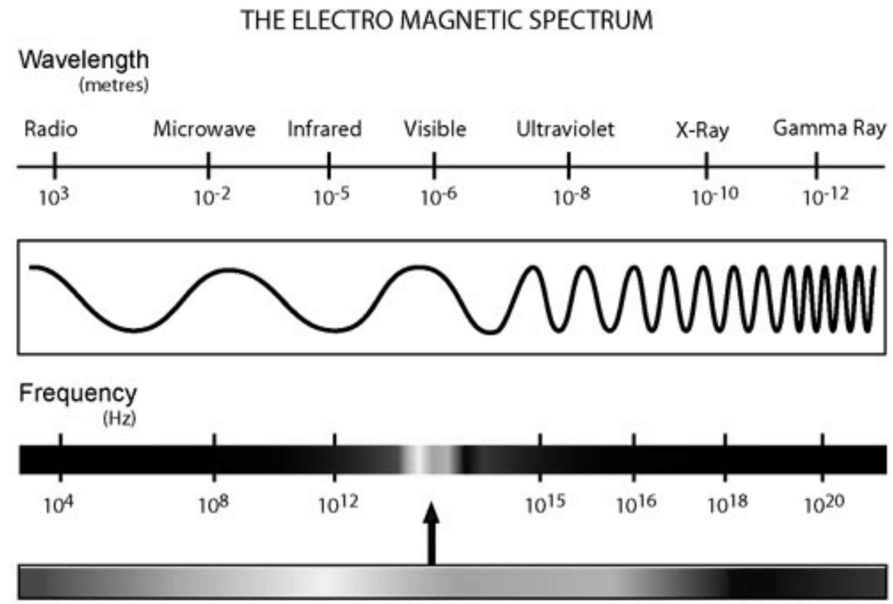
ATM S 111 Global Warming Exam Review

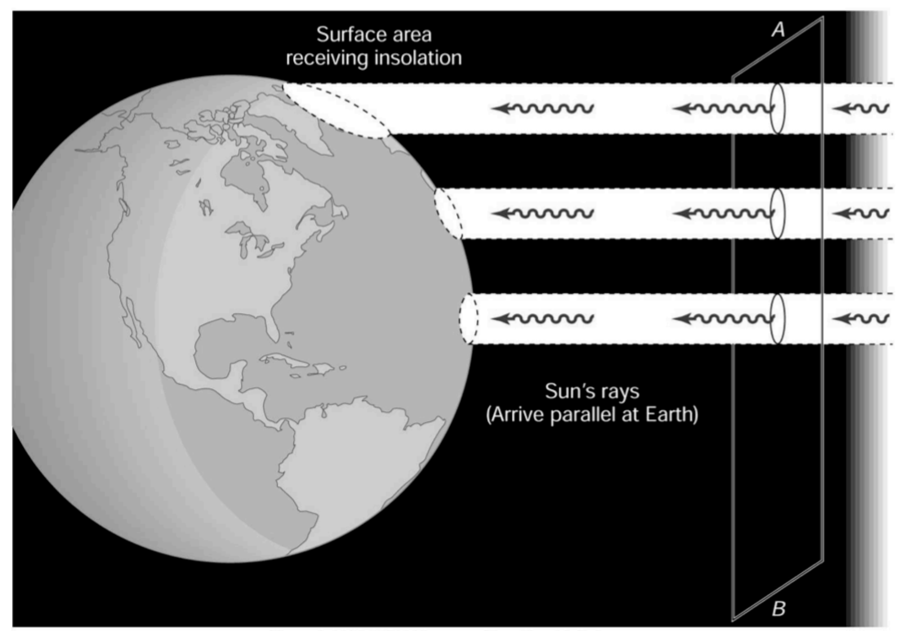
Jennifer Fletcher

Day 31, August 3, 2010

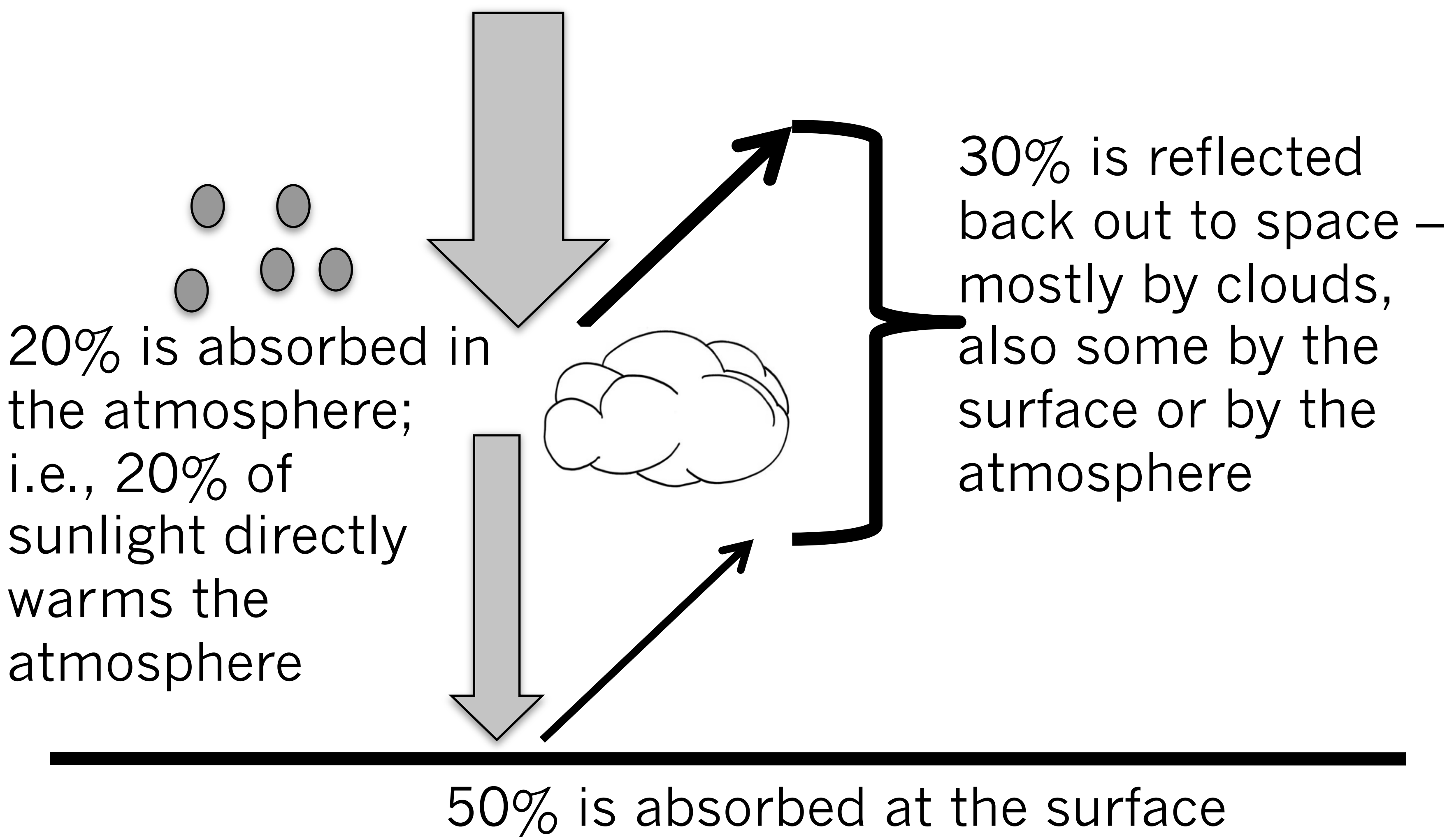
Solar Radiation

- Earth gets most of its energy from the sun.
- Solar radiation is mostly in visible, near infrared, and near UV wavelengths (shortwave)
- Earth's curvature reduces the intensity of sunlight closer to the North & South Poles
- Earth's tilt affects how intense the sunlight is as Earth revolves around the sun, causing seasons.





Solar Radiation on Earth

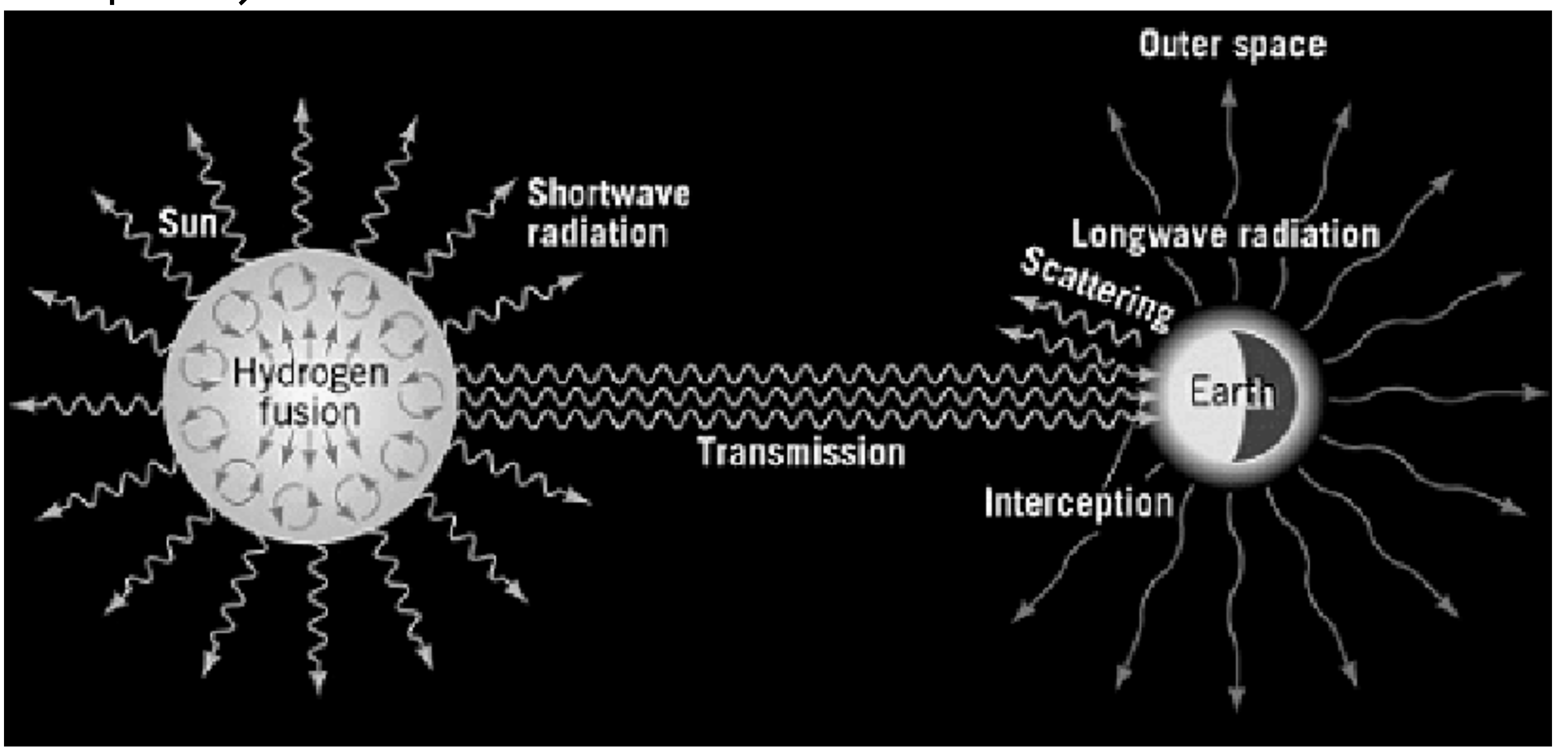


Summary So Far

- The Sun heats the Earth
  - Some is reflected back, a bit is absorbed in the atmosphere
  - But other than that, the atmosphere is pretty much transparent when it comes to solar radiation (half is absorbed right at the surface)
  - Clouds and snow/ice are primary contributors to the albedo (reflectivity) of Earth
- Next: how energy escapes from Earth and the greenhouse effect

Energy Into and Out of the Earth

- Heating/cooling of Earth
  - The Earth is heated by the Sun (shortwave radiation)
  - The Earth loses energy by longwave radiation (out to space)



Energy Balance on Earth

- If the **solar radiation** into Earth **is greater** than the **outgoing longwave radiation**, the temperature will **increase**
  - A temperature increase then results in an increase of the longwave radiation out (hotter things radiate more)
  - This will happen until:

$$E_{in} = E_{out}$$

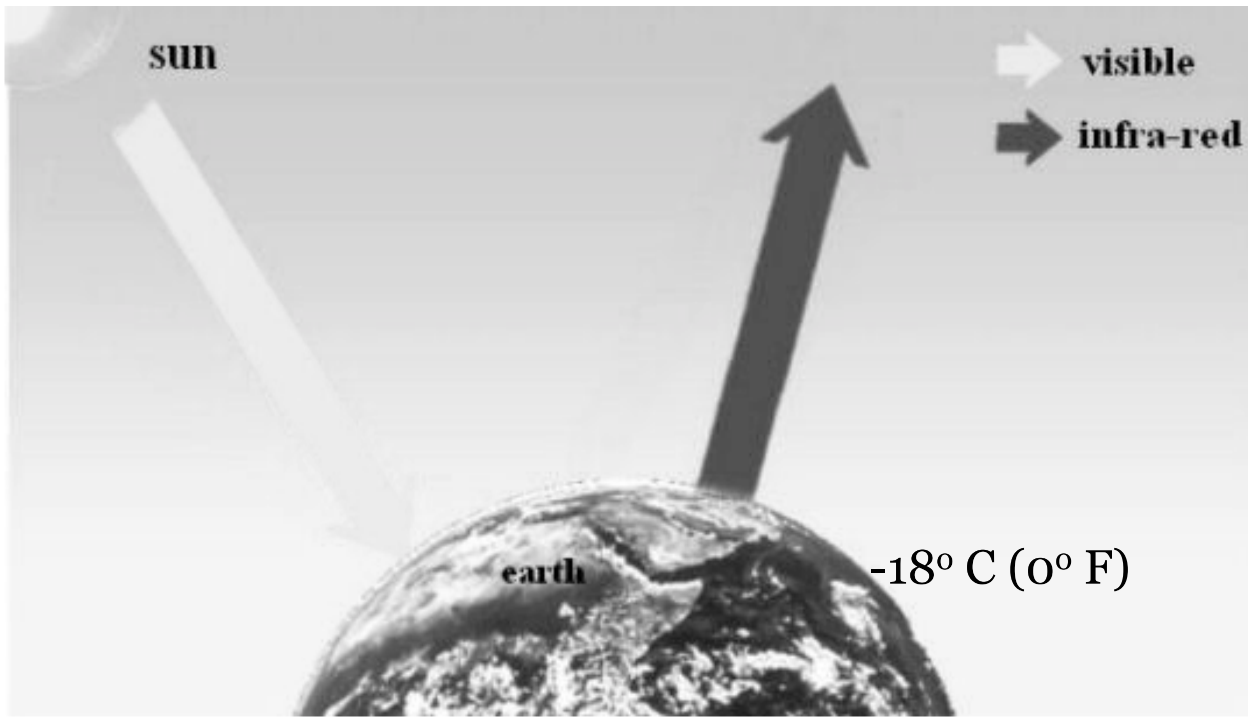
Shortwave in (E_{in})

Longwave out (E_{out})

- Global warming upsets the energy balance of the planet

Earth with No Greenhouse Effect

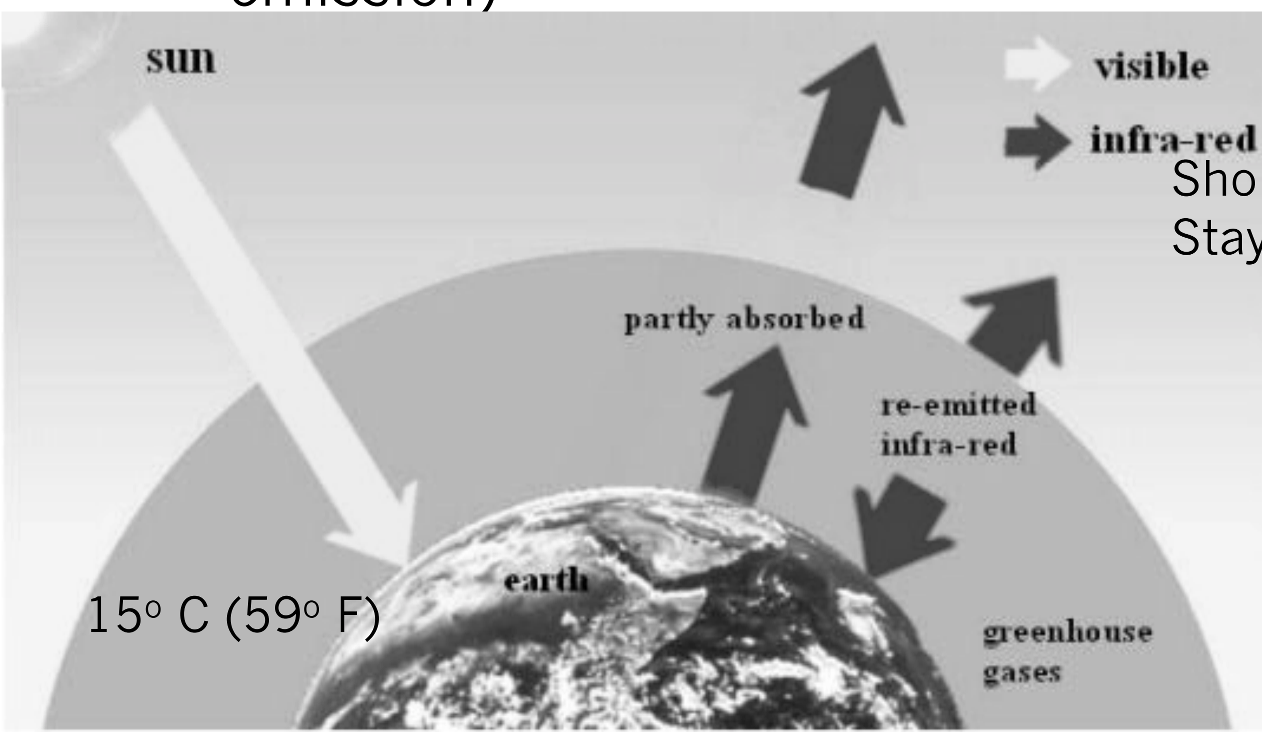
- If there was **no atmosphere**, longwave radiation from the surface would escape directly to space & Earth's temperature would be 0° F (-18° C)



- Missing piece: **the greenhouse effect**
  - All longwave radiation doesn't escape directly to space

The Greenhouse Effect

- Greenhouse gases cause the outgoing radiation to happen at higher levels (no longer from the surface)
  - Air gets much colder as you go upward
  - So the radiation to space is much less (colder → less emission)



$$E_{in} = E_{out}$$

Shortwave in
Stays the same

Longwave out
decreases

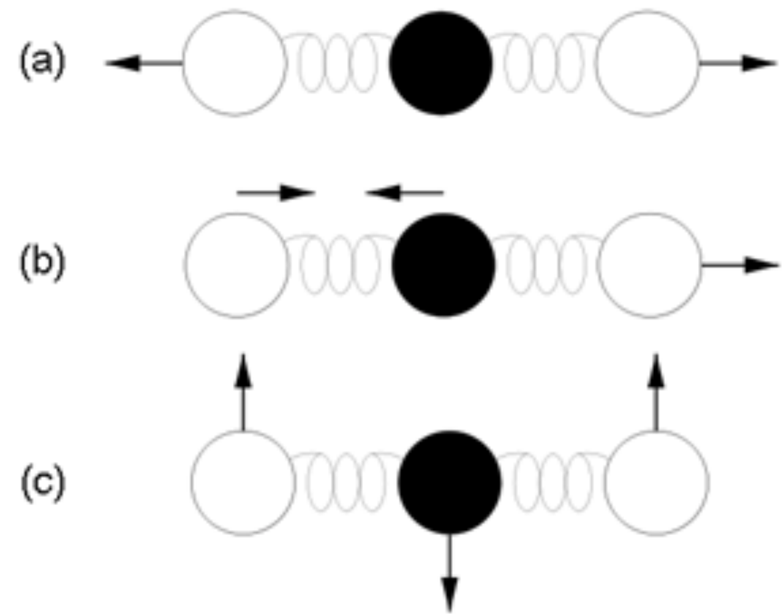
Earth is out of energy balance!
The whole system's temperature will increase until energy balance is restored.

Summary

- Earth receives energy from solar (shortwave) radiation, and looses energy by emitting infrared (longwave) radiation. Averaged over the globe and over an entire year, the warming from the sun equals the cooling (energy balance).
- If there were no greenhouse gases, radiation emitted at Earth's surface would escape to space and the surface would be very cold.
- Greenhouse gases block some of the surface radiation and emit their own radiation at a colder (atmospheric) temperature.
- This forces the entire Earth system to be much warmer (compared to if there were no greenhouse gases) to maintain energy balance.

Greenhouse Gases

- **Polyatomic** molecules (having three or more atoms) are greenhouse gases
  - **Water vapor** (H_2O)
  - **Carbon dioxide** (CO_2)
  - **Methane** (CH_4)
  - **Nitrous oxide** (N_2O)
  - **Ozone** (O_3)
  - **Chlorofluorocarbons** (the ozone depleting chemicals which have been banned)



Water Vapor

- Gas form of water
- The number one greenhouse gas!
  - Powerful because there's **a lot** of it
- Not controlled by humans
  - Water vapor concentrations are controlled by natural cycles of evaporation and precipitation
  - Observed to be increasing with global warming
  - Water vapor is not a forcing, but a feedback.

Carbon Dioxide

- CO_2
  - It's what we breathe out, what plants breathe in
- The primary contributor to the anthropogenic (human-caused) greenhouse effect
- Increases primarily due to fossil fuel burning and biomass burning
- Problematic because it's long-lived (~100 years)

Methane

- Natural gas like in stoves/heating systems
- Much more potent on a per molecule basis than CO_2
- But it has a much lower concentration and only lasts ~8 years
- Natural sources from marshes (swamp gas) and other wetlands
- Increases anthropogenically due to farm animals (cow burps), landfills, natural gas leakage, rice farming.
- Anthropogenic sources ~ natural sources

Climate Forcings vs Climate Feedbacks

- Climate forcings:
  - Things that can change global temperatures directly
  - Examples: intensity of sunlight, atmospheric CO_2 concentration
- Climate feedbacks:
  - Things that respond to temperature changes, but themselves affect temperature too
  - Example: Ice sheet extent on Greenland and Antarctica
- The key difference: forcings can initiate climate change, while feedbacks can only make that change stronger (if positive) or weaker (if negative).

Radiative Forcing

- **Radiative forcing** is calculated as the **change in shortwave in** or **longwave out** due to the particular climate forcing
  - Measured in **Watts per square meter (W/m^2)**
- Recall energy balance: $E_{in} = E_{out}$
  - Positive radiative forcing makes $E_{in} > E_{out}$.
  - Negative radiative forcing makes $E_{in} < E_{out}$.
  - In response to a positive radiative forcing, the climate must warm
  - In response to a negative forcing, the climate cools

Climate Forcings Summary

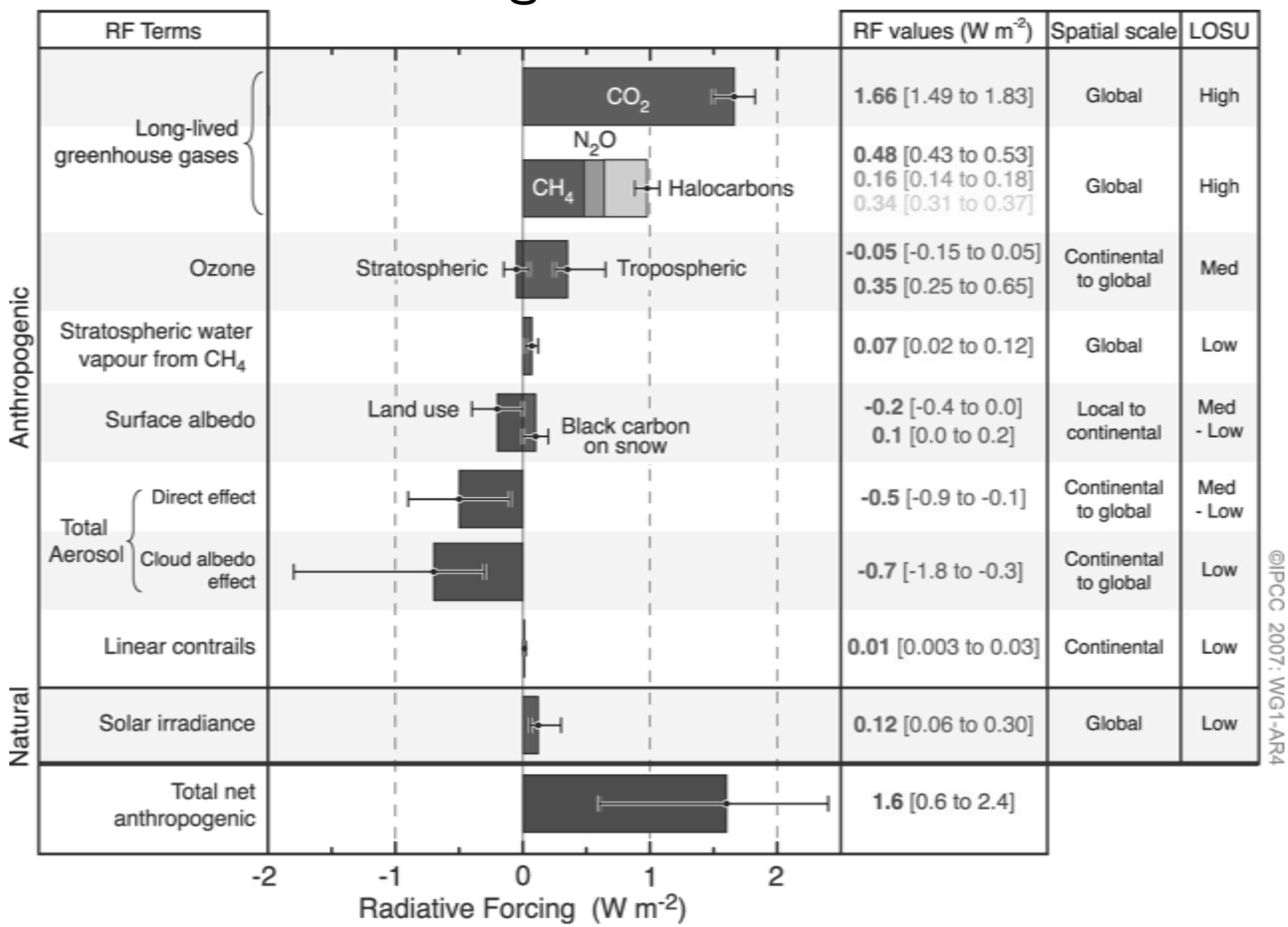
- Climate forcings either change shortwave radiation or longwave radiation
  - Longwave forcings are greenhouse gases and include:
    - Carbon dioxide
    - Methane
    - Nitrous oxide
    - Ozone
    - These are all positive forcings right now (all increasing)
  - Shortwave forcings include:
    - Changes in solar radiation (positive)
    - Changes in surface albedo by land use (negative) and soot on snow (positive)
    - Volcanoes (negative)
    - Aerosols (negative)

Radiative Forcings all Plotted Together

- Red = warming, blue = cooling
- Longwave and shortwave together here

Radiative forcing of present climate vs Preindustrial, with uncertainties

Aerosols (air pollution) are the biggest uncertainty



IPCC AR4 SPM

Climate Feedbacks

- Things that might change when the climate gets warmer or colder and in turn change the climate.
- Feedbacks are of critical importance in determining **temperature response** to climate forcings.
  - Positive feedbacks are things that amplify warming *or* cooling.
  - Negative feedbacks reduce (damp) warming or cooling.

Climate Sensitivity

- Global warming theory:

$$\Delta T = \lambda \, \Delta F$$

Δ = common symbol indicating the change in a quantity

ΔT = change in temperature (in degrees C)

ΔF = radiative forcing (in W/m^2)

λ = climate sensitivity

λ Tells us how much temperature change we can expect from a given climate forcing.

Climate Sensitivity

- Lots of **positive feedbacks** means a very sensitive climate (large λ)
  - Large change in temperature for even a small forcing

$$\Delta T = \lambda \, \Delta F$$

- Lots of **negative feedbacks** means small λ (λ must always be greater than zero)

Water Vapor Feedback

- Basic idea:
  - A warmer climate means a higher water vapor climate
    - 20% more humid climate with 3^{o} C temperature increase
    - Because water vapor is a greenhouse gas, this humidity will further increase the temperature.
- As with all feedbacks, water vapor doesn't care what the forcing is that caused the warming
  - Any kind of warming will result in an increase in water vapor content

Ice-Albedo Feedback

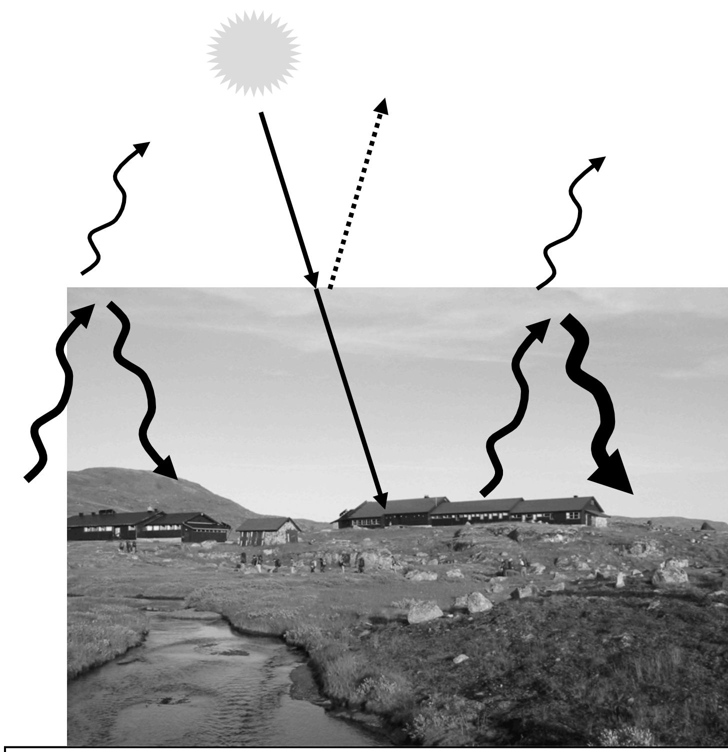
- Warming → ice melting → dark open ocean visible → more warming
- Similar feedback is present for snow (revealing darker land surfaces below)

Cloud Feedbacks

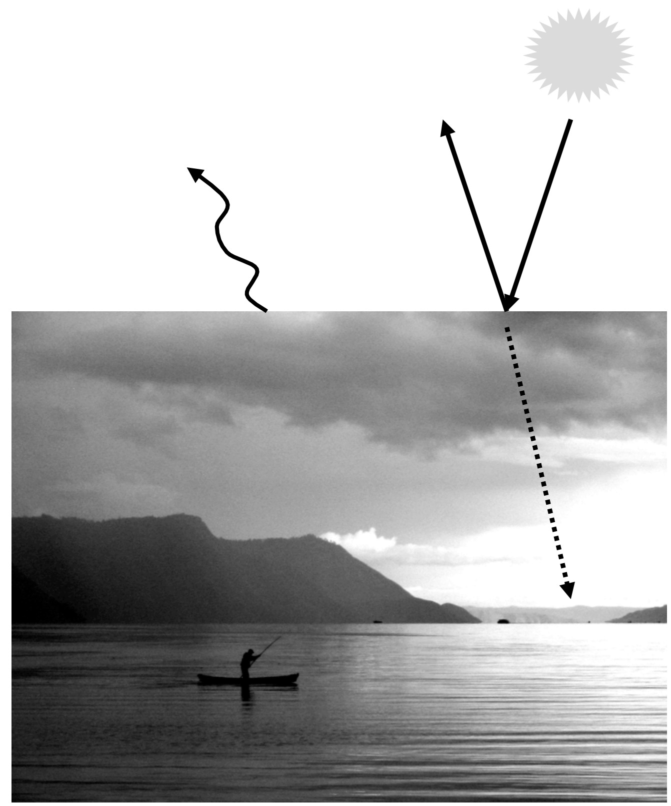
- Cloud feedbacks are much more uncertain
  - Partially because clouds have both an albedo effect and a greenhouse effect
  - Clouds with high tops (cirrus, cumulonimbus) have a large greenhouse effect because they are much colder than the surface. They block surface radiation and emit at a much colder temperature.
  - Thick clouds at any height have a large albedo effect because they block more sunlight.

Cloud Feedbacks

- Cloud feedbacks are much more uncertain
  - Partially because clouds have both an albedo effect and a greenhouse effect



High (thin) Clouds Warm



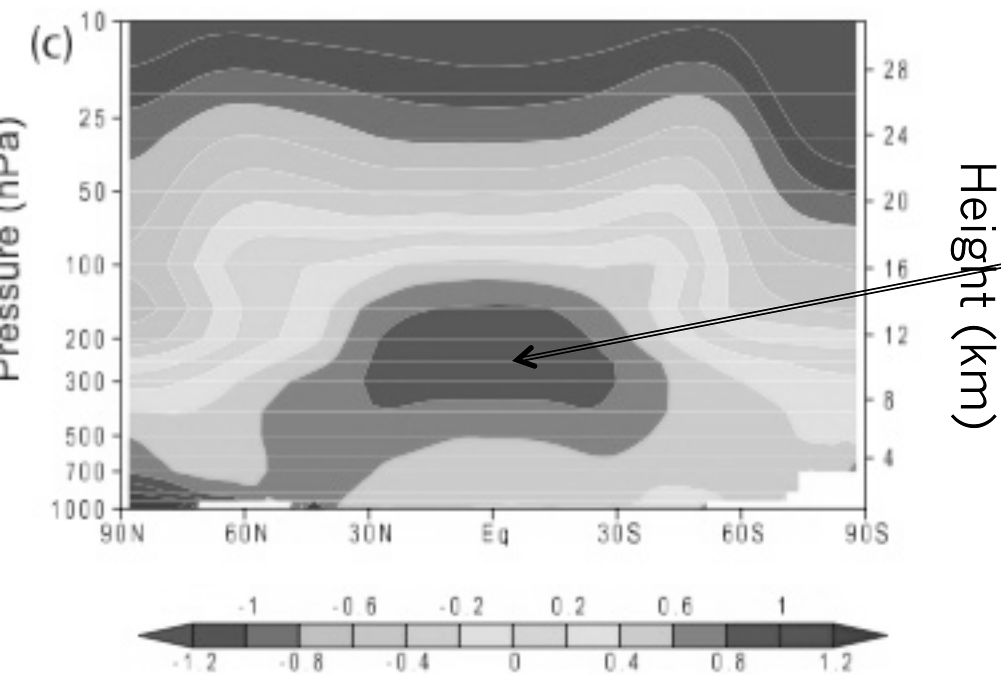
Low (thick) Clouds Cool

Cloud Feedbacks

- Cloud feedbacks lead to the largest uncertainty in global warming forecasts
- Currently, almost all climate models predict a **positive** cloud feedback.
- There is a chance these models are wrong though, as the physics of clouds aren't well-represented in climate models.

Lapse Rate Feedback

- Main **negative** feedback: “lapse rate feedback”



“Lapse rate” = how much the atmosphere cools as you go up in altitude.

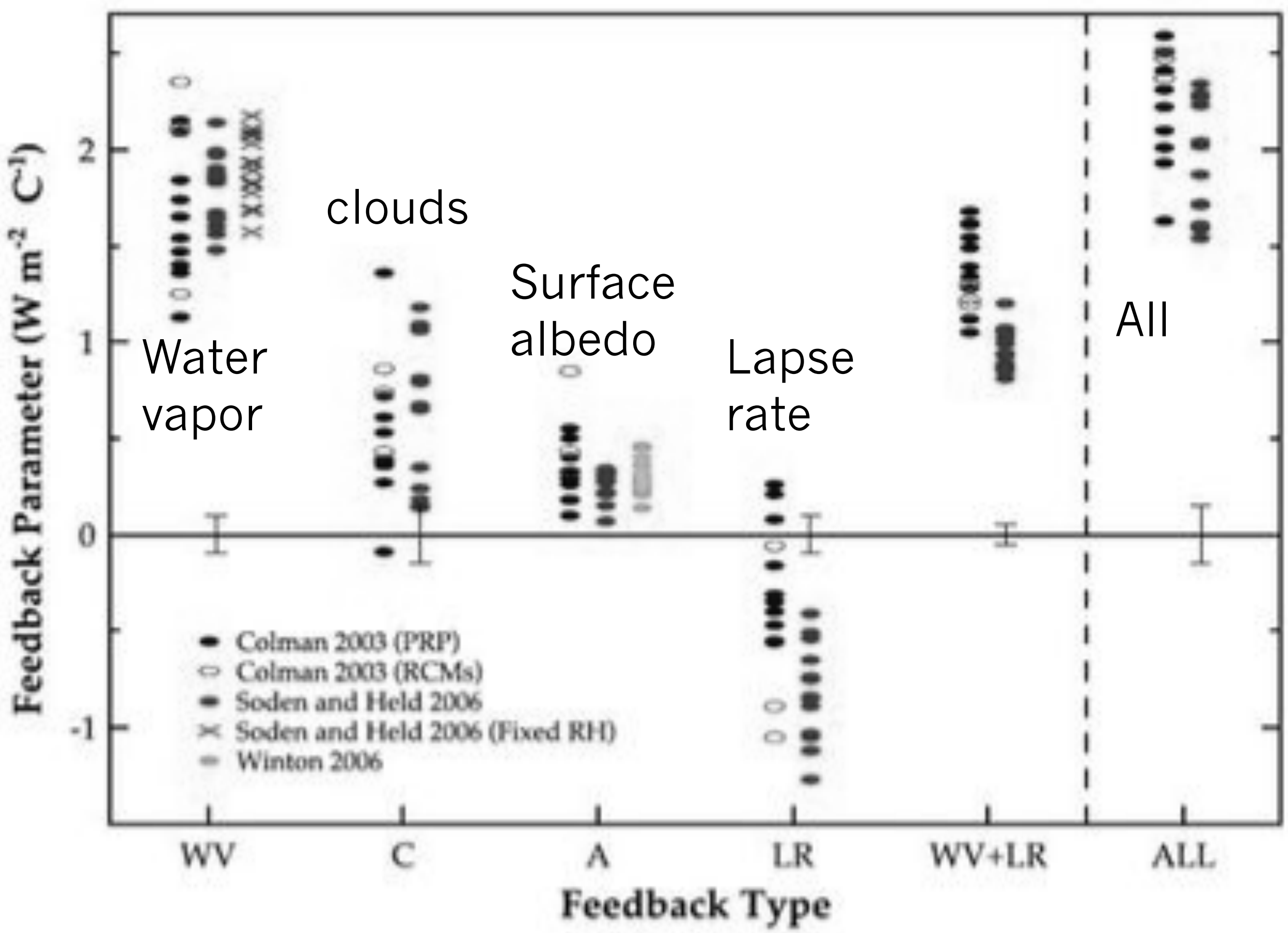
Upper atmosphere warms faster than lower atmosphere in climate models

This is where longwave radiation to space comes from.

If the upper atmosphere warms more than the lower atmosphere, the greenhouse effect isn’t as strong because more radiation will be emitted to space.

Summary of Feedbacks

• This represents the extra radiation the climate system receives due to a specific feedback per degree C of global warming.
• Different colors represent different studies, and different circles represent different climate models.



Extreme Heat

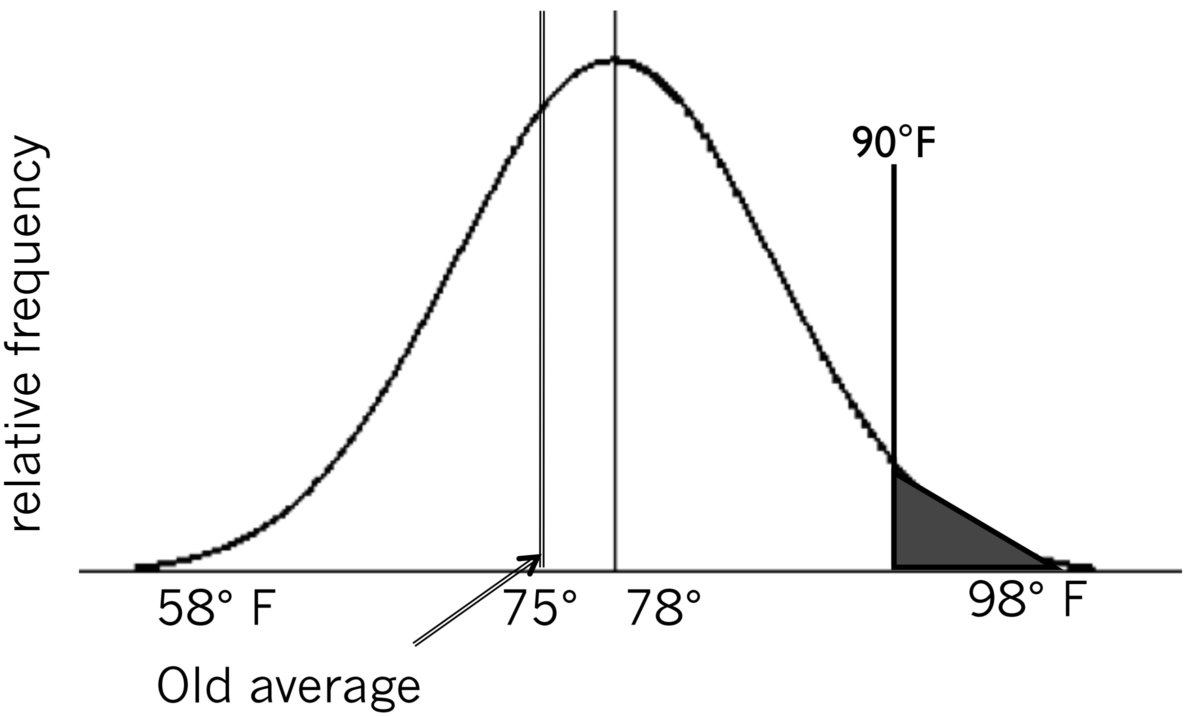
- Dry areas tend to have the worst extreme heat (because little moisture in soil/vegetation to evaporatively cool).
- So areas that are expected to see decreases in precip (subtropics) will also likely see increases in heat waves.
- However, added humidity makes heat more uncomfortable.
- Humidity is expected to increase almost everywhere.

Attribution of Extreme Heat to Global Warming

- Actual Temperature = **Natural** climate influence on temperature + **Human** influence on temperature
- The latter is now **0.7° C** globally averaged (more over continents: around 1° C). Will likely grow to 3°C or more by 2100 if no emissions controls.
- The natural range may be quite large compared to human influence depending on averaging area.
- The smaller the area you average over, the more natural variability is a factor.

Shifting the Distribution

- Simplest expectation of global warming: the distribution is shifted towards hotter temperatures
  - And the chance of a heat wave is much **more probable**



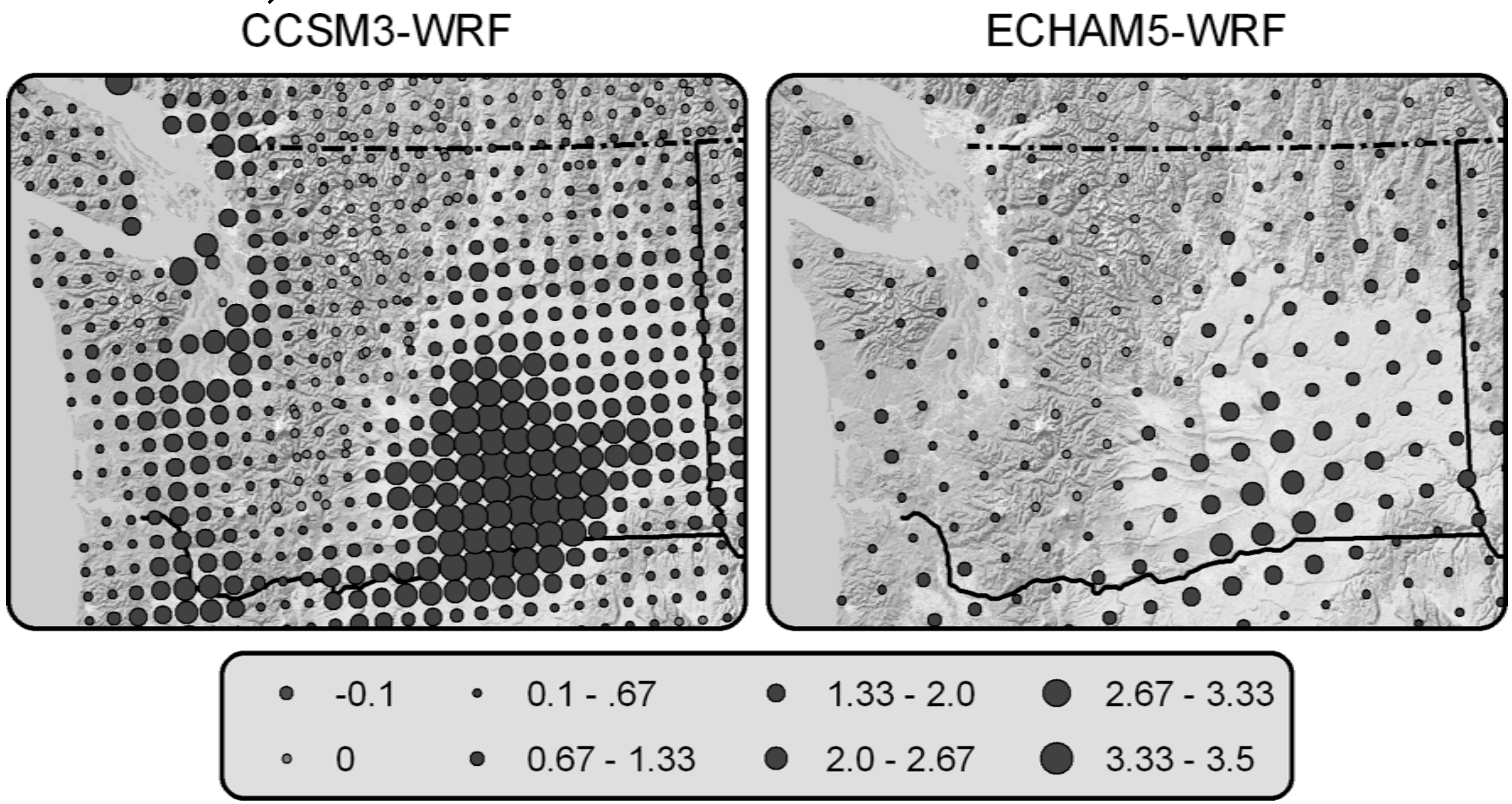
Model Predictions: Europe

- Summer of 2003 will become average summer by 2040
  - And by the end of the century the summer of 2003 would be considered unusually cool
- Days per summer that reach 30^o C (86^o F) in Paris:
  - From 6-9 days now to **50 days** by 2100
- Consecutive days over 30^o C in Paris:
  - From max of 3 to max of 19
- Drier summers over Europe lead to more warming there

Washington State Predictions

- Predictions of 2030-2059 compared with 1970-1999

Change in **number of heat waves** (heat wave = 3 straight days with heat index over 90° F)



From Climate Impacts Group report, part of UW's Joint Institute for the Study of the Atmosphere and Oceans.

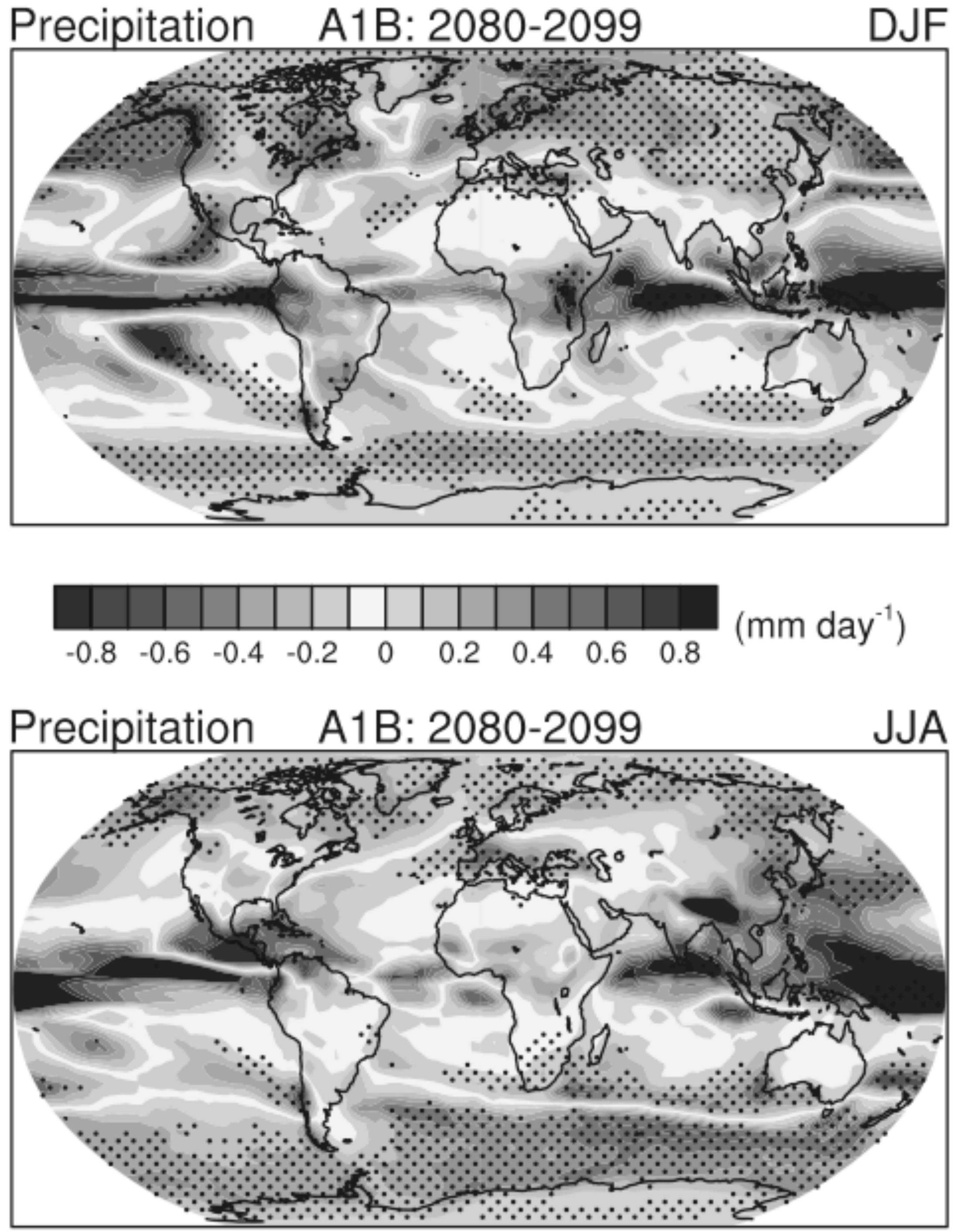
Global Warming Rain Responses

- Wet get wetter
  - More water vapor is brought into the regions that are already rainy
  - This extra rain is partially at the **expense** of dry areas
- Dry get drier
  - More water vapor taken out of the dry regions
  - And more evaporation from dry land surfaces
- There's a lot of uncertainty about specific precipitation responses though
  - Precipitation is much harder to predict than temperature
  - Regional responses could change significantly from changes in the winds

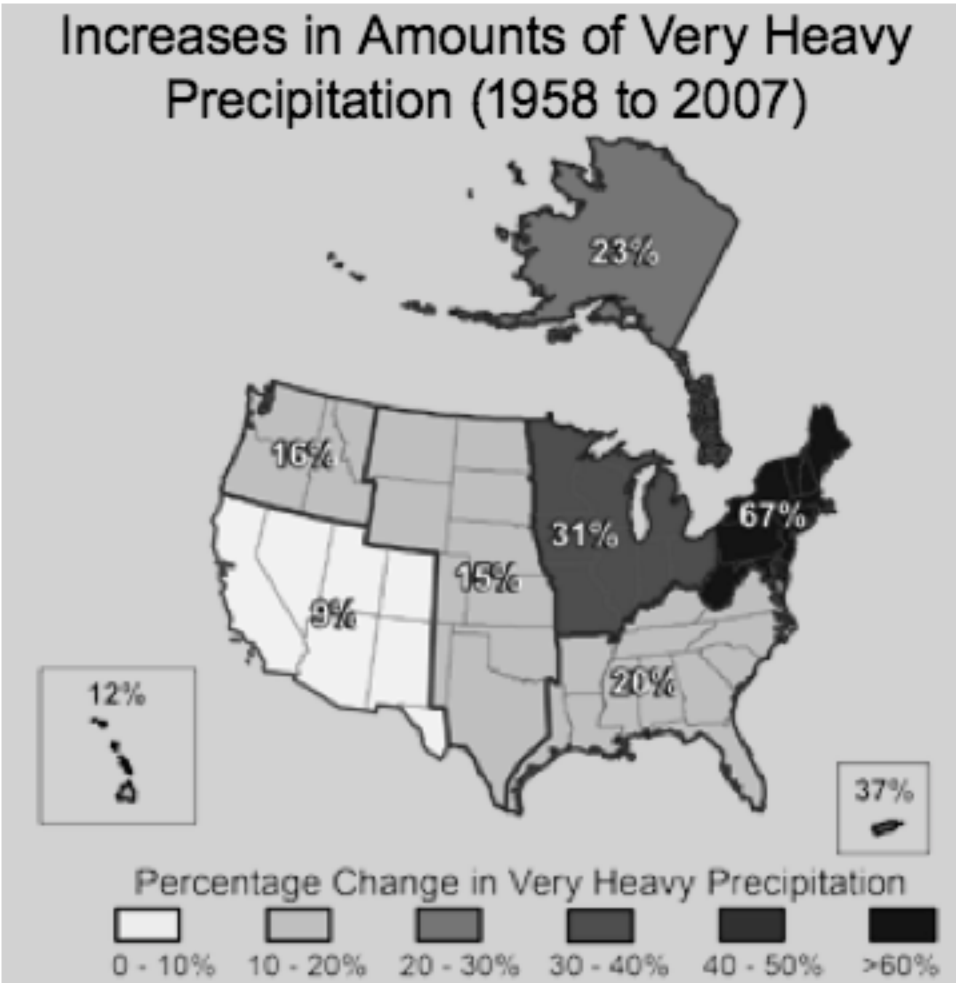
- Climate model projections of precipitation change

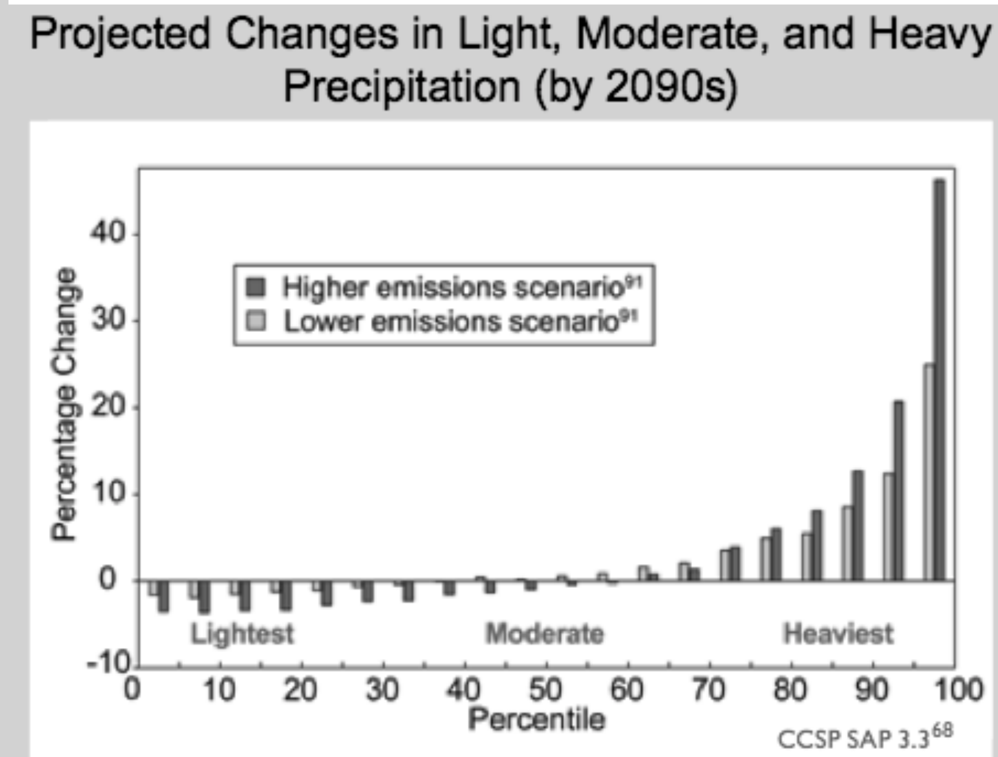
Wet gets wetter, dry gets drier

Stippling: where models agree



Are heavy rain events increasing?



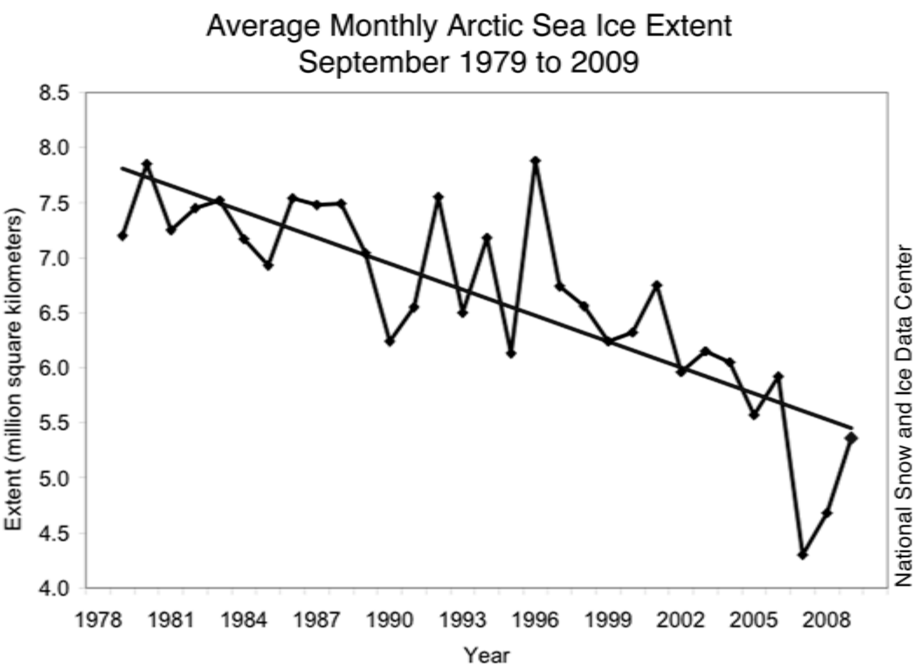


And heavy precipitation events in the US are **projected** to get worse

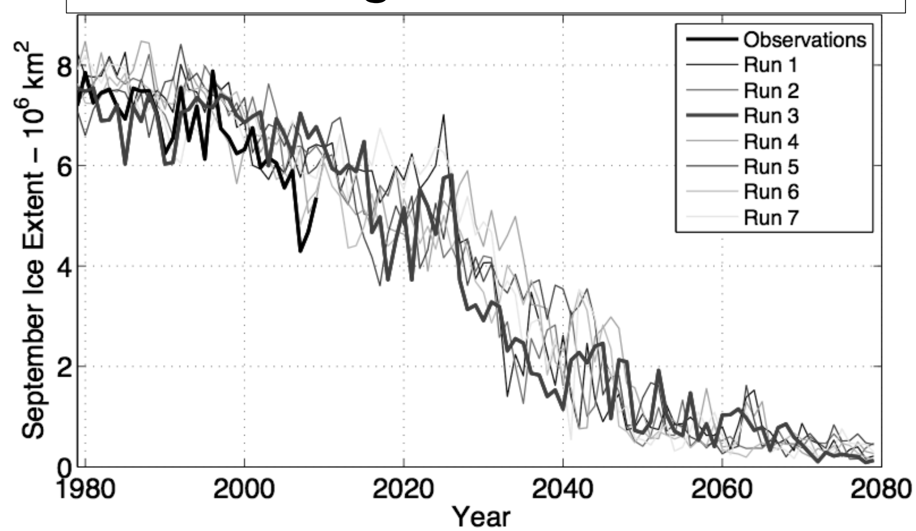
Very heavy events have been increasing

Arctic Sea Ice

- The Arctic is experiencing some of the most extreme climate change on the planet.
- Arctic sea ice is melting more and more in the summer.
- The Arctic Ocean may be ice free in the summers by the second half of this century.

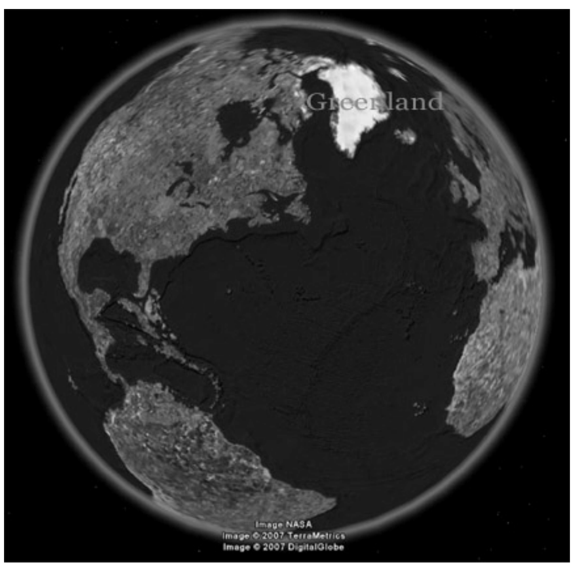


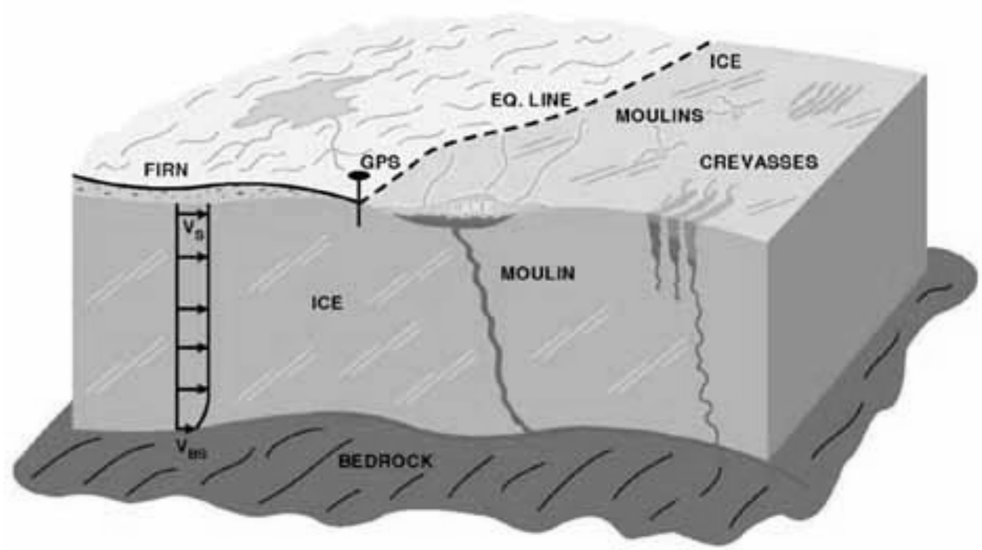
GCM with high emissions scenario



Greenland Ice Sheet

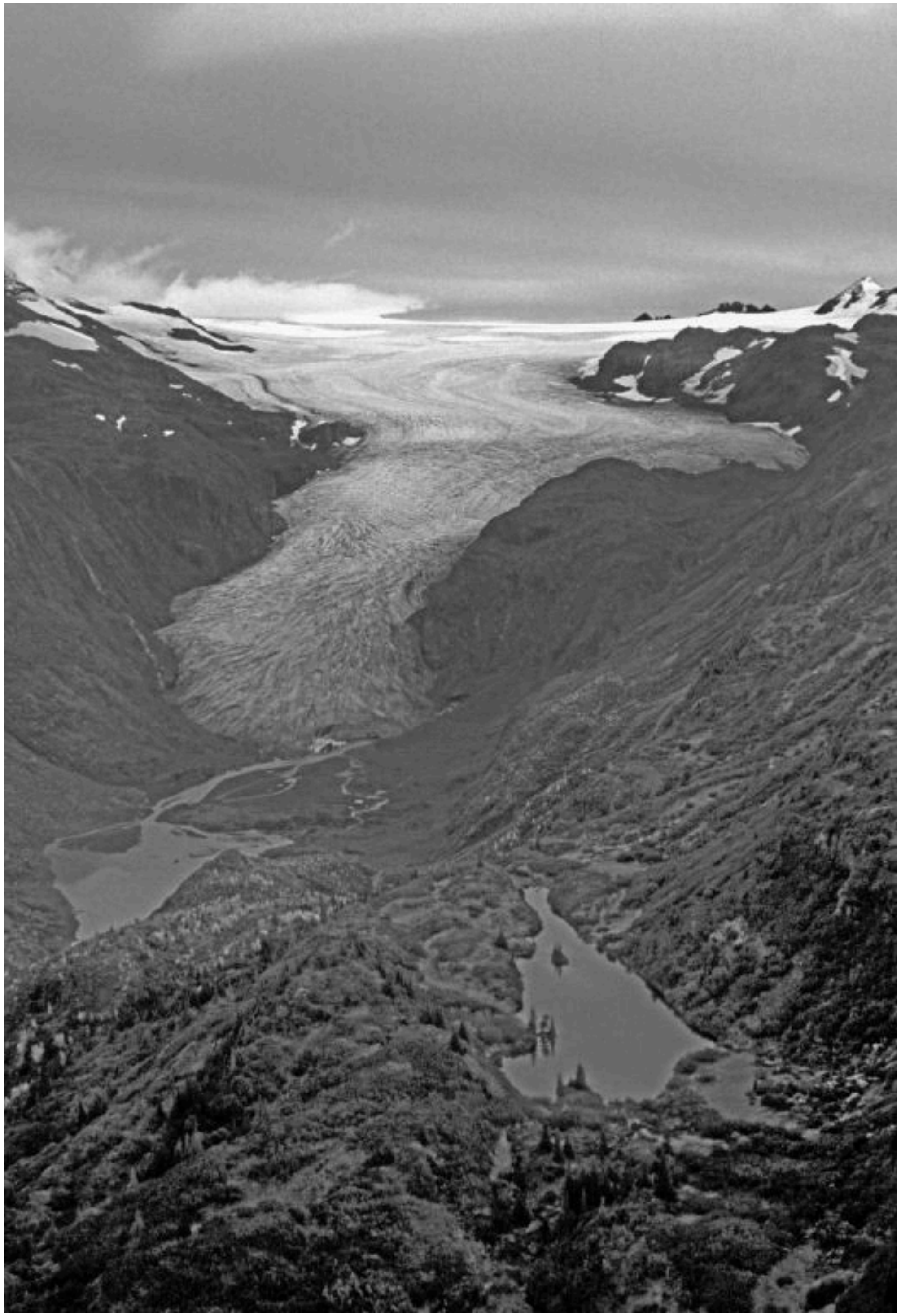
- The Greenland ice sheet is also melting faster.
- For an ice sheet (or glacier) to grow, the gain from snowfall must exceed the loss from melt, calving, and sublimation.
- On Greenland, the regions where the ice is melting more than it's accumulating have gotten bigger.
- Some melt may make calving happen faster and also increase the speed at which the ice flows toward the sea.





Antarctic Melting

- Antarctica has experienced relatively small warming to this point
  - Strong jet stream has kept warmer air out of high latitudes
  - Also ocean nearby has taken up heat
  - No sea ice decrease has happened in Antarctica either. (Although nearly all Antarctic sea ice melts each summer anyway)
- Antarctica has the most land ice (61 meters of potential sea level rise)
  - But East Antarctica (the big part) is thought to be safe
  - West Antarctica is potentially dangerous: 5 m of sea level rise



Mountain Glaciers

Presently **melting mountain glaciers** are contributing more to sea level rise (almost 30%) than Greenland and Antarctica **combined**.

This probably won't be the case in 50 years (the ice sheets are so much bigger...)

Sea Level Rise

- These **contribute** to sea level rise:
  - **Thermal expansion** of sea water
  - **Mountain glaciers**
  - **Ice sheets** (Greenland and Antarctica)
- These **don’t contribute** to sea level rise:
  - **Sea ice**
  - **Ice shelves** (these are connected to ice sheets but floating on ocean)
- Contribute only a **tiny amount**:
  - **Permafrost**
  - **Snow cover**
- IPCC projects 200-500 mm sea level rise by 2100.
- Studies that account for dynamic thinning estimate at least 0.5 m.

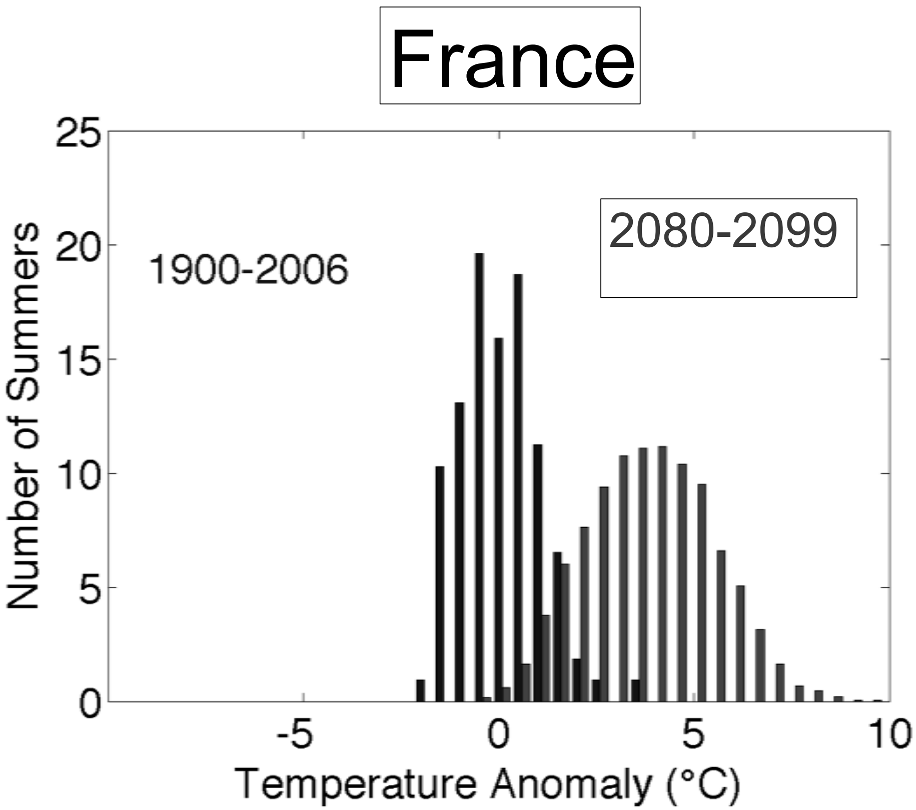
Tropical Cyclones

- Data seems to show an increase in strength globally
  - However, some argue that data quality is not good enough to make the case
  - Rare events need long data records; until 1970s the only hurricane observations were from land.
- Models suggest the strongest storms will become more frequent and stronger, but we'll also see a reduction in the total number of storms
- Should be much scientific progress in this field over the next decade, as model resolution increases and we get more data

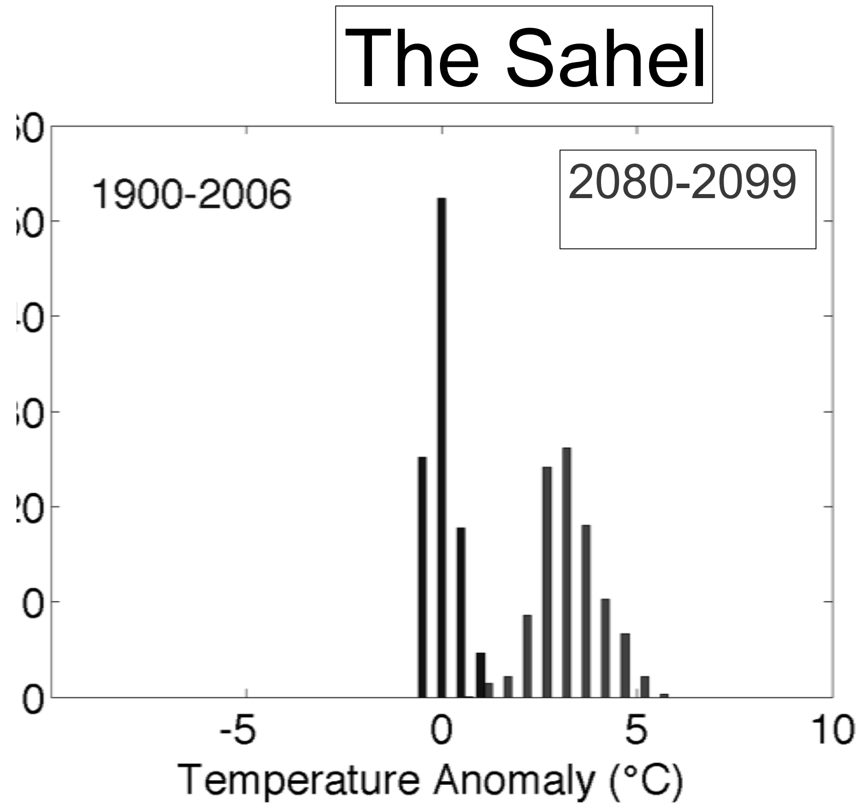
Global Warming Impacts on Agriculture

- Benefits:
  - Increased CO_2 could give some crops a boost, if there's enough nitrogen in the soil.
  - Longer growing season will likely help northern countries the most and is expected to increase production of cereals in North America and the former Soviet Union.
- Drawbacks
  - Droughts/floods in subtropics and tropics, where most food is grown, will likely reduce output.
  - Increased temperatures at least as harmful as changes in precipitation.

Projections of Growing Season Temperature



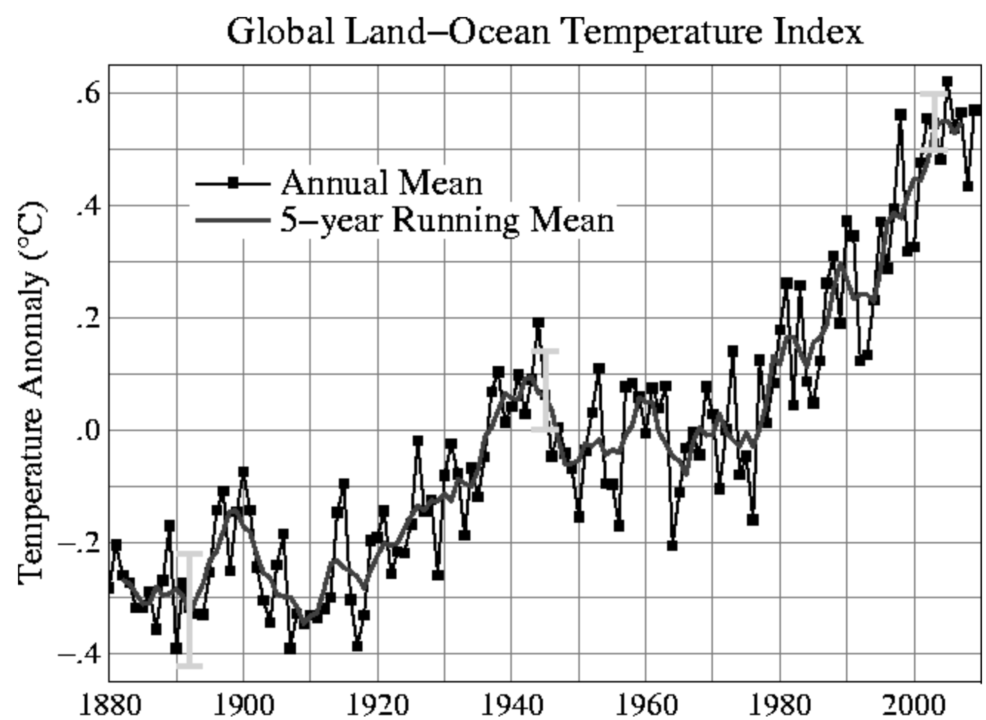
Extremes like 2003 are the norm



Every year exceeds extremes of past (mainly due to smaller variability)

Temperature Records

- Surface temperature is recorded at thousands of weather stations and on ships around the world.
- Climate data centers, run by NASA, NOAA, and the University of East Anglia in England, compile this data, attempt to account for errors, and compute the global average (accounting for differences in coverage).
- NASA surface record →

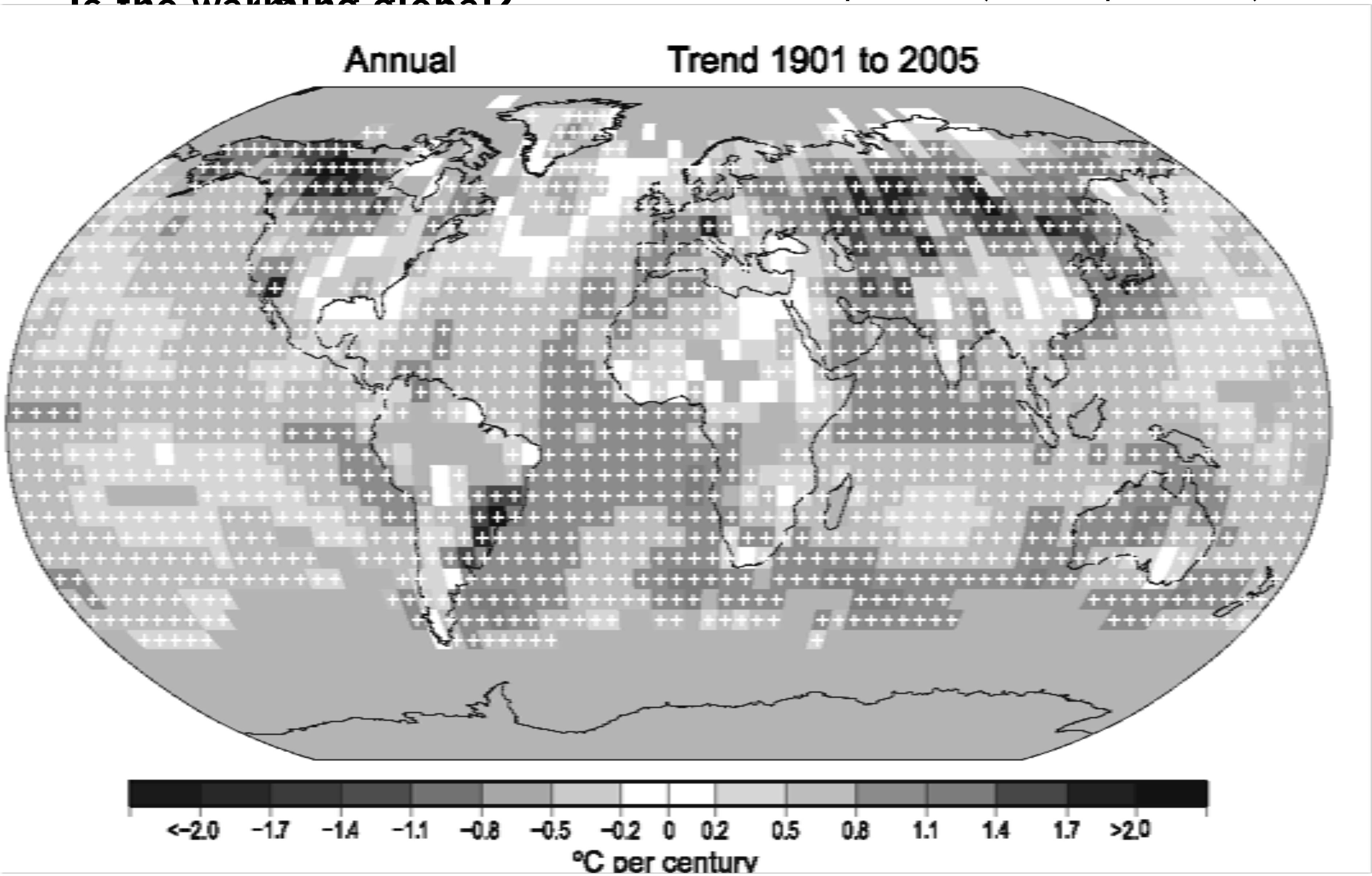


Temperature Records

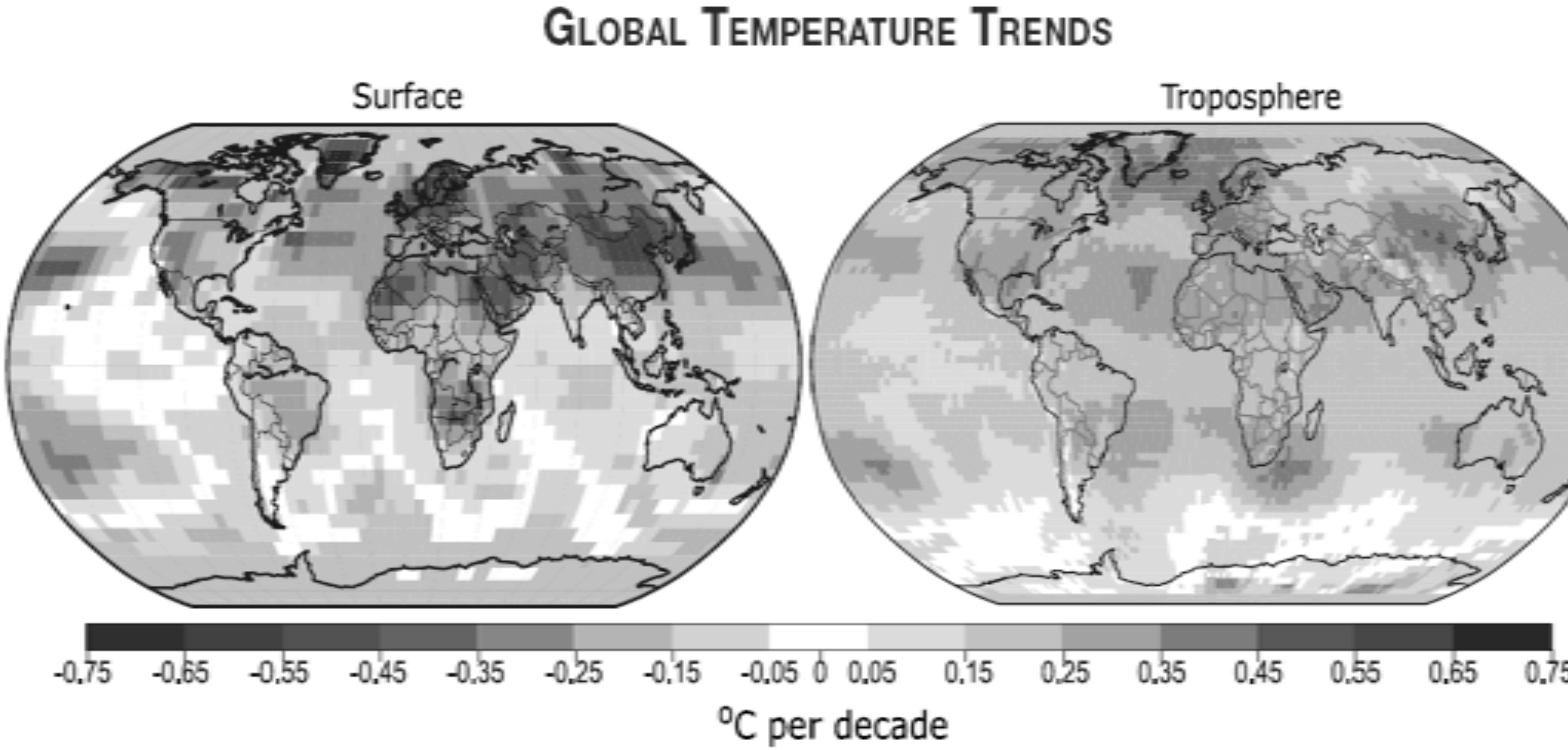
- Adjustments for errors and inconsistencies in weather records can be complicated and imperfect.
- However, three different groups, using different methods, give similar global mean surface temperature trends over the 20th Century.
- Some errors, such as the one leading to spurious cooling after WWII, have only recently been caught.
- In this case, the culprit was a shift from sea surface temperature records with a warm bias to those with a cold bias after 1945.

Temperature Record: the warming is global

Yes, although enhanced over land at poles (as expected)

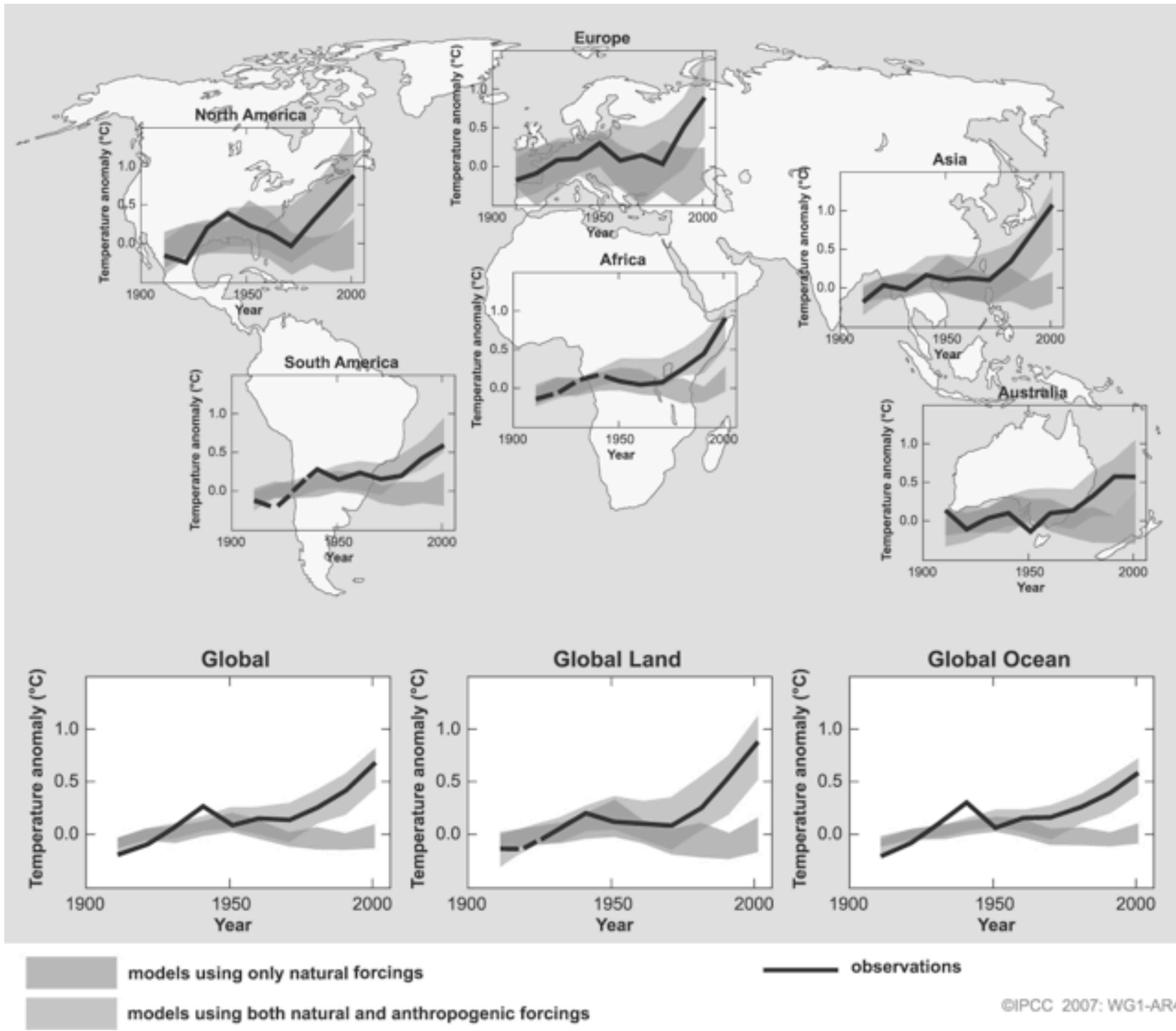


Warming extends above the surface



IPCC, 2007, WG I, Fig TS.6: Patterns of linear warming trends over the period 1979-2005 for the surface (left, from thermometers) and lower atmosphere (right, from satellite).

- Warming seen over all land and ocean regions
  - More in higher latitudes than in tropics; more over land than water



IPCC Fig SPM4

Evidence for Global Warming

- Records of global surface, ocean, and atmospheric temperature all show near-universal warming in the 20th Century. Only a few isolated parts of the world have shown cooling.

- Combined with other indicators – sea level rise, glacier melt, etc – this evidence for global warming is *unequivocal*.

- CO_2 and other greenhouse gases are the only cause that can explain the magnitude of the warming that we've seen so far. Models that only have natural forcings cannot reproduce the climate of the 20th century.