K35: Clouds and Aerosols – Effects on Climate

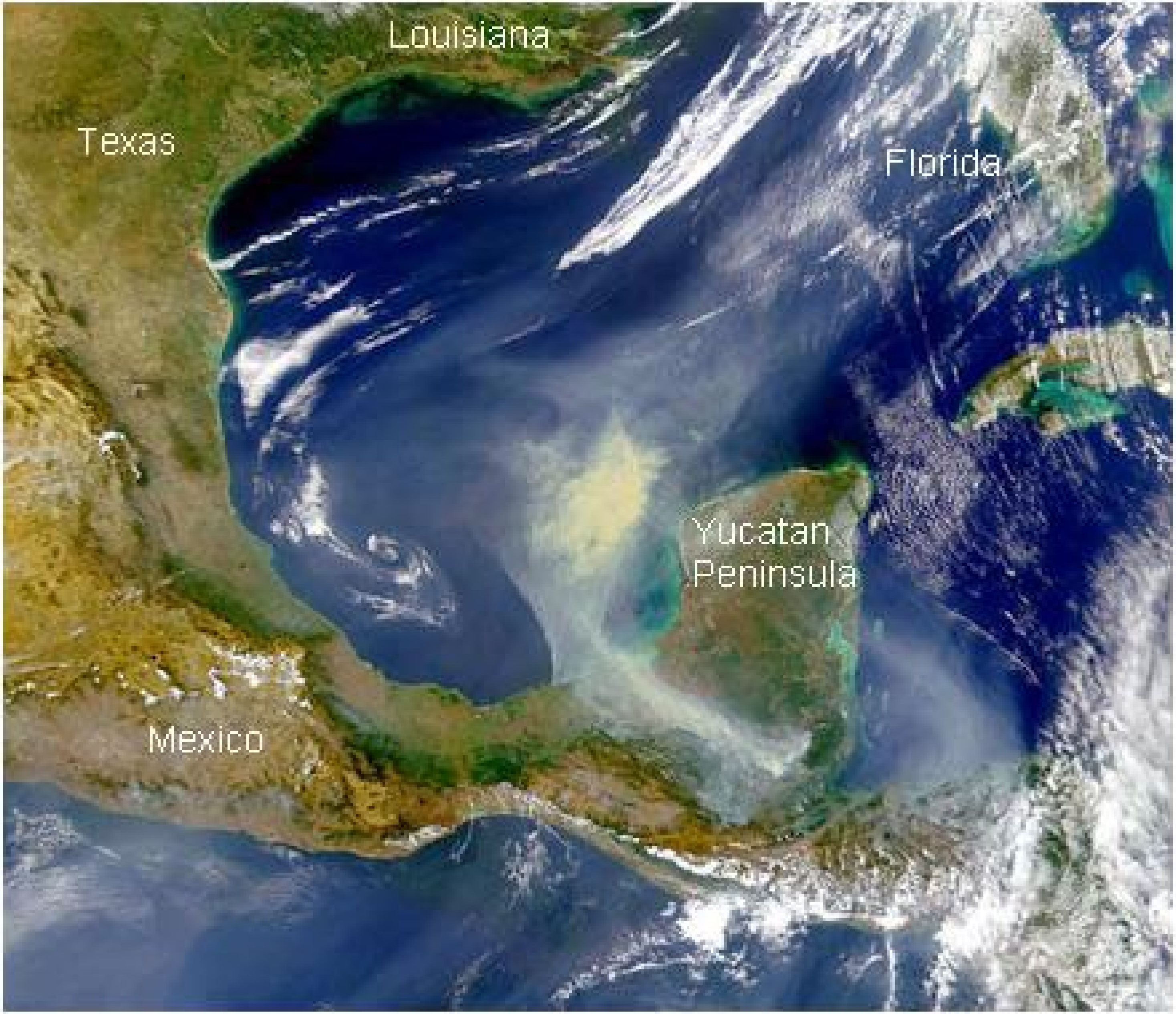
The Basic properties, causes and sources, how they affect scattering of sunlight and infrared radiation, and results on energy budget and climate of Earth

Part 1: Aerosols – Types and Sources

- Smoke and soot from burning; natural and human-caused
- Aircraft flying in troposphere and stratosphere
- Sulfate particles from human generated air pollution, or from volcanic eruptions
- Dust, from winds on deserts
- Sea salt, from ocean waves

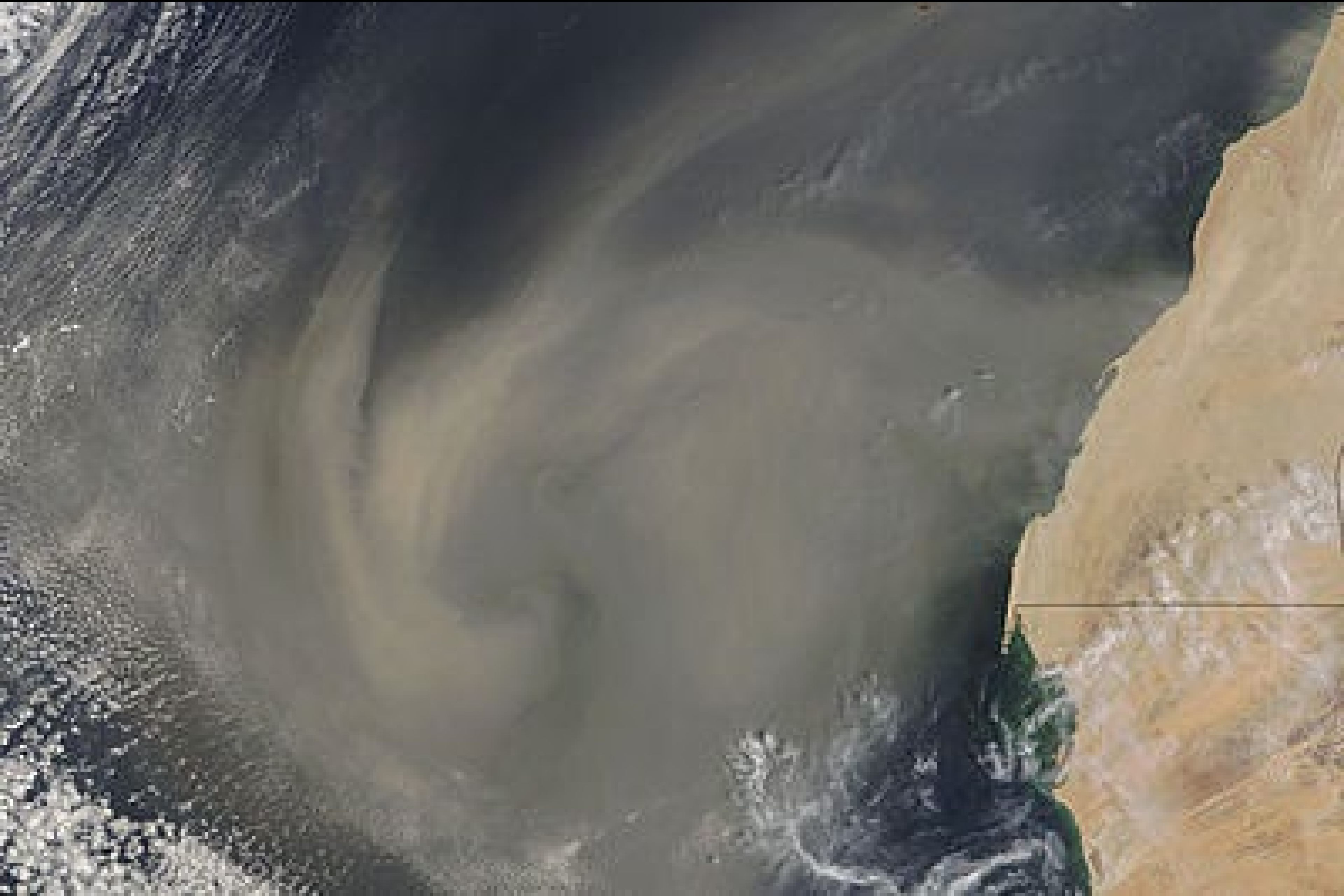
Sources of the key climate-affecting aerosol types

Source	Region	Dominant Species
Industrial pollution	Eastern North America, Europe, Eastern Asia	water-soluble inorganic (e.g., sulfate, nitrate, ammonium), organic carbon, elemental carbon
Biomass combustion	tropical/subtropical South America and Africa	organic carbon, elemental carbon
Wind-blown dust	disturbed arid soils	mineral dust
Natural	remote continental, remote marine, free troposphere	



Satellite image of smoke aerosols (milky white areas) from forest burning in Mexico and Central America (NASA).

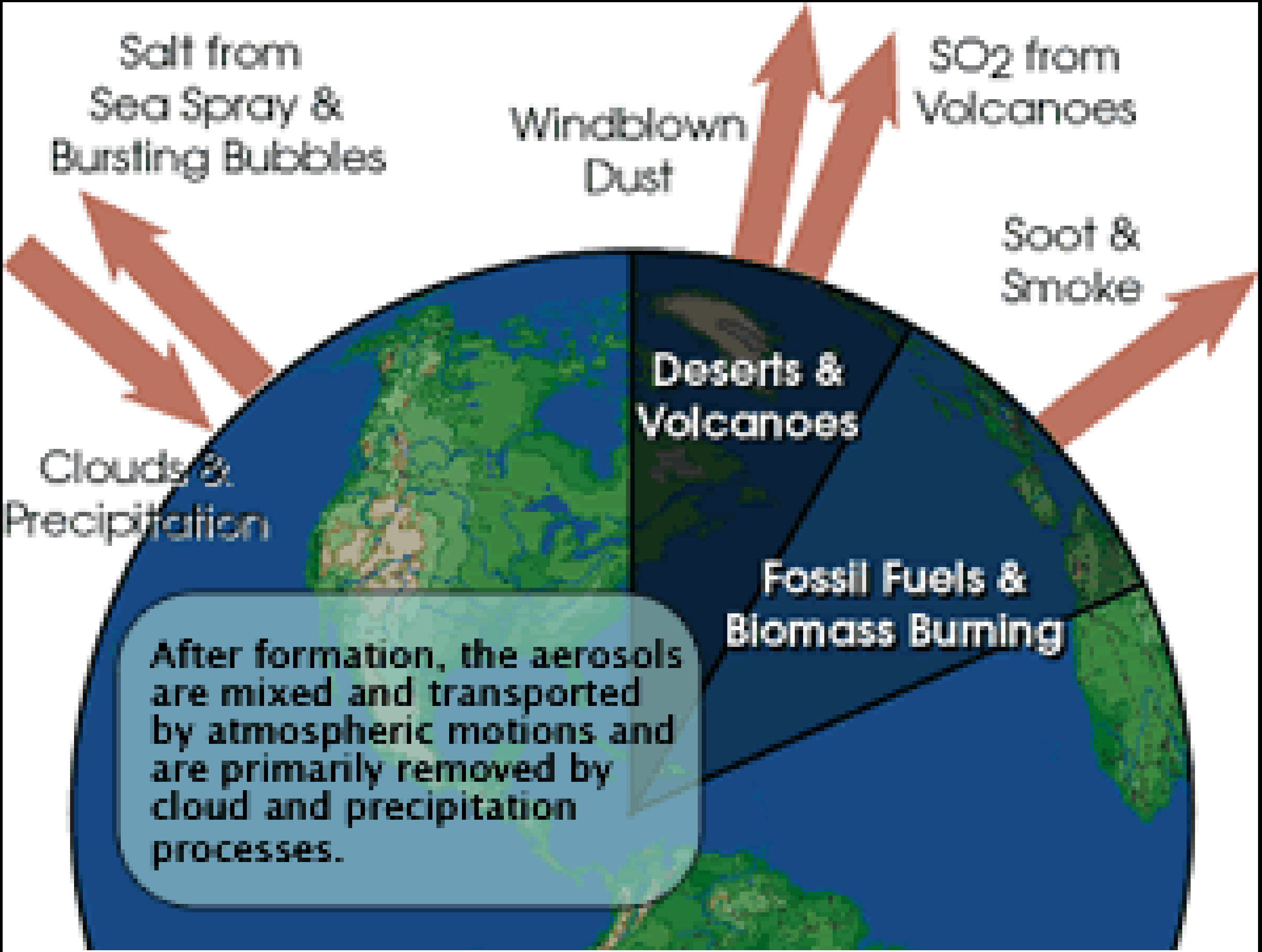
Dust from the Sahara (at right) Travels Across the Globe



My home town; a good smog producer

China and East Asia – New sources of aerosols

Aerosols affect climate in two primary ways… **Direct Effect:** reflecting incoming/outgoing radiation, and **Indirect Effect:** Seeding Clouds



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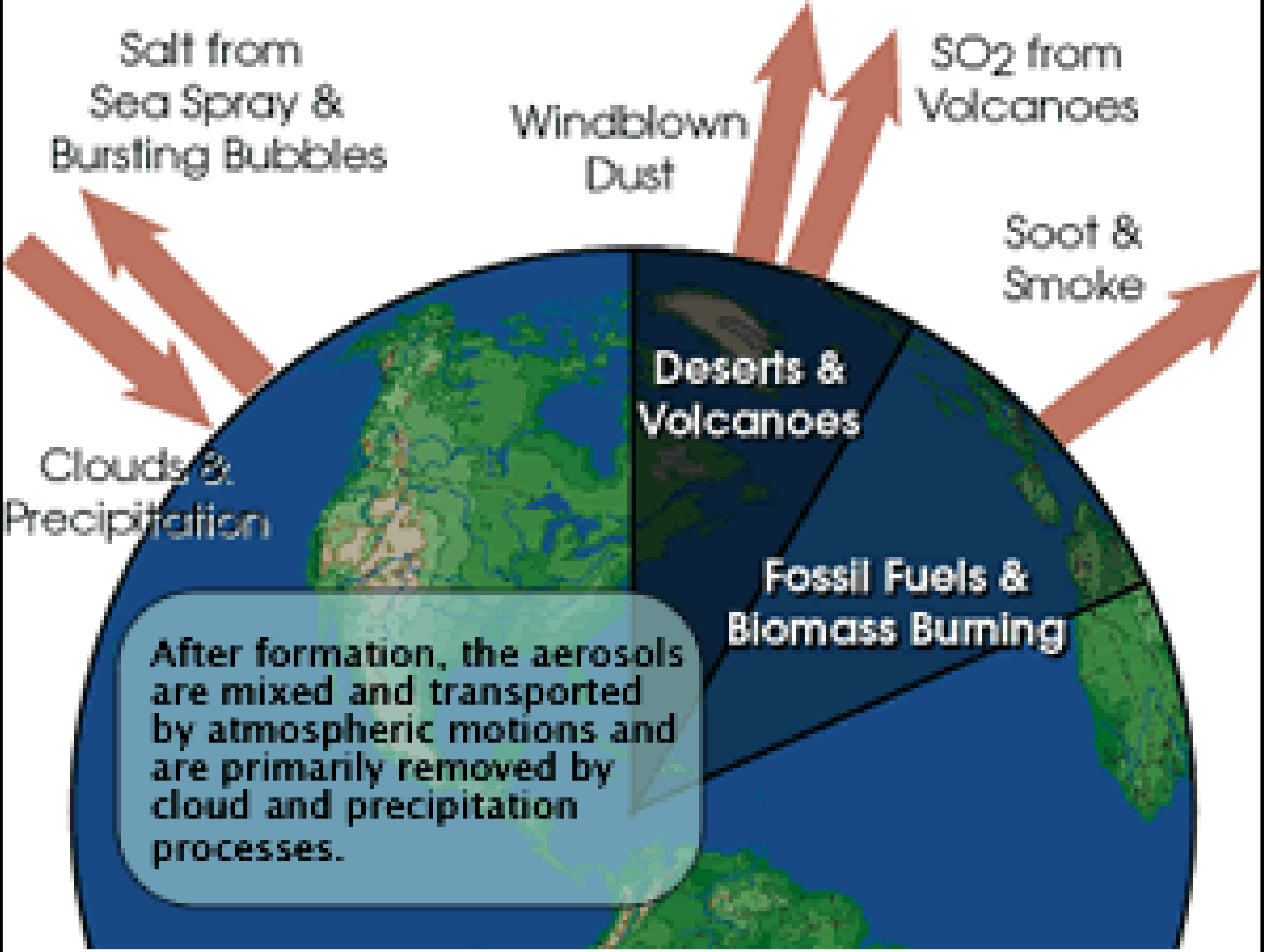
The Aerosol Direct Effect: Reflecting/Absorbing Radiation

- Aerosols come in a wide array of sizes. Generally, large enough that they will absorb or scatter light directly, even if not up-sized by nucleating water droplets around themselves.
- **Volcanic aerosols**; rich in sulfate and sulfuric acid droplets – highly reflective and so will cool climate.
- Blown into the stratosphere will last for months before gravity pulls them down into the troposphere where they can nucleate and rain out.
- Volcanic aerosols lofted into the stratosphere will intercept sunlight and warm the stratosphere, shielding the troposphere and cooling it.

The Mt Pinatubo eruption in 1991. Sent enough sulfate-rich cloud and ash into the stratosphere to cool Earth by <u>0.6C for a year or so</u>

Part 2: Aerosols and Clouds Together

Aerosols affect climate in two primary ways… **Direct Effect:** reflecting incoming/outgoing radiation, and **Indirect Effect:** Seeding Clouds



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The Aerosol Indirect Effect: Aerosols Seed Clouds

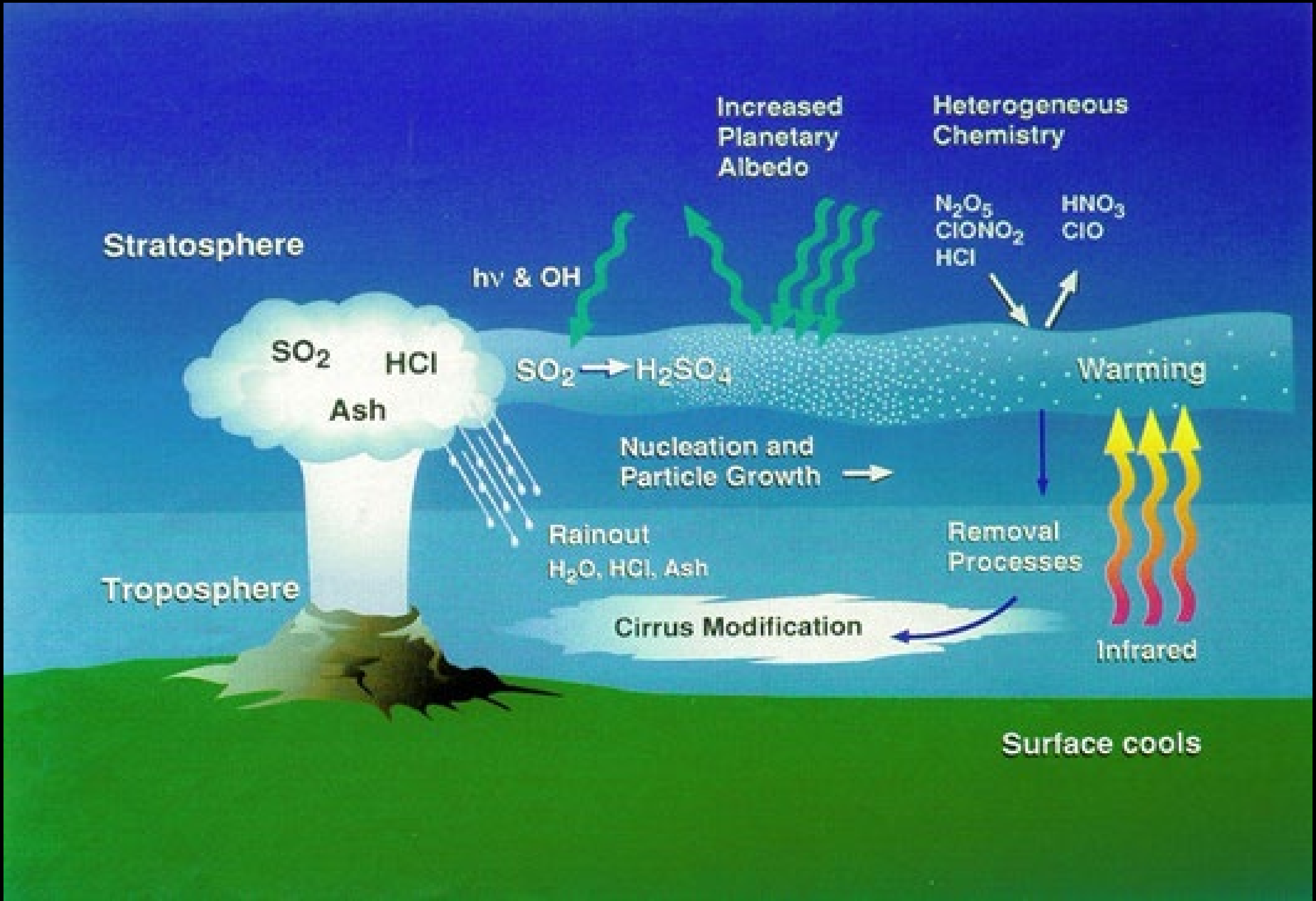
- On average, if there are a lot of aerosols in a volume, you get more cloud nucleation sites and you get larger number of small cloud droplet particles, which scatter light more effectively – brighter reflection off of clouds generated in this way. These clouds do not rain very well since the droplets are too small for gravity to win over turbulence.
- If there are fewer aerosols, you get fewer but bigger droplets of water, and these tend to scatter light less effectively and you get “darker” clouds which are also more likely to rain easily

Plenty of CCN's already: pollen, sea salt, pollution, desert dust, etc. then one would expect (and we observe that we get) water droplets which are tiny and numerous

- Additional aerosols will make the droplets smaller and hence more reflective
- Smaller droplets are more reflective: surface area/volume ratio is high, and droplet surfaces are what interact with light. They're efficient at reflecting incoming sunlight back out into space, and thus have a net cooling effect on climate
- This especially applies to stratus (because they blanket the landscape effectively) and cumulus clouds (because they are dense).
- We've all seen the brilliant white of **cumulus clouds** in sunlight (next page). And who has not seen the dark underbellies of the same clouds – dark because significantly less sunlight percolates down through the cloud to make it to your eyes

Cumulus clouds

Volcanic Aerosols heat the Stratosphere, but only for a couple of years before they fall and then rain out. They cool the troposphere beneath.



Non-Volcanic Troposphere Aerosols can Either Heat or Cool Climate

- Human-generated aerosols densest near the ground, can be sulfates and cool the local environment (we see this in China these days), but…
- can also be smoke and soot, which are large particles and are dark (low albedo) and <u>absorb</u> radiation, heating their environment.
- Desert dust can also be cooling (if light colored base source) or heating (if dark) to the air they are in.

Observational Evidence is -

- Human-generated aerosols are largely sulfate and other small-size aerosols which are highly reflective of sunlight, cooling climate.
- Soot is a much smaller fraction of aerosols (both natural and human-generated), so far.
- And so – in total – human-generated and volcanic <u>aerosols have acted to cool climate</u>, on net. It’s a large effect, but precisely how much, is not as well-determined as we’d like. More research needed.

So… albeit ugly and polluting, aerosols do offset some of the greenhouse heating caused by the very burning of the fossil fuels which created them. <u>Cleaning the air will therefore be BAD for Global Warming</u>

Part 3: The Main Climate Effects are from Clouds

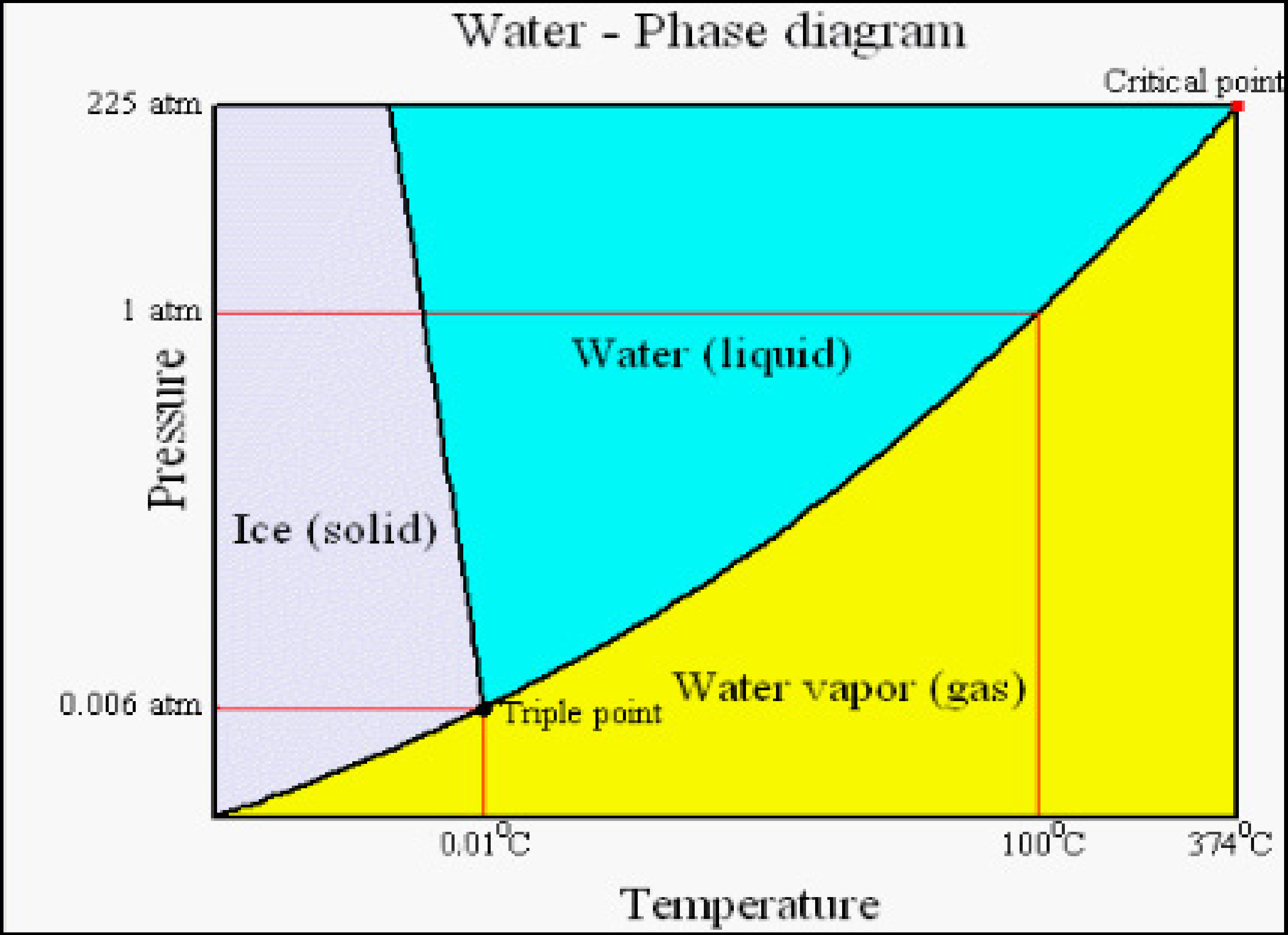
Just What IS a Cloud, Anyway?

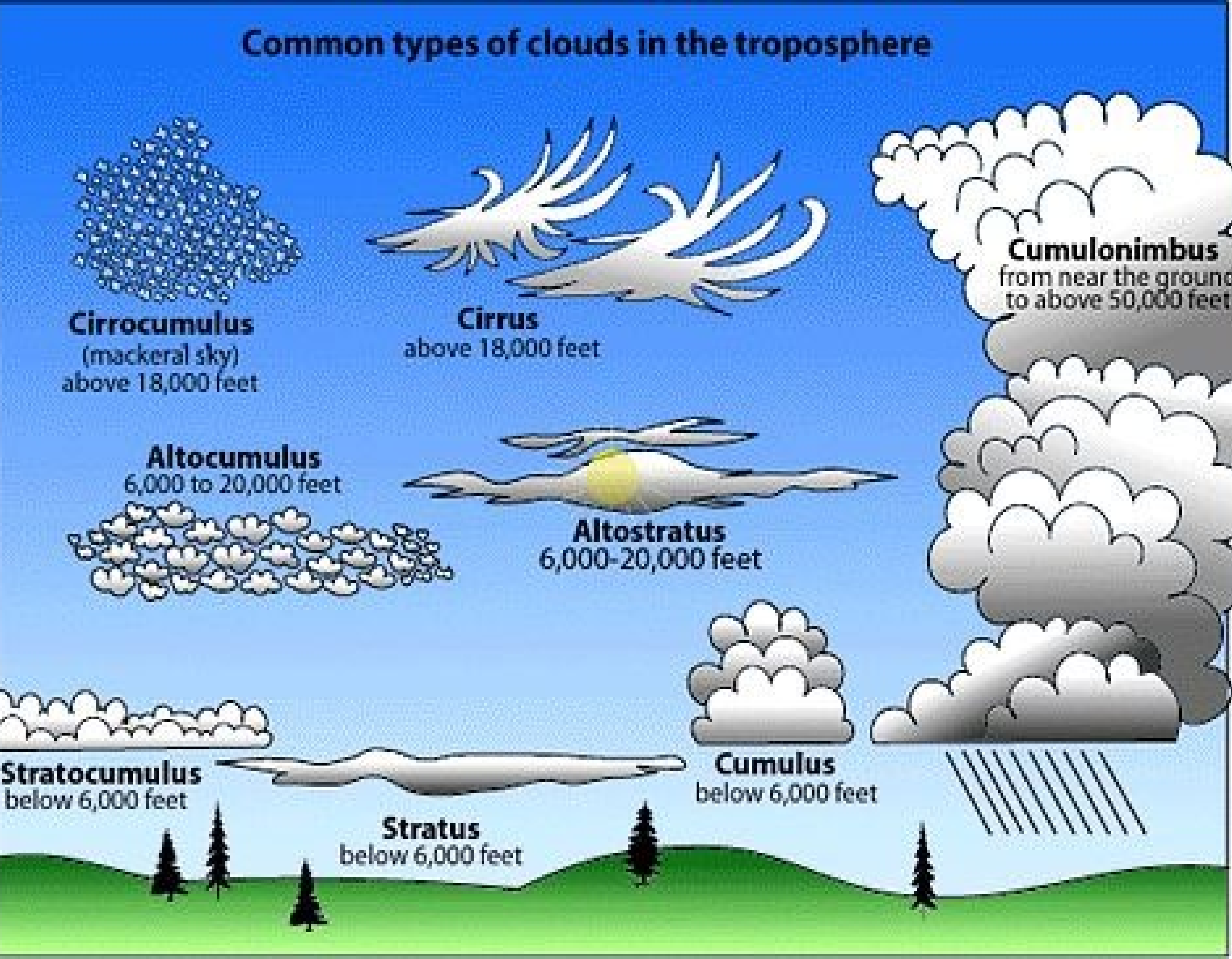
- Molecules, when they exist within an atmosphere, can be in a gas, liquid or solid phase.
- A cloud is a collection of droplets of liquid or solid (*e.g.* ice) suspended within an atmosphere of gas, dense enough to affect the scattering of light.
- Recall from earlier in the course – a gas is individual molecules with empty space around each. A liquid is a set of molecules (by the millions) which feel weak attraction forces which keep them “elbow to elbow” if pressure is high enough.
- Venus clouds are sulfuric acid. On Jupiter: often ammonia (in upper atmosphere layer). Uranus and Neptune: Methane clouds. On Earth, mostly they are made of water. Great link to properties of molecules and water relevant for Earth

We Know the Conditions Which Produce Clouds

- Rising air cools, air can’t hold water as vapor, condenses into clouds.
- Clouds are produced by upwelling air which has relatively high water vapor content. Clouds evaporate in descending air, heated by gravitational potential energy turned into random kinetic (heat) energy.
- Soggy air will condense clouds at low altitude. Drier air will need significant convection (*i.e.* heating from below and cooler air aloft) to get this air high enough and therefore cold enough to condense droplets

On average, the greater the pressure of the atmosphere, the greater the range of temperatures over which the molecule can exist in a liquid phase





Common types of clouds in the troposphere
Cirrocumulus
(mackeral sky)
above 18,000 feet
Cirrus
above 18,000 feet
Cumulonimbus
from near the ground
to above 50,000 feet
Altocumulus
6,000 to 20,000 feet
Altostratus
6,000-20,000 feet
Stratocumulus
below 6,000 feet
Stratus
below 6,000 feet
Cumulus
below 6,000 feet

Some Basic Cloud Physics

- Clouds form when rising air experiences lower pressure and therefore cools and condenses into droplets or ice crystals
- As long as the surrounding air temperature profile falls steeply enough, then even if the rising air cools, it can stay warmer (and hence less dense) than the surrounding air
- This will induce convective motion upward. Lower air pressure higher up means cooler temperatures.
- As it cools, air becomes less able to hold water vapor. Eventually the air is said to be **saturated**
- **Further cooling makes water or ice droplets. Unlike individual water vapor molecules, which only absorb certain wavelengths, cloud droplets are vastly larger and interact with ALL light waves, reflecting and refracting them. This is a cloud.**
- Water **vapor** in our atmosphere, condensed, would make only 1 inch depth covering Earth

However; Cloud droplets need a CCN = Cloud Condensation Nucleus, in order to form, even if the air is saturated

- CCNs will be aerosols of some kind: pollen, salt grains, soot, volcanic ash particles, smoke, desert dust, dust from under your bed...
- CCNs in the troposphere are everywhere.
- There is no lack of CCNs for making clouds, at least in the troposphere, especially the lower troposphere where most water vapor is.

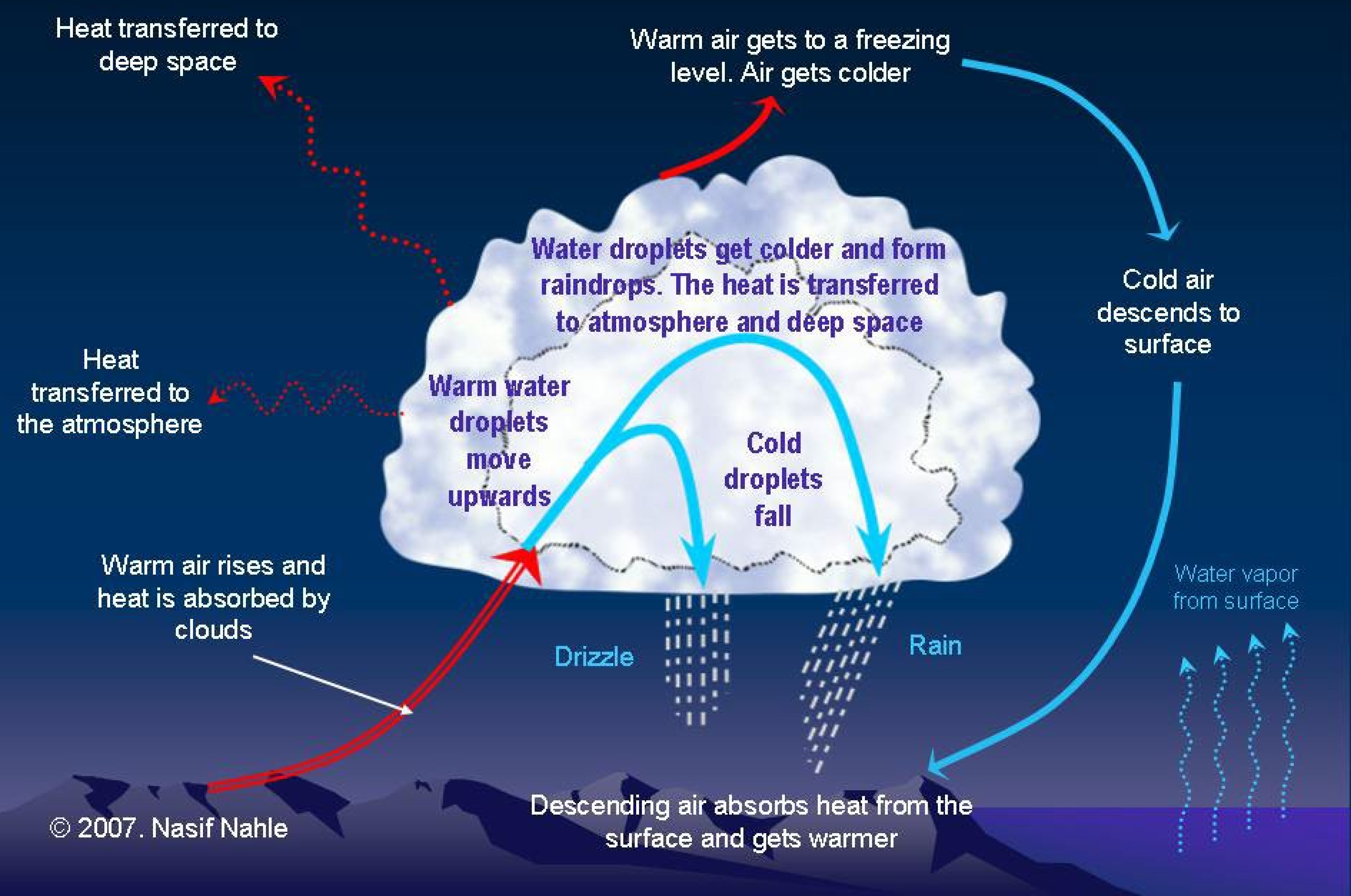
More Aerosols = Smaller Cloud Droplets

- CCNs, when surrounded by water vapor saturated air, make cloud droplets.
- The more CCNs, the more cloud droplets, and the smaller the droplets will be.
- The fewer the CCNs (i.e. cleaner air), the fewer are the droplets and the bigger the individual droplets tend to be
- Typical sizes are roughly 20 microns
- <u>Smaller</u> droplets make <u>whiter</u> clouds,
- <u>Bigger</u> droplets make <u>darker</u> clouds!

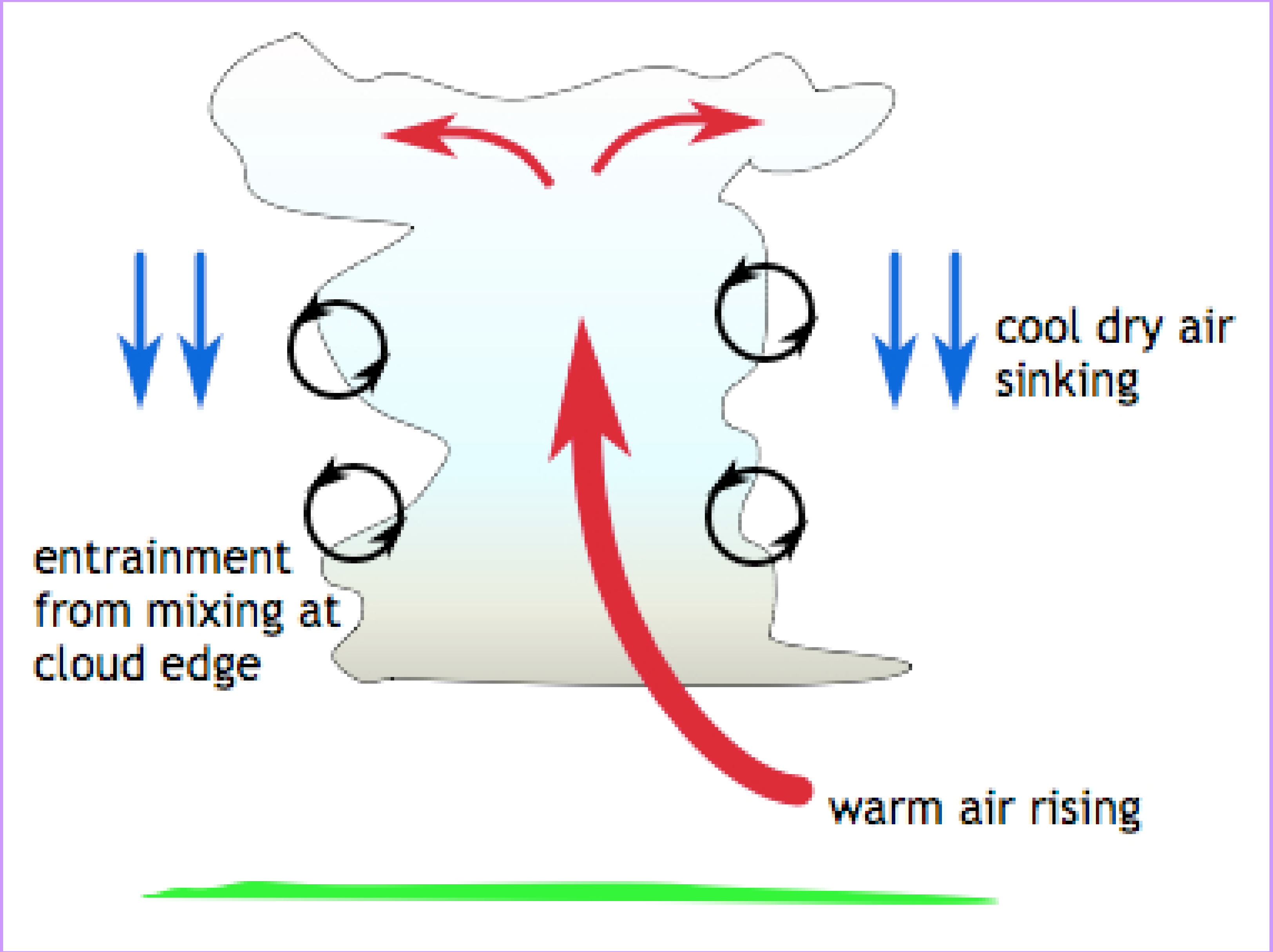
Cloud Interactions are Complex

- In addition to what we've said, there's heat exchange with the atmosphere… the formation of water droplets HEATS the surrounding air, as entropy (heat) leaves the water and enters the air
- The evaporation of water droplets COOLS the air… the "latent heat of evaporation", as heat (entropy) leave the air and enters the water droplets
- Clouds will shade the very ground beneath them, which can inhibit the heating that makes for the convection that creates them – non-linear behavior, sensitive to modelling

HEAT FROM SURFACE TO CLOUDS



Entrainment of Drier Surrounding Air is Poorly Constrained by Available Data, Modelling. Very Non-Linear Process, but Affects Clouds Significantly



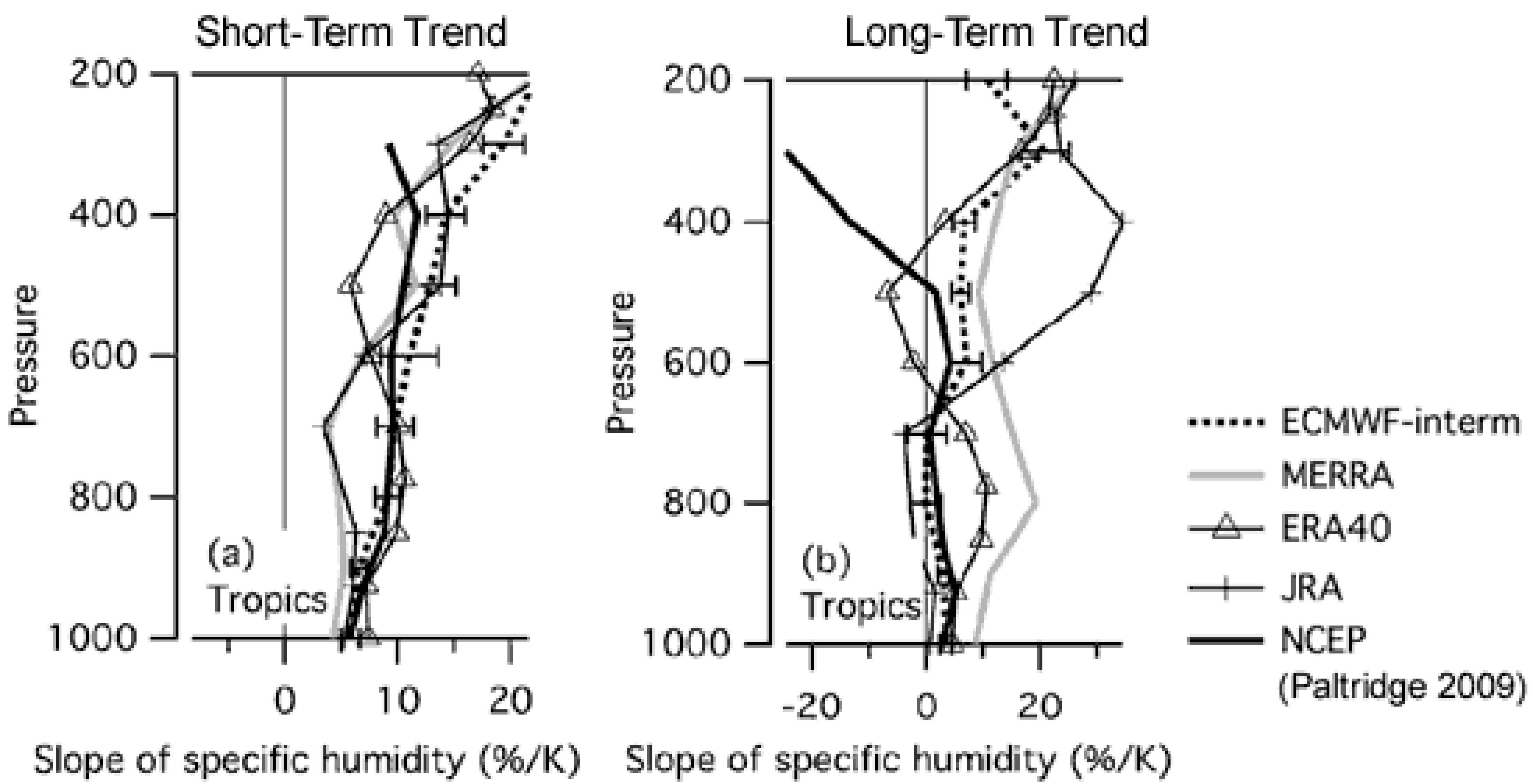
Another Basic Thermal Effect of Clouds

- **Latent Heat from Change of State.** Evaporating a pound of water into vapor will require energy equivalent to accelerating that pound of water from a speed of 0 up to Mach 7! (7x the speed of sound, or about 8,000 ft/sec!). This is the latent heat of evaporation of water – very large!
- Why? Because water is a polar molecule - the hydrogens stay on one side of the oxygen atom (like Mickey Mouse ears!) and make that side net positive, and the other side net negative charged, so water molecules really like to stick together in a liquid as they get negative on one molecule close to positive on another. Takes a lot of heat to break that bond.
- **So, evaporation and condensation of water takes heat from the site of evaporation and delivering it to the place of condensation (rain droplets)**
- Latent heat of evaporation of water = 540 cal/g, at 100C temperature

Saturation Humidity Rises Steeply with Temperature

- Think of this like juggling – Cooler air has slower moving molecules, which is like a juggler throwing things into the air more slowly – he won't be able to keep as many of them in the air. If he throws faster (higher temp) he can juggle more items.
- The saturation absolute humidity is a very steep function of temperature….
- **Raising air temperatures by 1 degree Celsius allows air to hold 7% more water vapor before it will condense and fall out as rain. This is a KEY CLIMATE FACT – Remember it!**
- Since water vapor is an asymmetric polar molecule, it is a powerful greenhouse gas and this is a powerful positive feedback to climate: **raising CO2 heats the atmosphere, making it more humid, raising greenhouse forcing even more. This is the #1 most powerful climate change feedback.**

Water Vapor Feedback at different altitudes



Short-term (a) and Long-term (b) plots of the slopes of the regression between specific humidity and surface temperature, in the tropics, from 6 different studies. Paltridge 2009's study stands out as in conflict with the theory and the analysis of other studies. Problems with the Paltridge analysis are discussed here. Trends are divided by the average specific humidity over the entire time period, so they are expressed in percent per degree K. Full data set spans 1973 to 2007. "Short term" is interval under 10 years within this set. "Long term" is greater than 10 years.

All Curves are to the Positive Side of 0, at all Altitudes. Bottom line: Except for Paltridge 2009, studies show indeed absolute humidity is rising at all tropospheric atmospheric altitudes, consistent with greenhouse theory of rising observed tropospheric temperatures.

Bottom line from Previous Page: Absolute humidity is rising at all tropospheric altitudes over past 40 years (There's no evidence for relative humidity changes)

- This is consistent with the observed greenhouse effect – it has been amplified by rising water vapor.
- An Amplifying Feedback: Rising temperature -> Rising Humidity -> Additional water vapor GHG -> Rising Temperature -> etc etc.
- A vicious cycle until radiation balance is finally achieved, at roughly twice the temperature rise if you didn't have this effect.

The Normal and Adiabatic Lapse Rate

- Take a column of air from ground to the top of the atmosphere, let it reach an equilibrium temperature.
- The troposphere is heated by sunlight being absorbed in the ground, from below, so the temperature gradient goes from hotter near the surface, to cooler as you go up.
- The Normal Lapse Rate is the rate at which air temperature drops with increasing altitude, for a static column of air.
- The **Normal Lapse Rate is about 6.5 C of temperature change per km** of additional elevation, for medium humidity air
- If instead you rapidly move a parcel of air upward so that it doesn't have time to absorb or release heat to/from surrounding air, you get…
- the **Adiabatic Lapse Rate**, which is steeper: **9.8 C per km (dry)**
- <u>**For Either Situation… Bottom Line: air, and the clouds with the air, are colder the higher they are. This reduces their ability to radiate heat into outer space**</u>

The Key Questions for Climate Change from Clouds

- Clouds affect the radiative heat balance of Earth in two key ways –
- They RADIATE from their cloud tops out to outer space
- They REFLECT incoming sunlight back out to space.
- Let’s see how LOW clouds are different from HIGH clouds in these ways…

Effect #1: IR Radiation from Cloud Tops

- The Ruling Question is: **How hot is the cloud top compared to what is below the cloud**? Hotter means it radiates more to outer space and cools surroundings better.
- It's hotter near the Earth's surface, so low altitude cloud tops are warmer, radiating more IR thus better **cooling** surroundings.
- High clouds are colder and so radiate less IR to outer space.
- **Low clouds are much better IR radiators than high clouds**

Effect #2: Reflection of Sunlight

- **Low Clouds:** are made of water droplets, not bigger ice crystals like high clouds are.
- For a given cloud mass, small droplets mean more droplets, and have higher surface area-to-volume ratio Droplet surface is where reflection happens. Small droplet clouds bounce sunlight back out into space.
- They shield the ground from sunlight and therefore lower the source of solar heating
- **Net effect – low clouds cause cooler temperatures near the ground. This is especially true over the ocean, whose dark blule absorptive surface is shielded by whitish reflective low clouds**

Low Stratus Clouds – Cool the Surface

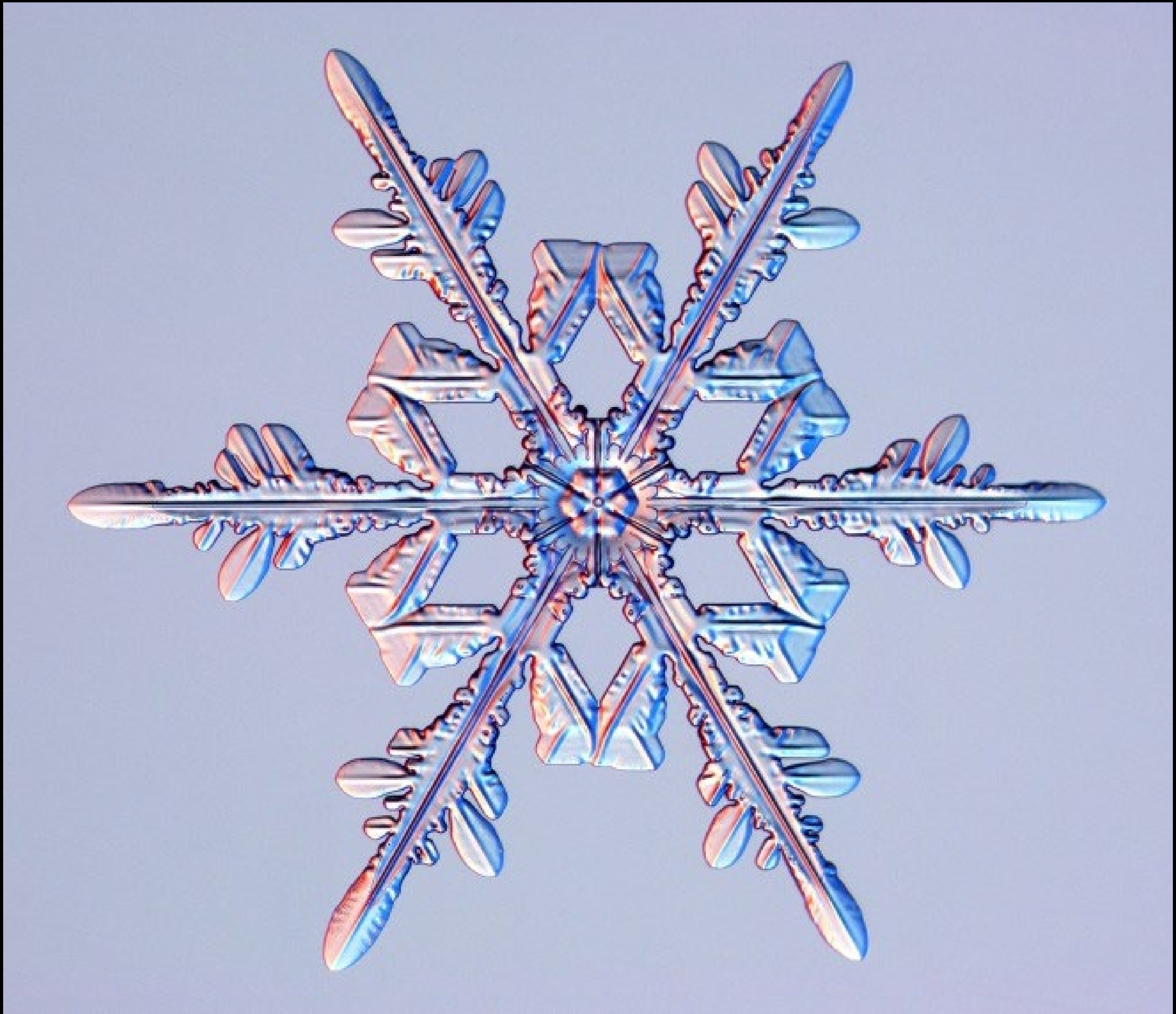
Stratus Clouds

Strato-cumulus Clouds – A bit of Convection

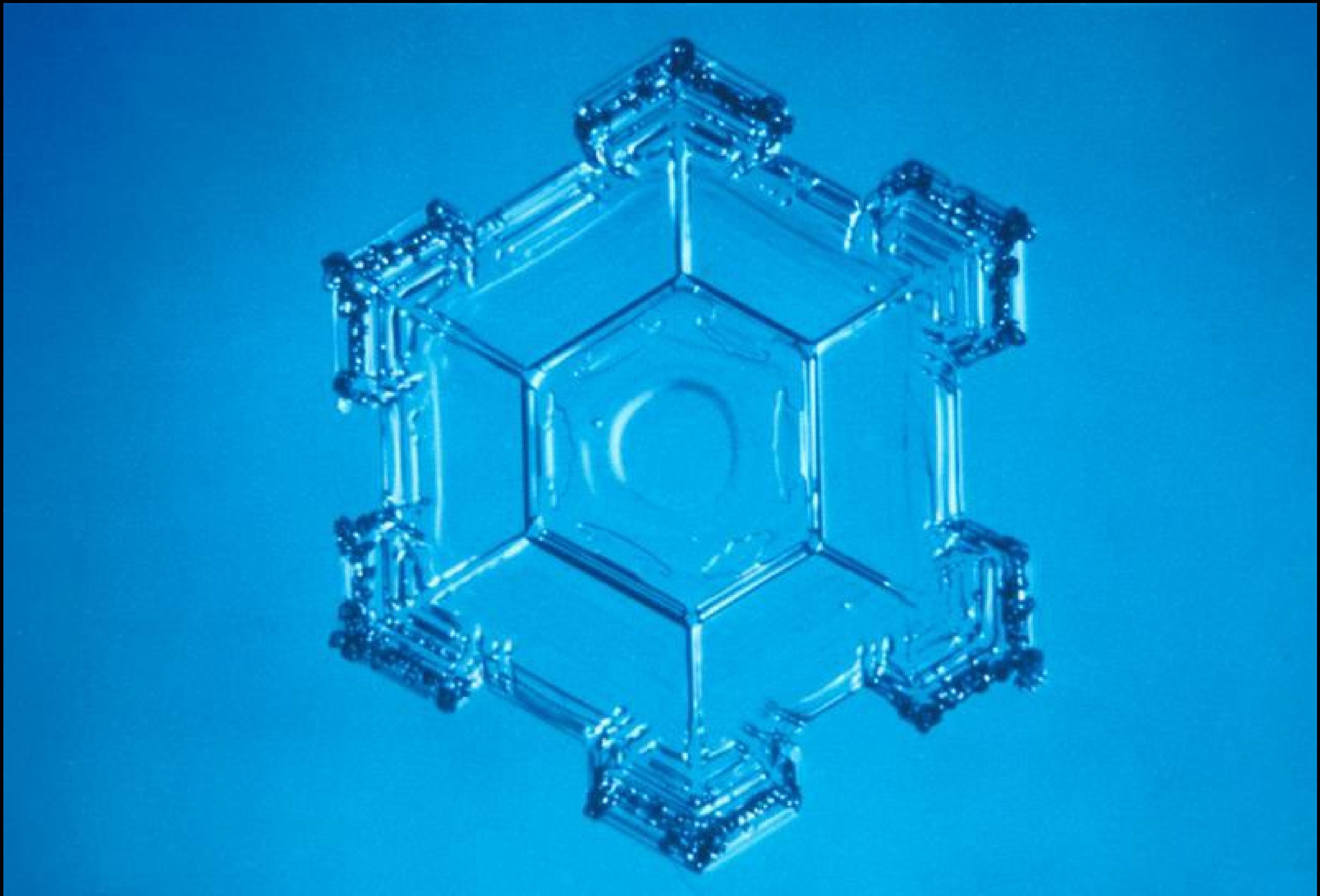
High Clouds – Ice Clouds

- High clouds are at colder altitudes and are generally made of ice crystals. These do not aggregate into droplets and fall
- They are therefore wispy, thin**, let visible light from the sun pass down through them fairly well.**
- Low clouds are thicker, it’s darker when they rule. High cirrus doesn’t block much sunlight. Days are still pretty sunny.

Ice crystals...



…Come in many shapes, depending on the temperature and types of condensation nuclei



Ice Crystals Make Cirrus Clouds

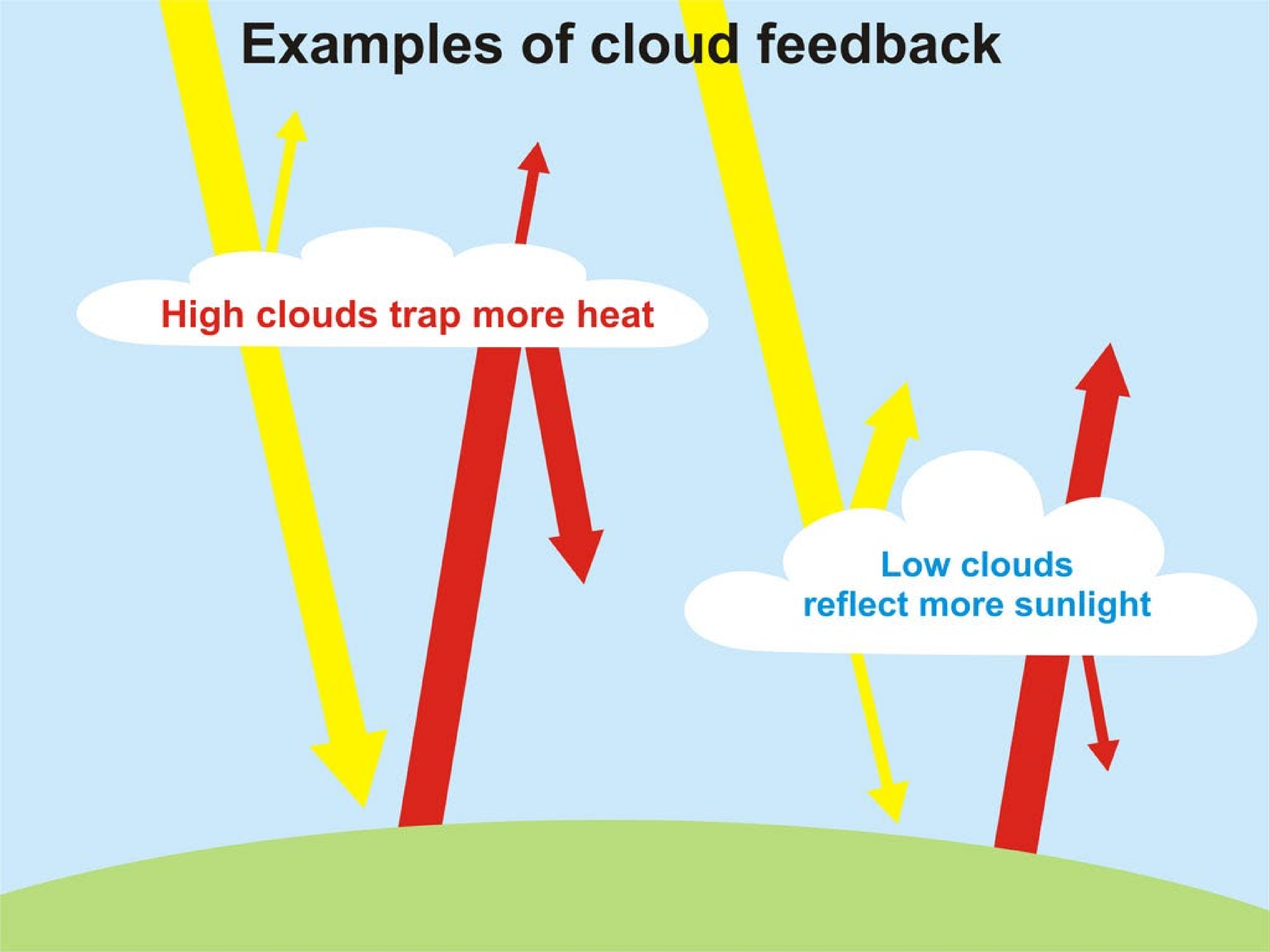
High Clouds, Especially Cirrus, will WARM the Earth's Climate

- **Cause #1:** High clouds are up at cold levels in the atmosphere, therefore have cold cloud tops and so they don't radiate well to outer space
- **Cause #2:** Atmosphere is cleaner these 20,000 ft + altitudes, so fewer aerosols and CCNs to nucleate clouds, so the droplets or ice crystals are farther apart, allow more incoming sunlight to reach the ground. They reflect sunlight much less effectively than low clouds.
- **Cause #3:** Usually are ice crystals up here, and they are not only sparser, but typically larger than cloud droplets, and have the same size - a few microns - as the wavelengths of longwave IR being radiated up from the surface of the Earth. This is a resonance, and so they are very effective at reflecting this upgoing IR back down to the ground, inhibiting the Earth from cooling to space.

- **All 3 Effects Reinforce Each Other: High clouds tend to warm the atmosphere and ground beneath them.**

Cirrus clouds are “optically thin” (*i.e.* reasonably transparent) to sunlight, allowing heating of the ground and air beneath them. The also are good at reflecting back downward the outgoing longwave IR radiation and thus have a net heating effect on climate. You’ve probably noticed how clear nights are colder, and cloudy nights are warmer

Examples of cloud feedback

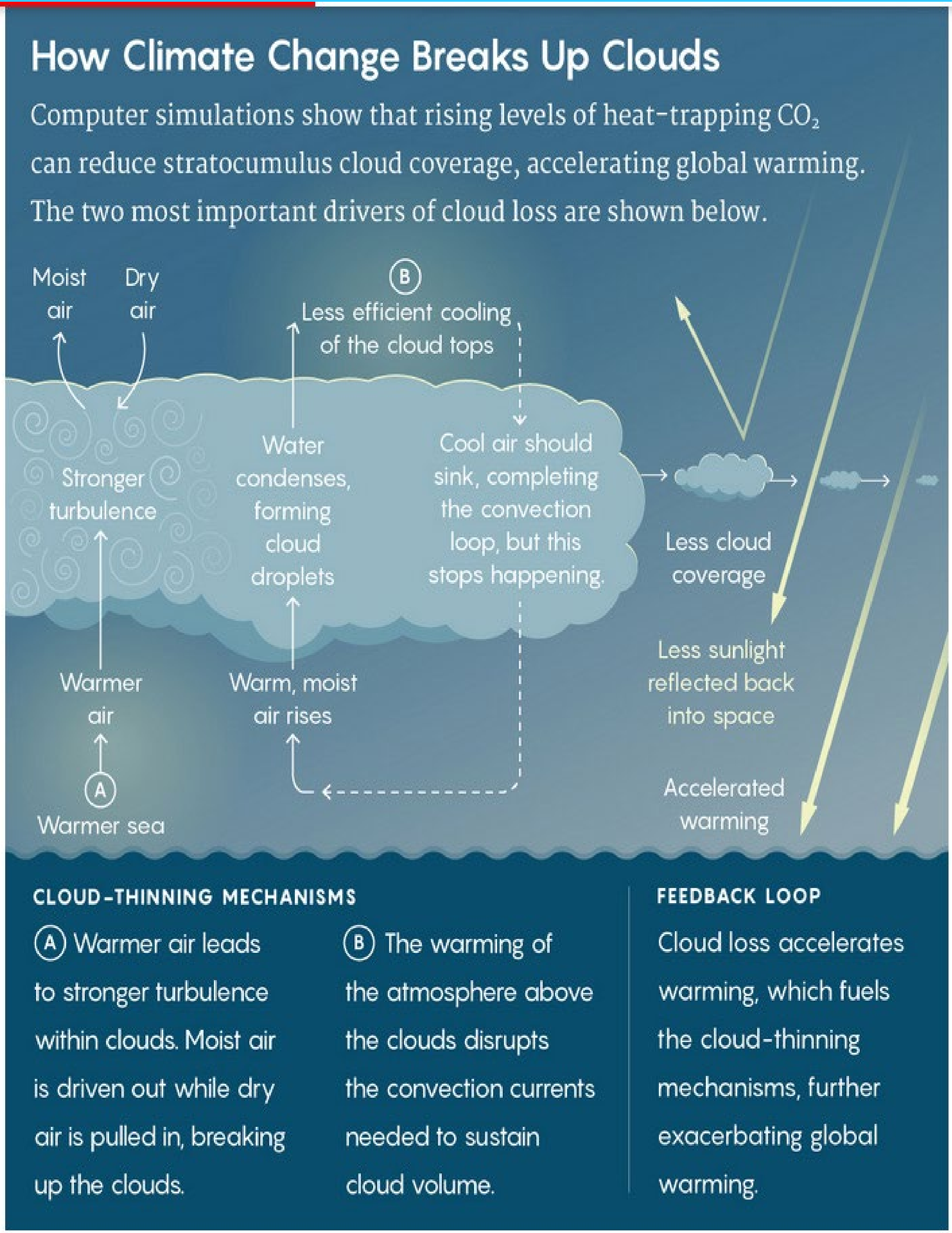


So How Is the Relative Amounts of Low and High Clouds Changing?

- Data still has large uncertainties, but… most observational data suggests **clouds are an AMPLIFYING feedback…**
- We're getting fewer low clouds over the ocean, and more high clouds.
- **Eastwood *et al.* 2011** uses 40 years of ground observations and de-biases for differing methods and that's their conclusion…

From their Conclusions Section:

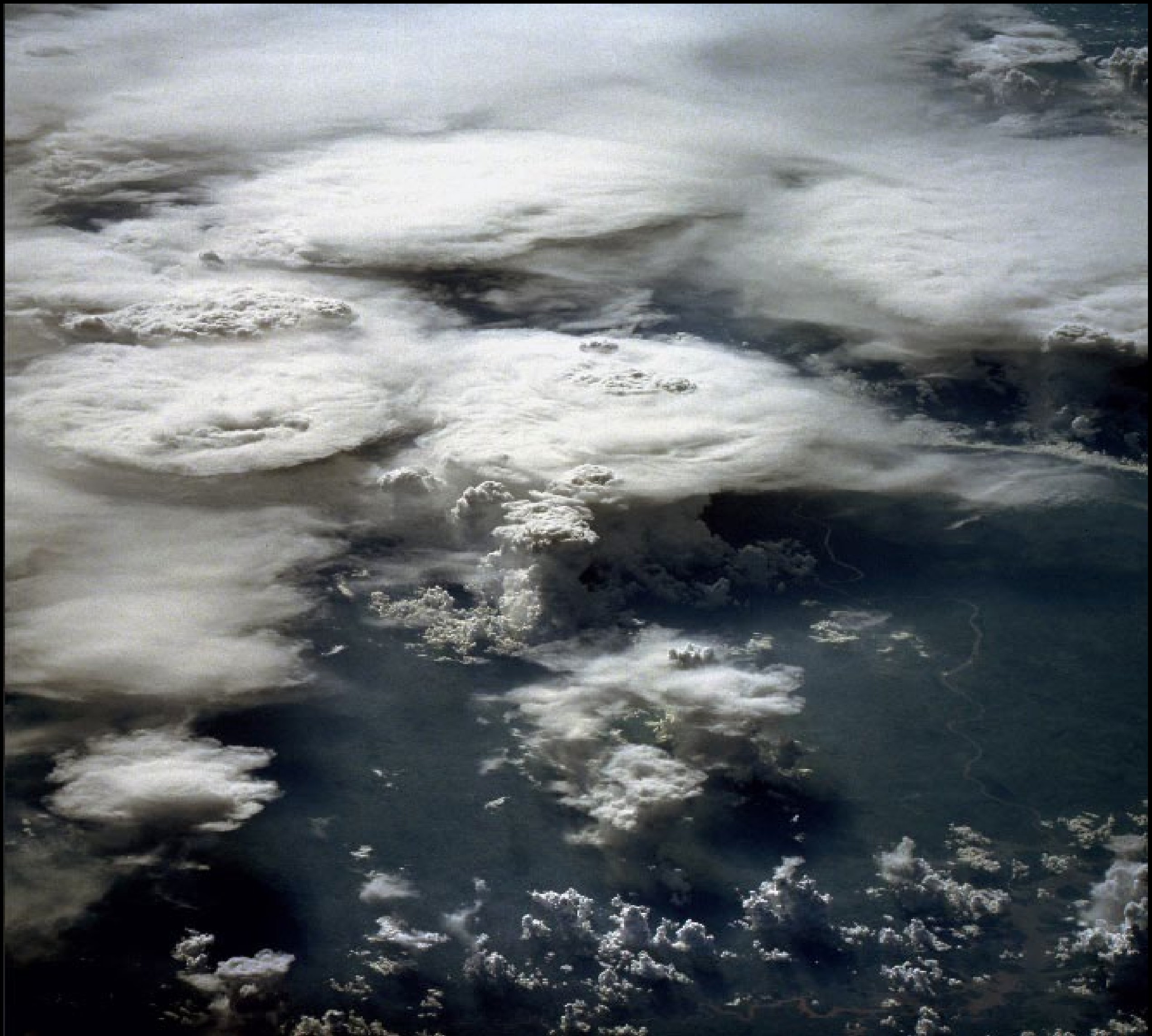
- *"Using adjusted data, anomalies of cloud amounts are shown to correlate with SST [**s**ea **s**urface **t**emperature] and LTS [lower tropospheric stability: how convective it is]. A strong negative correlation is seen between low stratiform cloud cover and SST, while a positive correlation is seen between low stratiform cloud cover and lower-tropospheric stability in regions of persistent marine stratocumulus. This is an expected result, given previous work. Other factors such as sea level pressure and relative humidity also correlate with variations in low cloud cover. <u>High clouds</u> show a less substantial, but consistent, <u>positive correlation with SST</u>."*
- **In other words… hotter ocean surface shows <u>fewer</u> low clouds and <u>more</u> high clouds -> amplifies warming of climate**



Rising CO2 inhibits cloud tops' radiative cooling, reducing convective support of clouds. It also leads to warmer ocean, causing higher turbulent mixing and entraining of dry surrounding air, dissipating the cloud margins.

A vicious cycle: Fewer clouds –> more surface warming -> fewer clouds ->…

Satellite image of Thunderstorms. Note these rising clouds (cumulo-nimbus) flatten when convection stops, which may not happen until the stratosphere boundary is reached at ~30,000 ft. Here, it's cold enough for ice crystals and you see cirrus tops spreading away from the tops. These may be more common as Earth's oceans warm further. This warms Earth Climate



More Confirmation that Clouds in a Warming World Provide a Feedback to Amplify Warming

- Norris *et al.* 2016 use improved re-analysis of 30 yrs of satellite data find confirmation of other climate models predictions in a warming world. Namely:
- **1.** Northward migration of storm tracks
- **2.** Cloud tops are higher (hence colder, hence less able to radiate to space, hence amplifying global warming)
- **3.** Expansion of the "desert zones" nominally at +30 and -30 latitude, poleward

A Rare Negative Feedback: Hotter climate means Mixed ice/water clouds will have more droplets, less ice -> Net coolant to climate. But this effect's been <u>overestimated</u>, unfortunately

- <u>Tan *et al.* 2016</u> from their abstract…
- ***"Global climate model (GCM) estimates of the equilibrium global mean surface temperature response to a doubling of atmospheric CO_2, measured by the equilibrium climate sensitivity (ECS), range from 2.0° to 4.6°C. Clouds are among the leading causes of this uncertainty. Here we show that the ECS can be up to 1.3°C higher in simulations where mixed-phase clouds consisting of ice crystals and supercooled liquid droplets are constrained by global satellite observations"***
- *As climate warms, mixed phase clouds will have increasing water droplets and decreasing ice fraction, making them more reflective and better coolants. This is a rare negative (de-amplifying) feedback. <u>The problem is, current models have too MUCH ice to be consistent with satellite data, and so this fortunate feedback has been overestimated.</u>*
- ***Net result: <u>ECS goes from 4°C to 5.1°C, roughly. Hotter World</u>***

Another Worrying Sign – Increasing Cirrus in the high Stratosphere

- Once thought to be mere curiosities, some polar stratospheric clouds (PSCs) are now known to be associated with the destruction of ozone. Indeed, an ozone hole formed over the UK in Feb. 2016 following an outbreak of ozone-destroying Type 1 PSCs.

Normally too dry to have clouds, the rapidly increasing methane content of our atmosphere, migrating to the stratosphere, oxidizes to form water vapor, and at the cooling stratospheric temperatures of -85C, form ice crystal clouds of 10 micron size. But Earth's outgoing IR radiation is also centered at ~10 microns, so these clouds are reflecting our outgoing IR back down to ground, further warming Earth.

At Even Higher Altitudes – Noctilucent Clouds – Used to be Confined to the Poles

- But they are **now being seen at temperate and even tropical latitudes**, indicating rising water vapor in the highest, coldest levels of the atmosphere.
- Again, these block very little sunlight, but are more effective at reflecting outgoing IR back to the ground, and therefore should be expected to amplify global warming.
- This is a new observational effect, not incorporated into any climate models as of 2020.
- Are they significant? What abundance would they need to reach to be climate significant? Is that to be expected on our current civilization course?

Cloud Modelling in Global Climate Models (GCMs)

- Clouds show significant structure on scales as small as 1 km and under. The Earth has 500 million square kilometers, so we would need a spatial dynamic range of 500 million to begin to resolve clouds well. Not possible now or in the near future with current computer technology!
- Does that mean we are groping in the dark about how clouds and climate work?
- No, but it does mean we can’t directly simulate clouds in GCMs. For now, we need to parameterize the modelling by fitting to observed data.

How we include clouds in GCM climate models today

- We can assign a fractional cloud cover to a grid cell in a climate model, which is a decent first approximation to modelling the detailed coverage of each small cloud
- We can use one-dimensional models (computer simulations using physics which include enthalpy, entropy, vapor content, temperature profile, etc, and see how clouds will form *vs.* altitude) and embed these into full 3-D models on the much coarser grid needed for GCM's (global climate models).
- We can parameterize how clouds behave by using real world data…
- We can use Principle Component Analysis in multi-variate systems to disentangle the effects of e.g. clouds in real-world systems which have other effects going on as well.

The 9/11 Attack and Jet Contrails

- In 2001, 3-day grounding of all aircraft after attack
- Contrail-free skies over the U.S.
- Contrails are high cirrus clouds (ice crystals). Observed after 9-11: With no contrails, observed day temperatures were warmer and nights were cooler, just as predicted.
- The net heating due to contrails is less. It is very regional – areas must be cold (winter) and heavy jet traffic. Night flights worse, as the day effect is reflection of sunlight, but night effect is trapping outgoing IR. GHG heating from jet CO2 is less than the contrail effects.
- **Net effect of contrails, globally, is very small net warming (Hansen 2004). Stuber *et al.* 2006 find ~2-3% of global CO2 is due to jets, although some argue it is less.**

MODIS Satellite, ISCCP

- MODerate resolution Imaging Spectroradiometer (MODIS) measures the outgoing infrared radiation from the Earth and the clouds above the Earth.
- Combined with visual wavelength data on clouds (ISCCP International Satellite Cloud Climatology Project), going back to 1982 for satellites, and farther back for ground-based observed data), we can parameterize how well cirrus clouds absorb and emit IR and visual light directly, w/o having to calculate from first principles.
- Use these parameterizations *vs.* the main independent variables of the climate model to assign properties to model clouds during a GCM run – this is how we model clouds even though we don’t have the resolution in our models to create them from first principles

Tropical Clouds ~ zero feedback?

- Recent work using quite different theoretical ideas from thermodynamics, by Garrett, Glenn and Krueger (2018 , summary) suggest cumulus cloud feedbacks in the tropics may be close to zero, because the product of cloud number and perimeter they predict to be a constant relative to temperature.
- Their work has decent agreement with a high resolution (billion grid points) numerical cloud simulation study of a small idealized region.

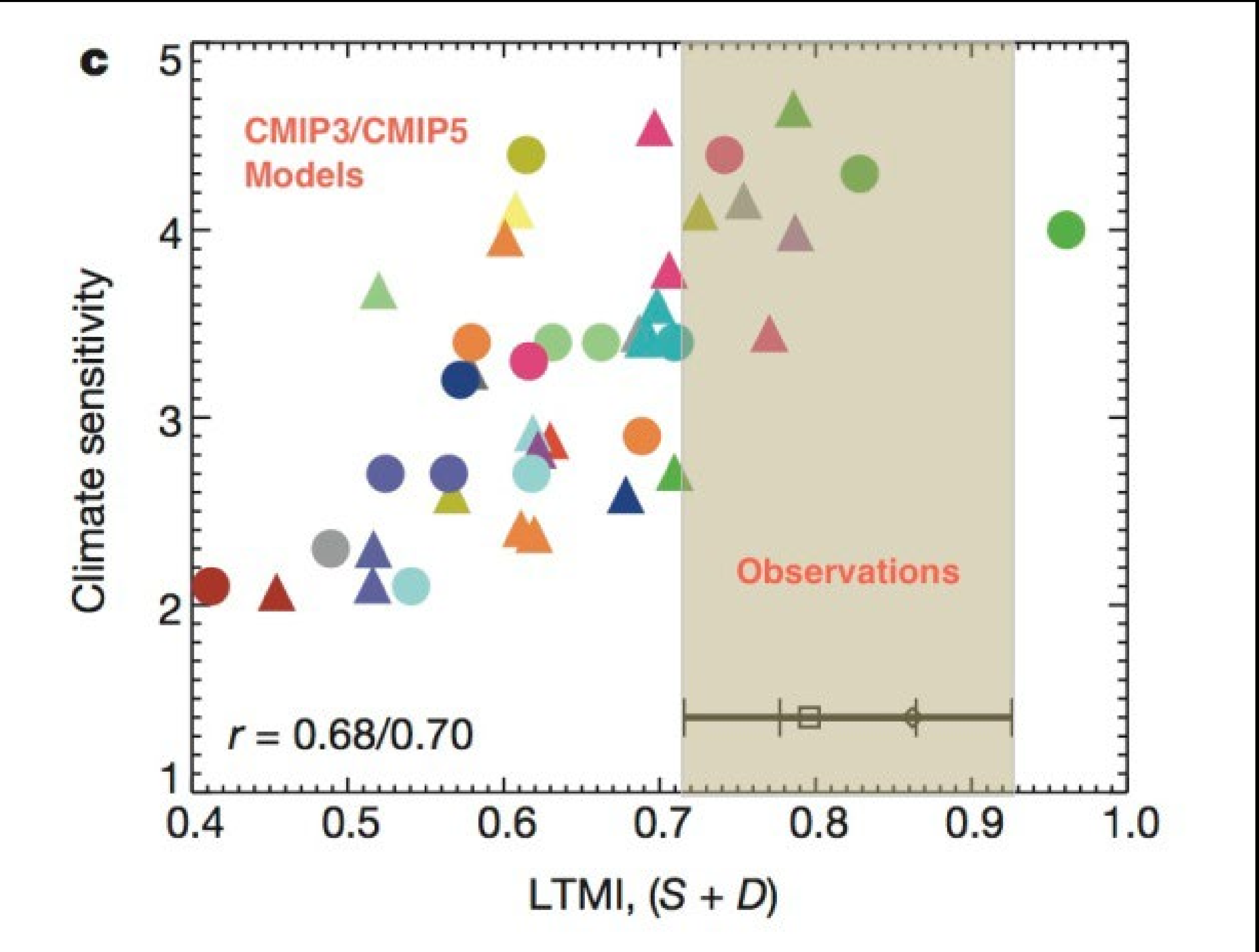
Uncertainties Remain Large, but…

- It would be more comforting to see studies showing a net negative cloud feedback in a warming world. We'd like this – they'd lessen our worries.
- **Unfortunately I'm not aware of any studies showing <u>net negative</u> cloud feedbacks to a warming climate.**

Warmer Climate -> Fewer Low Clouds-> Accelerated Warming

- **Sherwood *et al.* 2014** (summary here) find more CO_2 induces stronger convection in low troposphere, "mixing out" the low clouds
- LTMI: Lower Tropospheric Mixing Index
- They used different climate models and current observations to determine LTMI in a higher CO_2 world

LTMI= Lower Tropospheric Mixing Intensity. "Climate Sensitivity" = ECS = Temperature rise if CO2 doubles. ECS indicated is ~+4.2C; more than the +3.0C of IPCC AR5



Cautions concerning the Sherwood *et al.* study…

- While their methods include finding correlations between relevant variables in climate models and in observations which are physically reasonable, it is true that the sheer number of physical variables makes non-causative correlations a significant possibility.
- Also, their data is from the Indonesian tropics, while the low clouds which more sensitively effect global climate are in the mid latitudes.
- Nevertheless…

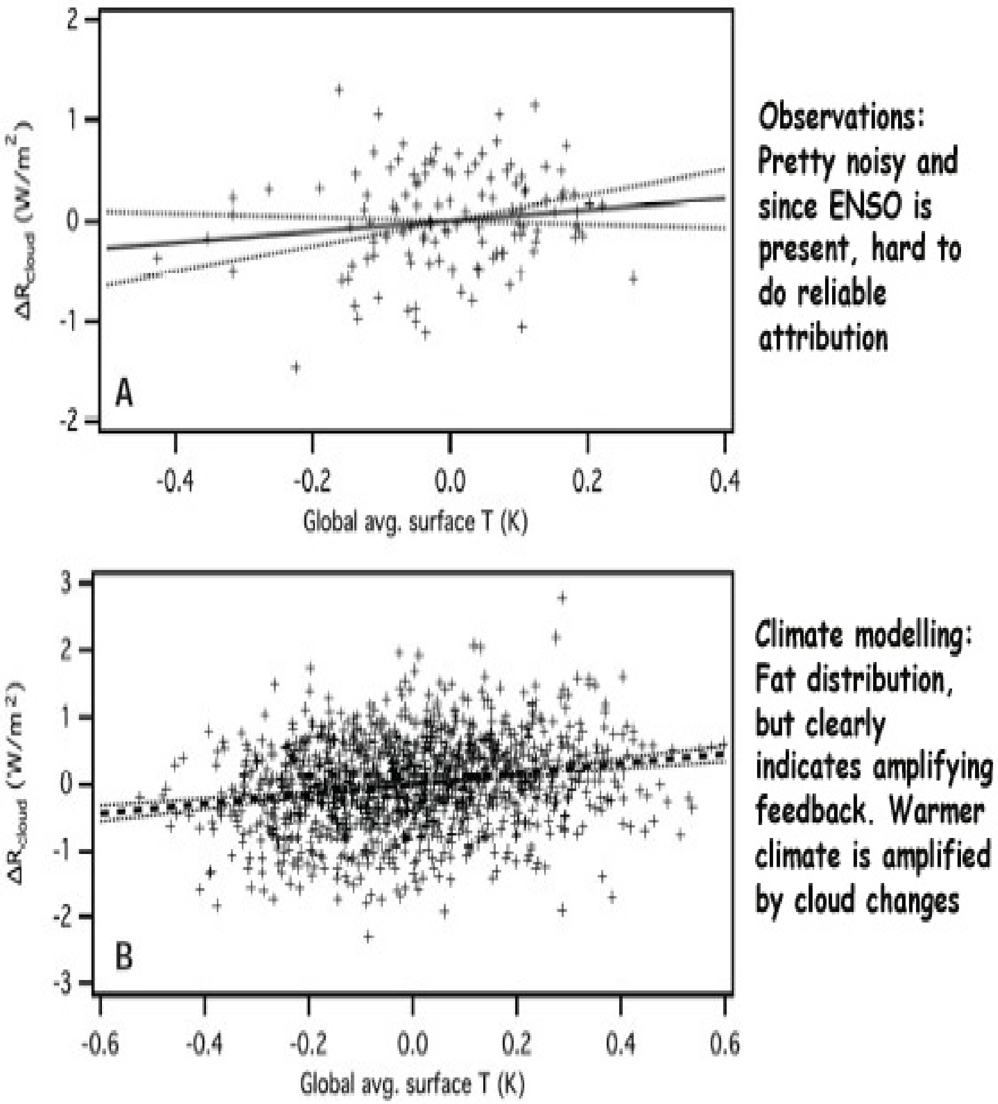


Figure 2: (A) Scatter plot of monthly average values of ΔR_{cloud} vs. ΔT_s using CERES and ECMWF interim data. (B) Scatter plot of monthly averages of the same quantities from 100 years of a control run of the ECHAM/MPIOM model. In all plots, the solid line is a linear least-squares fit and the dotted lines are the 2σ confidence interval of the fit.

Observations sparse and unclear, but other modelling studies also find a positive feedback from clouds (graph source)

Dessler finds both observation and theory Indicate Amplifying Cloud Feedback and Higher Equilibrium Climate Sensitivity = ECS

- **Dessler (2010)** studies the most recent decade of observations of climate and clouds and also finds a significant positive cloud feedback forcing of +0.54 W/m^2 per degree C of induced warming.
- 0.54 W/m^2 is significant; about half the current Earth radiative imbalance (as of the 2022 available data), which imbalance is raising Earth temperatures at an unprecedented rate.

Climate Sensitivity is higher – Fasullo and Trenberth (2012)

- **Fasullo and Trenberth** (2012 behind paywall but well-discussed here and here) use relative humidity, strongly related to clouds, and correlate models with observations and find… *"These results suggest a systematic deficiency in the drying effect of either subsident circulations or spurious mixing of moister air into the region in low-sensitivity models that directly relate to their projected changes in cloud amount and albedo. Although the lower-sensitivity models are clearly at odds with observations, extrapolating the consequences of these model biases to climate sensitivity is nontrivial**...***
- ***The results strongly suggest that the more sensitive (equilibrium climate sensitivity) models perform better, and indeed the less sensitive models are not adequate in replicating vital aspects of today's climate**. The correct simulation of the vertical structure of Relative Humidity and clouds should be a prerequisite for developing confidence in projections for the future."*

Cloud Feedbacks in Context: Comparison with water vapor, albedo, and temperature feedbacks in climate models (from Soden and Held 2006). **The "cloud" data points are all above 0 – Meaning, an amplifying feedback**

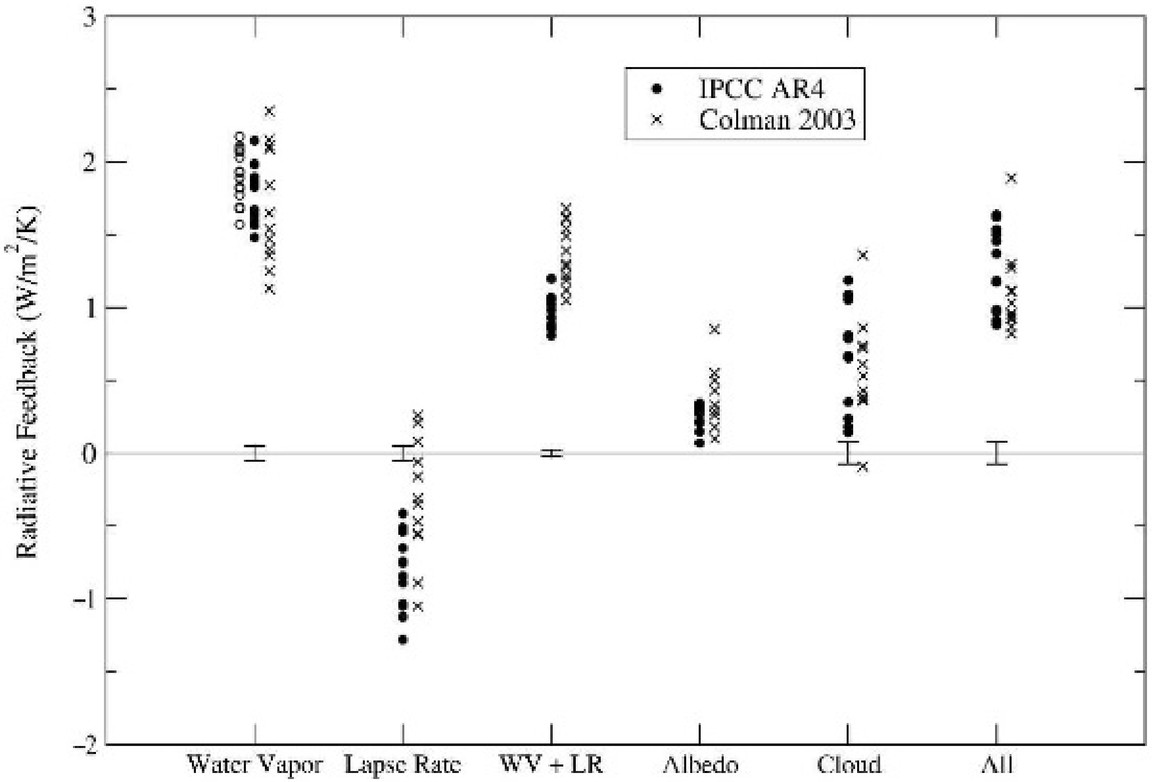


FIG. 1. Comparison of the climate feedback parameters for water vapor (λ_w), lapse rate (λ_T), the combined water vapor + lapse rate, surface albedo (λ_a), and clouds (λ_c) in units of W m^{-2} K^{-1}. All represents the combined feedback from water vapor, lapse rate, surface albedo, and clouds. Filled circles represent results from this study using the IPCC AR4 model archive. Crosses are previously published results taken from the survey of Colman (2003). Open circles for water vapor represent the water vapor feedback computed for each of the IPCC AR4 models assuming no change in relative humidity. Vertical bars depict the estimated uncertainty in the calculation of the feedbacks for each parameter.

To Note Now… and Later

- Eliminating uncertainty in clouds and aerosols would, climatologist Dr. David Randall estimates as of ~2012, reduce the overall future climate uncertainty by only 1/3.
- Remember again – if clouds do change because climate changes – then they are a feedback, and therefore even if, against the best studies to date, they somehow turn out to be a negative feedback, that would only lessen the rate of global warming, not stop it.
- Observational evidence indicates clouds exert a positive feedback, not negative, on climate, worsening the warming: enhanced high cirrus, reduced low stratus clouds, and probably both.

So. Did the Simulations used for IPCC AR4, AR5, AR6 reports include such cloud feedbacks?

- **No.**
- Given the poor understanding of cloud feedbacks, back then, they assumed no cloud changes in all their modelling of future climate scenarios.
- Rather than being noncommittal, think what this **actually** means - it is putting in a cloud feedback of precisely **zero**, even though evidence leans towards an amplifying non-zero positive feedback
- It would have been more accurate to put in a best guess feedback term, and qualify the results with an estimated uncertainty in the feedback value.

Key Points: K35: Clouds and Aerosols

- Sulfate aerosols (bright, sunlight reflective) will cool climate, mostly produced by humans (coal burning). Soot is dark and warms climate
- Stratospheric volcanic aerosols cool troposphere climate by reflecting sunlight, but heat the stratosphere itself by absorbing some of that sunlight.
- **More aerosols -> smaller seeded cloud droplets -> reflect sunlight better -> coolant**
- **Net effect of aerosols, which are mostly human-made, is to COOL surface climate. So eliminating coal, oil pollution will WARM Earth Climate.**
- **High cirrus clouds** will warm climate =ice crystal clouds, cold tops radiate little to space, yet efficiently reflect upward IR back downward
- **Low clouds** cool climate; water droplets reflect sunlight and warm tops radiate IR well to outer space
- **Studies suggest warming world reduces low clouds and increases cirrus clouds, both are positive feedback on warming climate.**
- The most important aspects of a cloud's effect on climate: **what is the temperature and reflectivity (albedo) of the cloud top (*vs.* the effective temperature and albedo of the ground that the cloud is hiding).** But water vapor cannot change alone since it saturates and rains out.
- Climate models and observations are consistent with constant RELATIVE humidity as climate warms.
- Global warming is producing higher (colder) cloud tops, storm tracks moving north, dry regions expanding north – all amplify global warming further
- Water vapor content at saturation rises 7% per degree Celsius! Rising temps mean much higher absolute humidity and is <u>**THE strongest positive feedback to CO2-induced global warming – remember this.**</u>
- Atmospheric water vapor, if condensed, would rain **1 inch** of rain around the whole Earth
- Clouds require a CCN (cloud condensation nucleus), plenty in troposphere, so clouds in lower troposphere are not CCN-limited. Troposphere clouds will always form if the temp is low enough and humidity high enough.