Climate Physics

David W. Carpenter 2012

Climate Physics Learning Objectives

1. What is the difference between weather and climate?
2. What are the main astronomical influences on climate change?
3. How does the greenhouse mechanism work?
4. What is a forcing mechanism?
5. What is a feedback mechanism?
6. What are the ocean's roles in climate?
7. How and why do ocean currents affect climate?
8. Why does CO_2 absorb a large portion of the radiation Earth emits, but very little of the sunlight that Earth receives?
9. How does the presence of larger amounts of CO_2 in the atmosphere change the equilibrium temperature of the atmosphere?
10. How are climate models validated?
11. What are methane hydrates, and why are they potentially dangerous?
12. How do humans affect the climate, and how much?
13. Could small changes in climate be hazardous?
14. What would a destabilized climate be like and what mechanisms would most likely cause a destabilized climate?

"To understand and predict the climate, we must draw from a wide range of disciplines in Physics. The following list, although far from exhaustive, contains the most obvious of these:

- The processes in the Sun that produce its electromagnetic spectrum;
- the interactions between solar photons and atmospheric molecules;
- the effect of solar radiation on atmospheric composition (photochemistry);
- the thermodynamics of the atmosphere;
- the fluid dynamics of the atmosphere and ocean;
- radiative transfer in the atmosphere;
- cloud physics;
- geophysicial measurements, including remote sensing observations from satellites;
- numerical climate modeling, including predictive coupled models of ocean and atmosphere."

Taylor, F.W., "Elementary Climate Physics." Oxford Univ. Press, 2005. p.1

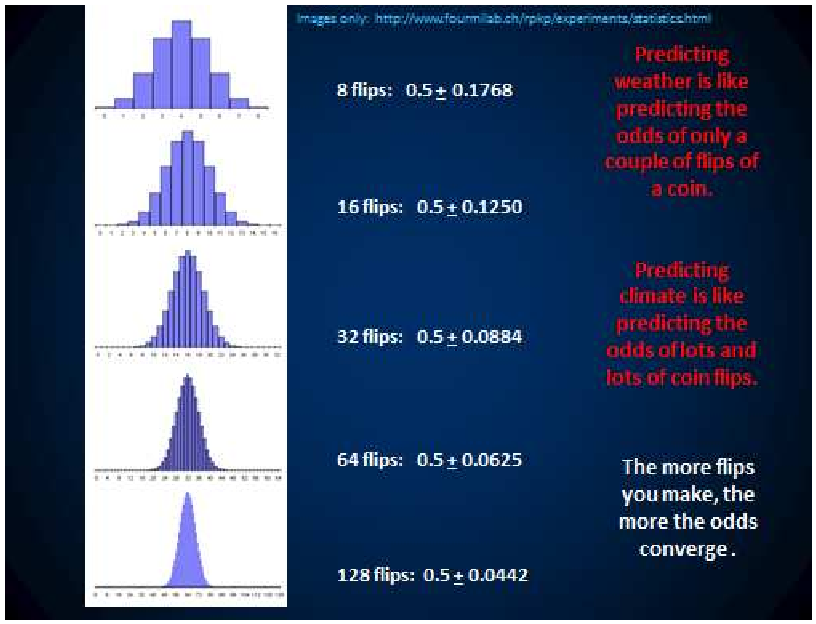
Weather vs. Climate

- Weather is harder to predict than climate because the variability in weather is huge compared to the variability in climate.

- **Weather** is the state of the atmosphere at a certain place at a certain time.

- **Climate** is a long–term average of the weather, usually over a larger region, if not the entire planet.

- A change of one degree is hardly anything for weather. The temperature can change by 50° F in a single day. But the change in the average temperature for a year changes by only fractions of a degree from year to year. For climate, a change of one degree is **huge**.
- This is similar to what happens when you flip a coin. The expectation when you flip a coin is that it will come up heads 50% of the time, but the odds of getting, say 80% heads, with 10 flips is still relatively large. The odds of getting 80% heads in one thousand flips, however, is hardly distinguishable from zero.
- The variance in an average of a large number of values is always far less than the variations in the values themselves. This makes the averages much easier to predict, and changes in the averages much more significant. Thus climate can actually be easier to model and predict than the weather.



- The effect is also illustrated by the variations in the amount of sunlight that reaches the solar panels on a house. The amount of power and energy produced by these solar panels is proportional to the solar energy that shines upon them.

- The amount of energy produced per day by these panels on each April 6 for the first four years in operation was 18.0 kWh +/- 48%.

- The amount of energy produced per year for the first four years was 5.88 MWh $^{+}$/- 1.8 %.
- The long term variation was much smaller than the short term variation, making it far more predictable.
- Just as with climate, it is also far more significant when there are changes of only a percent or two in the long term variation.

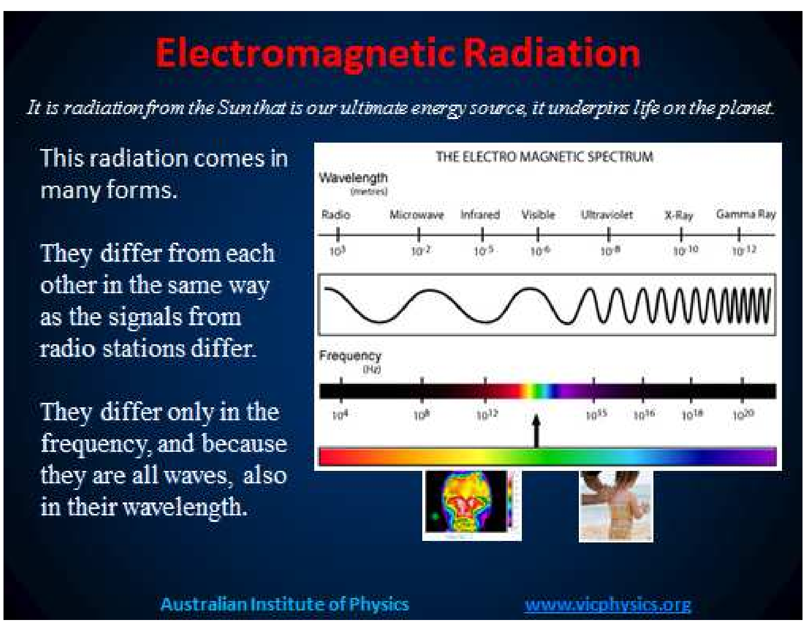
3 Types of Heat Transfer Review

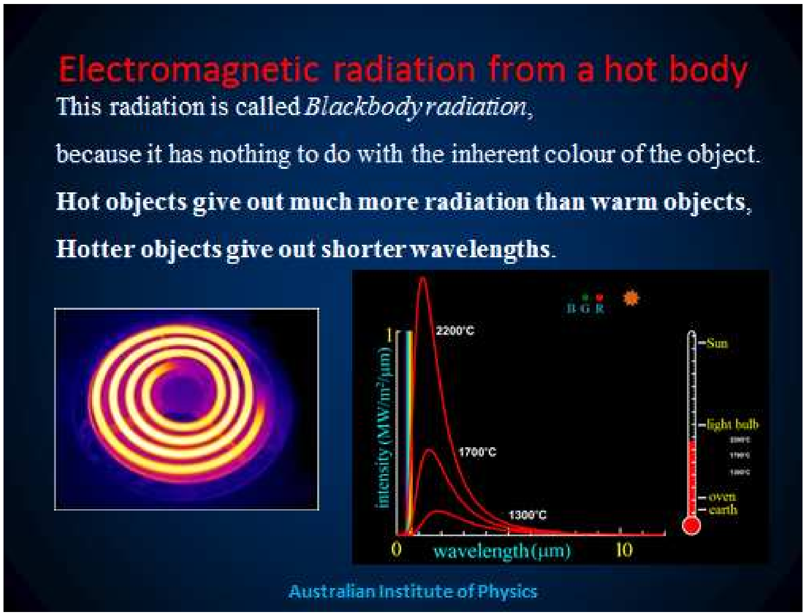
- **Conduction:** Transfer of molecular kinetic energy by collisions between molecules in contact with each other.
- **Convection:** Thermal energy is transferred by fluid of one temperature displacing a fluid with a different temperature. [Winds are driven by convection.]
- **Radiation:** Thermal energy is emitted or absorbed as electromagnetic radiation.

Natural Convection

- Occurs when a fluid (such as air or water) is heated from the bottom.
- Gravity pulls down the cooler, denser fluid on top, creating a buoyant force that displaces the warmer fluid at the bottom, causing the warm fluid to rise.
- This process causes air circulation in the atmosphere, and a modified version (with salinity instead of bottom heating changing the density) causes ocean circulation.

Electromagnetic Radiation

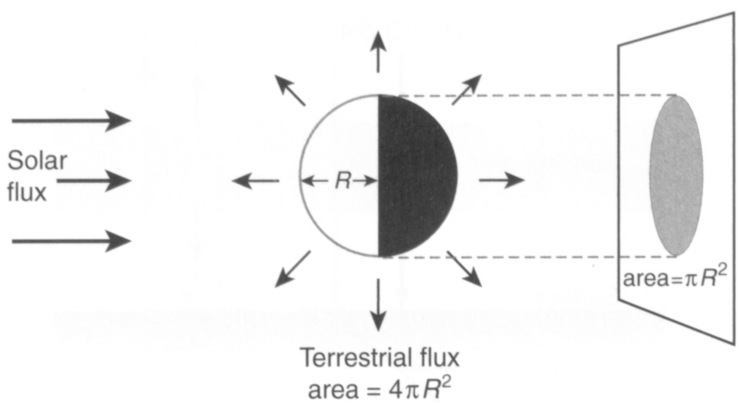




Solar Radiation

The sun may be powered by nuclear fusion, but at the surface it emits light (electro-magnetic radiation) simply because it is hot, like any other object would at 5800 K.

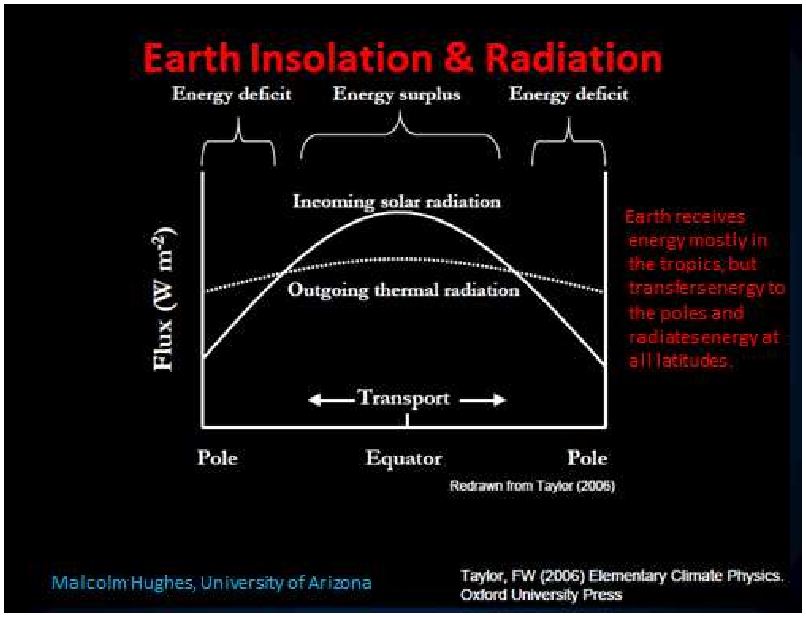
This light spreads out with increasing distance, decreasing in intensity by the inverse-square law. By the time this light reaches the distance to the Earth, 1360 watts per square meter of radiation can reach the Earth.



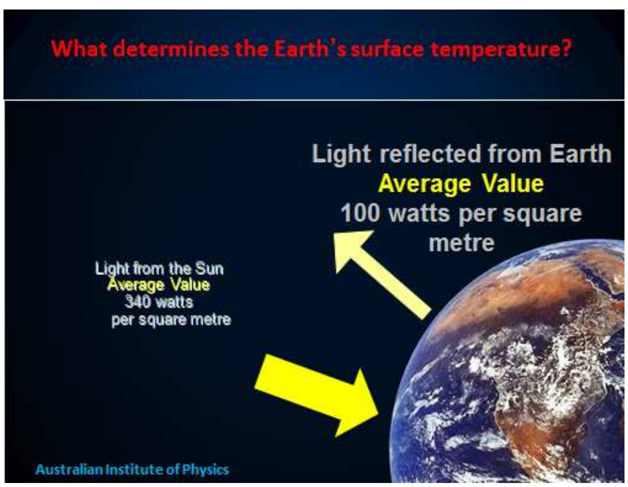
Taylor, F.W., "Elementary Climate Physics." Oxford Univ. Press, 2005.

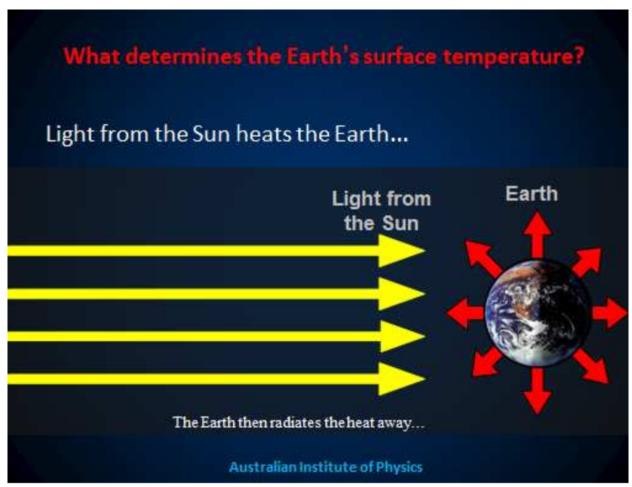
- The sunlight intercepted by a planet is proportional to πr^2, the area of a circle.
- The energy radiated from a rotating planet is from the entire surface area of the sphere, equal to $4\pi r^2$.
- To balance the input radiation with the output radiation, it is necessary to divide the input energy by 4, to get an equivalent input energy per area over the entire planet.

Thus the effective energy input averaged over the entire surface of the Earth is 340 watts per square meter. The input energy is concentrated at the tropics on the sunward side of Earth. But the output radiation is spread out more evenly across the entire surface of the planet.



Of the 340 watts per square meter that reach Earth, 100 watts per meter are reflected away by the surface and by clouds. Thus the amount of energy that actually heats the Earth averages to 240 watts per square meter.





Energy Balance without the Greenhouse Effect

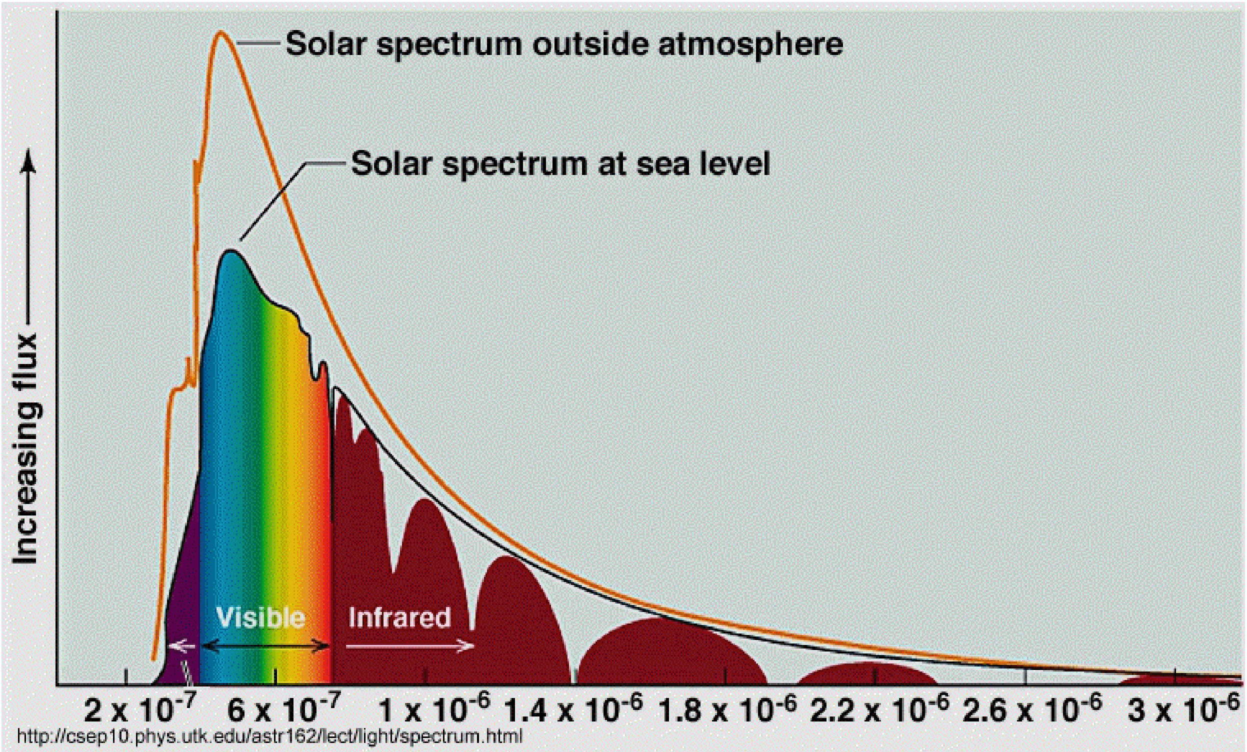
"What determines the Earth's surface temperature?

Light from the Sun heats the Earth, then the Earth radiates the heat away. The Earth's average temperature is stable when there is a balance between heat input from the Sun and heat lost from the Earth by radiation. The average input value is 240 watts per square meter. The average output value is also 240 watts per square meter.

How hot must the Earth be to radiate 240 W/m^2? To radiate 240 watts per square meter, the Earth would be -18^{o}C. But Earth's actual average surface temperature is 15^{o}C. The 33^{o} difference is due to the atmosphere and the resulting greenhouse effect.

A planet's atmosphere absorbs more light at some frequencies than it does at others, based on the composition of the atmosphere. Nitrogen (N_2), oxygen (O_2) & argon (Ar) comprise more than 99% of the atmosphere. These molecules have **one** or **two** atoms. They block some **ultra-violet** light, but allow **infra-red** and **visible** radiation through.

With an atmosphere of Nitrogen Oxygen & Argon, what would the surface temperature be? **-18^{o}C** (255K)**!**
The narrow absorption lines of these gases hardly affect the absorption and emission of solar or terrestrial ("Earth light") radiation at all. So 99% of the atmosphere makes almost no contribution to the greenhouse effect.



Energy Balance with Natural Greenhouse Effect

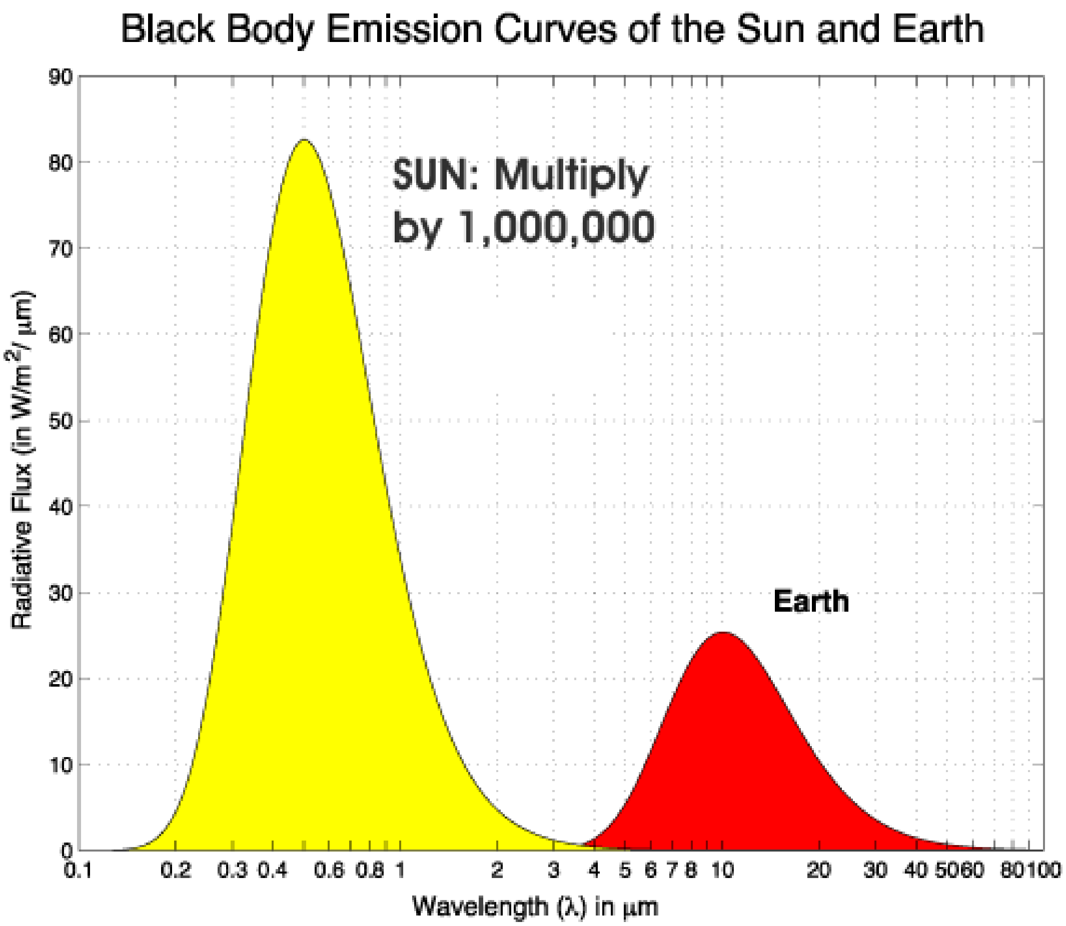
How does a Greenhouse Work?

- Sunlight passes through the glass to heat the ground. The ground heats up and emits infrared "earthlight" (terrestrial radiation, with the spectral wavelength distribution of a black object near 300K).
- Glass is transparent to sunlight (visible light), but opaque to earthlight (infrared light).
- The glass, which is opaque to earthlight, absorbs this energy and heats up. It re-radiates energy upward out of the greenhouse and also downward into the greenhouse.
- The energy radiated back into the greenhouse is also absorbed by the ground, which heats up further (while also heating the air inside the greenhouse).
- The greenhouse gets hotter and hotter until the amount of radiation (which increases with temperature) emitted outward from the glass is exactly equal to the amount of sunlight coming into the greenhouse.
- This occurs at a much higher temperature than the outside temperature, as much as 180^o F inside of parked car on a summer day.
- For the atmospheric greenhouse effect, greenhouse gases (such as water vapor, carbon dioxide, methane, nitrous oxide and ozone) take the place of the glass, raising Earth's natural average temperature by 33 K.

Radiation

The Earth also emits radiation, but the Earth is much cooler and dimmer.

The earth radiates in the longer wavelengths of *infrared*, and with much less intensity.



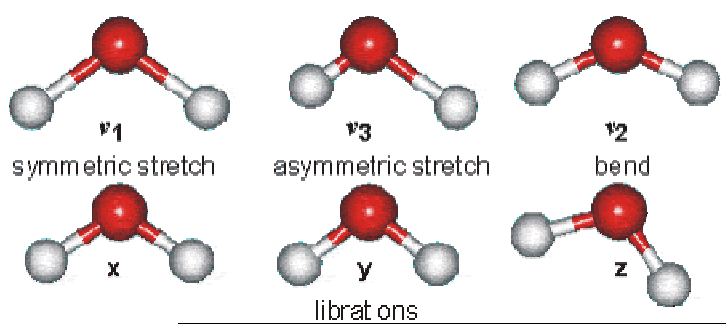
Images: Australian Institute of Physics

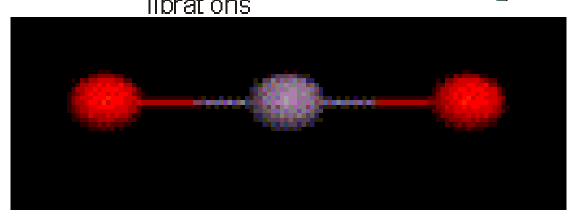
[95% of] "Greenhouse warming is caused by

water (H_2O) and carbon dioxide (CO_2)

What is special about H_2O and CO_2?

- Their molecules have **three** atoms,
- Their **natural frequencies** of vibration are in the **infra-red,**
- They are the earth's blanket for reflecting [*and remitting*] certain **infra-red** frequencies back down to earth.
- Their molecules vibrate or jiggle in a variety of ways.
- So, many infrared frequencies can make them move.
- All these frequencies are absorbed."





Source: Australian Institute of Physics

Atomic & Molecular Absorption of Light

Atoms and diatomic molecules absorb and remove only very narrow regions of the solar spectrum.

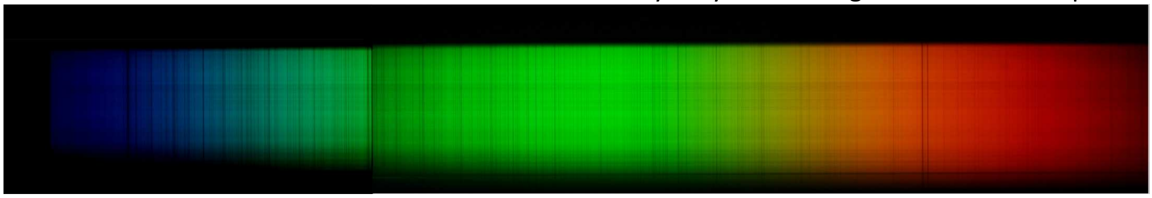


Image: bu.edu

More complex molecules absorb wide bands of the solar spectrum.

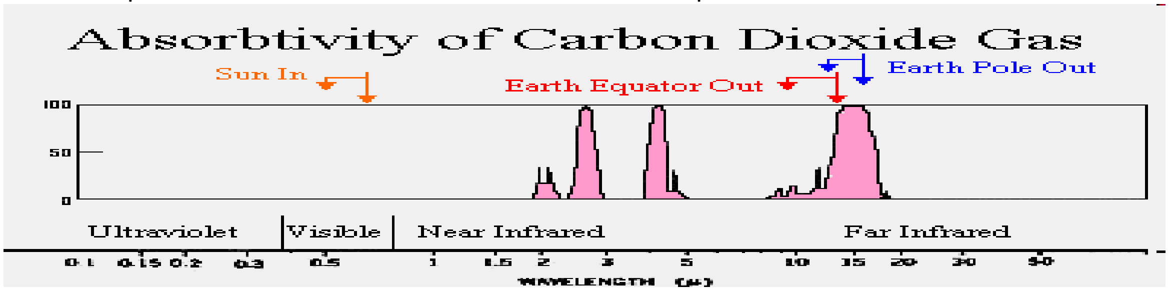


Image: mb-soft.com

For Earth's temperature to be in equilibrium, the amount of energy absorbed by the planet (orange) must equal the amount of energy radiated by the Earth (red). In this diagram, equal energy can be visualized as equal area.

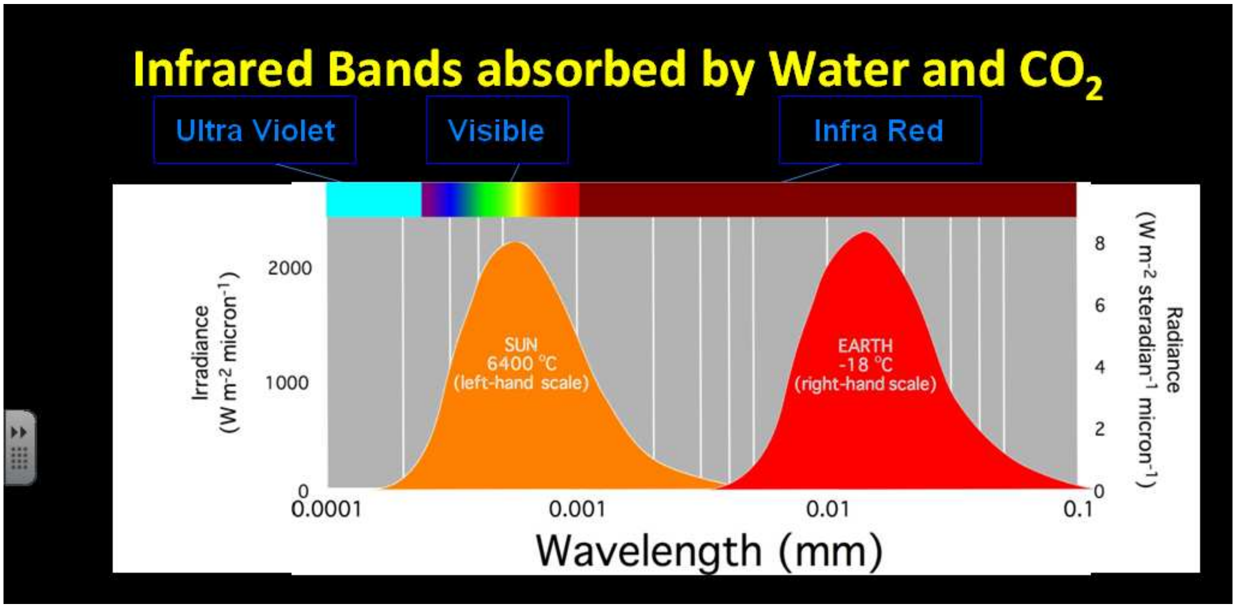


Image: AIP

The absorption bands of water (each absorption band represents a mode of vibration of the water molecule) reduce the wavelengths at which Earth can radiate more than it affects the amount of sunlight coming in. To equalize the energy (area on the chart) radiated, the temperature has to rise so that the same amount of radiation is emitted in that narrow band of frequencies.

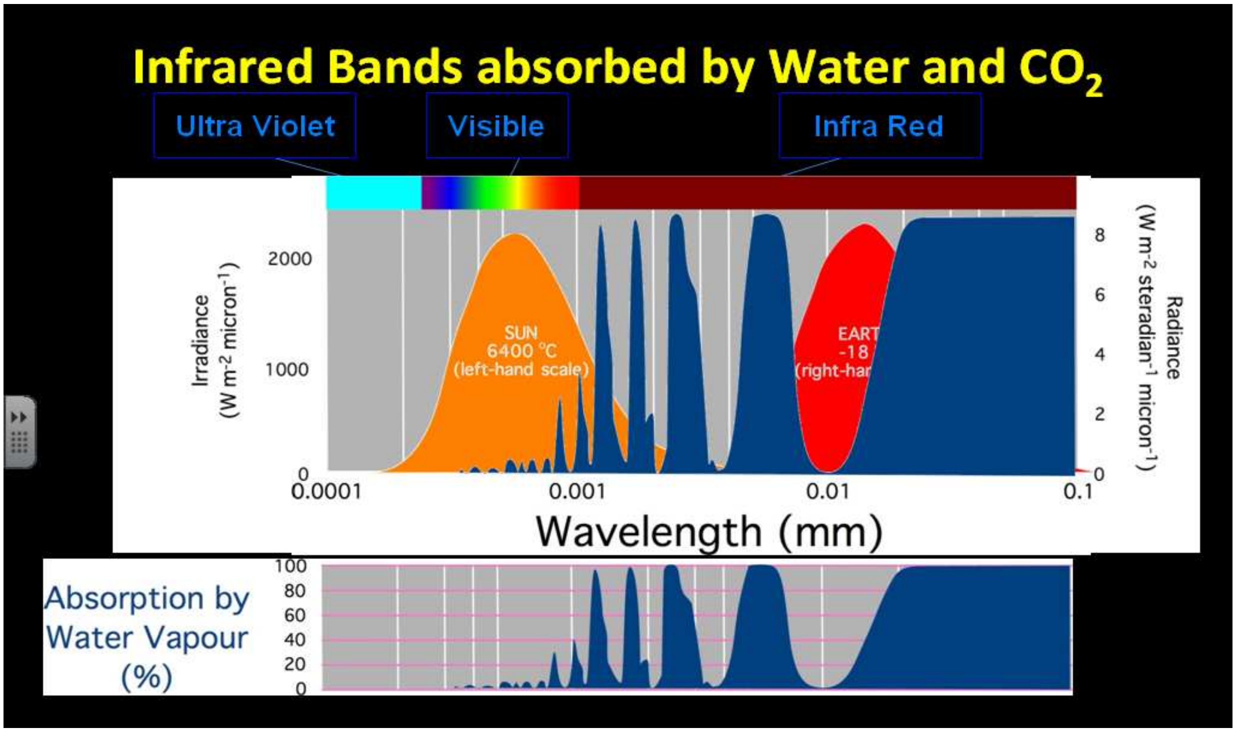


Image: AIP

The 15 micron carbon dioxide band reduces the available wavelengths for Earth to radiate even more, also forcing Earth's temperature to rise to achieve radiation balance. [Remember that the amount and frequency of radiation increases with temperature. The other CO_2 bands have little effect since they either coincide with a water band, or they are where there is almost no solar or Earth radiation.]

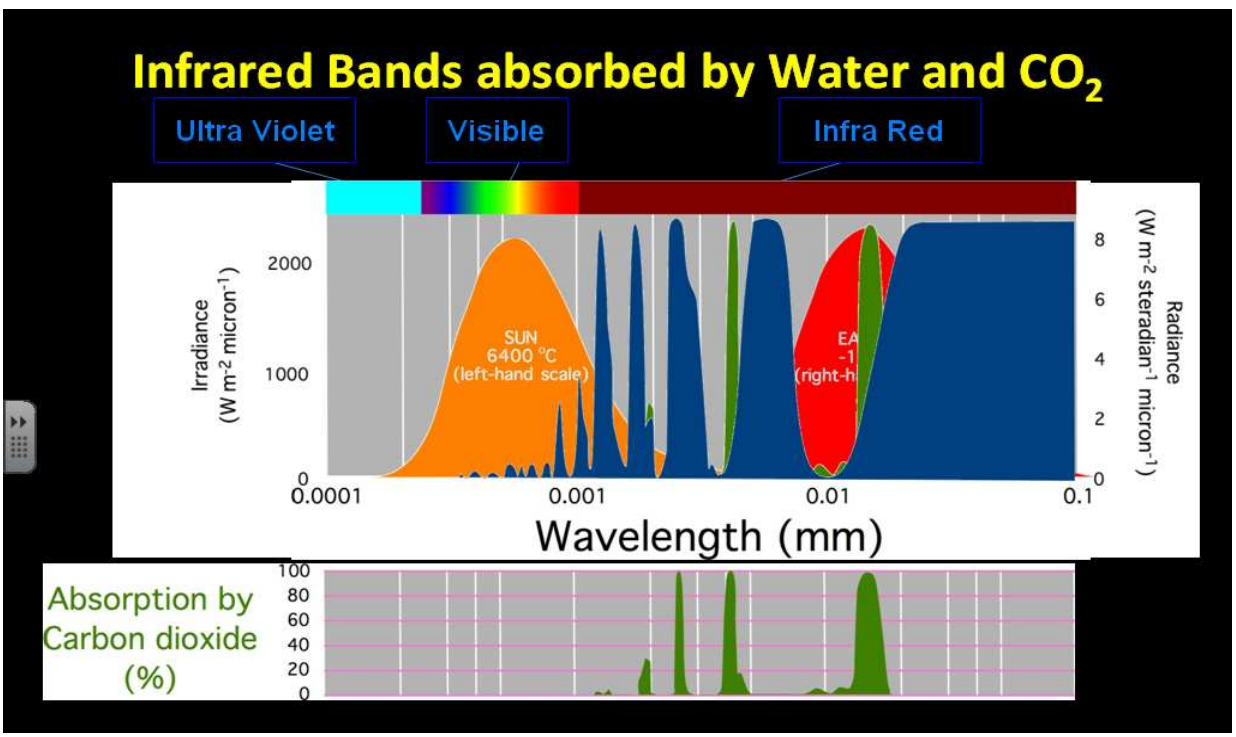
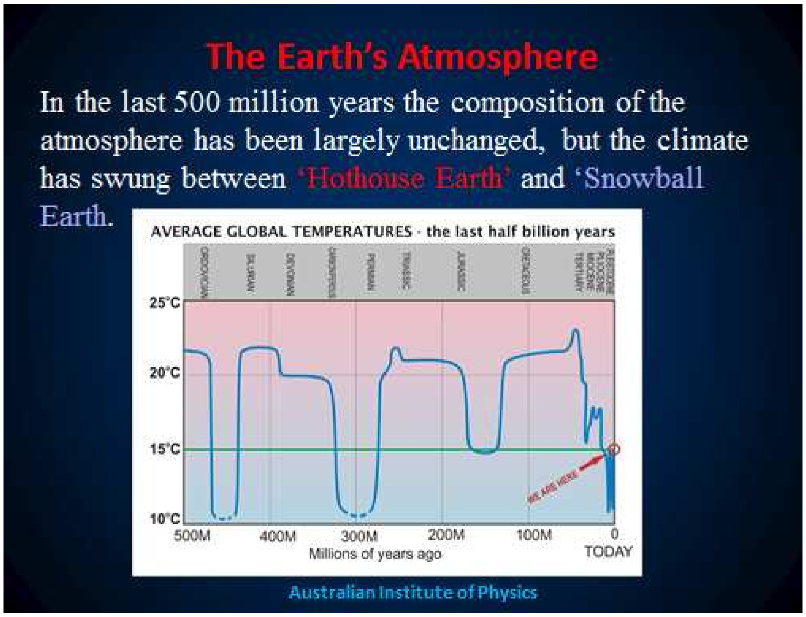


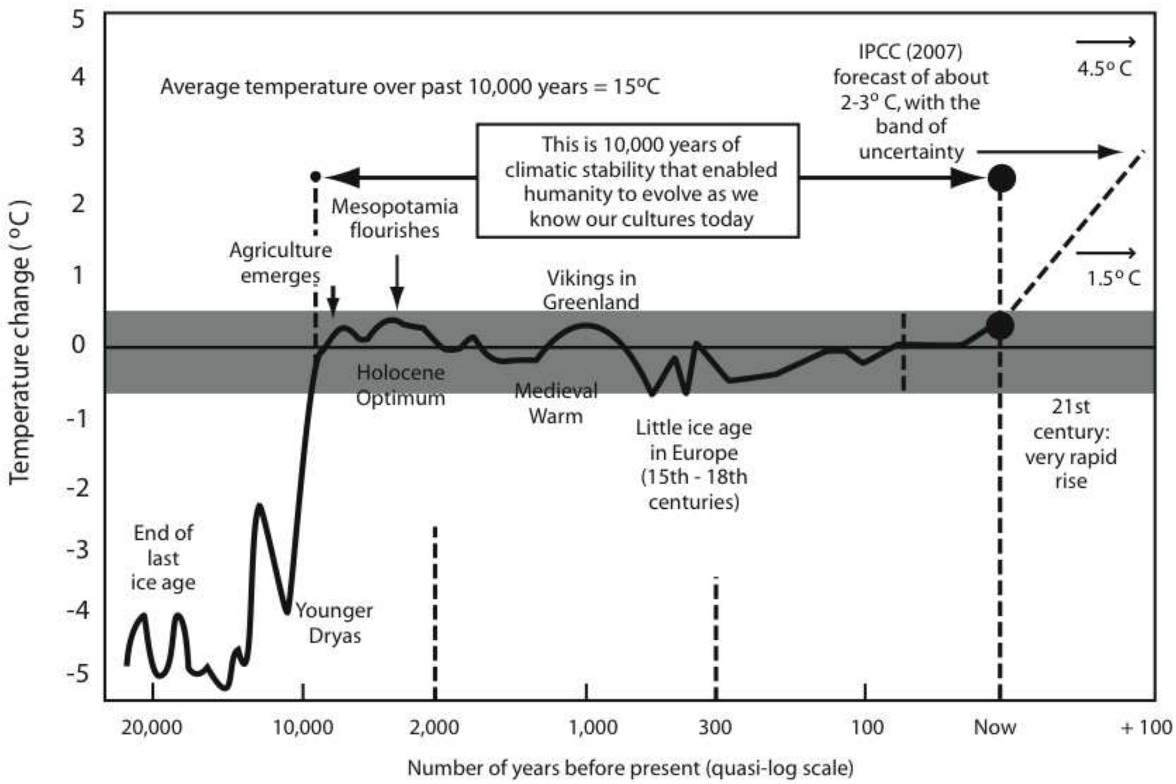
Image: AIP

Forcing Mechanisms

- **Forcing mechanisms** are processes that alter the radiation equilibrium of the planet, creating a new equilibrium temperature.
- These can be **natural** (like those associated with the changing orbit of the Earth) or **anthropogenic** (caused by humans).
- **Astronomical**: solar variability, earth tilt, precession, orbit eccentricity, cosmic rays (cloud seeding)
- **Terrestrial**:
    - Natural: volcanoes, continental drift, etc.
    - Anthropogenic: CO_2, aerosols, etc.



The Last 20,000 Years seems to have been Ideal for the Development of Human Societies. Is this a Historic "Sweet Spot" that Enabled Humans to Flourish?



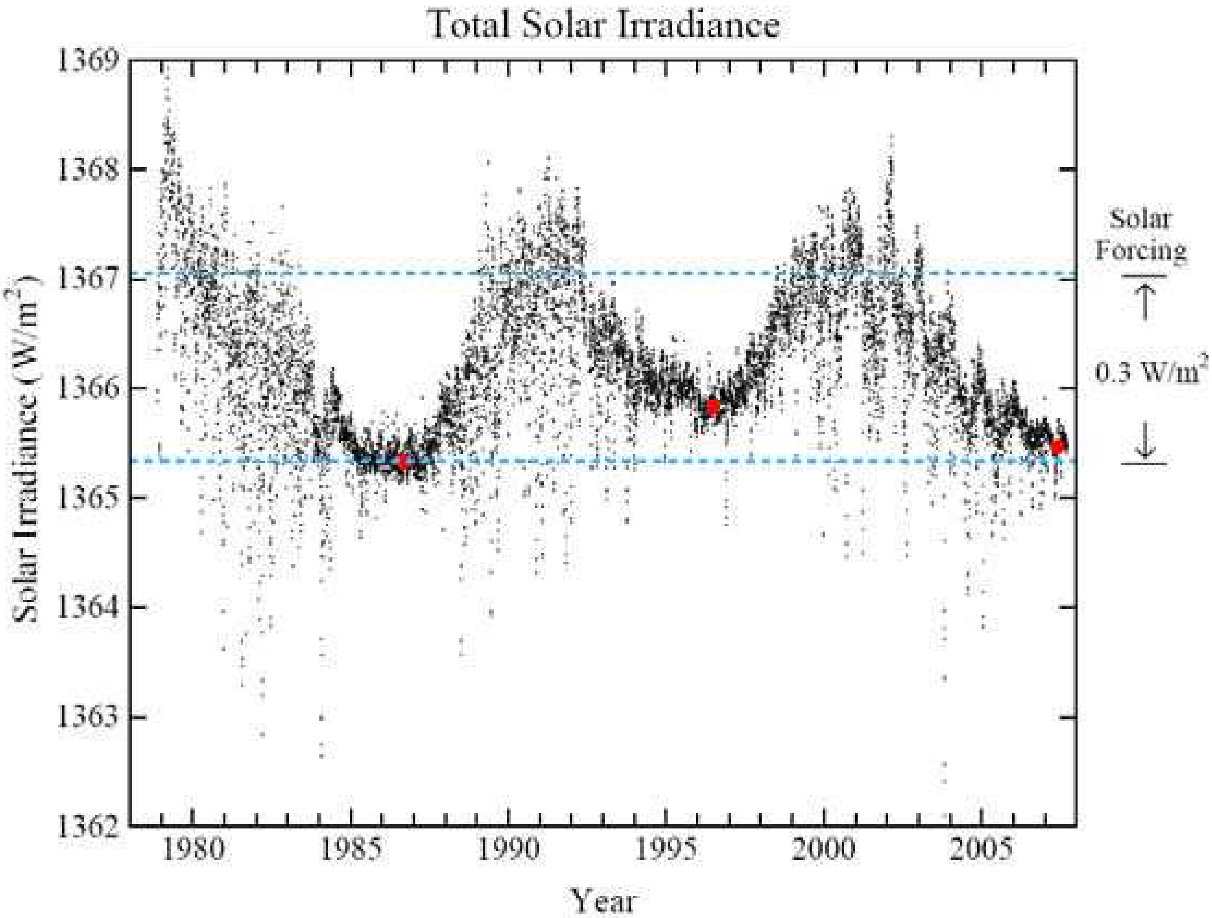
Australian Institute of Physics

The Sun-Climate Connection

- The rate at which energy from the sun reaches the top of Earth's atmosphere is denoted by the term "total solar irradiance" (or TSI). TSI fluctuates slightly from day to day and week to week. Superimposed on these rapid short-term fluctuations is a cycle related to sunspots in the outer layers of the Sun that lasts approximately every 11 years.
- The current TSI varies with season, time of day, and latitude. Yet it is thought that small changes in this relatively small amount of absorbed solar energy can make a difference to our climate.

http://www.ucsusa.org/global_warming/science_and_impacts/science/effect-of-sun-on-climate-faq.html

Solar Variability



Solar irradiance from analysis of satellite measurements by Willson and Mordvinov (Geophys. Res. Lett. 30, no. 5, 1199, 2003) and update (private communication). Hansen, J., L. Nazarenko, R. Ruedy, M. Sato, J. Willis, A. Del Genio, D. Koch, A. Lacis, K. Lo, S. Menon, T. Novakov, J. Perlwitz, G. Russell, G.A. Schmidt, and N. Tausnev. 2005. Earth's energy imbalance: Confirmation and implications. Science 308:1431-1435

Radiative Forcing (RF)

- The average solar radiative forcing since 1750 has increased by about 0.12 W/m^2. This contributes to a small fraction of the increase in global temperature since that time.
- [Placed in perspective, this is smaller than anthropogenic forcings (~1.5 W/m^2), it is also more than offset by cooling from other natural forcing mechanisms such as aerosols from an abnormally high rate of volcano eruptions.]
- There is evidence that changes in solar radiation are bigger in the ultraviolet (UV) part of the spectrum, which could affect the equilibrium amount of ozone, and in turn affect the absorption and radiation of UV radiation.
- Changes in the solar wind and magnetic field might also cause more cosmic rays to enter the atmosphere, and potentially seed cloud formation.
- Further research is ongoing for both of these issues, but the amounts of either effect on the energy balance of the atmosphere do not appear to be dominant factors.

Continental Drift

- There are three major climate effects of continental drift. None of these cause quick changes in climate; they take millions of years.
  1. Moving continents affect how much solar radiation directly hits water versus land.
  2. Moving continents affect ocean circulation patterns.
  3. Moving continents can release carbon into the atmosphere by disturbing carbon-rich sediments on the ocean floor.

Volcanoes

- Volcanoes throw aerosols (tiny particles suspended in the air) that reduce the amount of radiation that is absorbed by the Earth because they reflect more sunlight away.
- This results in a cooling effect that is relatively short-lived (months to a few years) for each eruption.

Feedback Mechanisms

- Feedback mechanisms are both caused by and effect forcing mechanisms and other feedback mechanisms.
- Some feedback mechanisms amplify and increase the effects of forcing mechanisms. These result in what is called positive feedback.
- Some feedback mechanisms reduce the effects of forcing mechanisms. These result in what is called negative feedback.

Examples of Feedback Mechanisms:

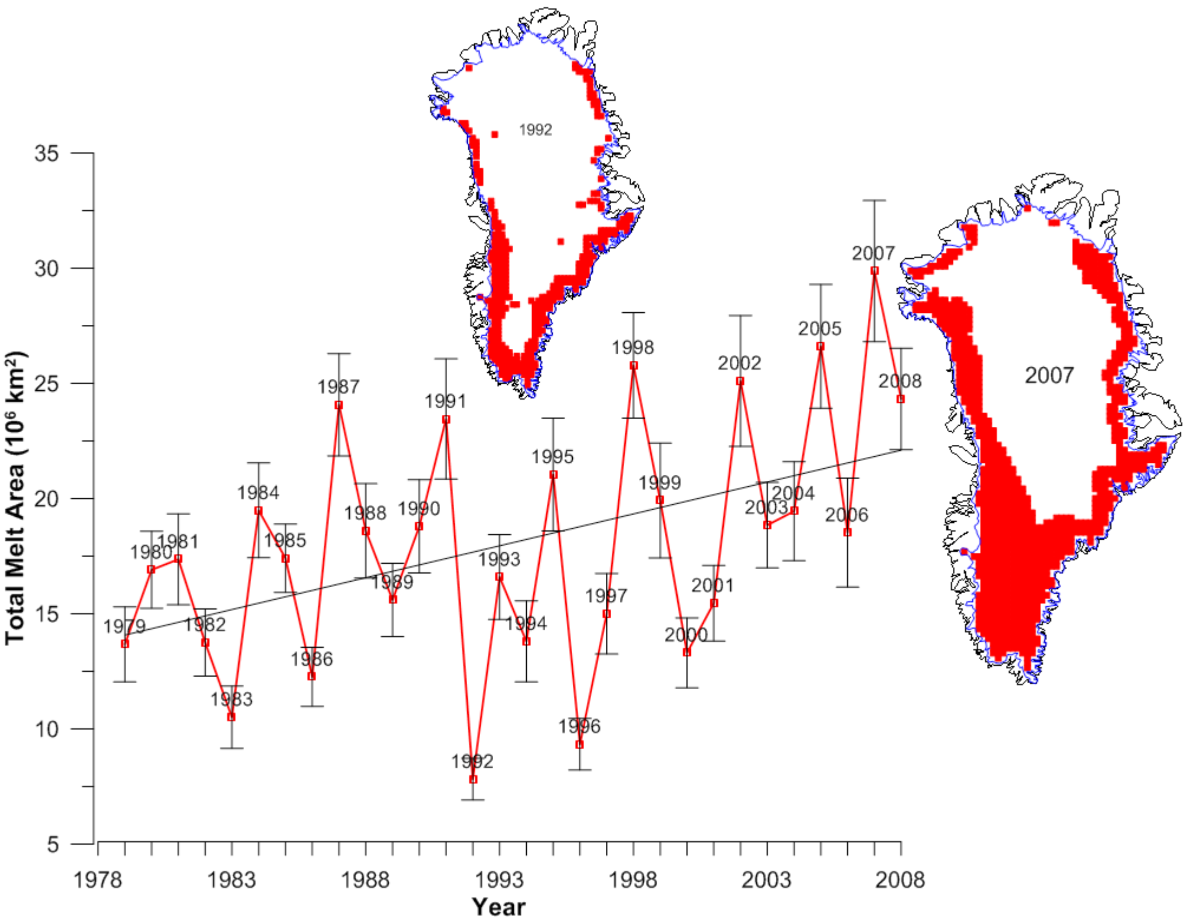
- Humidity & Cloud cover
- Ice cover
- Thermohaline cycle
- Carbon sources
- Carbon sinks
- Methane hydrates

Humidity & Cloud Cover

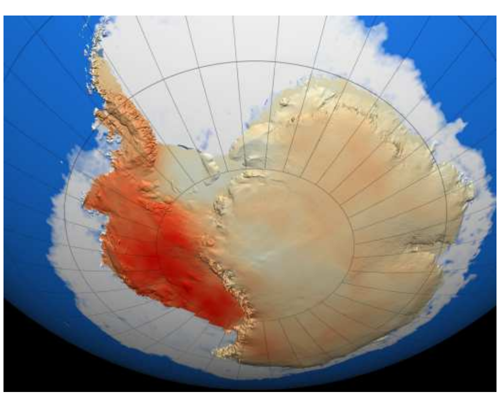
- Increased temperature causes increased evaporation, and enables the air to hold more moisture.
- In general, increased moisture causes positive feedback, by increasing the amount of terrestrial radiation that is absorbed by the atmosphere.
- Increased moisture can also cause a negative feedback, when more low-altitude clouds reflect more sunlight into space.
- At temperatures near current levels, the warming feedback due to increased absorption exceeds the cooling feedback from cloud reflection.
- The net effect of increased humidity is a slight positive (warming) feedback.
- It is a **feedback mechanism** because increased temperature increases the humidity, which increases the temperature more, etc.

Ice Cover

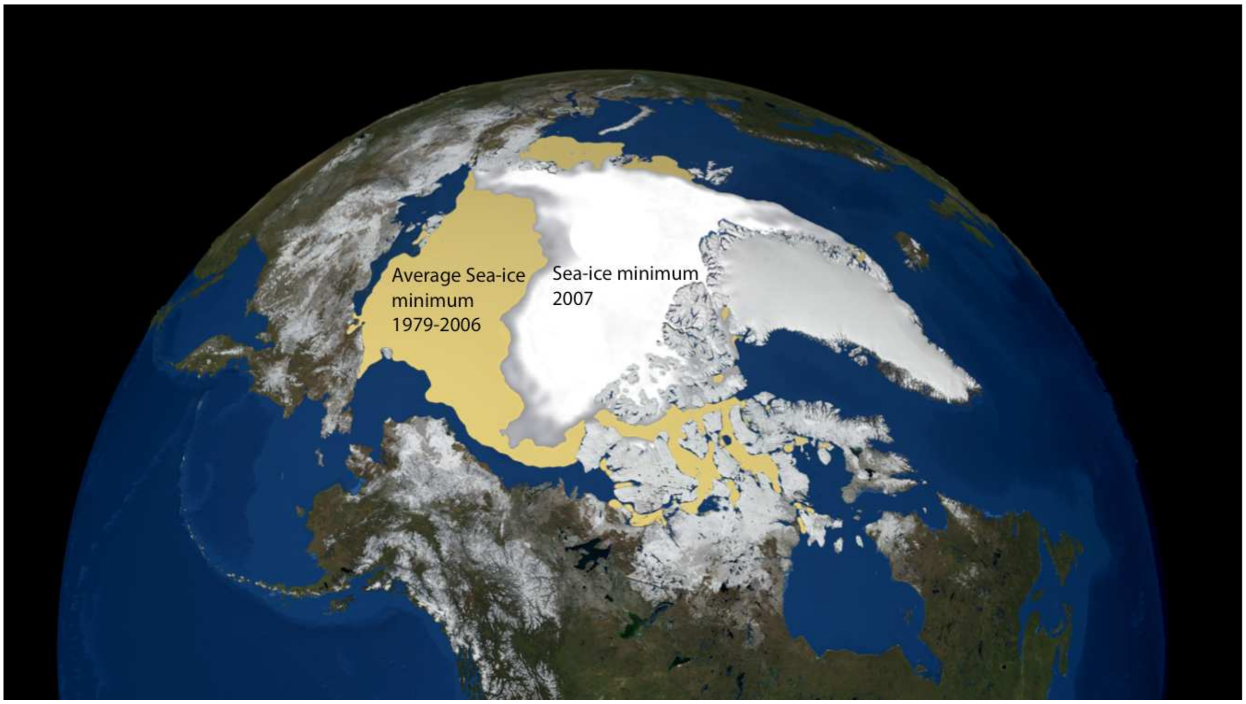
- Higher temperatures cause Arctic and Antarctic ice to melt, which decreases the amount of sunlight reflected off the ice, which increases the absorption of solar radiation at the poles. This causes positive feedback for increased temperatures.
- Melted ice has less salt in it than normal ocean water, which decreases the density of the water, which in turn reduces the subduction of polar water that powers the ocean currents.



Greenland ice-melt since 1979 Source: The Copenhagen Diagnosis



Antarctic ice-melt. Source: The Copenhagen Diagnosis

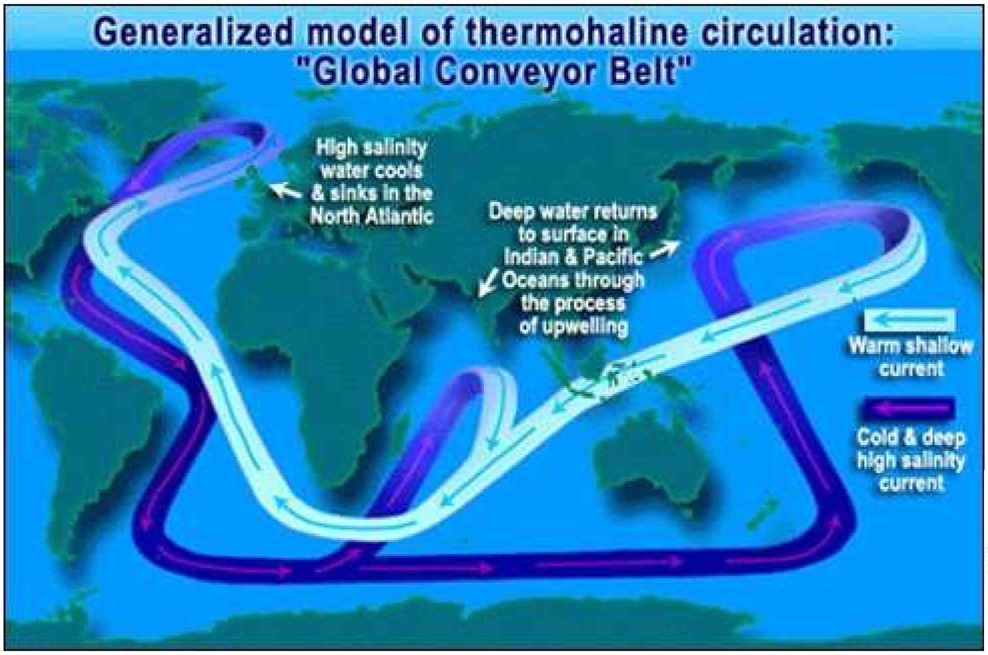


Minimum arctic sea-ice extent from 1979 to 2007. Source: The Copenhagen Diagnosis

Ocean Currents

- Shallow water currents are driven mainly by the wind.
- Deep water currents are driven by the thermohaline cycle.

Thermohaline Cycle



"Thermohaline circulation begins in the Earth's polar regions. When ocean water in these areas gets very cold, sea ice forms. The surrounding seawater gets saltier, increases in density and sinks"

- Water has a much higher specific heat than air.
- The thermohaline (heat – salinity) "conveyor belt" is the primary mechanism for transferring heat from the tropics to the poles.
- Melting polar ice is capable of slowing down or completely changing the ocean currents, which could severely alter or destabilize climate in a relatively short period of time.

http://svs.gsfc.nasa.gov/vis/a010000/a010000/a010031/a010031_H264_640x480.mp4

Atmospheric & Oceanic Heat & Mass Transport

- "While we experience the effect of the climate mainly through the atmosphere, 71% of the surface of the Earth is covered by water, including 6% of ice cover, and this represents a huge reservoir of heat, as well as moisture, which is available for exchange with the atmosphere. The large heat capacity of the ocean delays the effect of any warming trend in the lower atmosphere: only about 60% of the effect of industrial activity since 1700 is manifest in the surface temperature increases currently being recorded."
- "The atmosphere and the global ocean are coupled together dynamically, and both have global circulation patterns that have a key role in redistributing heat from the tropics to higher latitudes. Although the ocean moves less rapidly than the atmosphere, its energy storage is much larger. In fact, the top 3.2 m of the ocean has the same heat capacity as the entire atmosphere, and the total ocean heat content is about 1000 times that of the atmosphere."

Taylor, F.W., "Elementary Climate Physics." Oxford Univ. Press, 2005.

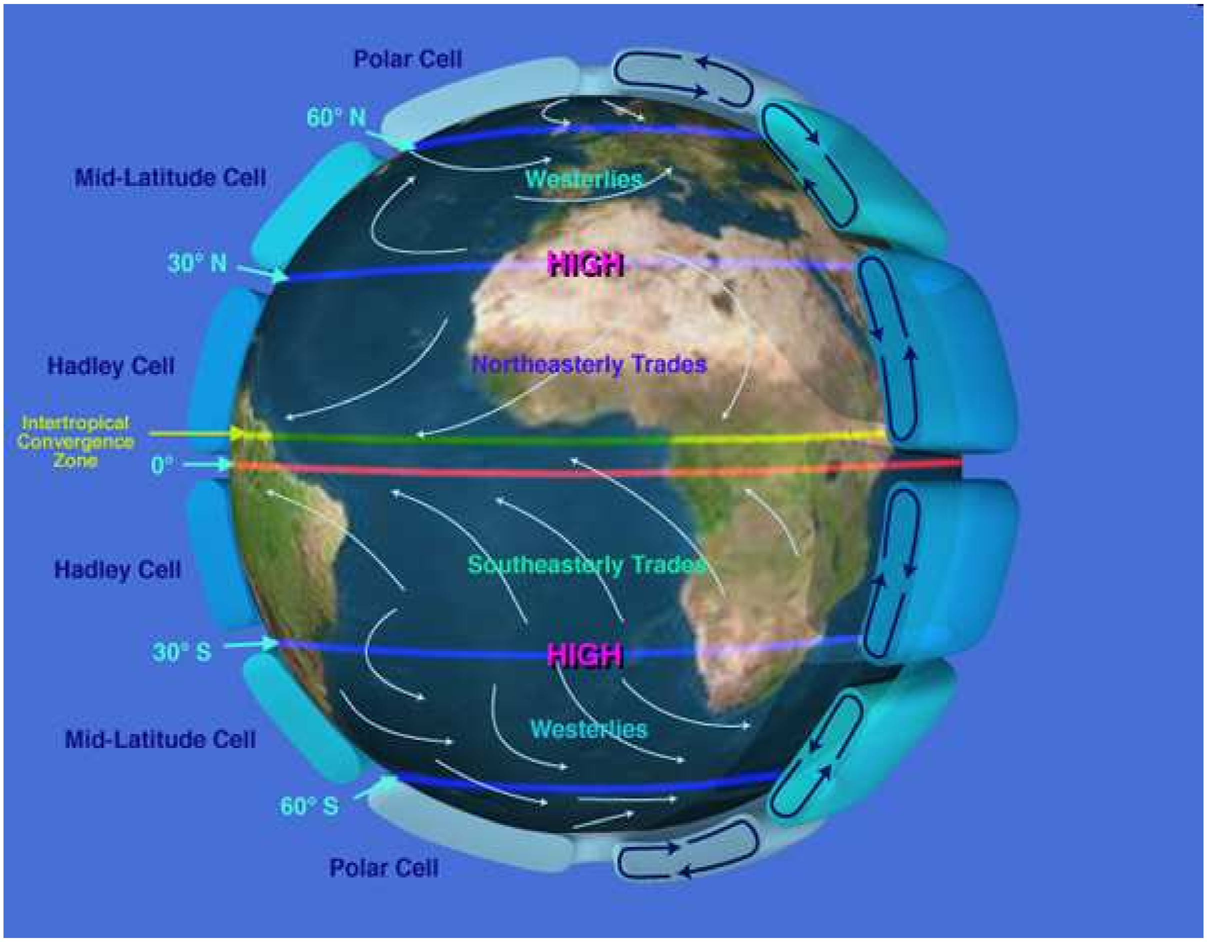


Image: NASA

Atmosphere

Heat is transferred mainly by convection in the troposphere, and mainly by radiation in the stratosphere.

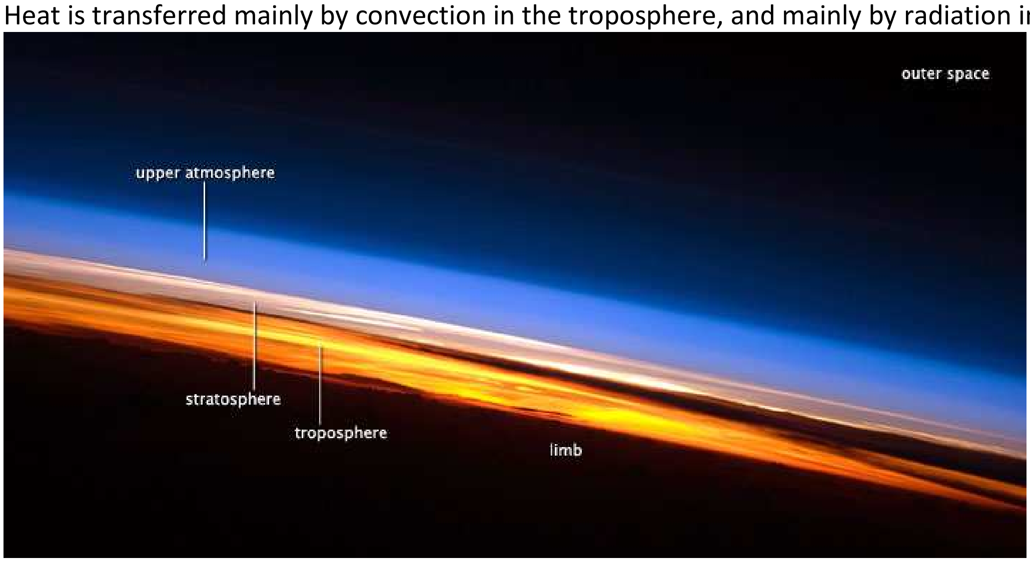
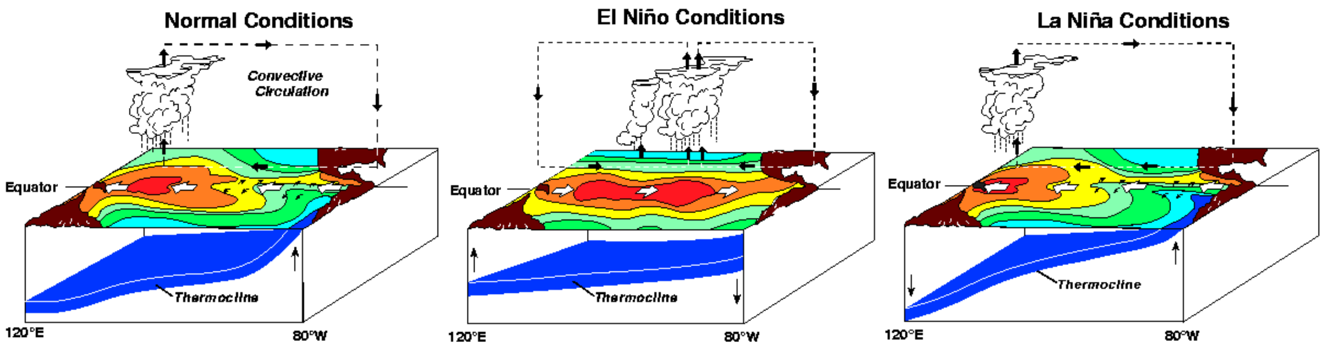


Image: NASA

Regional Oscillations (i.e., El Niño)

"…the rate of exchange of CO_2 between ocean and atmosphere in the midlatitude Pacific varies from year to year by as much as a factor of 4. The cause is apparently differences in the temperature structure and the degree of upwelling in the ocean, and the weakening of the winds in the eastern half of the Pacific during 'El Niño' events.

F.W. Taylor: Elementary Climate Physics



Images: NOAA

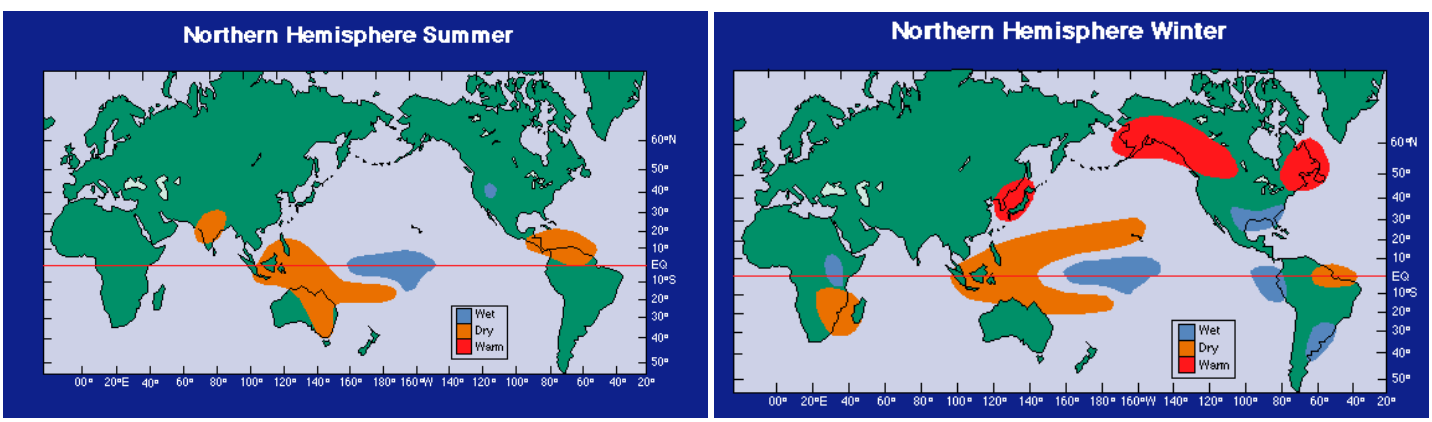
ENSO

"El Niño/La Niña-Southern Oscillation, or **ENSO**, is a quasiperiodic climate pattern that occurs across the tropical Pacific Ocean with on average five year intervals. It is characterized by variations in the temperature of the surface of the tropical eastern Pacific Ocean—warming or cooling known as *El Niño* and *La Niña* respectively—and air surface pressure in the tropical western Pacific—the *Southern Oscillation*. The two variations are coupled: the warm oceanic phase, El Niño, accompanies high air surface pressure in the western Pacific, while the cold phase, La Niña, accompanies low air surface pressure in the western Pacific." *Wikipedia*

Regional Effects

El Niño affects tropical rainfall, which causes shifting wind patterns in other parts of the globe.

Global Effects of El Niño



Images: NOAA

Aerosols

> "Aerosols are tiny particles suspended in the air, generally much smaller than the particles that make up visible clouds. Aerosols may be invisible to the eye, or at most present the appearance of a fine haze or 'turbidity,' and still be very important within the climate system, primarily as

1. Nuclei for cloud droplet formation and growth
2. Scatterers of incoming sunlight, increasing the albedo [reflectivity] of the planet,
3. Absorbers of both solar and long-wavelength radiation."

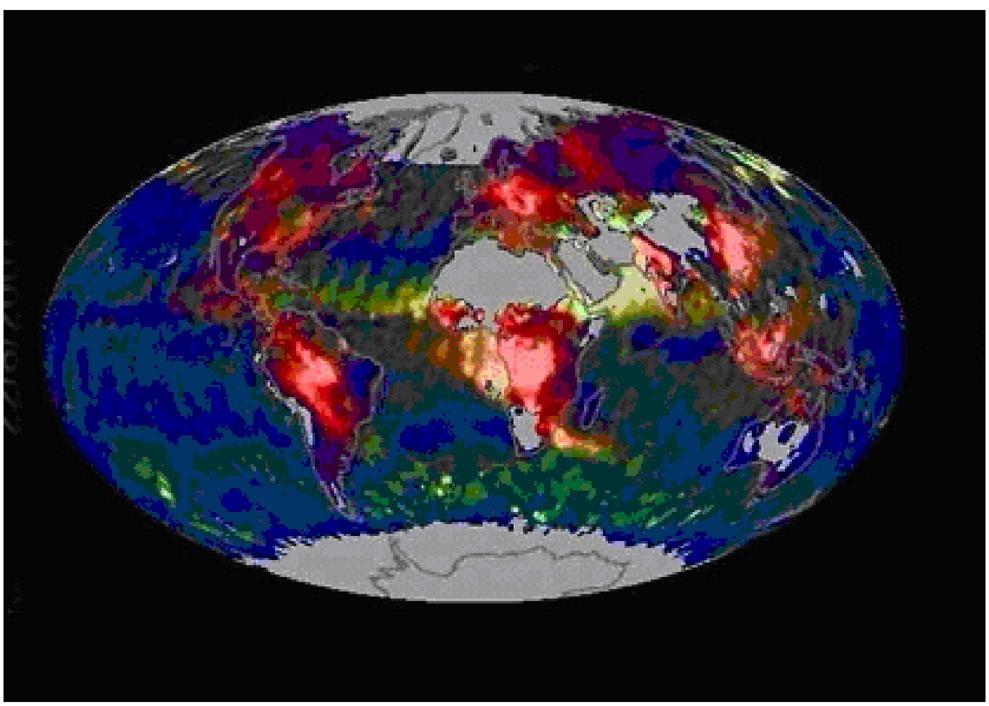
Types of Aerosols

1. Sulphates: from natural sources (volcanoes and burning biomass) and anthropogenic sources (burning fossil fuels).
2. Sea-salt particles, lifted by the wind as sea-spray evaporates.
3. Fine dust, raised by winds from deserts and other dry plains.
4. Carbon particles (soot) and other organics from combustion (mostly anthropogenic).

Effects of Aerosols

- Sulphates and salt are water soluble, and play a key role in the growth of cloud droplets.
- Sulphates scatter visible light, which results in atmospheric cooling (negative forcing).
- Dust and soot absorb infrared radiation, which results in atmospheric warming (positive forcing).

Taylor, F.W., "Elementary Climate Physics." Oxford Univ. Press, 2005.



Small particles suspended in the Earth's atmosphere (aerosols) include fine aerosols such as pollution and smoke (red) and coarse aerosols such as dust and sea-salt (green). Image shows aerosol levels on April 13, 2001 as seen by a NASA satellite. *Source: NASA*

Methane Hydrates

Methane hydrates are produced when organic materials settle to the ocean floor onto the continental shelves due to high amounts of biological activity. The methane forms because of the low-oxygen content of these sediments. If the temperature is right, this methane gets frozen in the form of methane hydrates.

If the temperature then warms enough to melt the methane hydrates, methane can bubble to the surface and be released in large quantities into the atmosphere. Methane absorbs more long-wavelength radiation than comparable amounts of CO_2. Large releases of methane due to warming temperatures could create a huge positive feedback mechanism, causing the average global temperature to surge upward.

Greenhouse Effect

- About 60% of the greenhouse effect is due to water vapor,
- About 35% is due to carbon dioxide,
- The remaining 5% is due to methane, nitrous oxide and ozone in about equal quantities.

Taylor, F.W., "Elementary Climate Physics." Oxford Univ. Press, 2005.

Carbon Dioxide

- CO_2 causes the most radiant heat absorption of all anthropogenic sources because of its much greater abundance (and because of the strong infrared absorption band in the gap between water absorption bands) .
- However, increases in absorption are proportional to the increase in the square root of the amount of CO_2. [Increases in absorption due to increases in methane and nitrous oxide are linear since no portion of their absorption bands are saturated.]

US Emissions

All Greenhouse Gases: ~2 GtC/y (equiv)   Carbon Dioxide: ~1.5 GtC/y

- 33% Electrical Power Industry
- 27% Transportation
- 20% Industry
- 7% Agriculture
- 6% Commercial
- 5% Residential

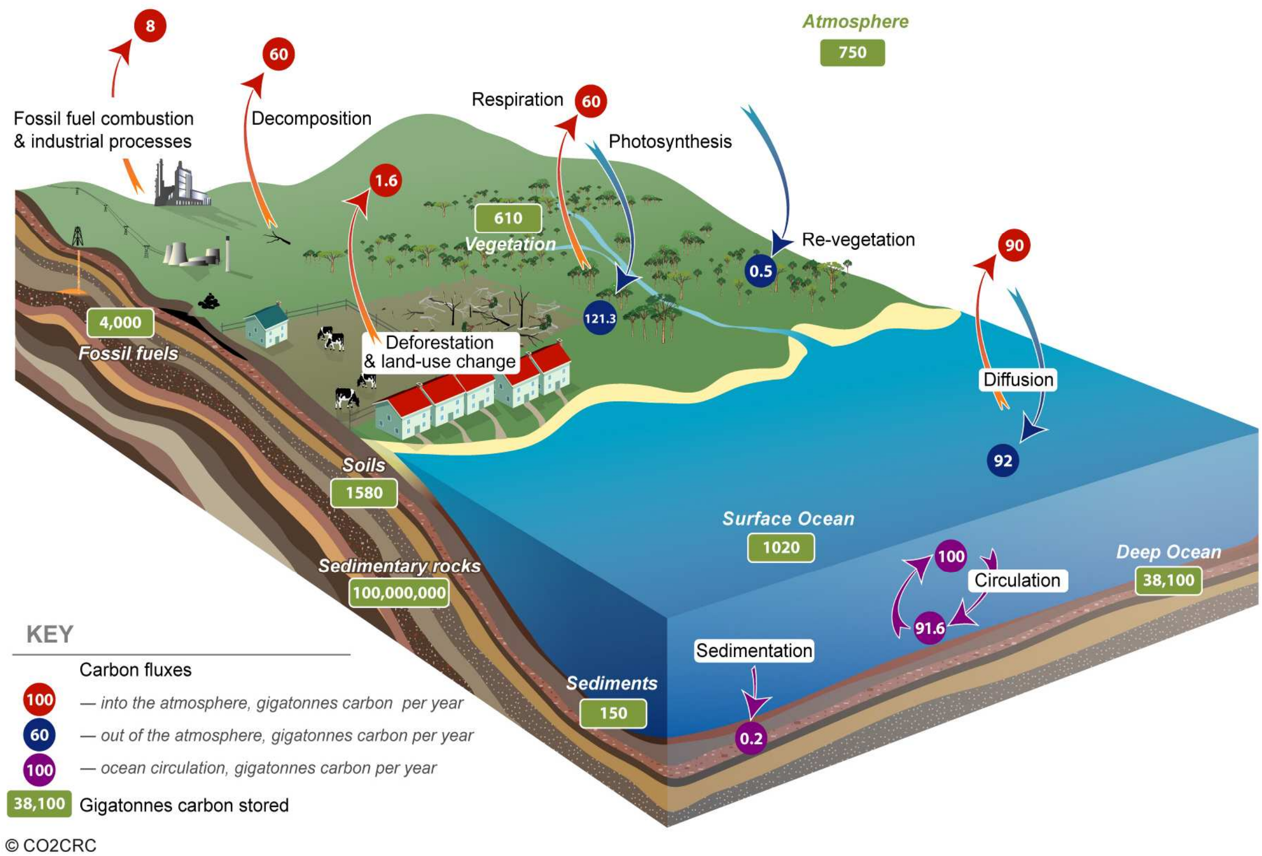
2009 EPA

Carbon Dioxide Exchange with the Oceans

"Carbon dioxide is slightly soluble in water, so it tends to get washed out of the atmosphere and into the ocean by the action of rainfall and wave breaking. About one-third of the carbon dioxide released annually from fossil fuels…is taken up by the ocean, providing an important reduction in the greenhouse warming caused by the gas."

"It is not clear how long the ocean can go on providing this service. It is estimated that the ocean currently contains around 50 times as much carbon dioxide as the atmosphere does; eventually it could become saturated, and the rate of uptake would then slow down. In fact, bearing in mind that the ocean may be warming up, and that CO_2 solubility in water decreases with increasing temperature, it could become a net source of CO_2 and provide serious levels of positive feedback to global warming trends."

Taylor, F.W., "Elementary Climate Physics." Oxford Univ. Press, 2005.



Data & Measurement Methods

Measuring Earth's Climate

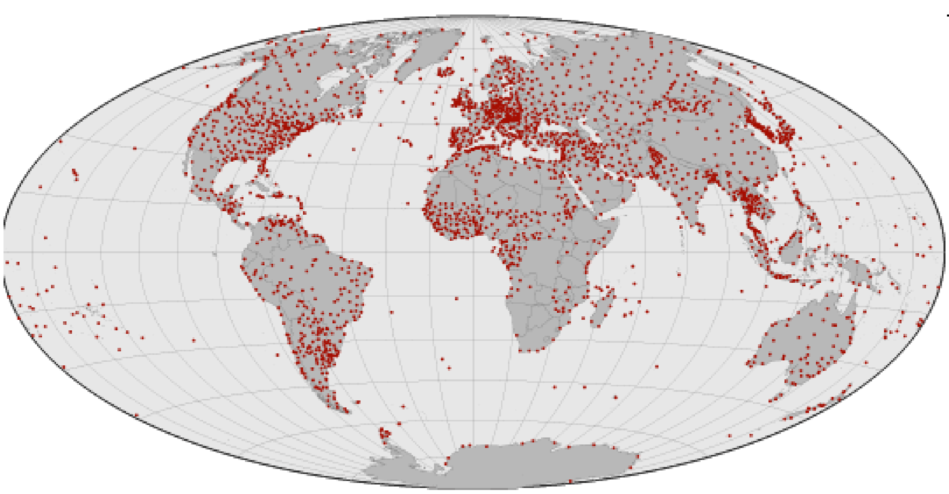
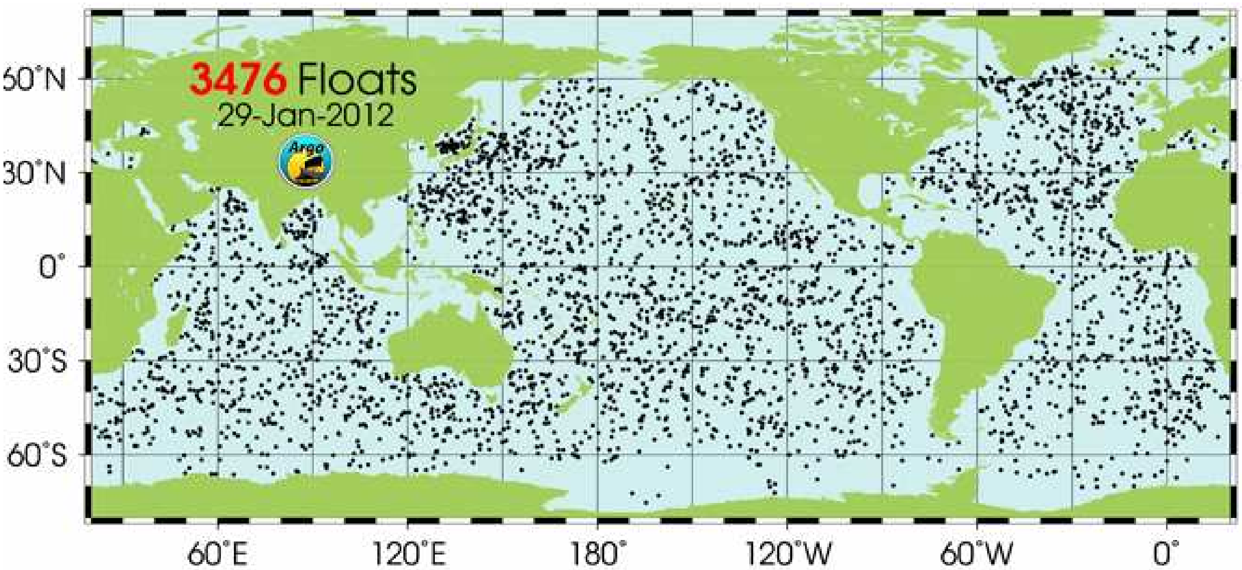


Image: nature-education.org

- Weather stations around the nation and around the world gather surface temperature data.
- Satellites continuously monitor the atmosphere and the surface of Earth.
- Thousands of weather buoys, including Project Argo Floats, monitor the ocean to a depth of 2000 m.



Positions of Project Argo Floats Source: *argo.ucsd.edu*

Measuring the Sun's Influence

The SOHO satellite and others monitor the sun continuously. SOHO is in a fixed position (at a LaGrange point) between the Earth and the Sun.

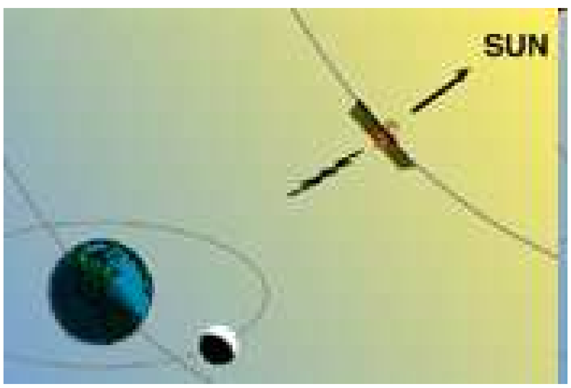


Image: NASA

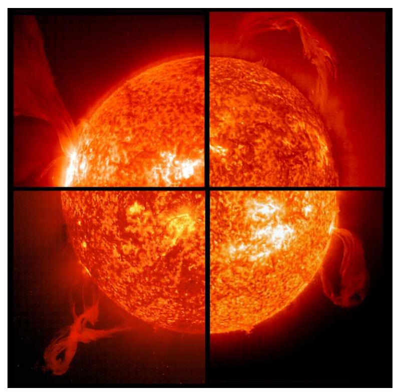
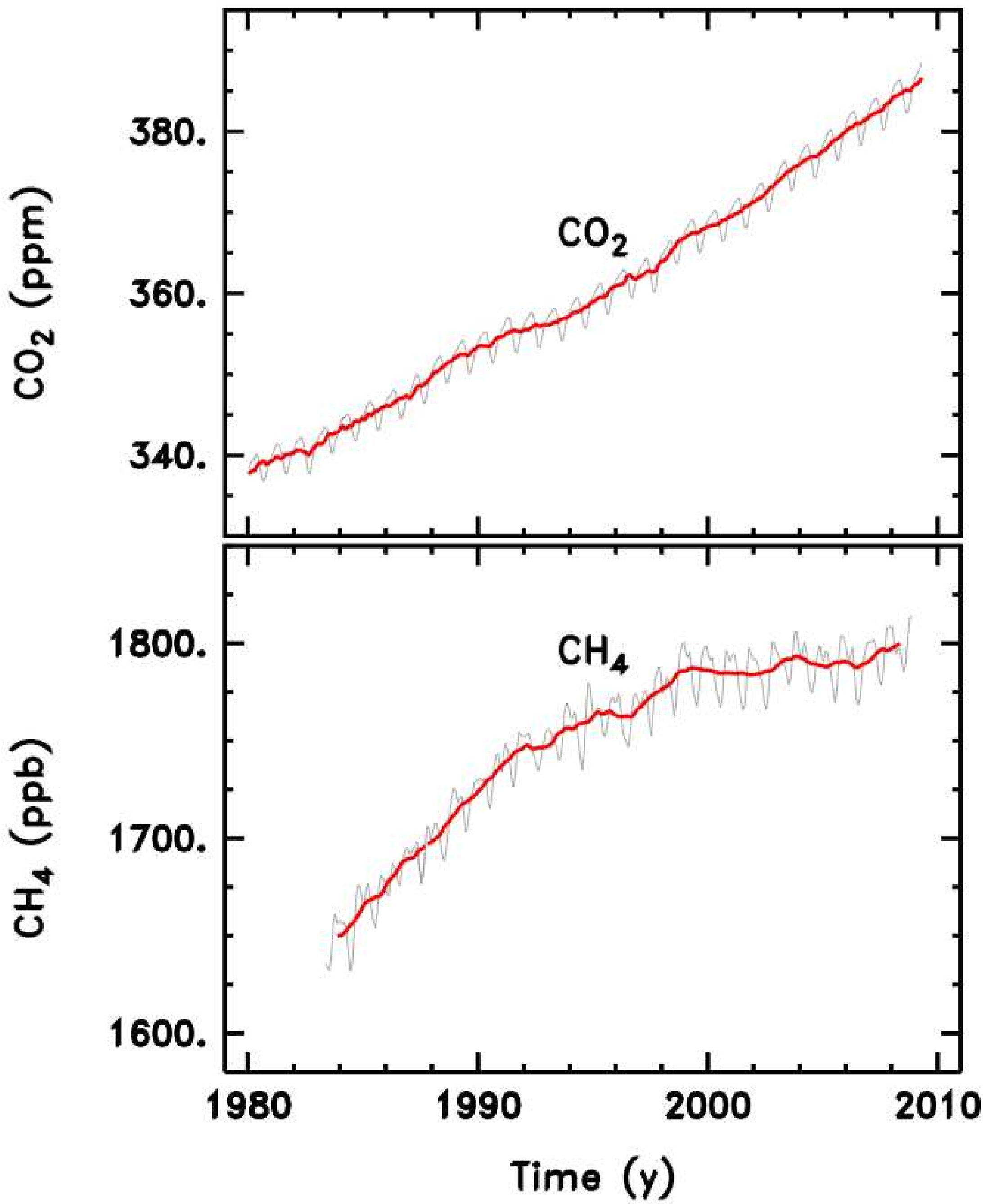


Image: NASA

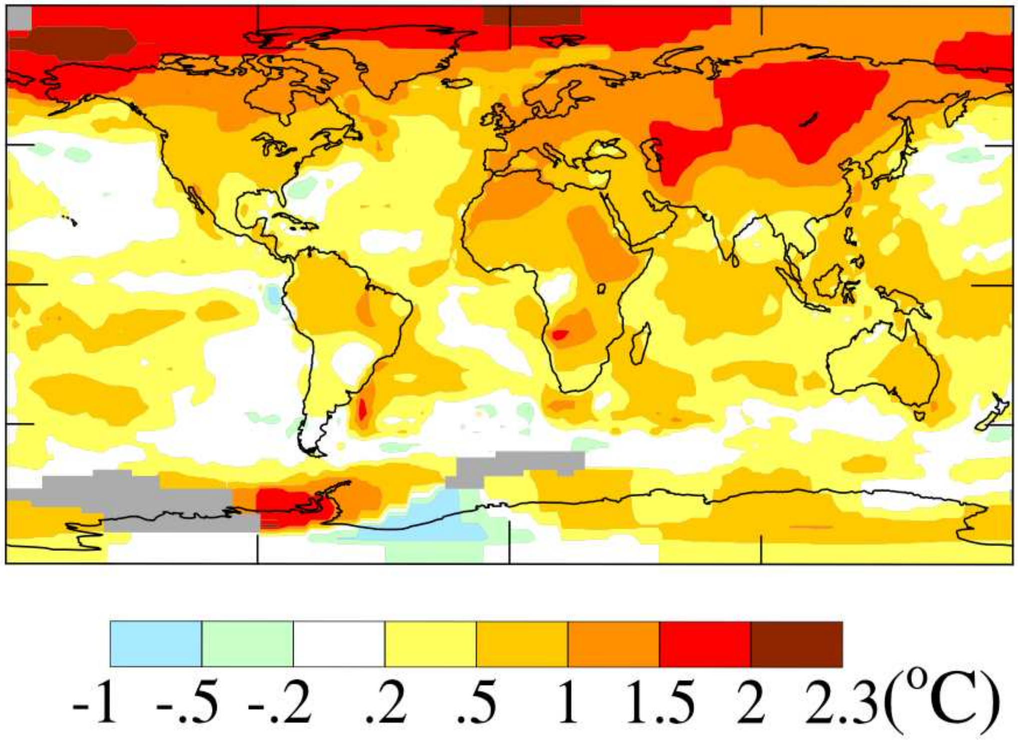
Climate Scientists are also

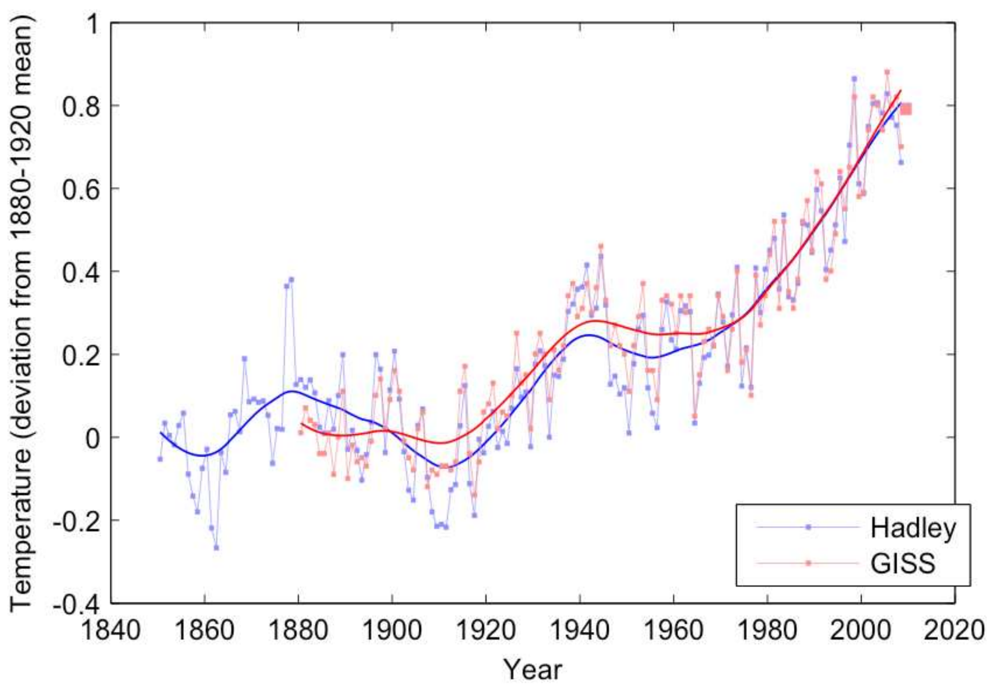
- Measuring the influence of geological activity.
- Measuring the influence of biological systems and the effects on biological systems.
- Measuring human influences.

Atmospheric concentration of carbon dioxide (CO_2) and methane (CH_4)



Source: The Copenhagen Diagnosis



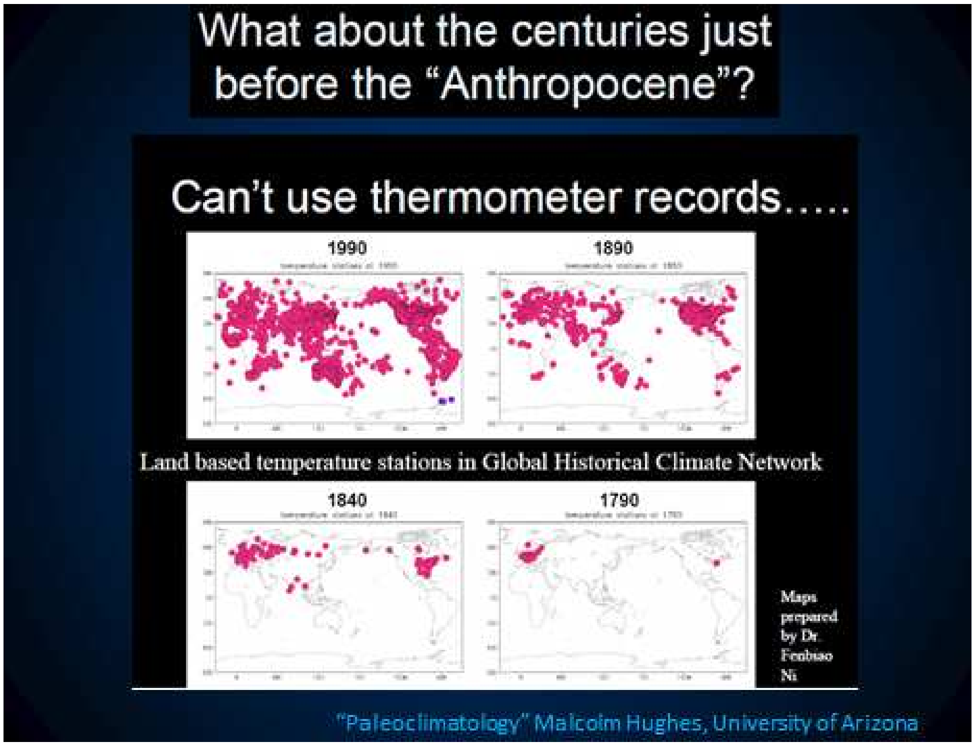


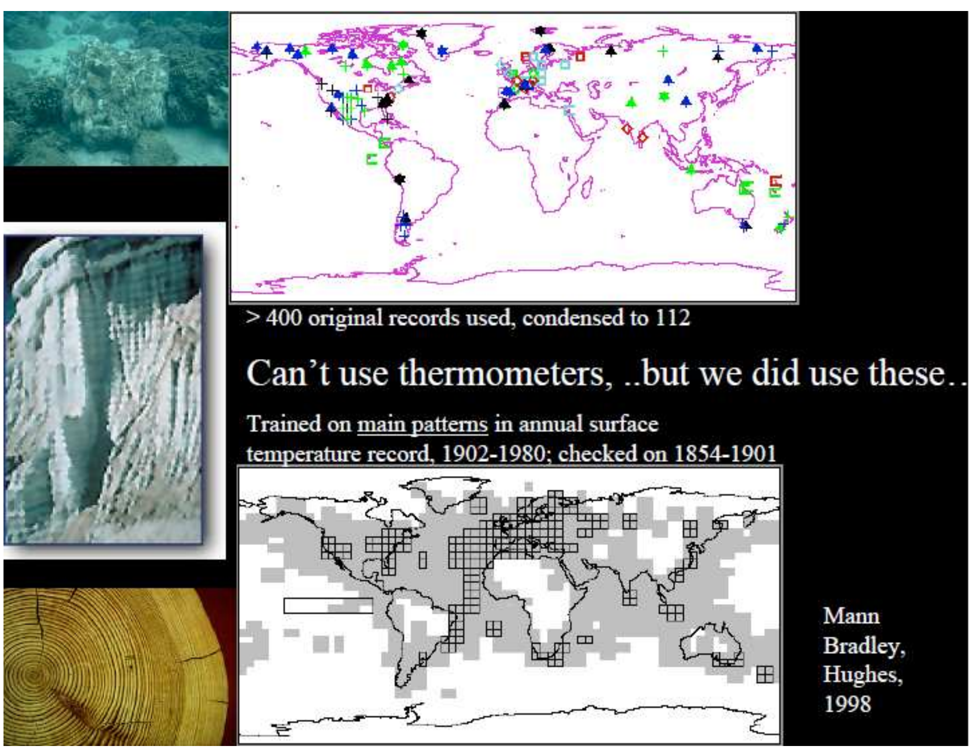
(Top) Mean temperature change between 1950's and 2000's: (Bottom) Global average temperature change from 1850

Source: The Copenhagen Diagnosis

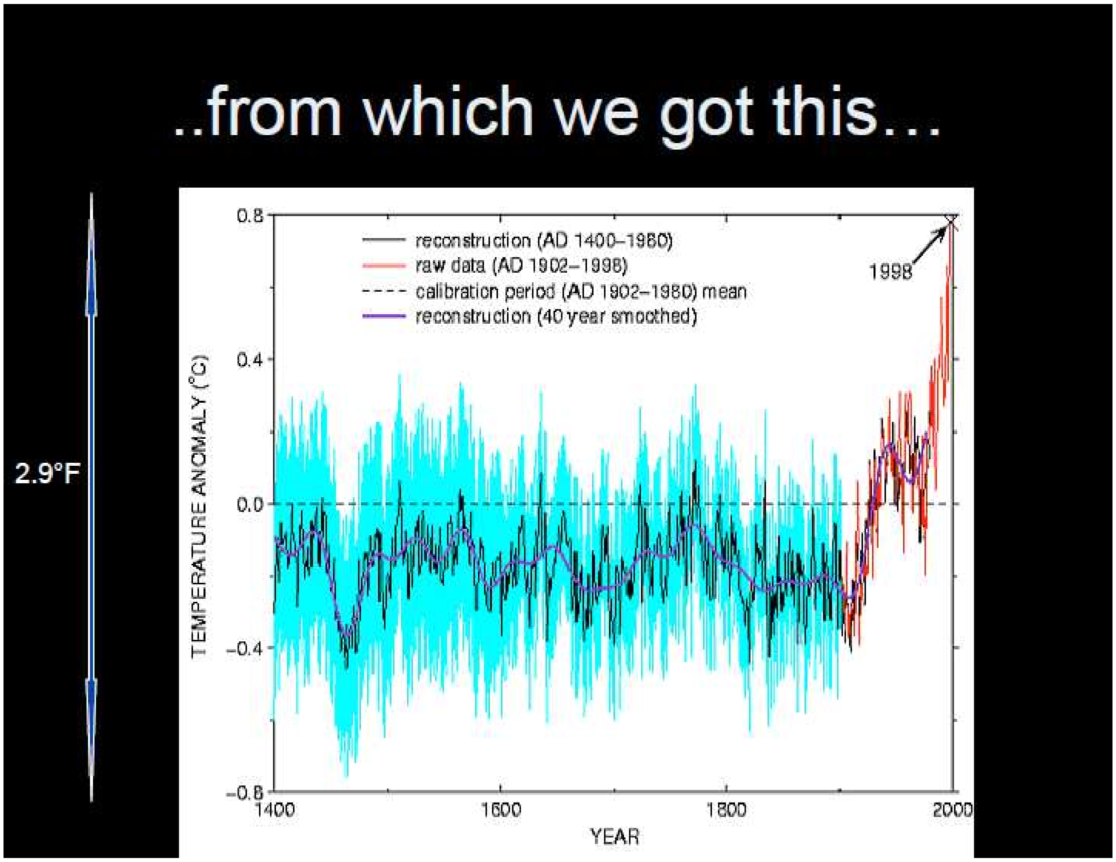
Measuring the Past

- Understanding climate change requires that we know information from the past, before accurate measurements were made and before records were kept.
- There are many indirect ways to measure previous conditions on Earth.
- Studying the climate of the past is known as paleoclimatology.

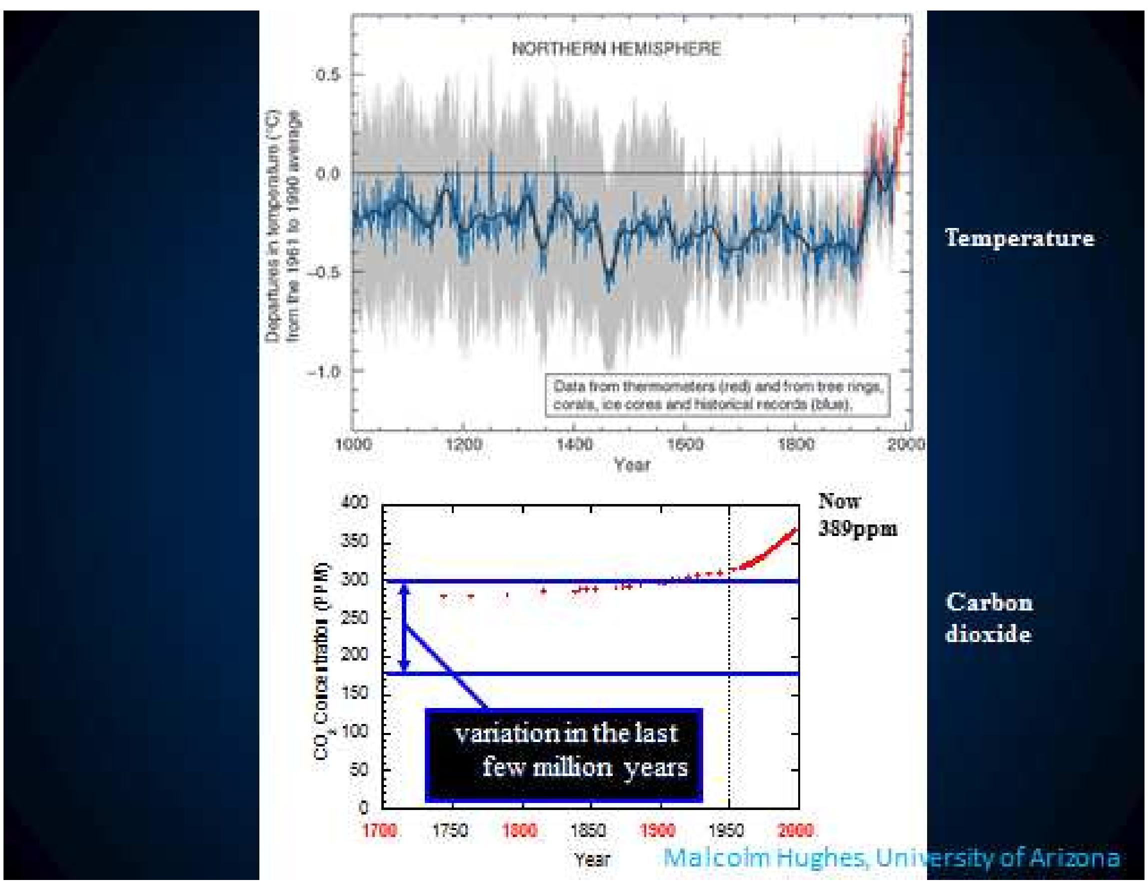


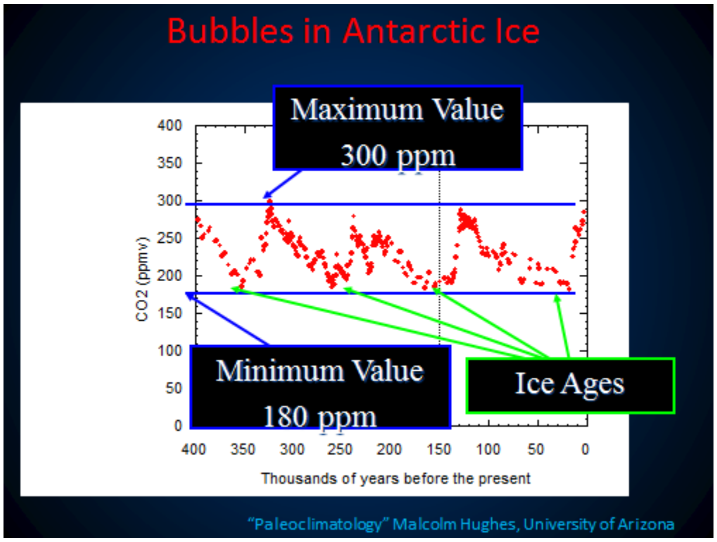


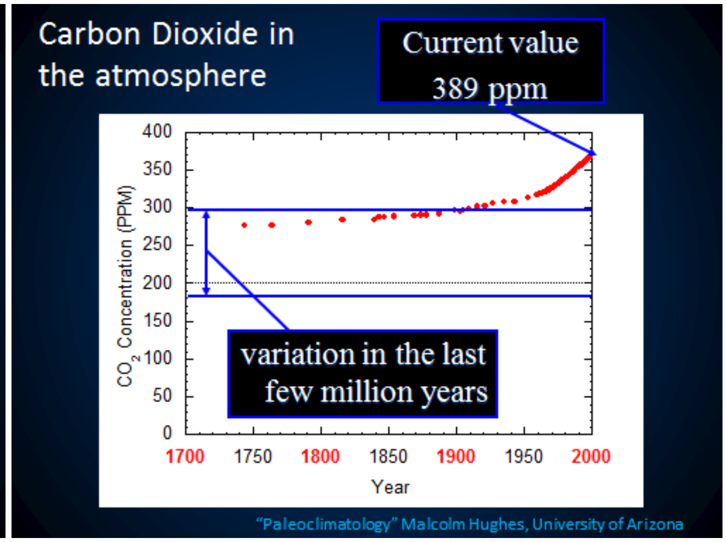
Source: "Paleoclimatology" Malcolm Hughes, University of Arizona

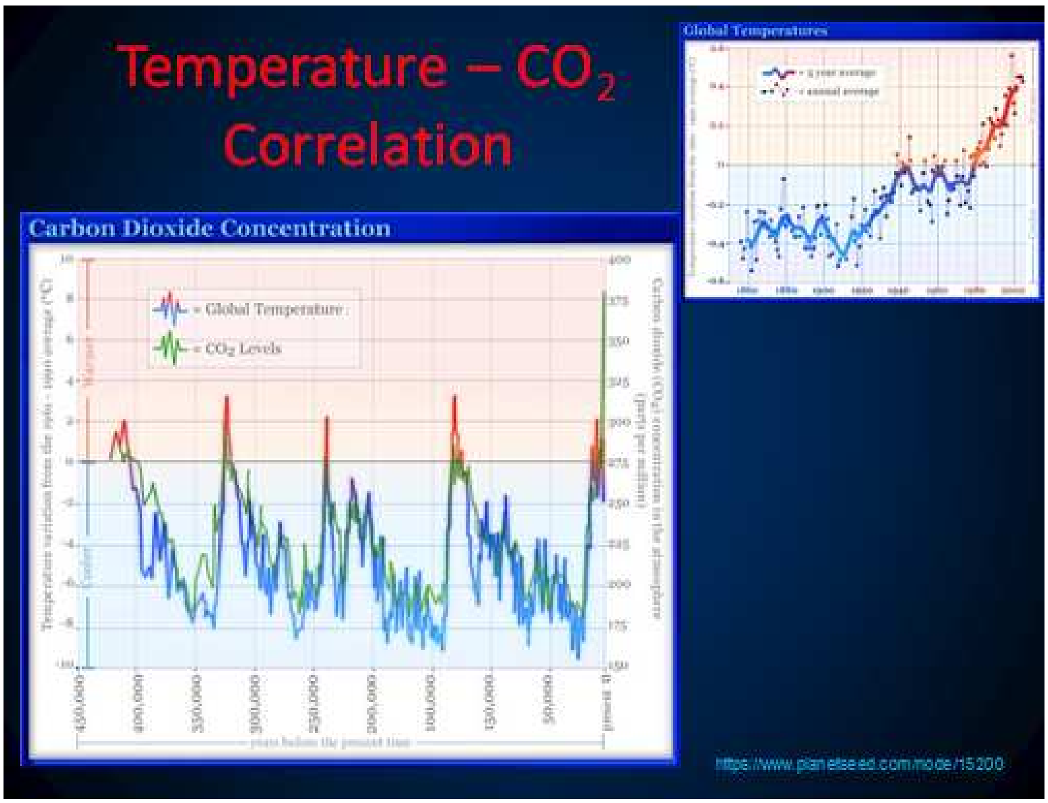


Source: "Paleoclimatology" Malcolm Hughes, University of Arizona




Bubbles in Antarctic Ice
Maximum Value
300 ppm
Minimum Value
180 ppm
Ice Ages
CO2 (ppmv)
400
350
300
250
200
150
100
50
0
400 350 300 250 200 150 100 50 0
Thousands of years before the present
"Paleoclimatology" Malcolm Hughes, University of Arizona


Carbon Dioxide in
the atmosphere
Current value
389 ppm
variation in the last
few million years
CO2 Concentration (PPM)
400
350
300
250
200
150
100
50
0
1700 1750 1800 1850 1900 1950 2000
Year
"Paleoclimatology" Malcolm Hughes, University of Arizona


Temperature – CO2
Correlation
Global Temperatures
Carbon Dioxide Concentration
= Global Temperature
= CO2 Levels
https://www.planetseed.com/node/15200

Climate Models & Validations

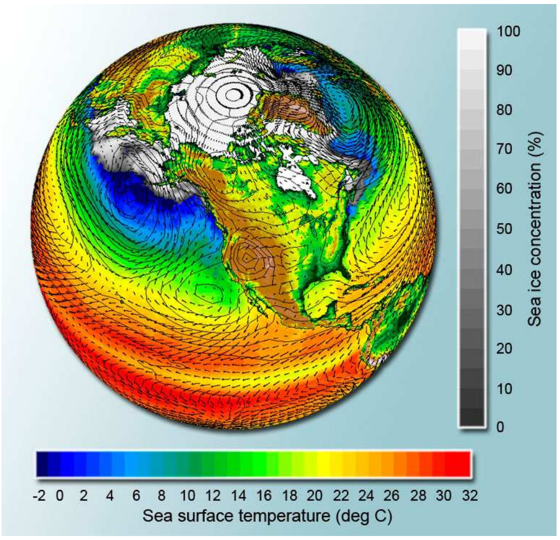


Image: fnal.gov

What is a Climate Model?

Global climate models (GCMs) use math – a lot of math - to describe how the atmosphere, the oceans, the land, living things, ice, and energy from the Sun affect each other and Earth's climate.

Thousands of climate researchers use global climate models to better understand how global changes such as increasing greenhouses gases or decreasing Arctic sea ice will affect the Earth. The models are used to look hundreds of years into the future, so that we can predict how our planet's climate will likely change.

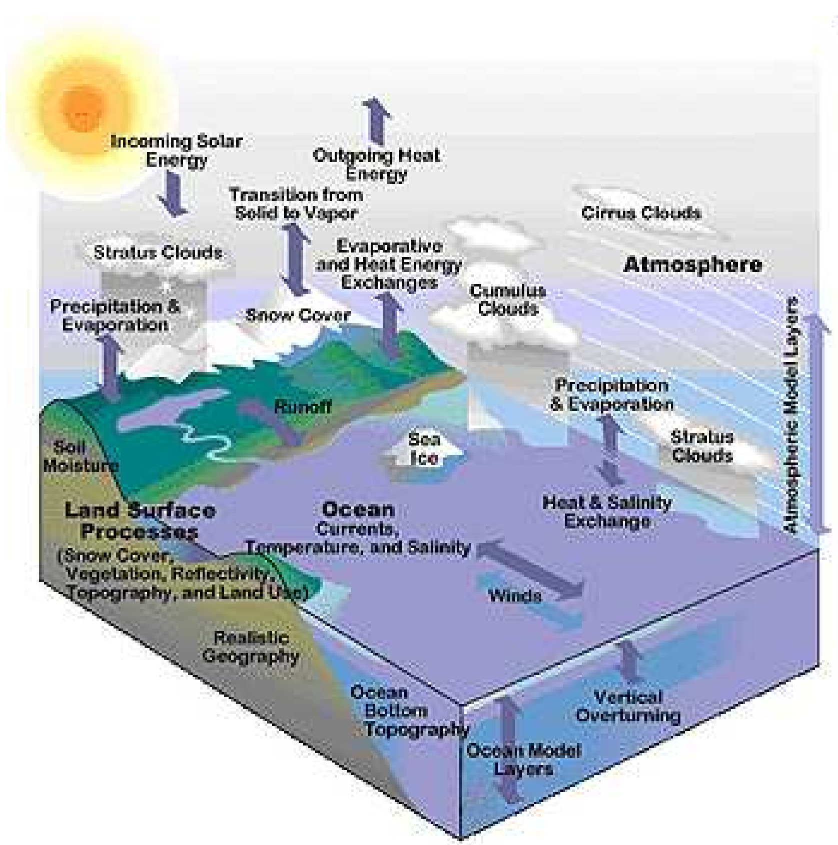
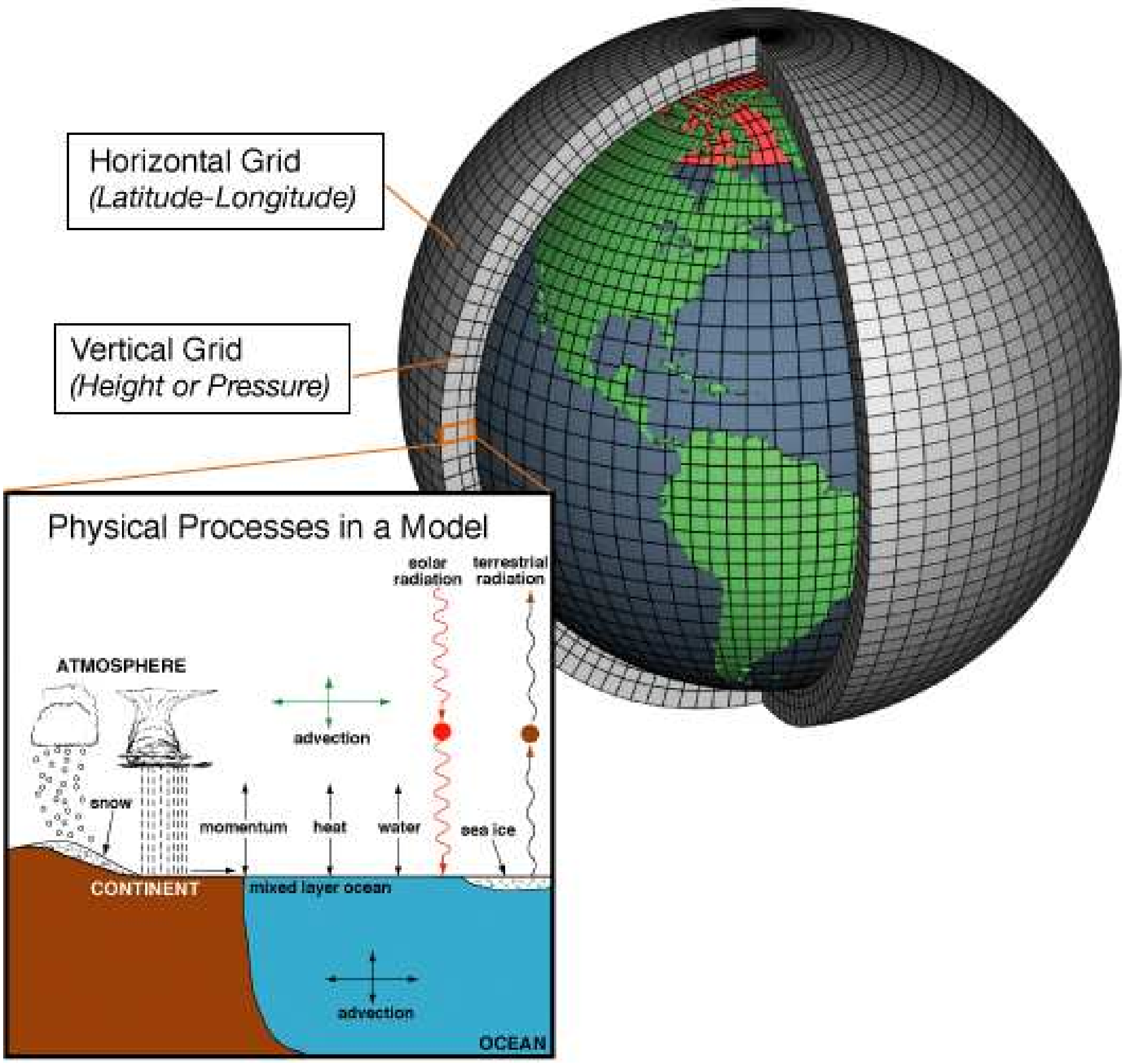


Image: http://www.windows.ucar.edu/tour/link=/earth/climate/cli_models2.html&portal=vocals

Climate Models

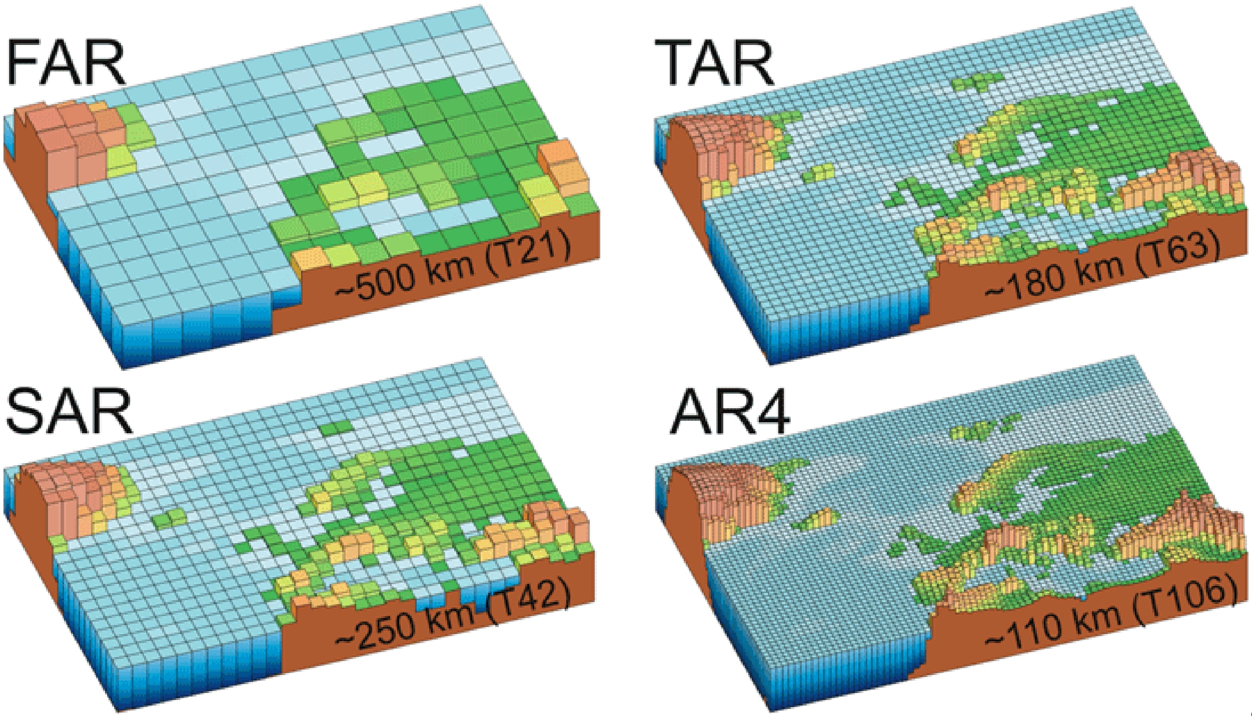
There are various types of climate models. Some focus on certain things that affect climate such as the atmosphere or the oceans. Models that look at few variables of the climate system may be simple enough to run on a personal computer. Other models take into account many factors of the atmosphere, biosphere, geosphere, hydrosphere, and cryosphere to model the entire Earth system. They take into account the interactions and feedbacks between these different parts of the planet. Earth is a complex place and so many of these models are very complex too. They include so many math calculations that they must be run on supercomputers, which can do the calculations quickly.

Climate models divide the atmosphere and oceans into small regions and calculate the thermodynamics of each portion as each affects the next.



Source: NOAA

Smaller regions, more variables, better measurements and more calculations provide better models with better accuracy.



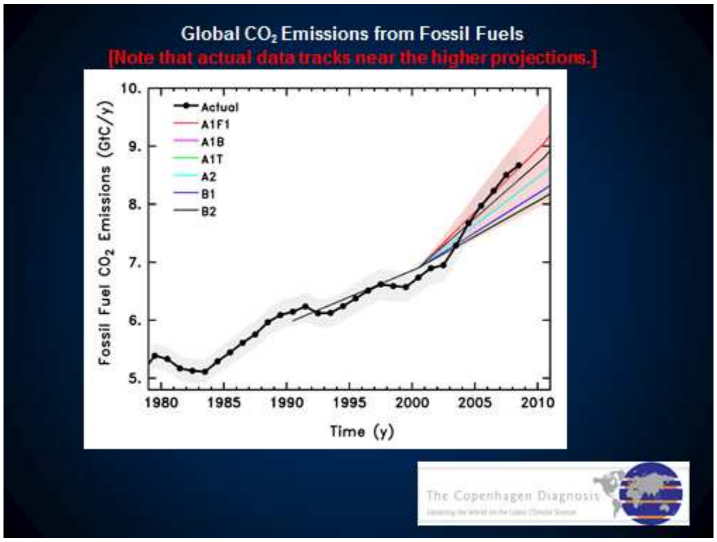
IPCC AR4

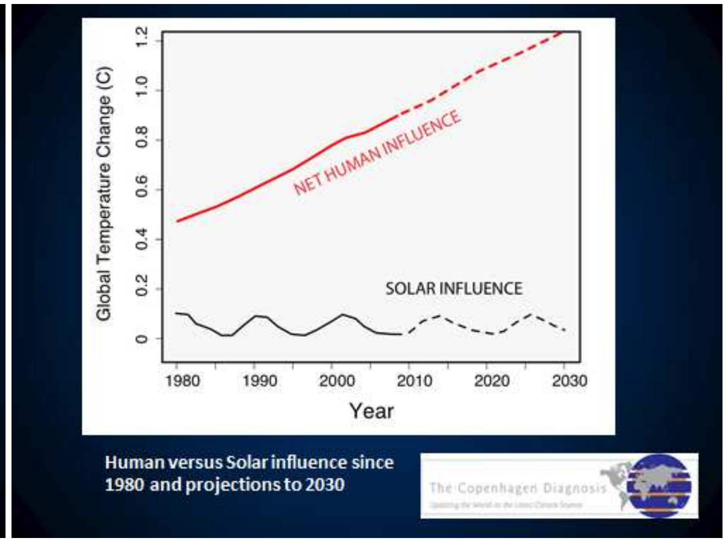
- All climate models must make some assumptions about how the Earth works, but in general, the more complex a model, the more factors it takes into account, and the fewer assumptions it makes. At the National Center for Atmospheric Research (NCAR), researchers work with complex models of the Earth's climate system. Their Community Climate System Model is so complex that it requires about three trillion math calculations to simulate a single day on planet Earth. It can take thousands of hours for the supercomputer to run the model. The model output, typically many gigabytes large, is analyzed by researchers and compared with other model results and with observations and measurement data.
- http://www.windows.ucar.edu/tour/link=/earth/climate/cli_models2.html&portal=vocals

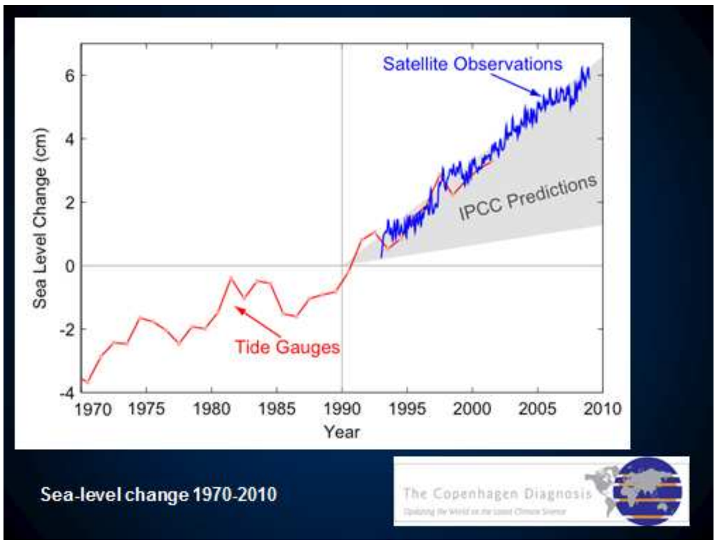
Significant Findings

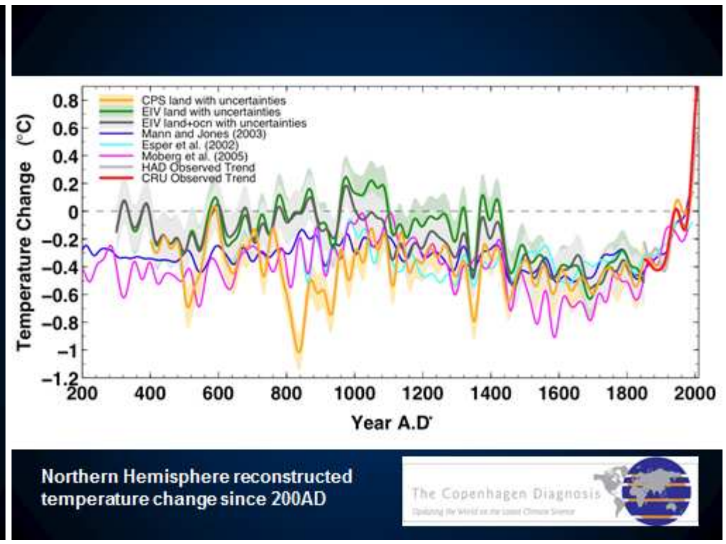
- **Recent global temperatures demonstrate human-induced warming**: Over the past 25 years temperatures have increased at a rate of 0.19°C per decade, in very good agreement with predictions based on greenhouse gas increases. Even over the past ten years, despite a decrease in solar forcing, the trend continues to be one of warming. Natural, short-term fluctuations are occurring as usual, but there have been no significant changes in the underlying warming trend.

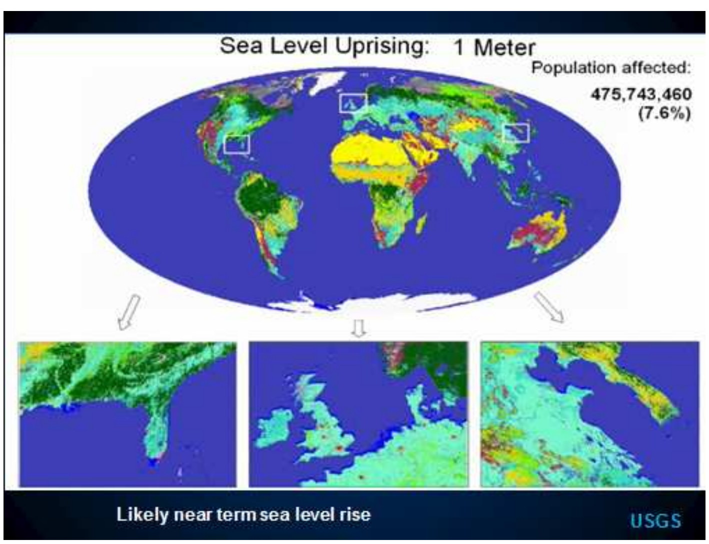
  Source: The Copenhagen Diagnosis

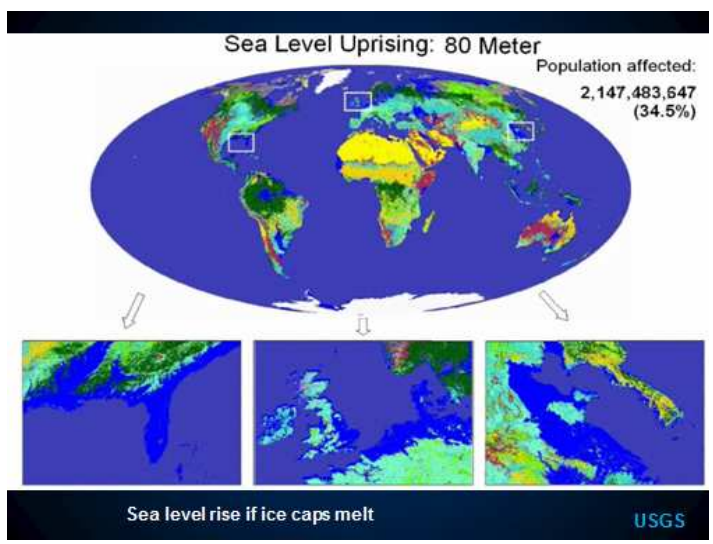

Global CO2 Emissions from Fossil Fuels
[Note that actual data tracks near the higher projections.]
Fossil Fuel CO2 Emissions (GtC/y)
Time (y)
Actual
A1F1
A1B
A1T
A2
B1
B2
The Copenhagen Diagnosis


Global Temperature Change (C)
NET HUMAN INFLUENCE
SOLAR INFLUENCE
Year
Human versus Solar influence since 1980 and projections to 2030
The Copenhagen Diagnosis

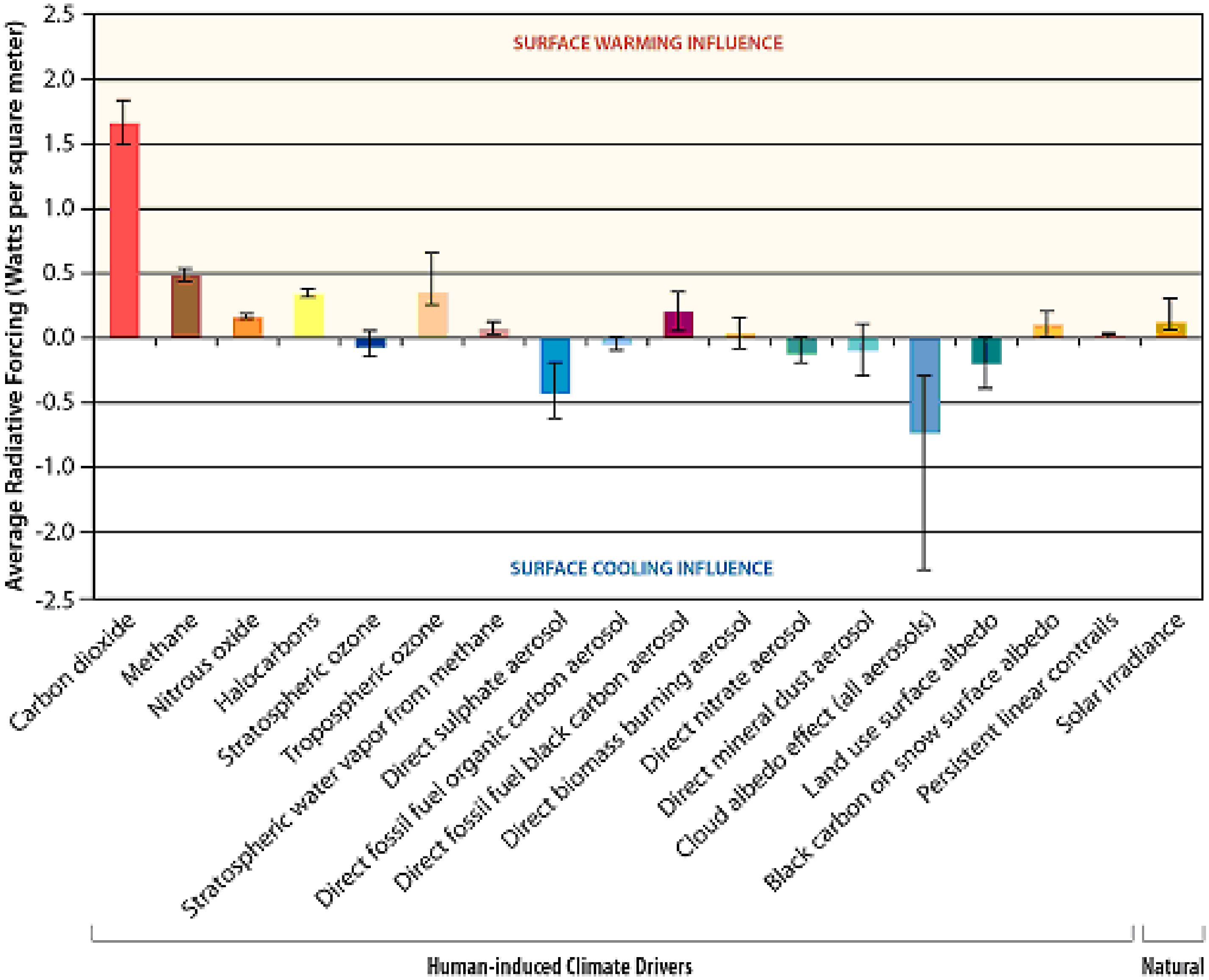

Sea Level Change (cm)
Satellite Observations
IPCC Predictions
Tide Gauges
Year
Sea-level change 1970-2010
The Copenhagen Diagnosis


CPS land with uncertainties
EIV land with uncertainties
EIV land+ocn with uncertainties
Mann and Jones (2003)
Esper et al. (2002)
Moberg et al. (2005)
HAD Observed Trend
CRU Observed Trend
Temperature Change (°C)
Year A.D
Northern Hemisphere reconstructed temperature change since 200AD
The Copenhagen Diagnosis

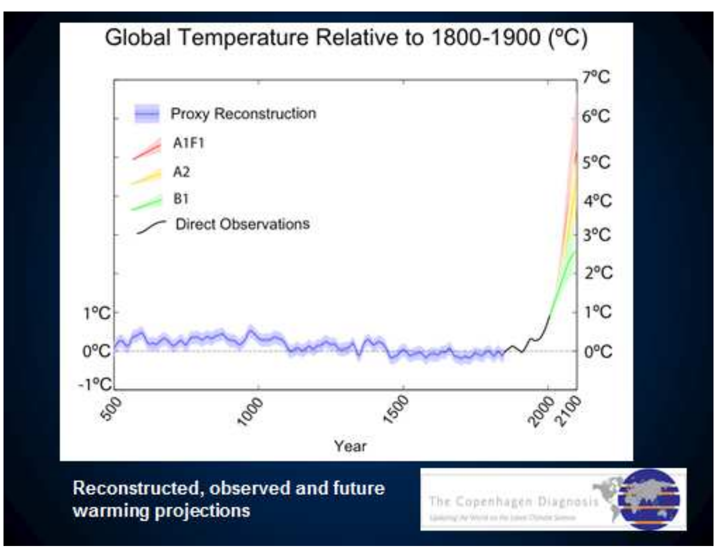

Sea Level Uprising: 1 Meter
Population affected:
475,743,460
(7.6%)
Likely near term sea level rise
USGS

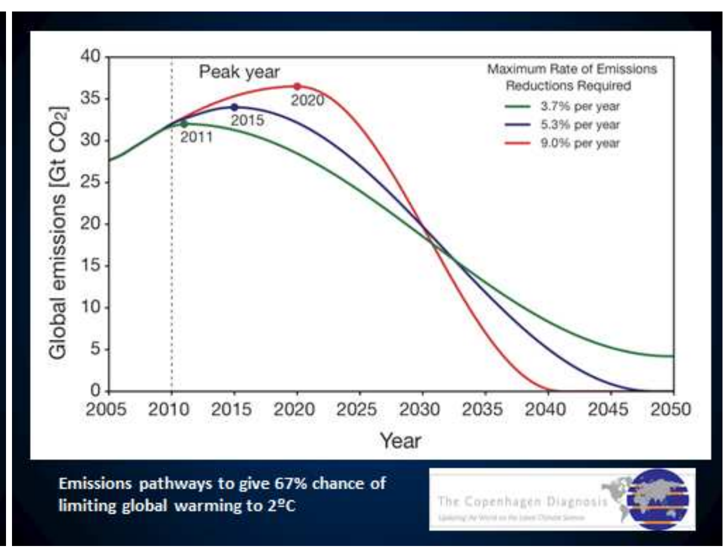

Sea Level Uprising: 80 Meter
Population affected:
2,147,483,647
(34.5%)
Sea level rise if ice caps melt
USGS

Climate Influence Between 1750 and 2005



Source: IPCC 2007 WGI Table 2.12; Figure: Union of Concerned Scientists





Climate Destabilization

- A stable climate is a climate in equilibrium with only small oscillations in climate conditions.
- An unstable climate has either severe weather and large, and perhaps rapid, oscillations in climate conditions (violent storms and large swings in temperature), or a run-away extreme condition (to very hot or very cold).
- An unstable climate could make agriculture, transportation and construction very difficult, if not impossible, and be deadly to wildlife.
- Events that we fear could trigger climate destabilization include a halt in the thermohaline circulation and the melting of methane hydrates.
- Even the best climate models today are not capable of predicting the conditions and thresholds that would lead to climate destabilization. Current conditions could be very close, or nowhere near destabilizing the climate, implying that more research is imperative.
- Although near-term, catastrophic climate destabilization is unlikely, the likely effects of human induced climate change are still severe.

Carbon Dioxide

- 1950 global CO_2 emissions: 1.8 GtC/y
- 2009 global CO_2 emissions: 8.5 GtC/y
- Sink ~ 4 GtC/y
- Surplus ~ 4.5 GtC/y
- 1 ppm => 2.12 GtC
- Atmospheric CO_2 increasing at 2 ppm/y
- Atmospheric CO_2 retention ~56% =>sinks ~44%
- CO_2 forcing: ~ +1.5 W/m^2
- Sensitivity: doubling CO_2 => 3 $\pm$ 1^{o}C
  Source: James Hansen "Storms of our Grandchildren," Bloomsbury USA, NY 2009

Current Climate Conditions

- CO_2 levels are 40% above natural maximum.
- Disequalibrium: Earth currently receives 0.58 W/m^2 * more energy than it emits.
- Temperature has increased at least 0.3^o C in the last 25 years, between 0.5^o C and 0.75^o C in the last 100 years (a 2% enhancement of the natural greenhouse effect).
- Isotherm migration: 3.5 miles/year poleward. [Isotherm: imaginary line on the Earth connecting places with the same average annual temperature.]
- Rate of sea level rise: 3.4 mm/y.

James Hansen "Storms of our Grandchildren," Bloomsbury USA, NY 2009 * NASA update 2012

Predictions

- More rise in sea levels.
- More severe storms and droughts.
- More severe hurricanes & tropical cyclones.

Probable Consequences

- Displacement of coastal populations and capital assets (with redesign and construction).
- Species extinctions.
- Altered land use (displacement of agriculture, etc.).
- Multiple secondary effects.

Primary Sources:

Taylor, F.W., "Elementary Climate Physics." Oxford Univ. Press, 2005

"The Science of Climate Change." Australian Institute of Physics (AIP)
http://www.vicphysics.org/.../Climate/AIPPowerPointNo3.ppt

"Paleoclimatology and Climate Change," Malcolm Hughes, University of Arizona
www.agci.org/dB/PDFs/07S2_PGroisman_PreSesDoc3.pdf

The Copenhagen Diagnosis: Climate Science Report *www.copenhagendiagnosis.com*

National Oceanographic and Atmospheric Administration (NOAA)

National Aeronautics and Space Administration (NASA)