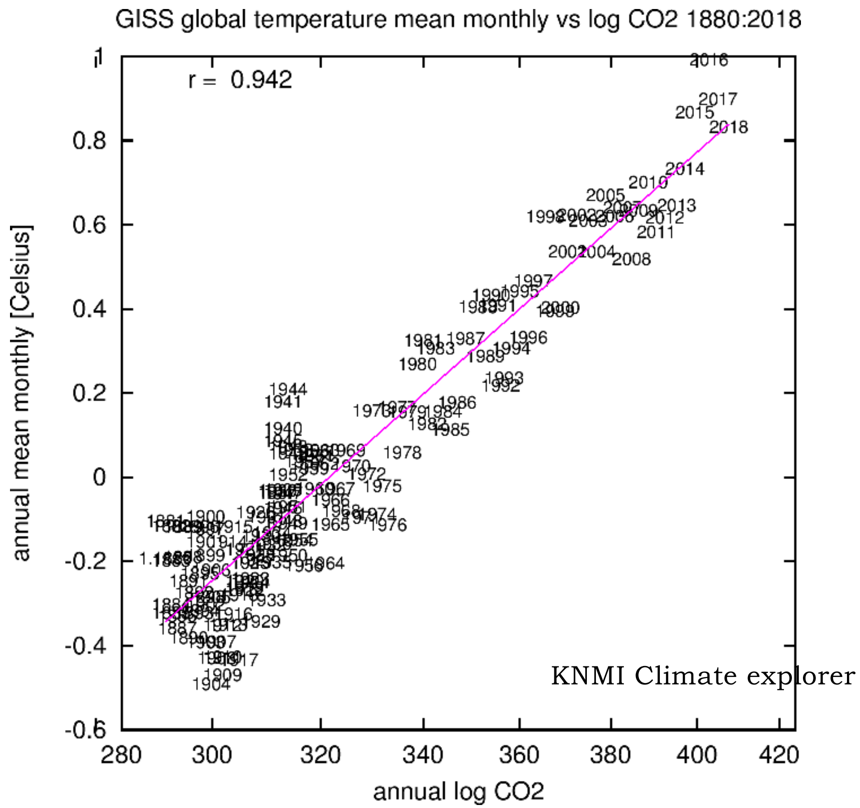
Climate change and engineering

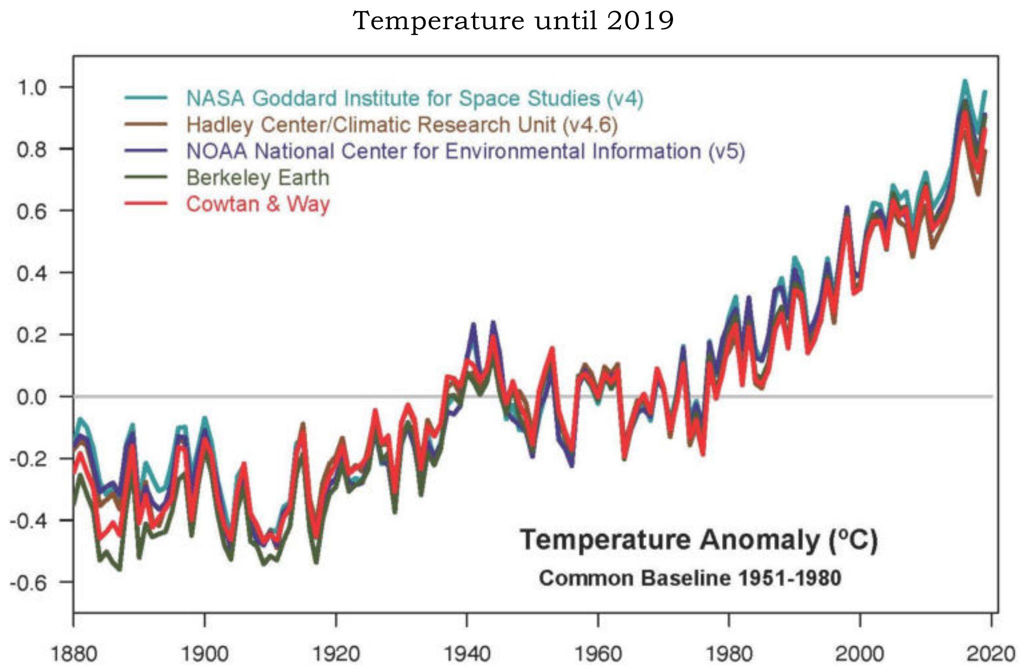
Herman Russchenberg

TUDelft Climate Institute

h.w.j.russchenberg@tudelft.nl

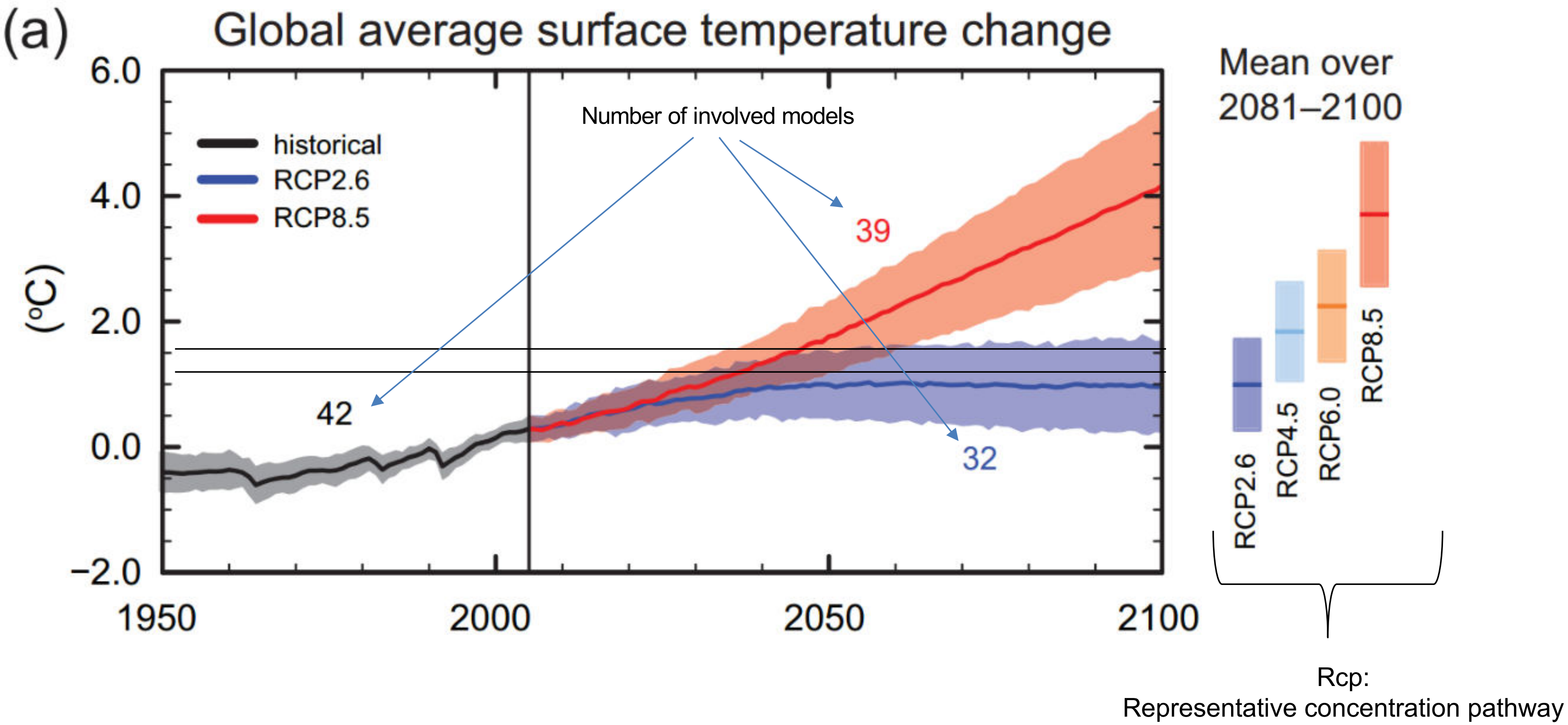
Climate 101: What has happened?



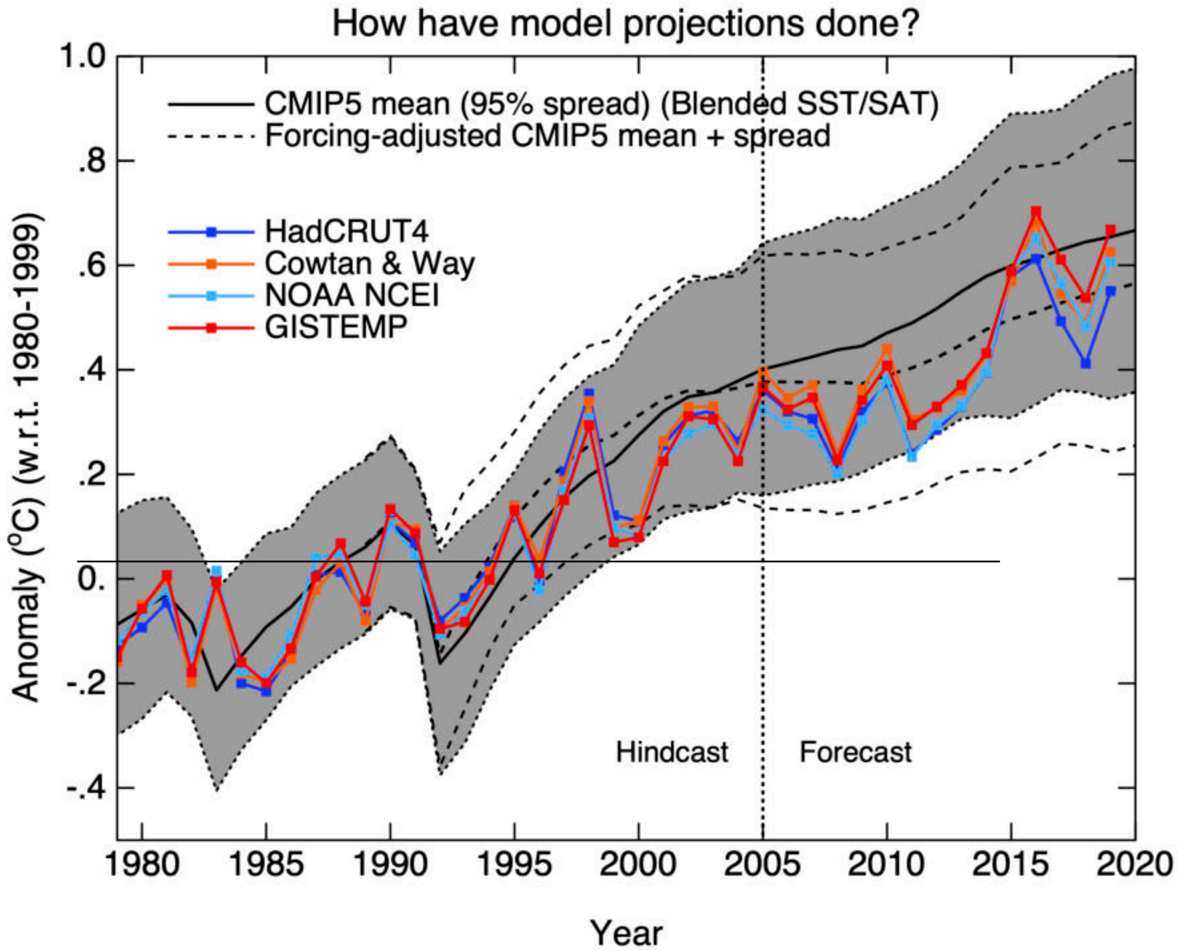


https://climate.nasa.gov/internal_resources/1986/

Climate 101: What might happen?

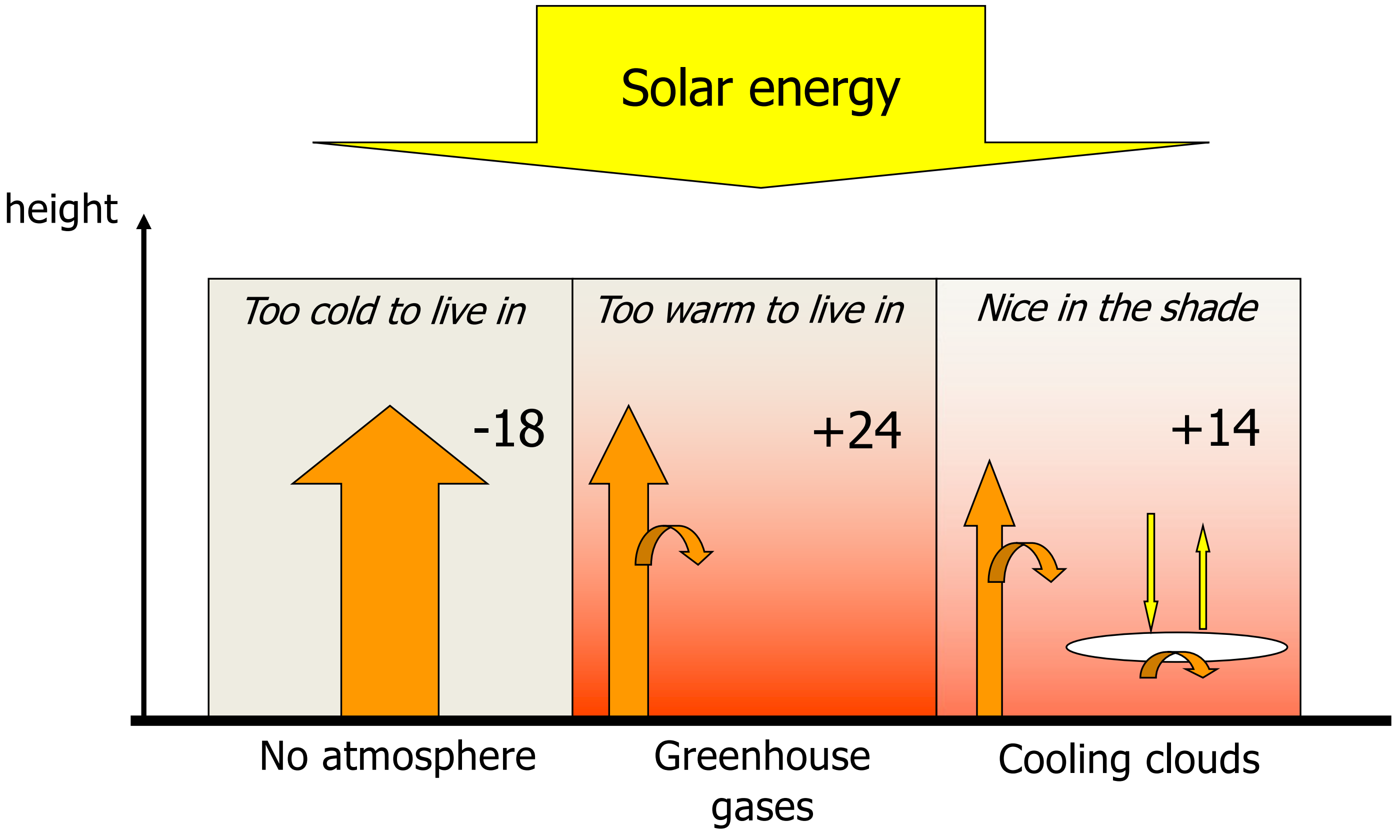


How good are climate models?

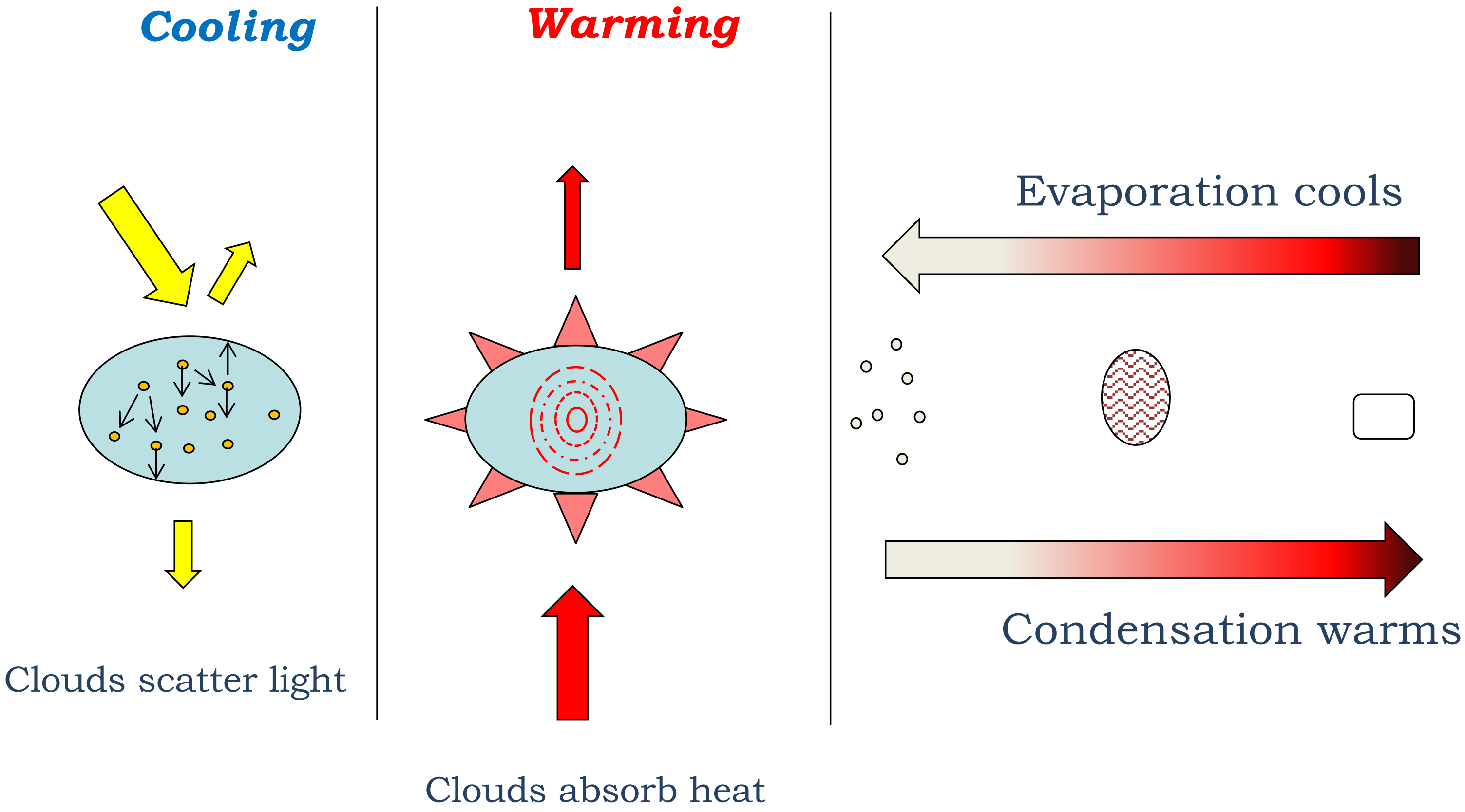


http://www.realclimate.org/images//cmp_cmip3_sat_blend_ann.png

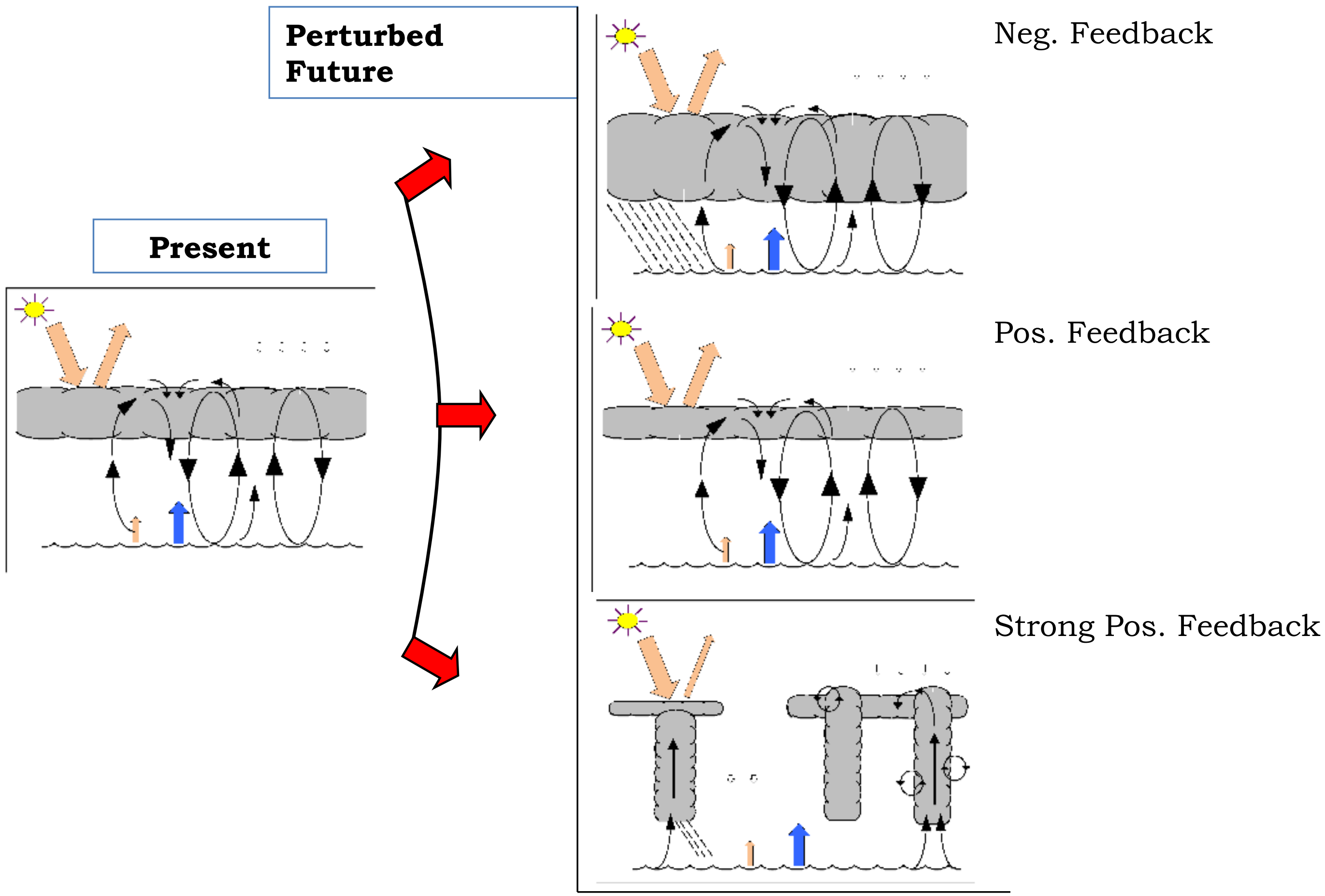
The radiation balance: a status quo?



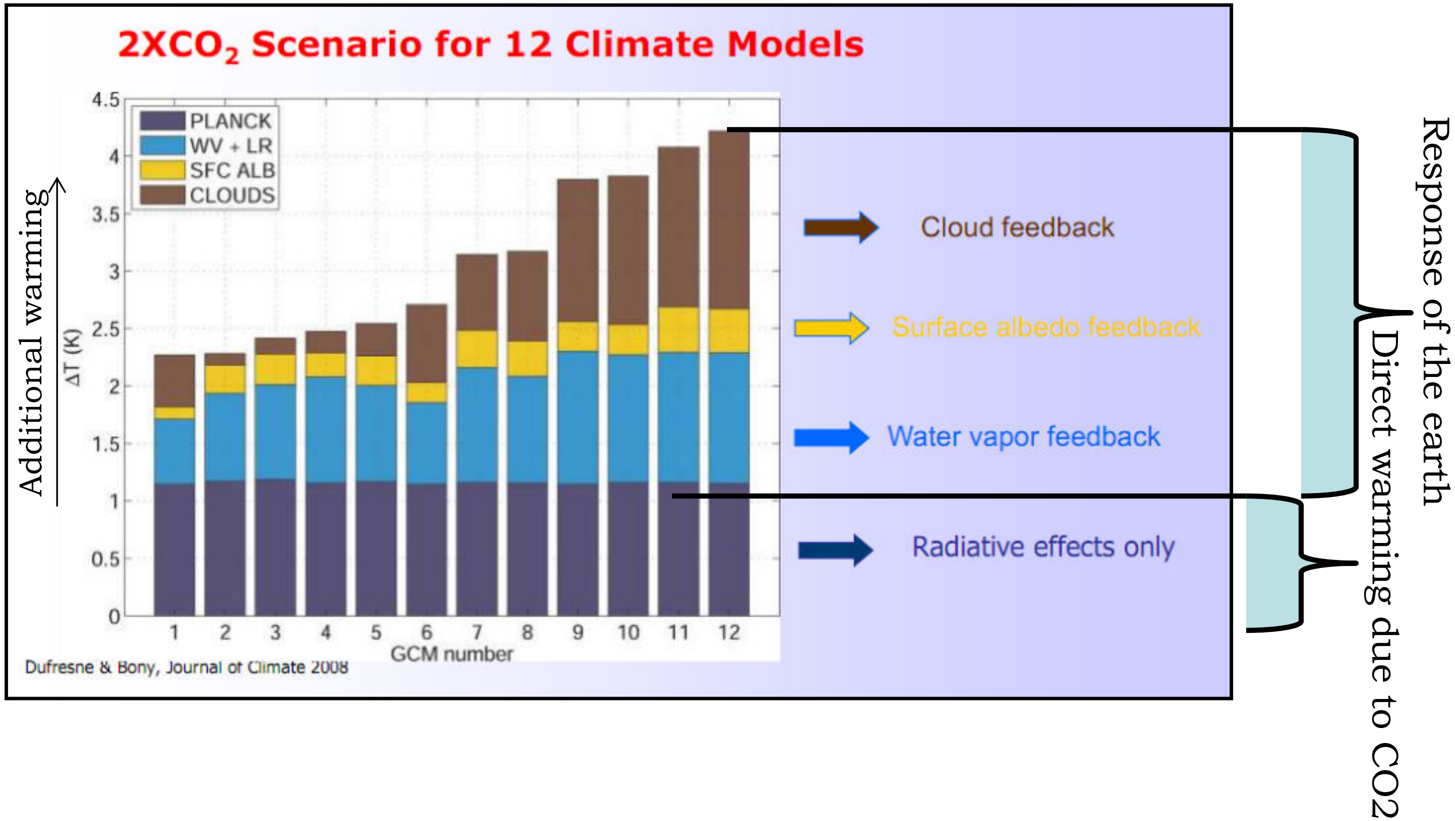
Clouds and climate



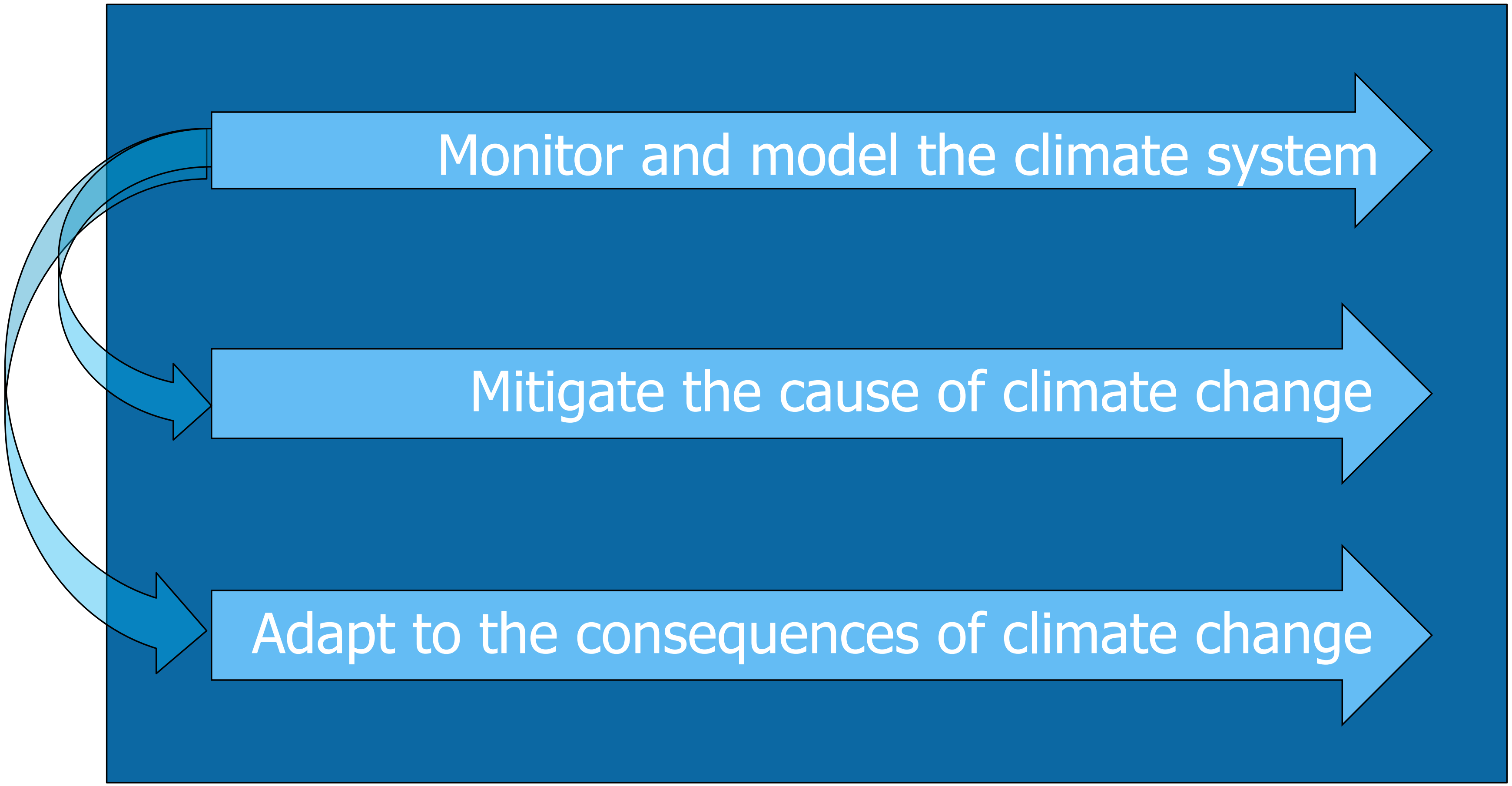
Possible cloud responses to warming



Global warming: state of the art



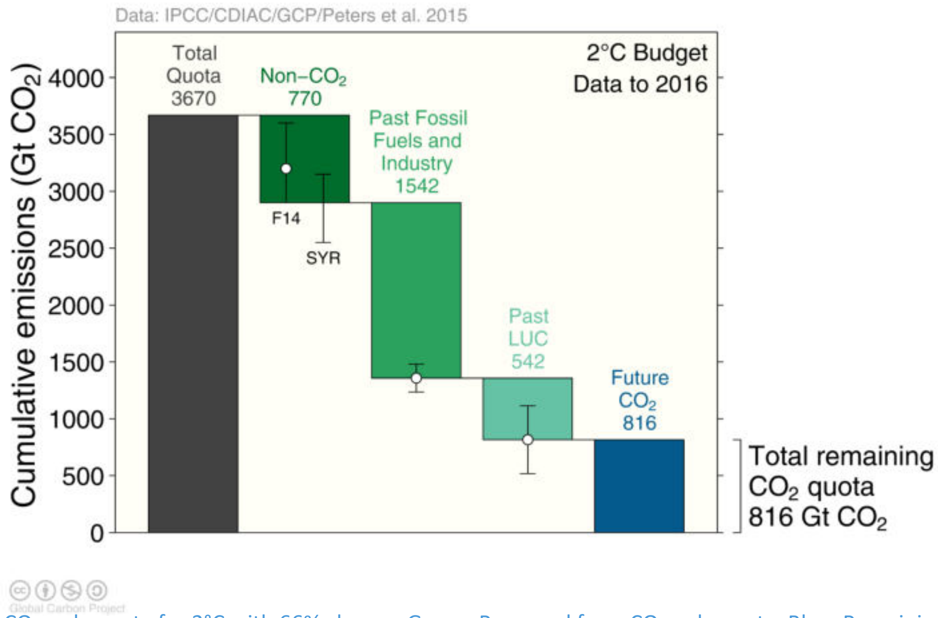
What to do against climate change?



Carbon Quotas to Climate Stabilization

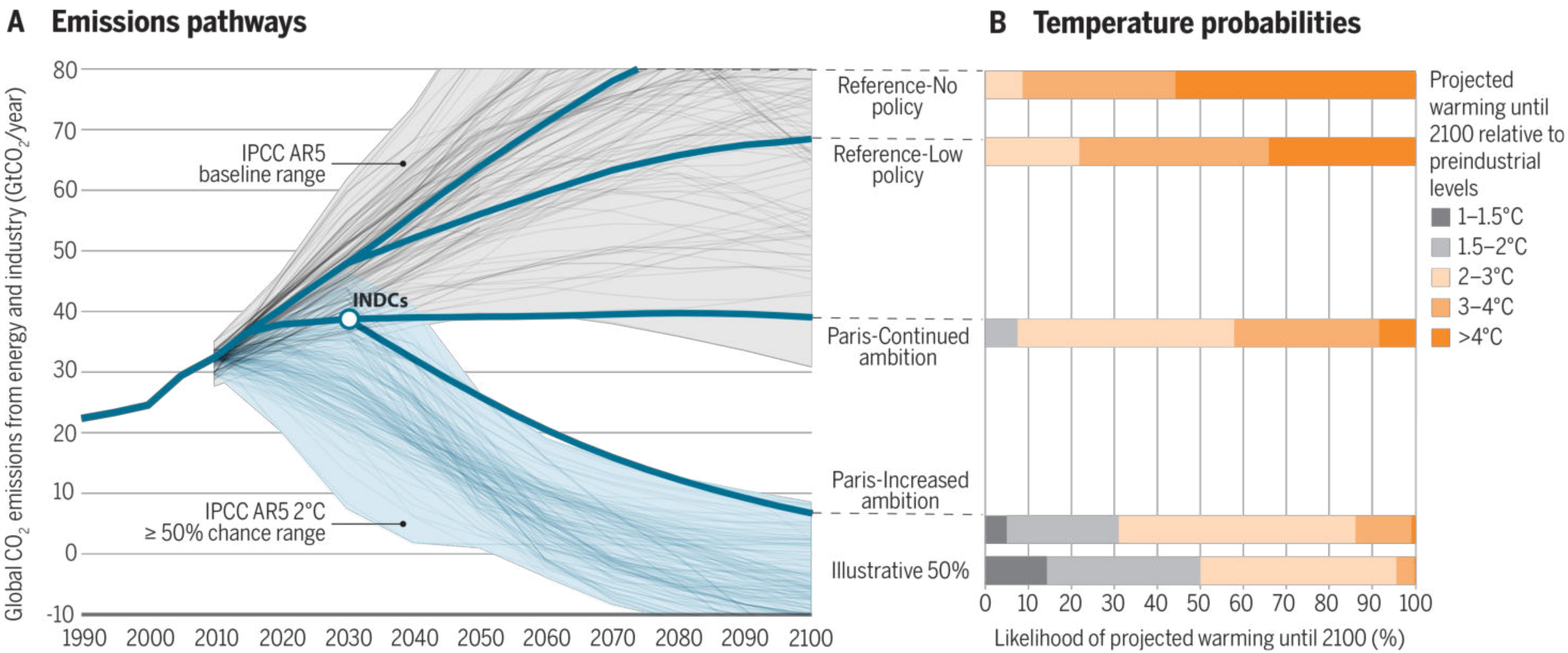
Carbon quota for a 66% chance to keep below 2°C

The total remaining emissions from 2017 to keep global average temperature below 2°C ($800GtCO_2$) will be used in around 20 years at current emission rates



Grey: Total CO_2-only quota for 2°C with 66% chance. Green: Removed from CO_2 only quota. Blue: Remaining CO_2 quota.
The remaining quotas are indicative and vary depending on definition and methodology
Source: Peters et al 2015; Global Carbon Budget 2016

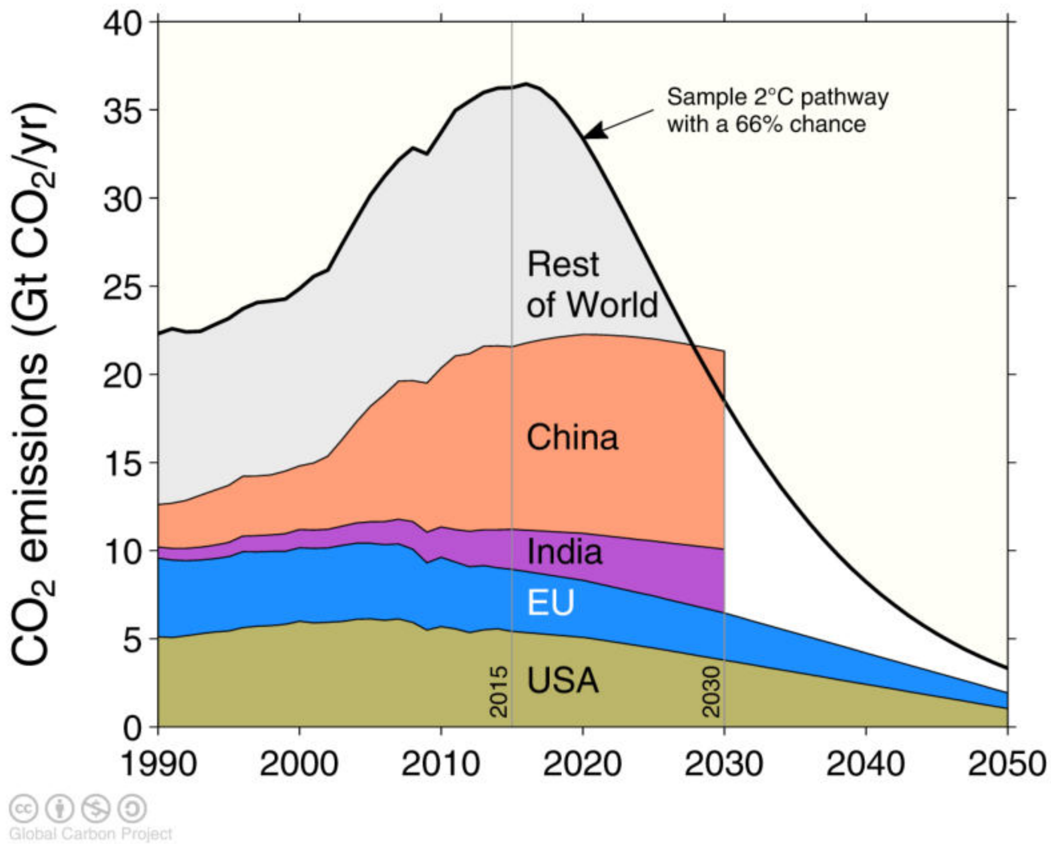
In the wake of the Paris pledges



https://science2017.globalchange.gov/chapter/14/

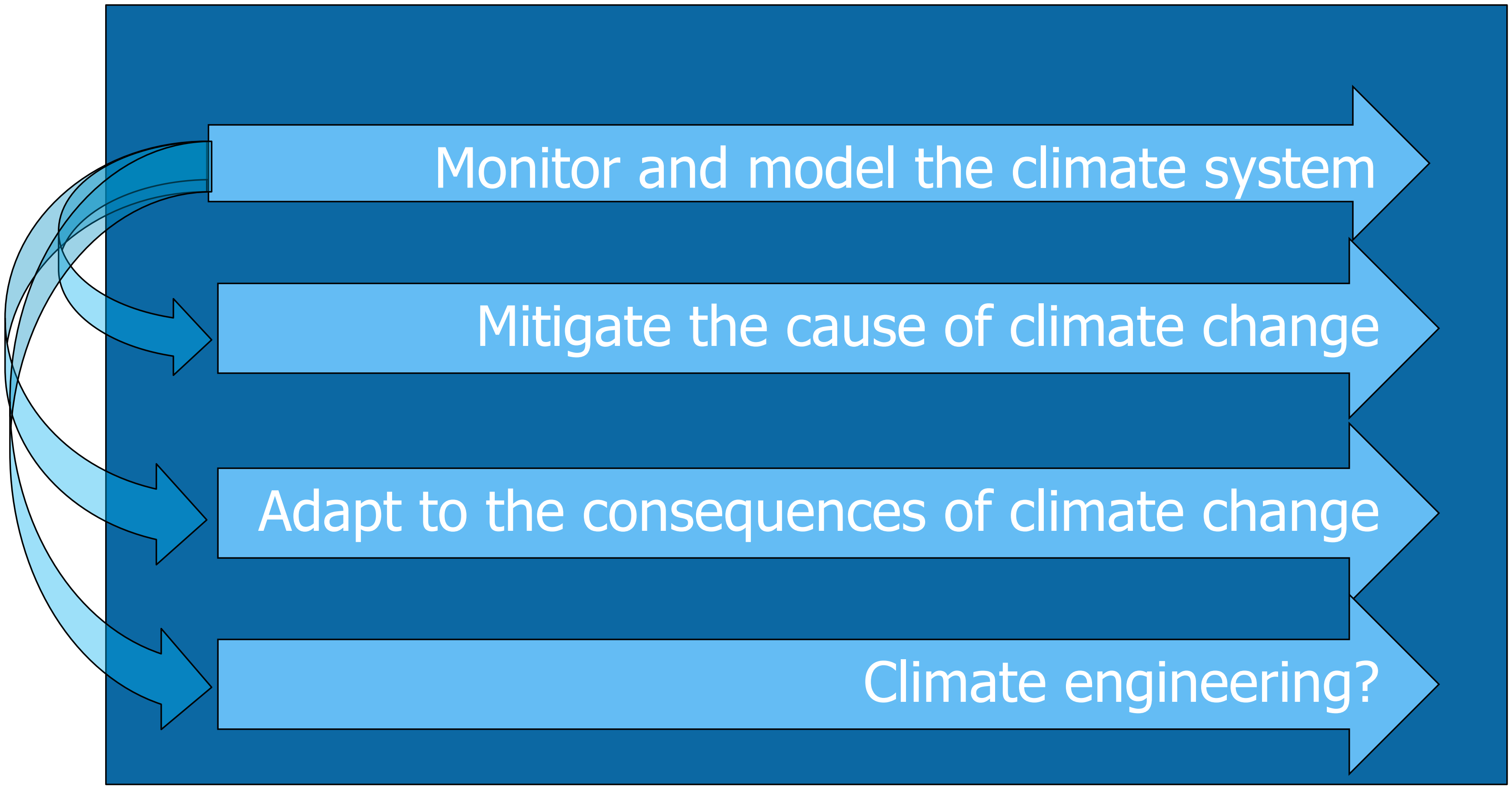
The emission pledges (INDCs) of the top-4 emitters

The emission pledges from the US, EU, China, and India leave no room for other countries to emit in a 2°C emission budget (66% chance)



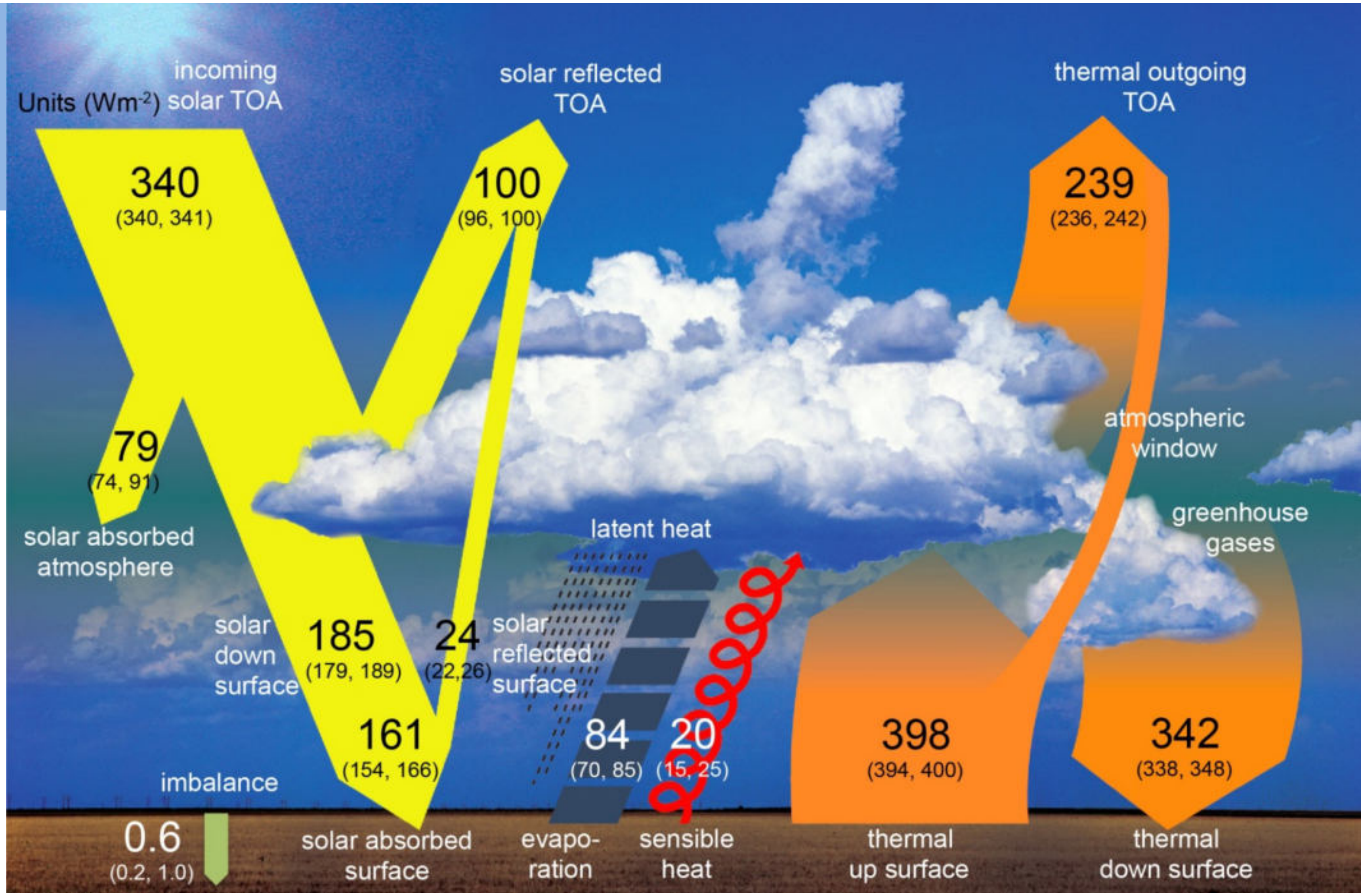
Source: [Peters et al 2015](); [Global Carbon Budget 2016]()

And what if it gets too warm?



The Earth's energy balance

Solar radiation management



Carbon dioxide removal

Various schemes for cooling

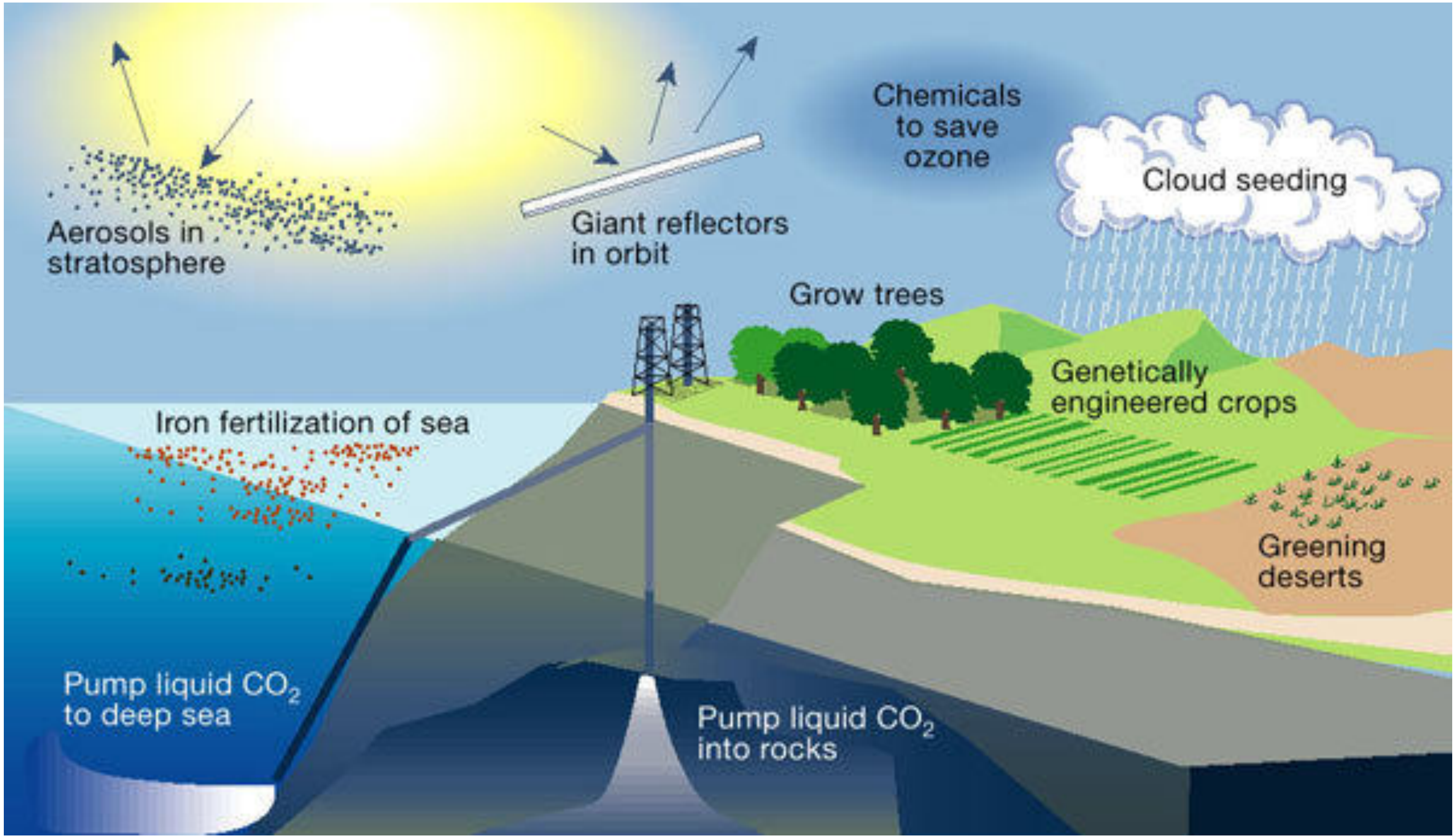
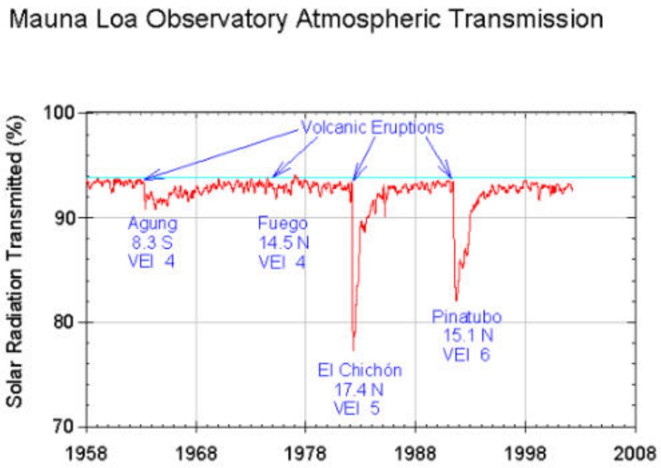
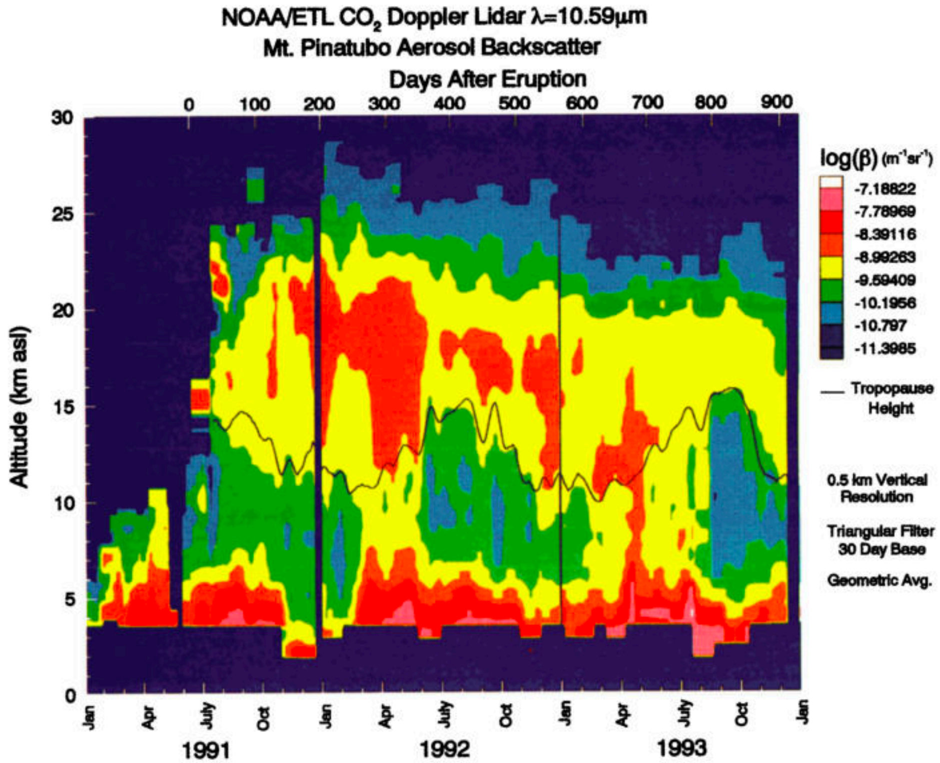


Image B. Matthews/Nature.

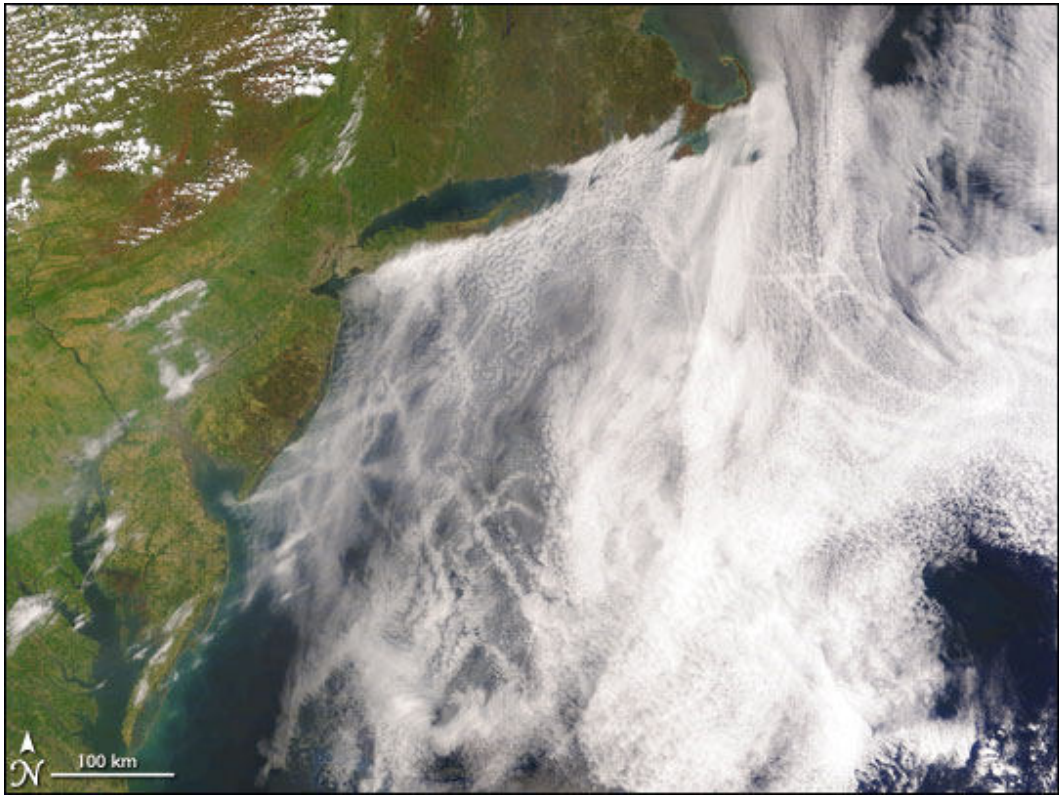
Nature itself shows an example





https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/95JD02926

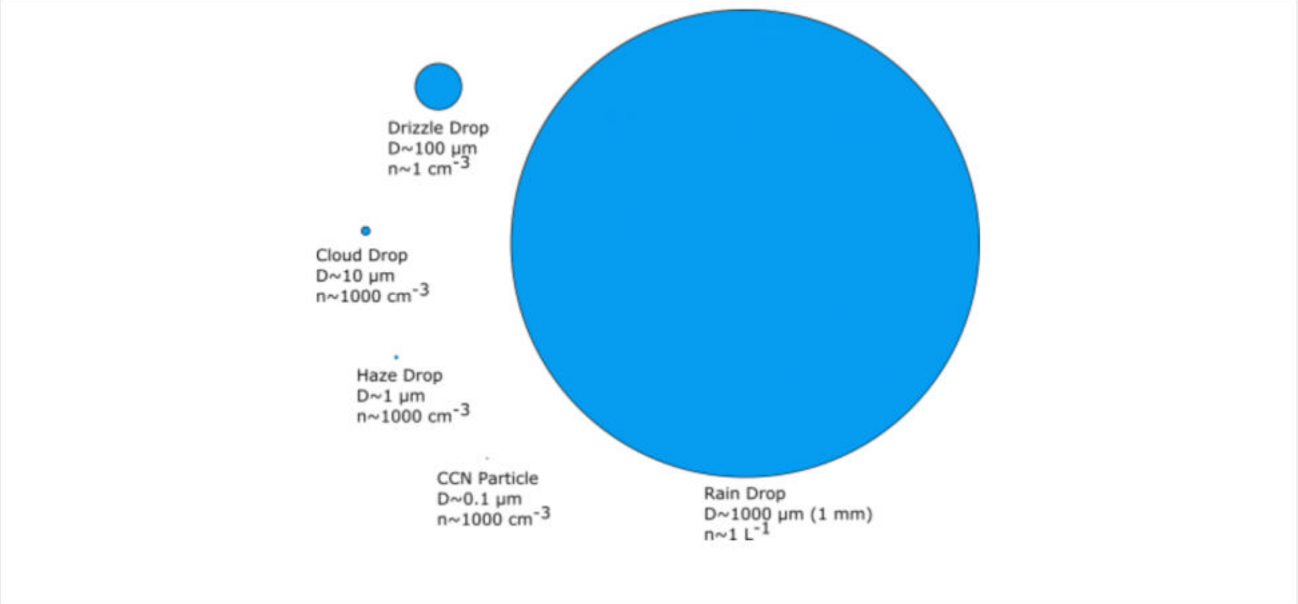
And men too: ship exhausts into the clouds



http://earthobservatory.nasa.gov/IOTD/view.php?id=5488

Clouds and aerosols

Typical droplet sizes

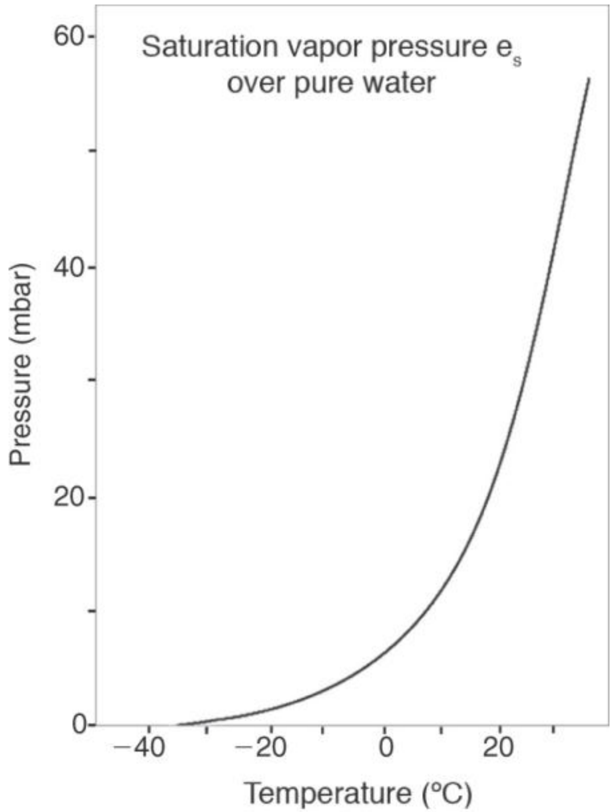


Cloud drop sizes and characteristics. D is the typical diameter; n is the typical number per volume of air. Sizes are almost but not quite to scale.

Credit: W. Brune (after Lamb and Verlinde)

https://www.e-education.psu.edu/meteo300/node/537

Clausius-Clapeyron and implications for our atmosphere



(From Wallace & Hobbs, (2006).)

$$e_s = Ae^{\beta T}$$

$$A = 6.11\,\text{hPa}, B = 0.067\,°\text{C}^{-1}$$

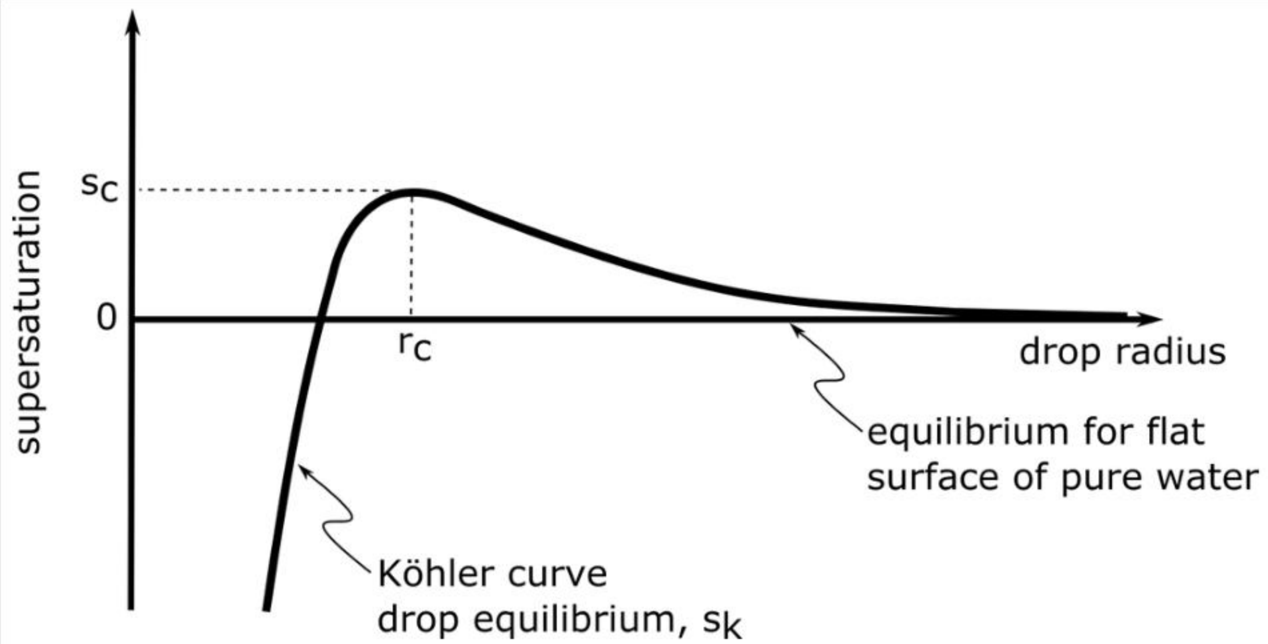
T in °C

saturation $S = {}^{e}/_{e_s}$

Supersaturation

$$s = S - 1 = {}^{e}/_{e_s} - 1$$

Koehler curve example

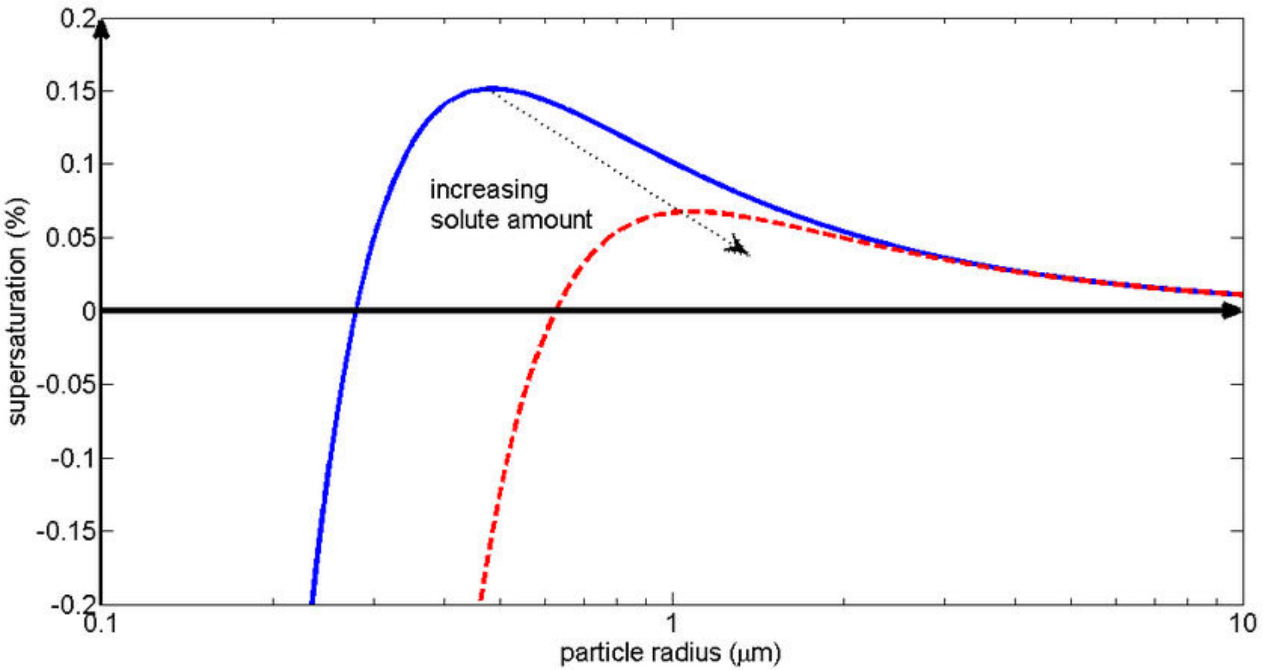


Koehler curve, which is the supersaturation of a particle as a function of the particle radius. The radius increases as the particle takes on water.

Credit: W. Brune

https://www.e-education.psu.edu/meteo300/node/537

Koehler curve for two solutions

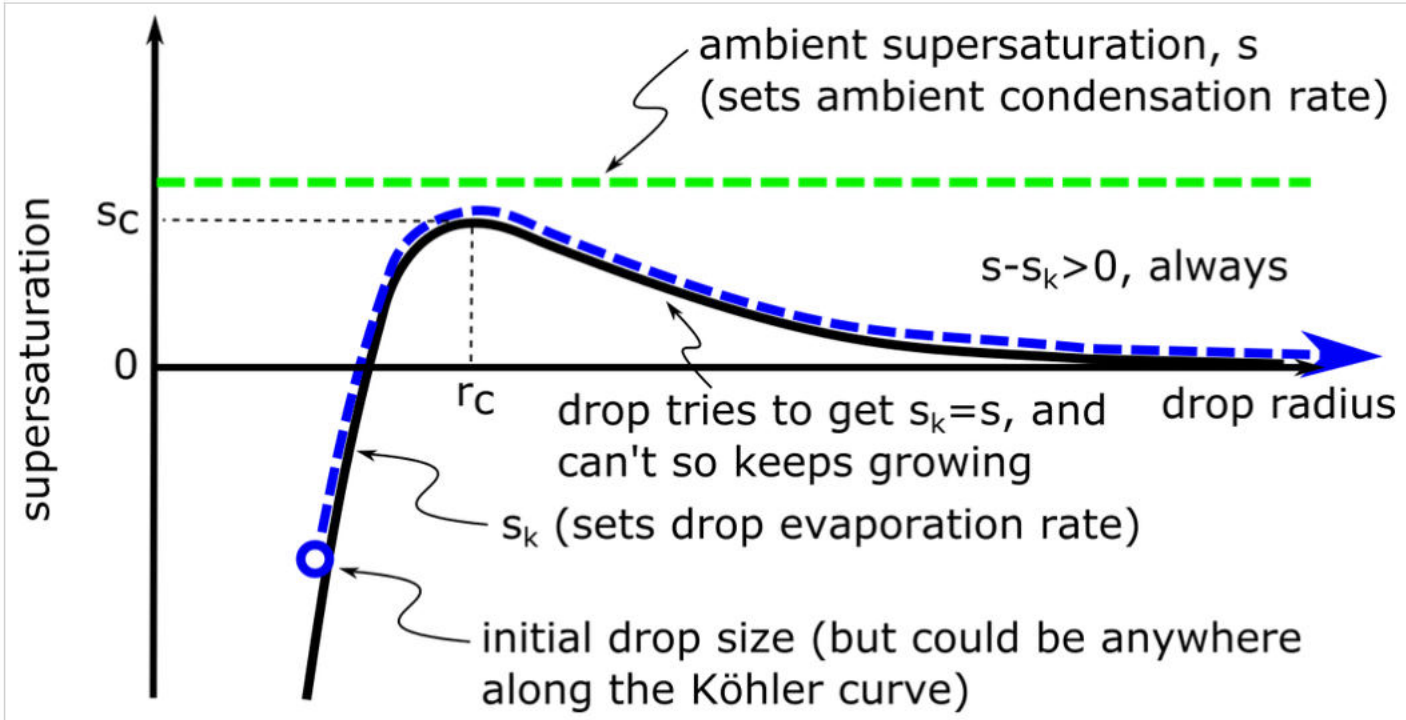


Koehler curve for two drops: $N_s=1\times10^{-17}$ moles (blue solid line), $N_s=5\times10^{-17}$ moles (red dashed line).

Credit: W. Brune

https://www.e-education.psu.edu/meteo300/node/537

Droplet growth, 1

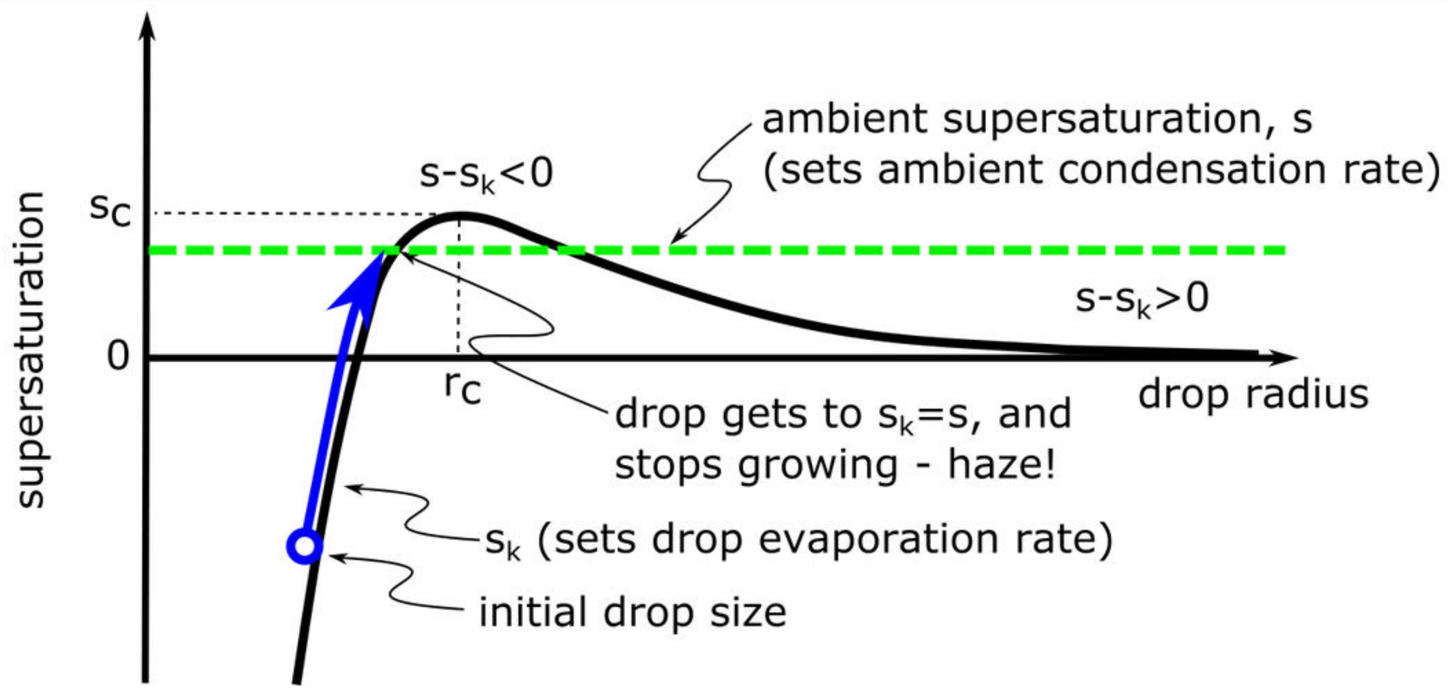


Koehler curve for a drop in an environment where the ambient supersaturation is greater than the entire Koehler curve.

Credit: W. Brune

https://www.e-education.psu.edu/meteo300/node/537

Droplet growth, 2

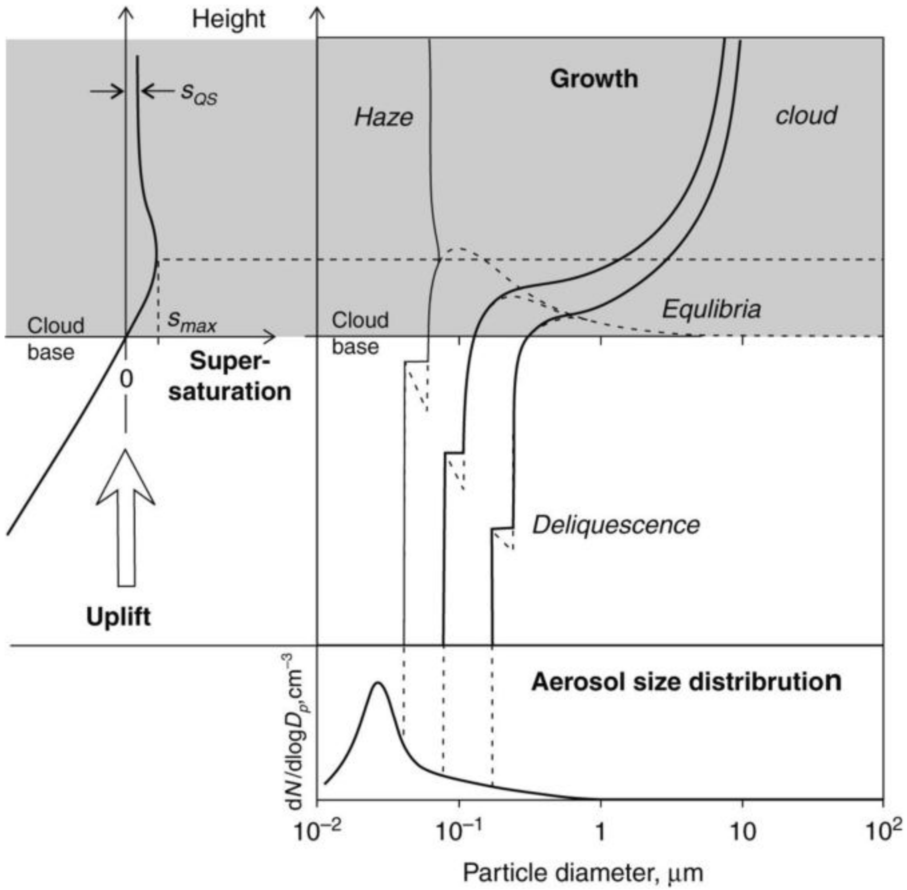


Koehler curve for a drop in an environment where the ambient supersaturation intersects the Koehler curve.

Credit: W. Brune

https://www.e-education.psu.edu/meteo300/node/537

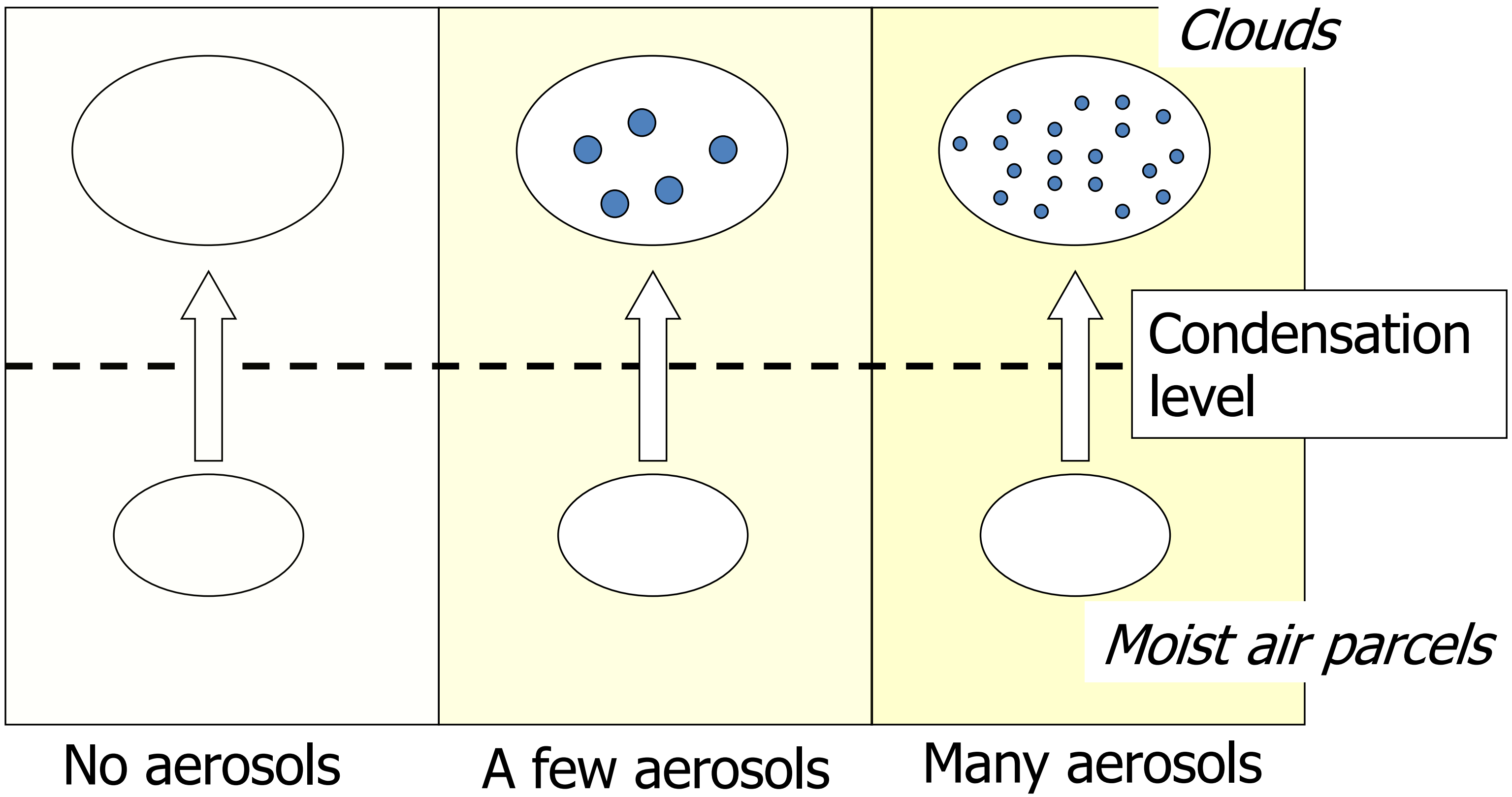
Evolution of a liquid water cloud



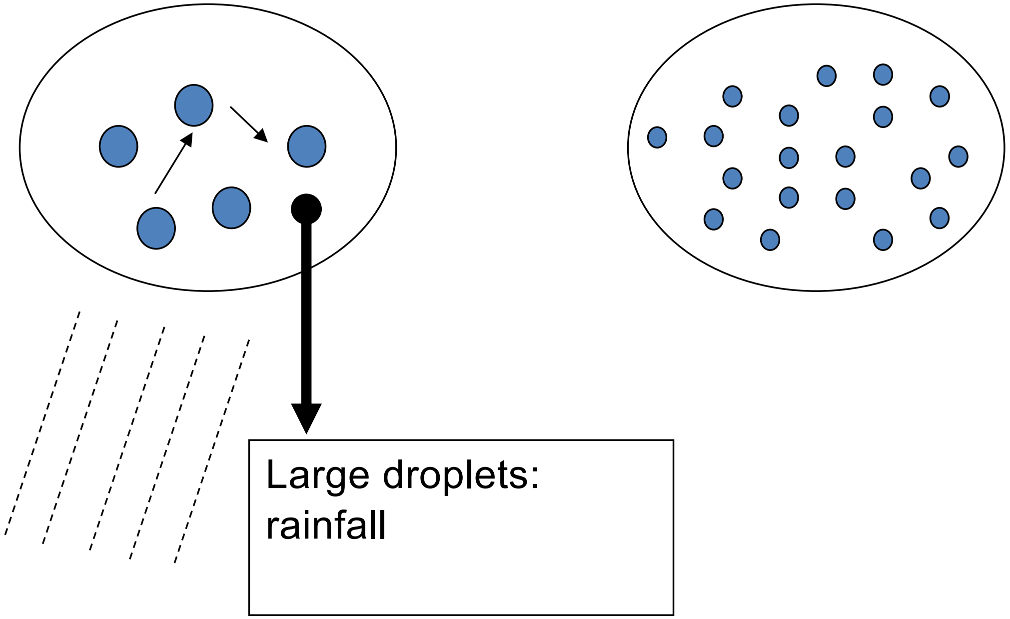
Source: *Lamb D., Verliende J. "Physics and Chemistry of Clouds"*

1. Aerosol become cloud droplets when they **grow through the peak of the Köhler** function
2. **Aerosol diameter** does **not matter** much for the resulting **cloud droplet size**
3. **More aerosol** result in **more cloud droplets**

A bit about cloud formation



And a bit more: rainfall formation



More aerosols

↓

Delayed rainfall

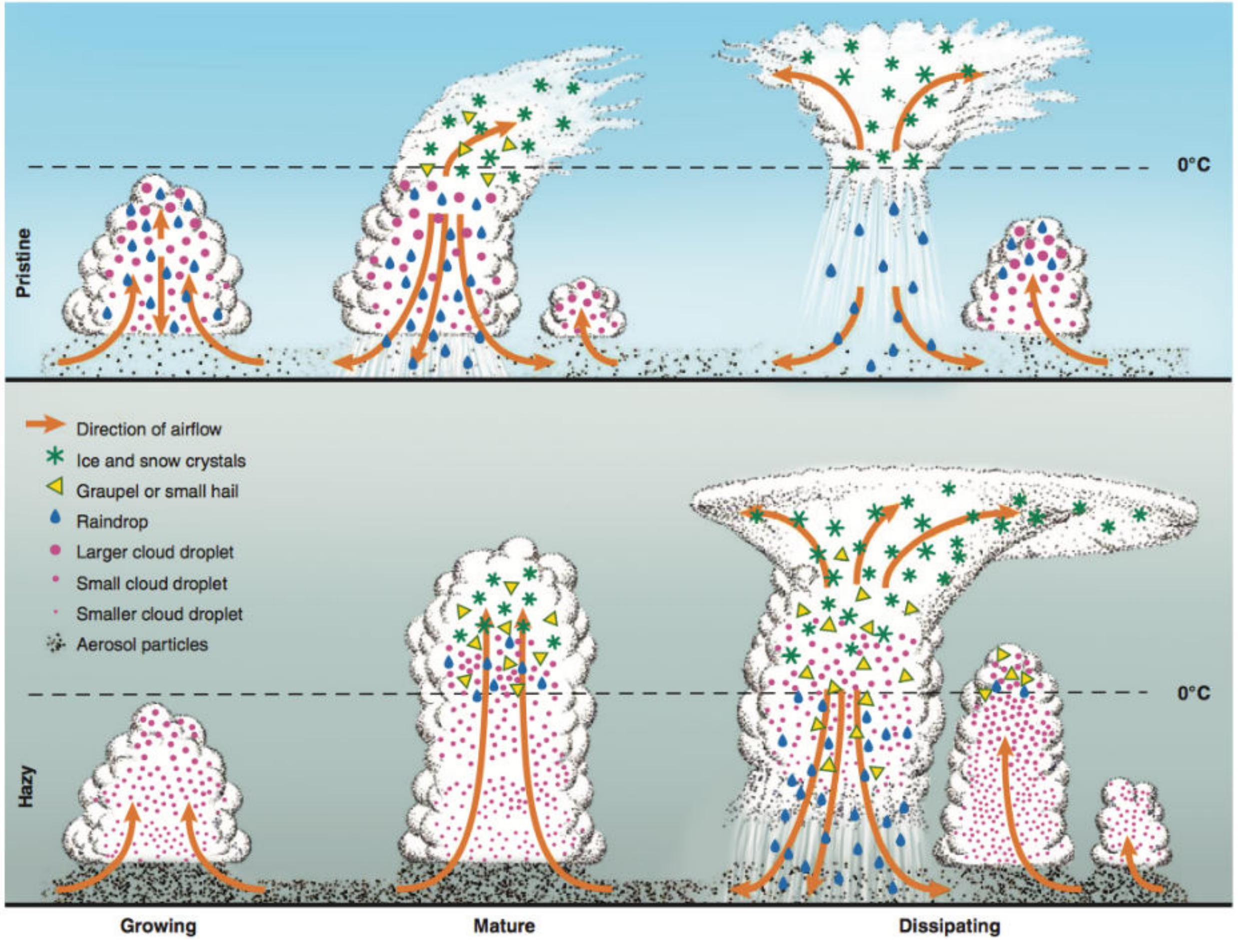
↓

Longer cloud lifetime

↓

Sustained impact on radiation

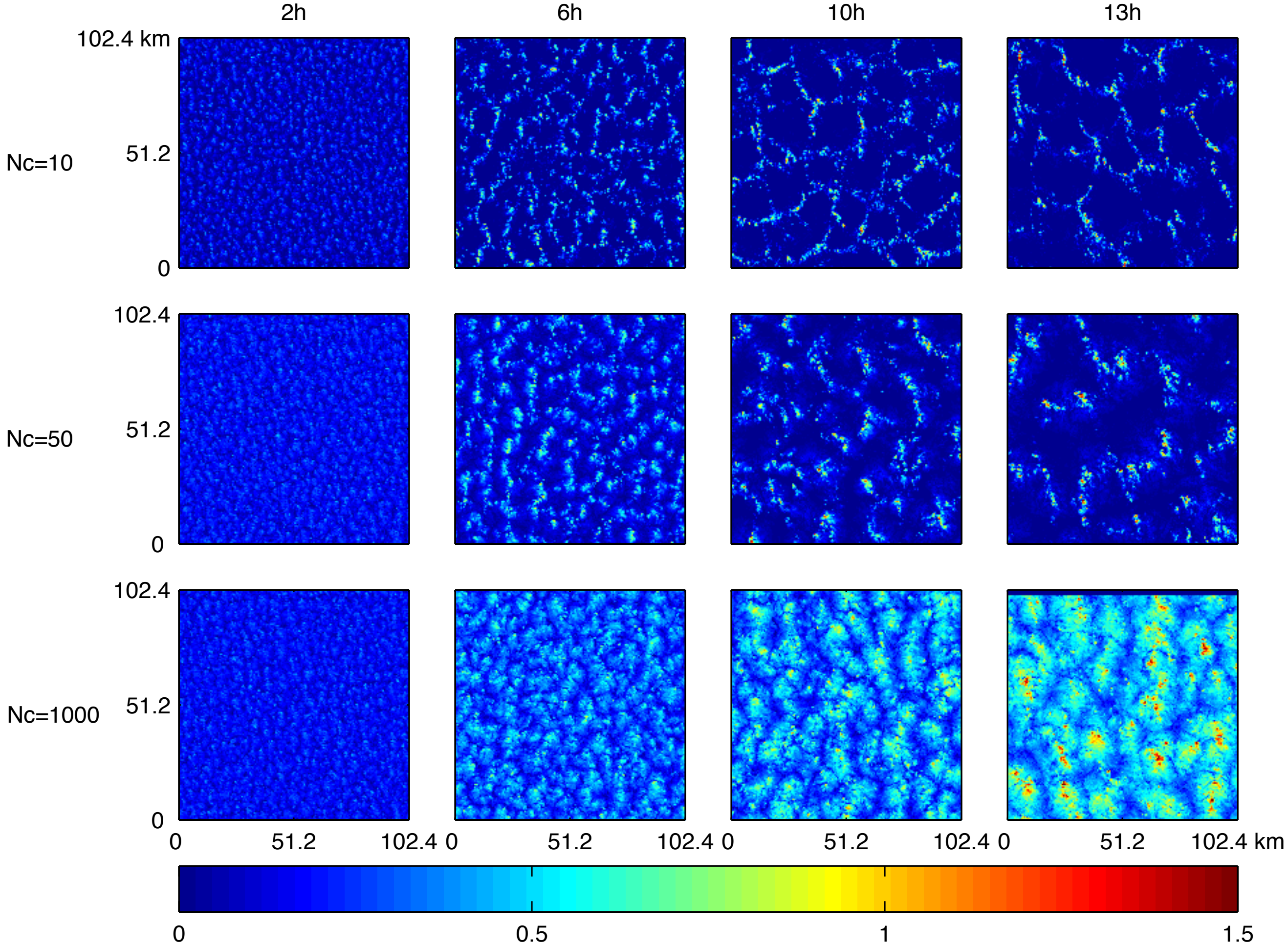
Aerosols and cloud evolution (Rosenfeld et al. 2008)



How can aerosols influence cloud fields?

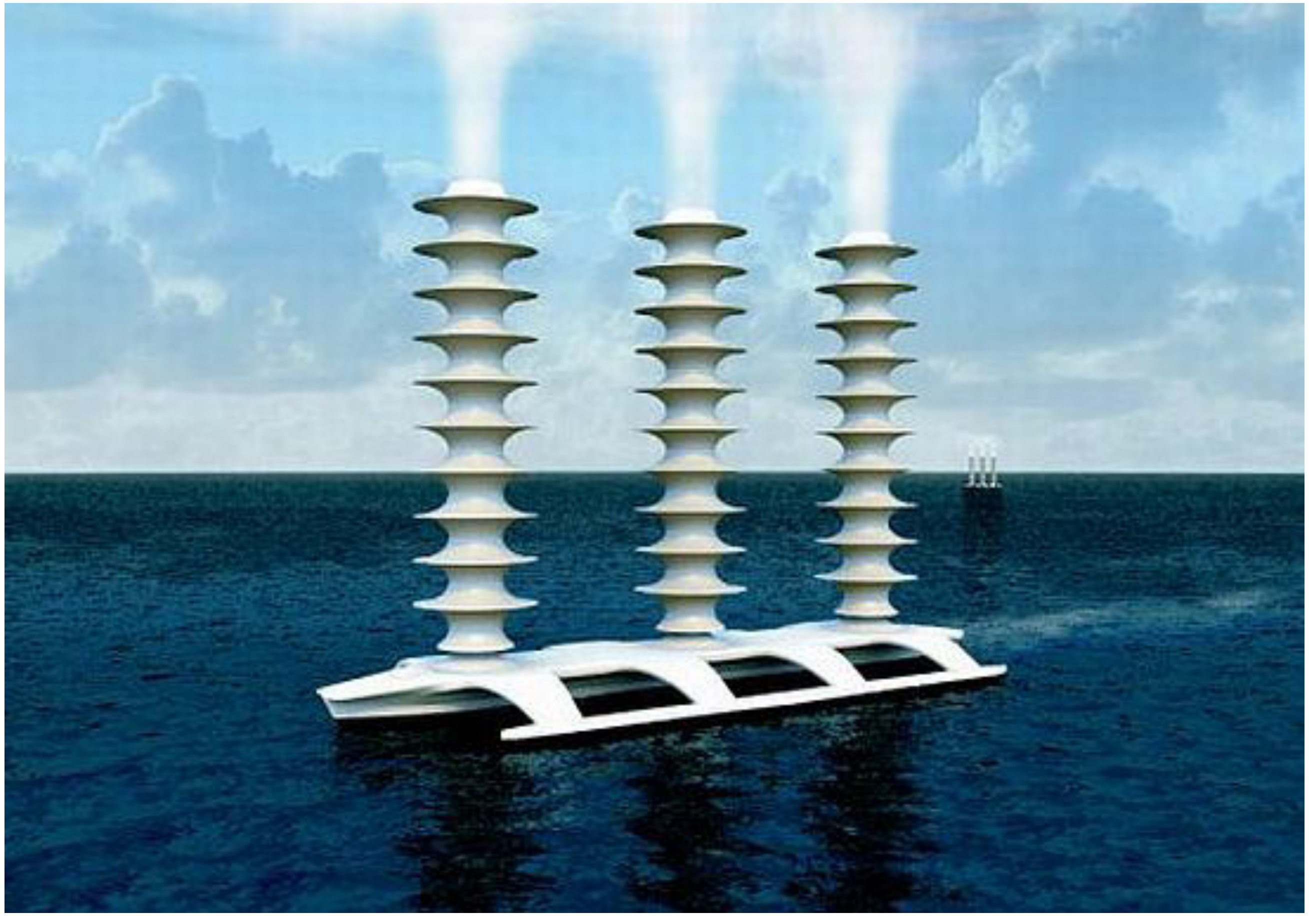
low droplet concentration, **open cells**

high droplet concentration, **closed cells**



Courtesy Stephan de Roode, TU Delft

Seeding clouds with sea salt spray



Cloud brightening and the energy balance

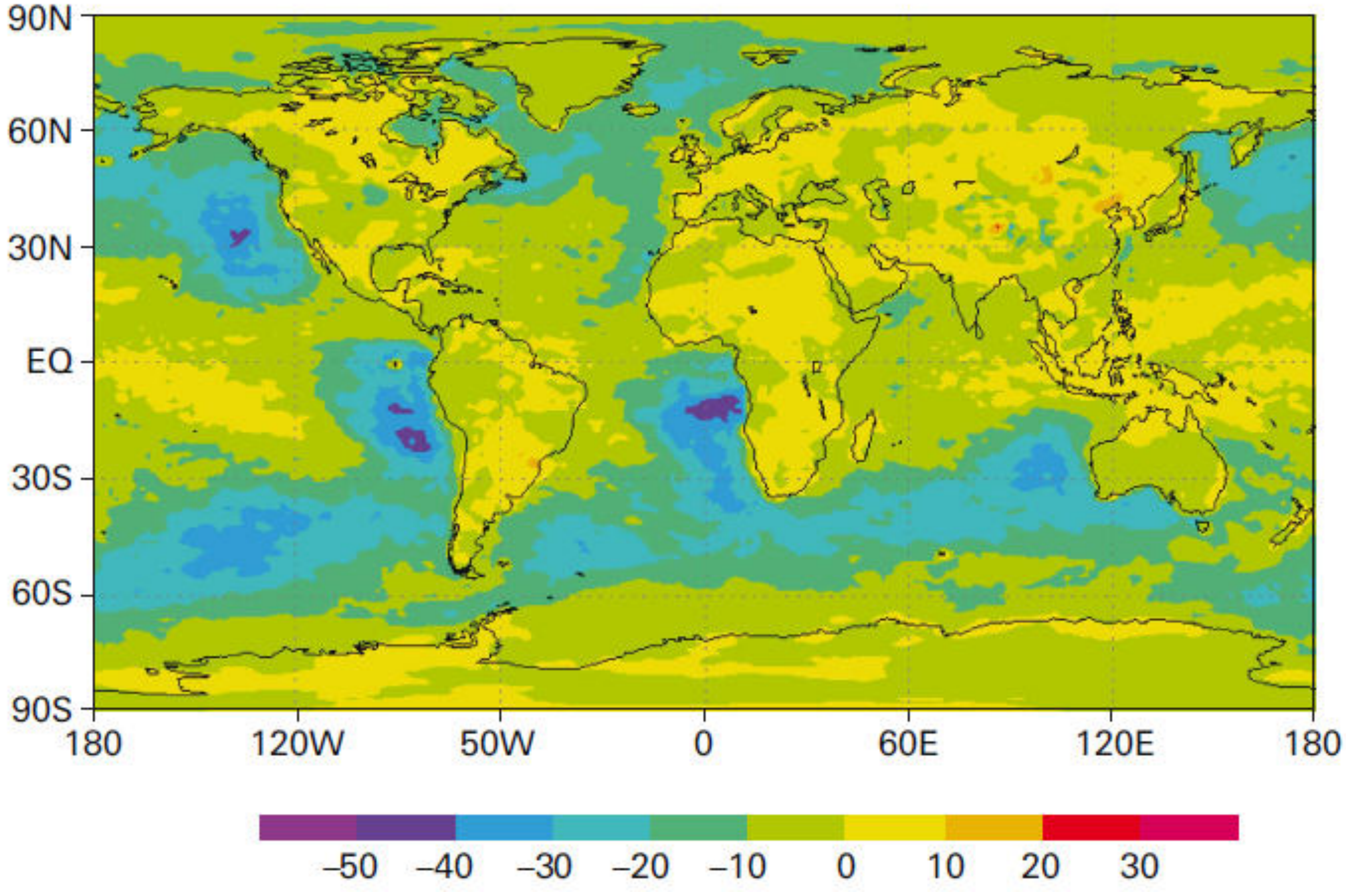
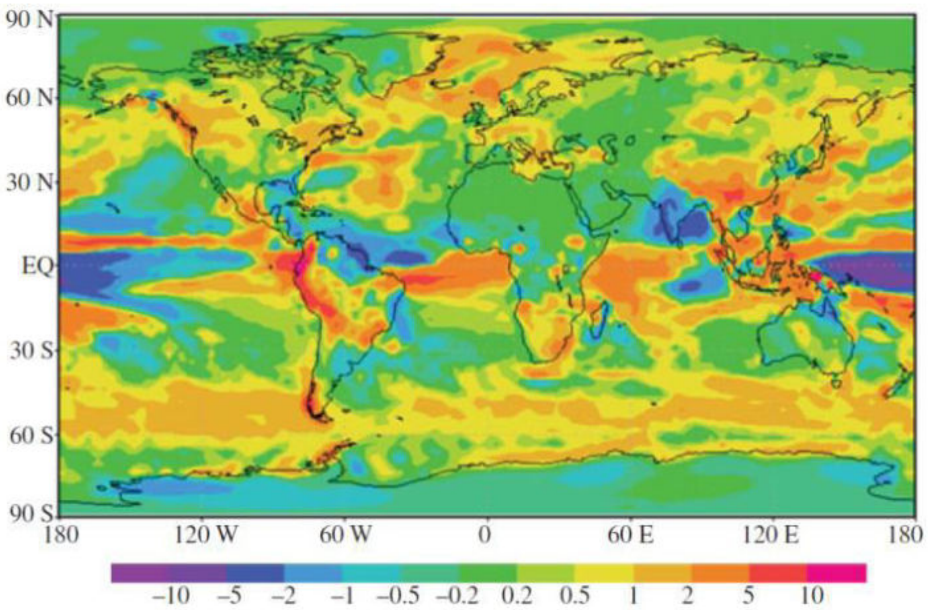


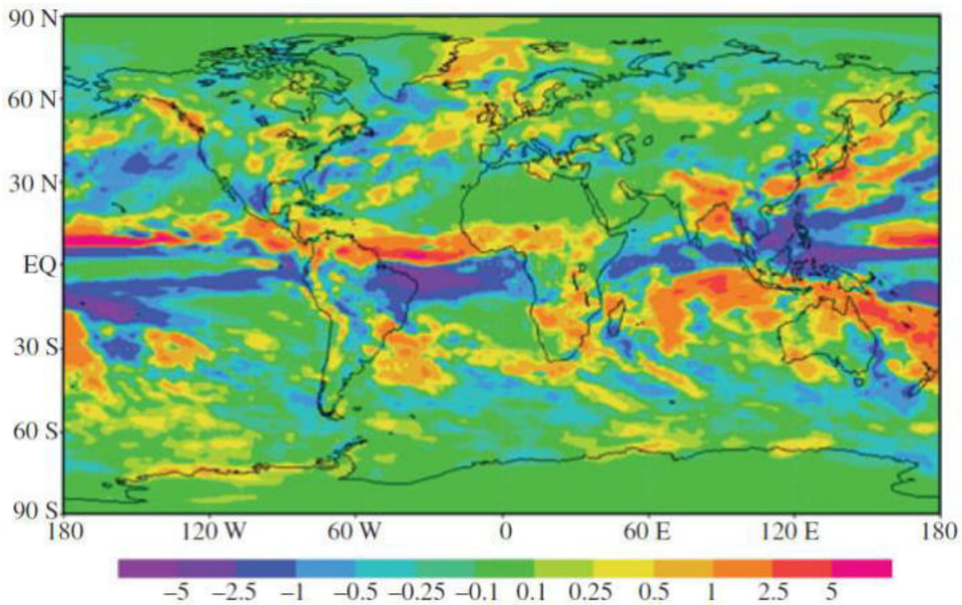
Figure 3.2. Five-year mean difference (W/m2) in radiative forcing at the top of the atmosphere between a control simulation (with CCN of 100/cm3) and a test run with CCN of 375/cm3 in regions of low-level maritime cloud (an extension of results from Latham et al. 2008)., Royal Society, 2009

Cloud brightening and precipitation

10 year sim – CMAP observations



Effect of cloud brightening



Total amount does not change much, but regional differences occur.

(Latham et al, 2012)

Mean effect of albedo changes

Option	Area (m^2)	Fraction of Earth f_{Earth}	Albedo change within area $\Delta\alpha$	Scaled albedo change of layer	Transmittance factor f_a	Planetary albedo change $\Delta\alpha_p$	Solar radiation at TOA S_0 ($W\,m^{-2}$)	Radiative forcing RF ($W\,m^{-2}$)
Increase marine cloud albedo				$\Delta\alpha_a$				
Mechanical	8.9×10^{13}	0.175	0.074	0.013	0.84	0.011	345	−3.71
Biological	5.1×10^{13}	0.1	0.008	0.000067*	0.84	0.000056	345	−0.019
Increase land surface albedo				$\Delta\alpha_s$				
Desert	1.0×10^{13}	0.02	0.44	0.0088	0.73	0.0064	330	−2.12
Grassland	3.85×10^{13}	0.075	0.0425	0.0032	0.48	0.0015	330	−0.51
Cropland	1.4×10^{13}	0.028	0.08	0.0022	0.48	0.0011	330	−0.35
Settlements	3.25×10^{12}	0.0064	0.15	0.00096	0.48	0.00046	330	−0.15
Urban areas	1.5×10^{12}	0.0029	0.1	0.00029	0.48	0.00014	330	−0.047

Lenton and Vaughan (2009)

If we go for it: criteria for techniques

Effectiveness

Timeliness

Safety

Costs

Reversibility

And now the hard part: policy and ethics

Moral hazard:

will thinking of climate-engineering stop mitigation?

Who's in charge of the Earth?

local climate-engineering has global impact

How much does it cost and who will pay?

risks, impact, prevention

Last words

Monitor and model the climate system

Mitigate the cause of climate change

Adapt to the consequences of climate change

Prepare for climate engineering

Including governance, policies and ethics

TU Delft