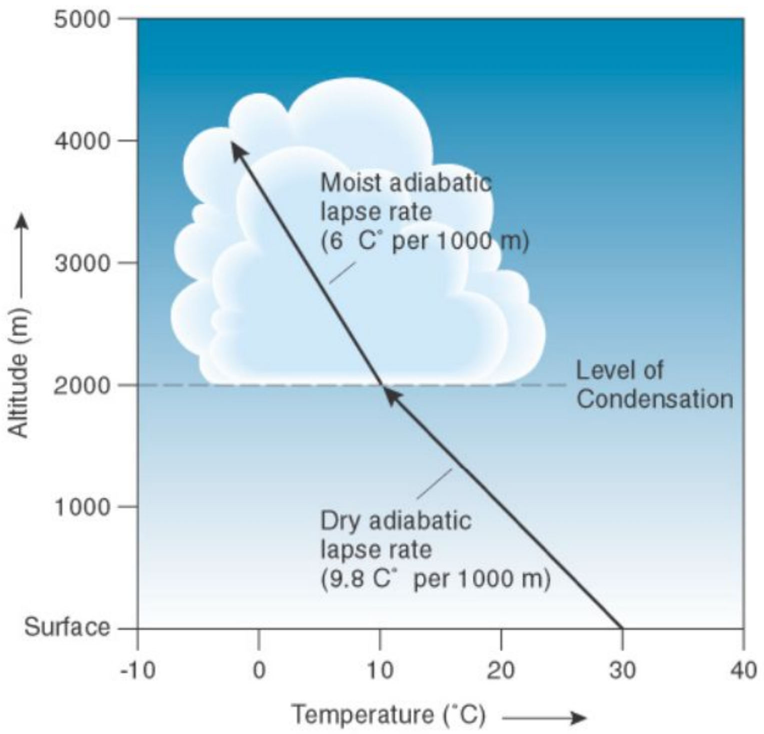
Cloud formation

Cloud formation by flow over topography.
(University of Wyoming)

https://www.youtube.com/watch?v=XH_M4jItiKw

How do clouds form?

- Clouds generally form in rising air (updraft).
- As a moist parcel of air rises, it expands due to lower pressure & cools adiabatically.
- Thus temperature in troposphere decreases w/height
- Eventually, air parcel humidity matches the decreasing saturation humidity, & the parcel becomes saturated.
- Further ascent & cooling causes droplets to condense as saturation humidity falls further, heat is released into the parcel, and it further rises. Positive feedback!
- Updrafts can happen in fronts, flows over mountains, or when warm air over land or ocean becomes buoyant and rises.



Schematic of Cloud Formation

Adiabatic heating demo: *fire syringe*

https://www.youtube.com/watch?v=4qe1Ueifekg

Adiabatic cooling demo: *clouds in a bottle*

https://www.youtube.com/watch?v=cXpuo3YHOn0

Moist convection and cloud formation

Moist static energy (MSE), the energy per unit mass of a moist air parcel, is conserved when the parcel is lifted adiabatically in the atmosphere,

$$MSE = c_p T(z) + Lq(z) + gz.$$

Parcel starts at surface, with $MSE_s = c_p T_s + Lq_s$. Initially, the rising air parcel is not saturated & there is no condensation, $q(z) = q_s$ so that the conservation may be written in terms of the *Dry Static Energy* as:

$$DSE(z) = c_p T(z) + gz = c_p T_s$$

This leads to a solution for the temperature profile and lapse rate,

$$T(z) = T_s - gz/c_p \qquad dT/dz = -g/c_p = -9.8\ \mathrm{K/km}$$

The parcel keeps rising & cooling, until the saturation moisture is smaller than the parcel's moisture & condensation occurs, $q(z) = q^*(T(z), p(z))$. The conservation law is $c_p T(z) + Lq^*(T(z), p(z)) + gz = MSE_s$ which may be solved graphically for $T(z)$.

Both the initial unsaturated & the later saturated MSE conservation of the air-parcel ascent may be written as,

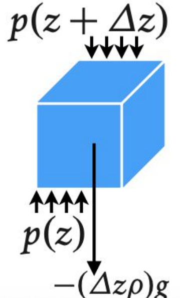
$$\mathrm{MSE}_s = c_p T(z) + L \min\left(q_s, q^*(T(z), p(z))\right) + gz$$

To solve, need to find $p(z)$ from the vertical momentum (hydrostatic) balance for an air parcel: $dp/dz = -\rho g$. Using $\rho = p/(RT)$ this becomes $dp/dz = -pg/RT$, or $d \log p = -g/RT dz$.

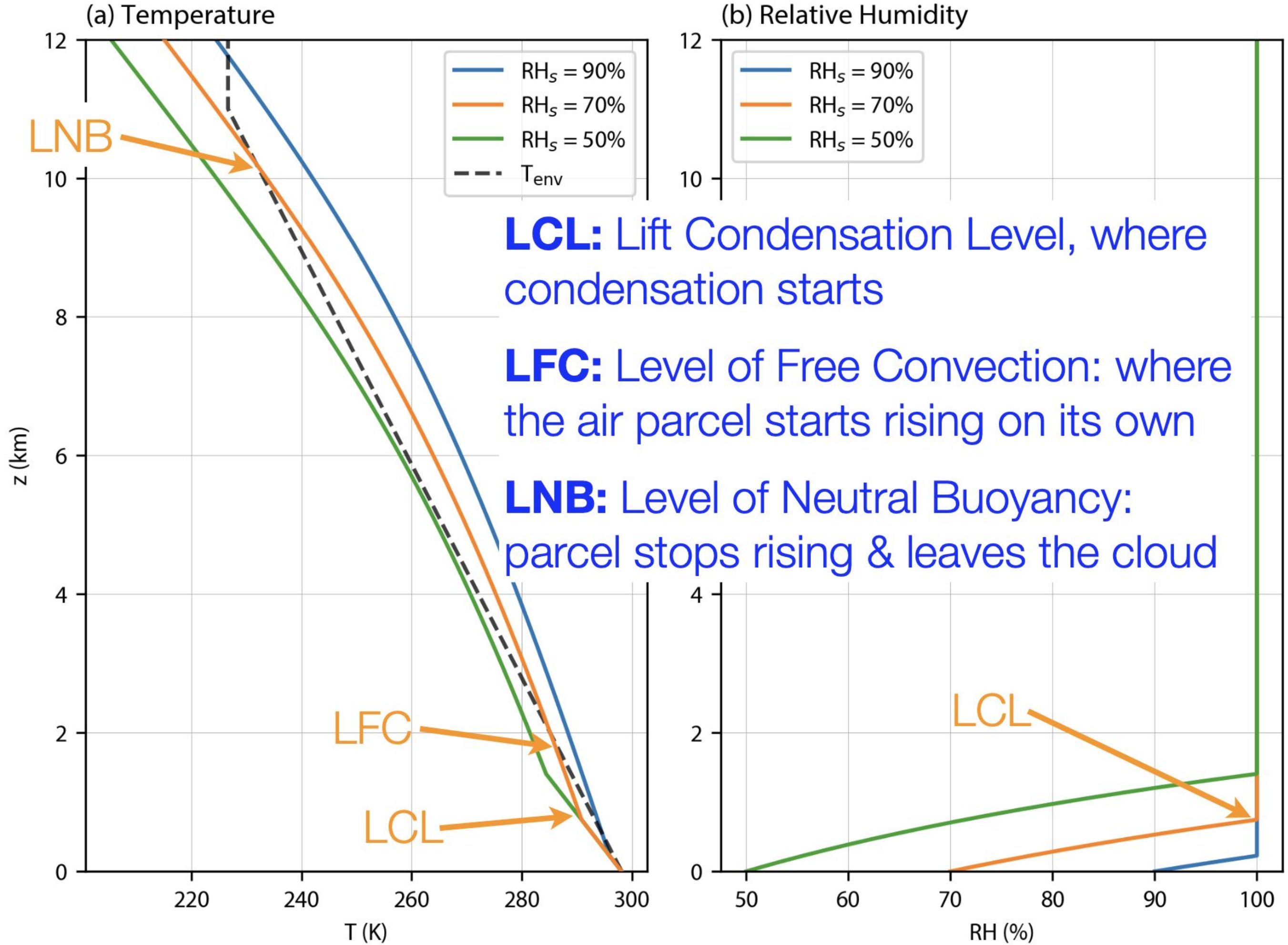
Integrating, we find $\ln p(z) - \ln p_s = -gz/R\bar{T}$,

so that $p(z) = p_s e^{-gz/(R\bar{T})}$

➡ pressure is exponential in height.



Moist Convection: LCL and LFC



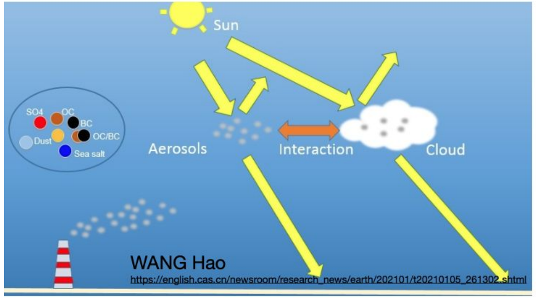
LCL: Lift Condensation Level, where condensation starts

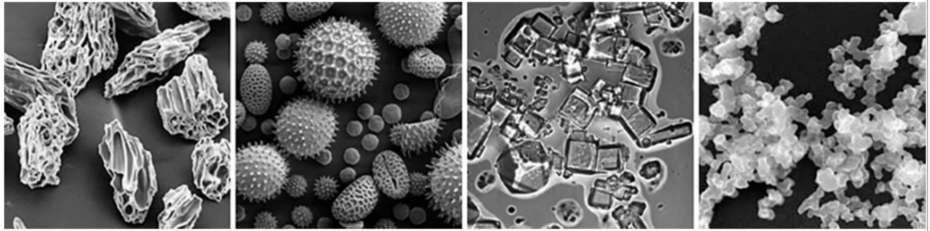
LFC: Level of Free Convection: where the air parcel starts rising on its own

LNB: Level of Neutral Buoyancy: parcel stops rising & leaves the cloud

Microphysics

- Cloud formation depends on processes on the scale of cloud hydrometeors (water droplets, ice crystals, aggregates, graupel, hail), referred to as cloud microphysics.
- Cloud formation is strongly accelerated by aerosols, small liquid/solid particles, natural (dust, salt particles, volcanic) or human-caused (fire, combustion, pollution).
- Aerosols act as cloud condensation nuclei (CCN)/ice nuclei (IN) & lead to much faster water droplet/ice particle formation.
- Droplets grow by deposition of water vapor, followed by collision and coalescence of small particles that can grow all the way to raindrop size.
- Uncertainty increases because we need to estimate the density of aerosol sizes & their phase (water/ice), which strongly affects cloud SW albedo & LW emissivity.
- Further uncertainty due to radiative effects: Aerosols absorb/ reflect sunlight (***direct effects***) & affect the number/size of cloud droplets/ice particles, and therefore the radiative effects of clouds (the ***indirect effect***).





Scanning electron microscope images (not same scale) of aerosols. volcanic ash, pollen, sea salt, and soot. NASA, from USGS, UMBC, (Chere Petty), Arizona State Univ (Peter Buseck)
https://scied.ucar.edu/learning-zone/air-quality/aerosols

Life cycle of a cloud

- Clouds dissipate occurs both via droplets/ ice crystals falling toward the ground and via the continuous evaporation of droplets.
- Timelapse of clouds (2 hours of footage in 2 minutes):

https://www.youtube.com/watch?v=Qu7mcKZgqv0

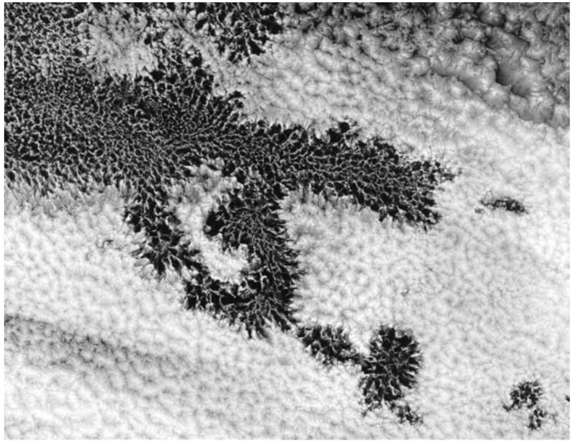
Note the complex evolution, and the small scale relative to climate model's grid, hence the large uncertainty

Low Cloud: Stratocumulus

- Cover broad regions over the subtropical oceans.
- Characterized by lines, waves, and cellular structures.
- Radiative cooling from the cloud tops drives mixing with surface air that replenishes the liquid water in these clouds.
- Can often be seen out of an airplane window while flying.
- Large SW albedo, strong cooling effects on climate.

Stratocumulus clouds from a plane

http://www.pilotfriend.com/training/flight_training/met/clouds.htm



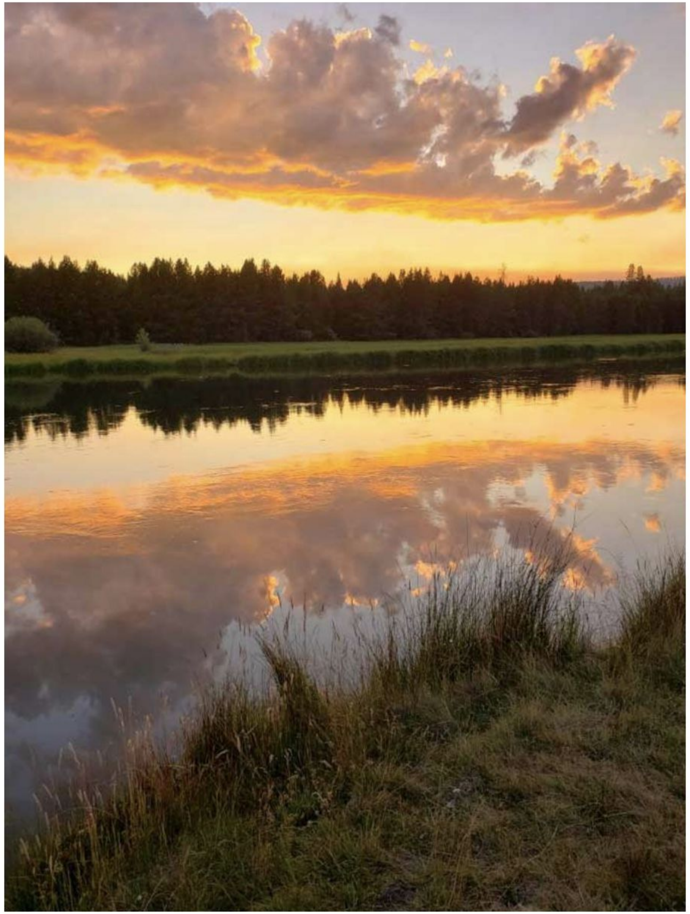
Cellular convective structures

https://visibleearth.nasa.gov/images/98570/clouds-in-eastern-south-pacific-ocean?size=small

Low Cloud: Shallow cumulus

- The most familiar type of cloud.
- Low level clouds that do not precipitate.
- Small size and thus small radiative impact, comparatively less important to climate.

https://cloudappreciationsociety.org/gallery/photo/photo-n-357365



https://cloudappreciationsociety.org/gallery/photo/photo-n-359960/

High Cloud: Deep Cumulus

- Strongly convecting updrafts that may reach up to the tropopause (9–17 km above the surface).

- Often characterized by a flat anvil-like top.

- Most common in tropical regions.

- **Cover a very small fraction of tropical areas** but are important for setting moisture and temperature profiles in the tropics.

https://cloudappreciationsociety.org/gallery/photo/photo-n-357970

https://cloudappreciationsociety.org/gallery/photo/photo-n-358495

Deep cumulus clouds with associated anvil tops.

High Cloud: Cirrus clouds

- Thin wispy clouds formed of ice crystals.
- Very high in altitude (4–20 km).
- Can form at the outflow of deep cumulus clouds or in warm fronts.
- **Large LW emissivity, strong warming effect on climate.**

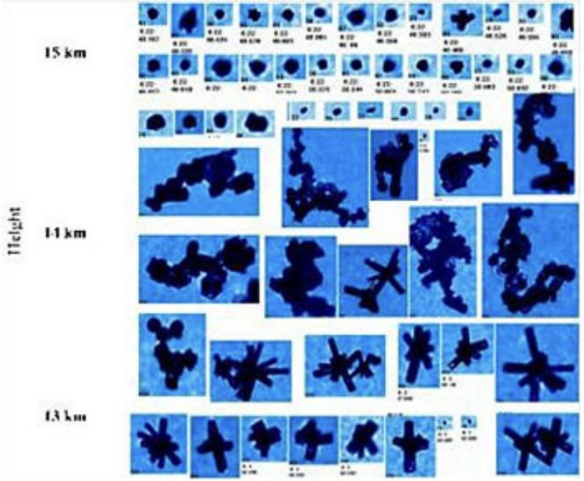
https://cloudappreciationsociety.org/gallery/photo/photo-n-359475

https://cloudappreciationsociety.org/gallery/photo/photo-n-285941

Water vs Ice Clouds

- Smaller particles yield a larger aggregate cross-section area of cloud particles for the same total water content.
- Ice clouds tend to be composed of larger particles. Their high altitude and cold environment also lead to small water content.
- Hence, they are not as good as low water clouds at scattering SW radiation.
- However, they are still, to a very good approximation, black bodies in the LW.
- **Thus thin ice cirrus clouds, are effective at warming: a strong longwave but little shortwave CRF.**

Sky filled with cirrus clouds.
(Wikipedia commons)
https://en.wikipedia.org/wiki/Cirrus_cloud#/media/File:CirrusField-color.jpg



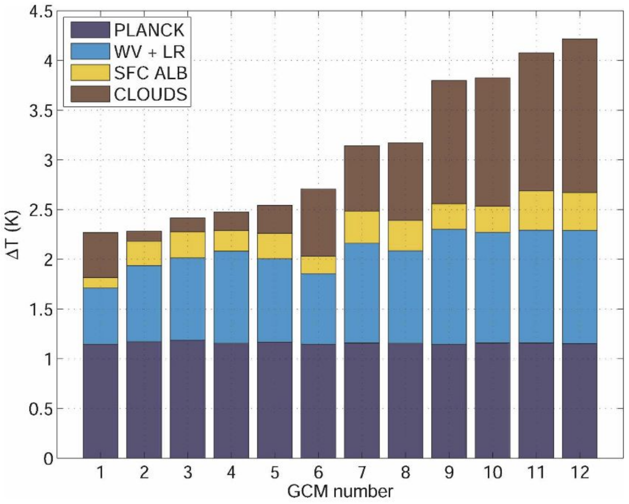
Cloud Ice Particles (ARM) (Lawson et al 2006)

Clouds and climate uncertainty

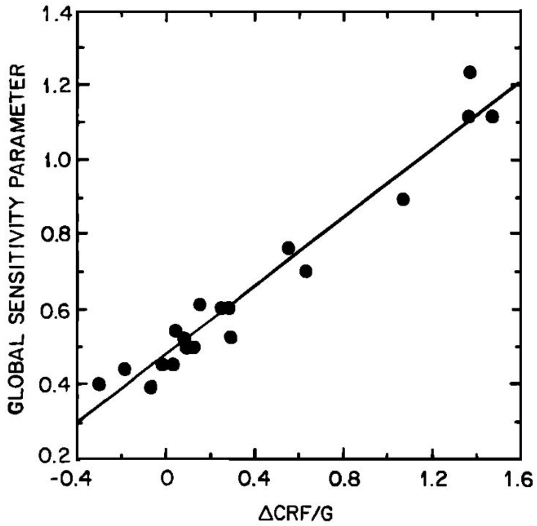
CRF: Primary Source of Climate Uncertainty

★ Cloud feedback on higher CO_2 is generally estimated to be positive, although highly uncertain in magnitude. This uncertainty is partly because CRF is composed of two large competing effects.

★ **Future change in CRF is the dominant source of difference between models and of uncertainty in climate model prediction.**

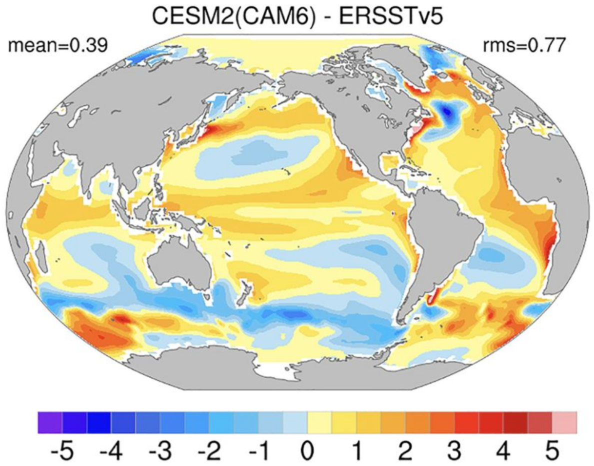


Modern models: Equilibrium temperature response to feedbacks for 2xCO_2 using Inter-model variability is primarily due to cloud feedback. (Dufresne and Bony 2008)

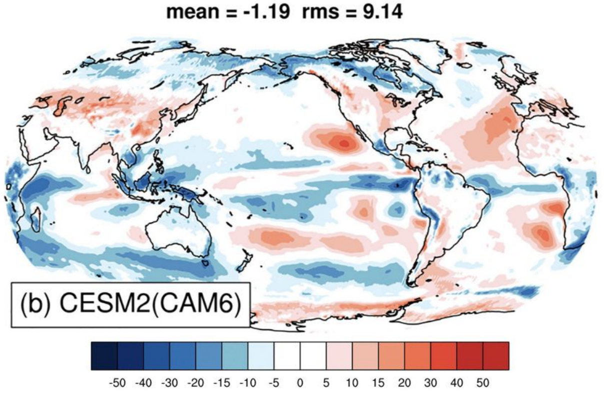


Old models: Global climate sensitivity plotted against CRF/CO_2 Radiative Forcing for 19 Models: a strong linear fit between ΔCRF and global climate sensitivity. (Cess et al. 1990)

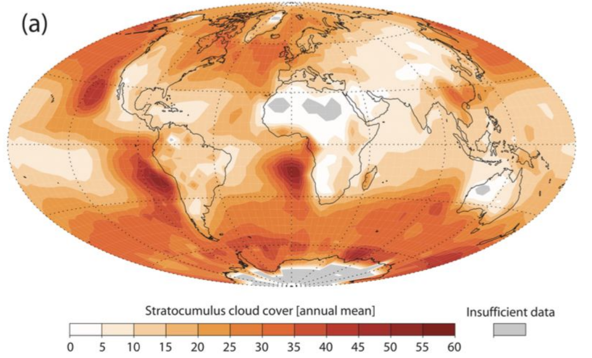
Stratocumulus cloud model bias leads to significant SST errors



Model SST minus observations (°C)



shortwave CRF: model minus observations

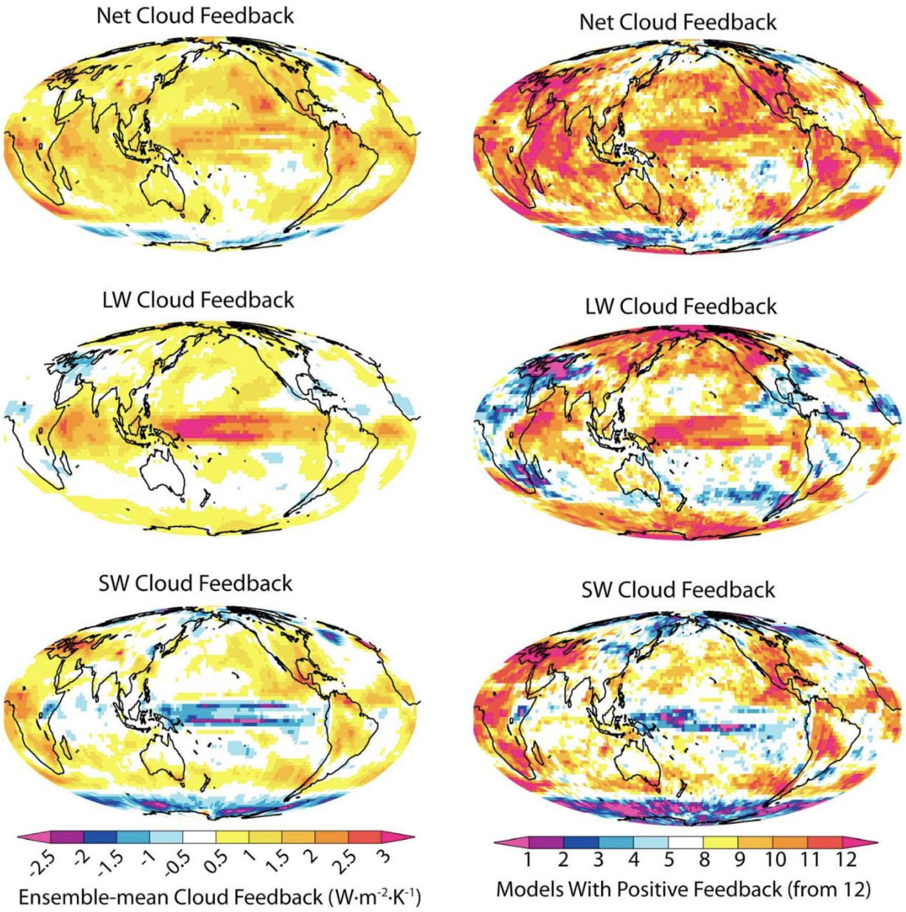


observed stratocumulus cloud fraction (%)

G. Danabasoglu et al 2020, https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2019MS001916

SST error (difference between model and observations) is large, ~2.5C in regions with underestimated stratocumulus cloud cover

Model Disagreement on Cloud Feedbacks



- **Clouds drive climate uncertainty, but which cloud types?**
- Right panel: number of models out of 12 with a positive cloud feedback.
- Right panels: n<6 are areas of highly uncertain feedback.
- The subtropics, characterized by broad stratocumulus cloud coverage, tend to have the lowest model agreement.

Spatial distribution of cloud feedback values and their uncertainties (Soden et al. 2011)

Clouds and climate uncertainty

Two-layer energy balance again:

$$C_{\text{surface}} \frac{dT}{dt} = \frac{S_0}{4}(1-\alpha(T)) + \epsilon(\text{CO}_2, T_a)\sigma T_a^4 - \sigma T^4$$

Surface/upper ocean energy balance

$$C_{\text{atm}} \frac{dT_a}{dt} = \epsilon(\text{CO}_2, T_a)\sigma T^4 - 2\epsilon(\text{CO}_2, T_a)\sigma T_a^4.$$

Atmospheric energy balance

With cloud feedbacks given by:

$$\alpha(T) = \alpha_0 \left(1 + \Delta_{SW}(T - T_0)\right)$$

Low clouds' albedo depends on surface temperature

$$\epsilon(T_a) = \epsilon_0(\text{CO}_2) \left(1 + \Delta_{LW}(T_a - T_{a,0})\right)$$

High clouds' emissivity depends on atmospheric temperature

$$\epsilon_0(\text{CO}_2) = 0.75 + 0.05 \log_2(\text{CO}_2/280).$$

Emissivity dependence on CO_2

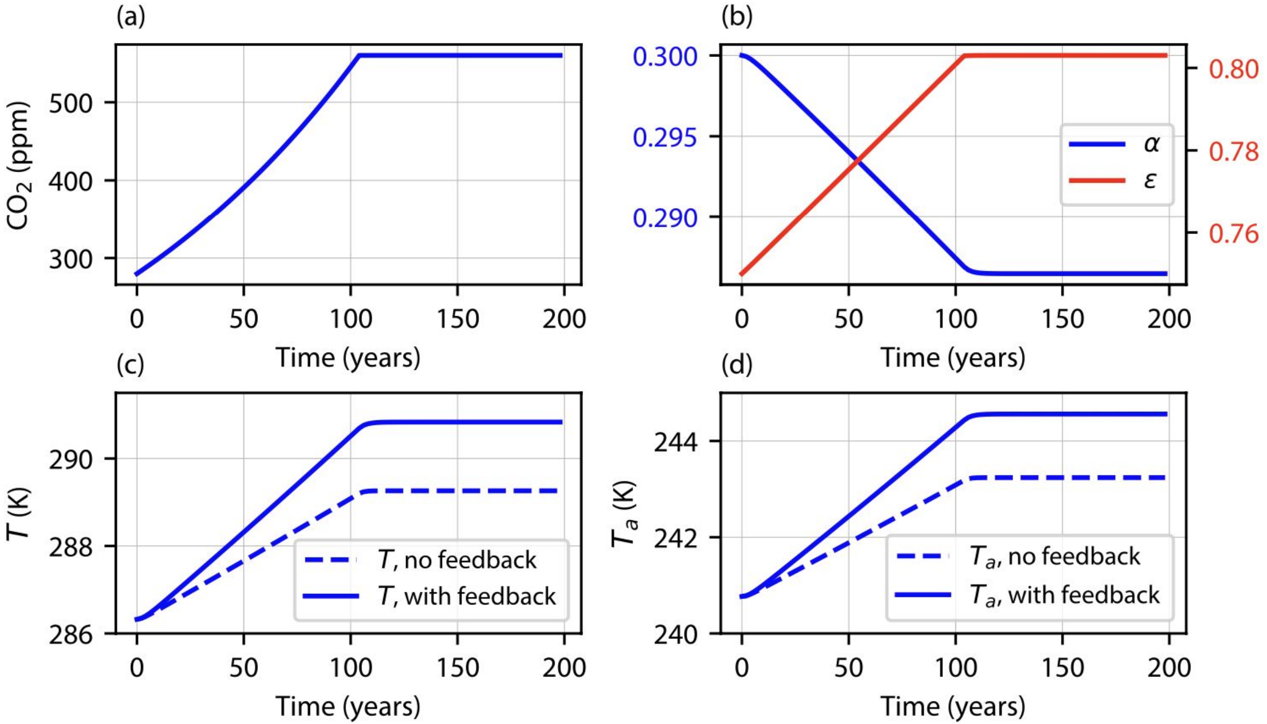


Figure 7.3: Cloud feedbacks in a two-layer energy balance model. Response of a two-level energy balance model to SW and LW cloud feedbacks. (a) Atmospheric CO_2 as a function of time, representing a doubling scenario. (b) The change to cloud albedo and emissivity resulting from the formulation in eqn (7.3). (c) The surface temperature as a function of time with and without cloud feedbacks. (d) Same, for the atmospheric temperature.

Summary

- Clouds are characterized by an outsized radiative impact; their shortwave and longwave radiative forcing are large and partially offset each other.
- Clouds, in particular low subtropical clouds, are responsible for much of the uncertainty in climate sensitivity.
- Despite uncertainties, cloud feedbacks to warming are generally believed to be positive.
- Although some negative feedbacks such as those involving high cirrus clouds have been proposed, so far no robust negative cloud feedbacks that can significantly reduce global warming have been identified.
- **Clouds have been, & continue to be the most important yet poorly understood aspect of climate's response to CO_2.**

stein egil liland: Nordland, Norway, https://www.pexels.com/photo/clouds-over-mountains-12035615/

- We covered MSE conservation $$c_p T(z) + Lq^*(T(z), p(z)) + gz = MSE_s$$ and used it to understand convection (LCL, LFC, LNB), cloud formation, and the atmospheric lapse rate.