International Energy Agency

- *The IEA is an autonomous organisation which works to ensure reliable, affordable and clean energy for its 30 member countries and beyond. The IEA's four main areas of focus are: energy security, economic development, environmental awareness, and engagement worldwide.*

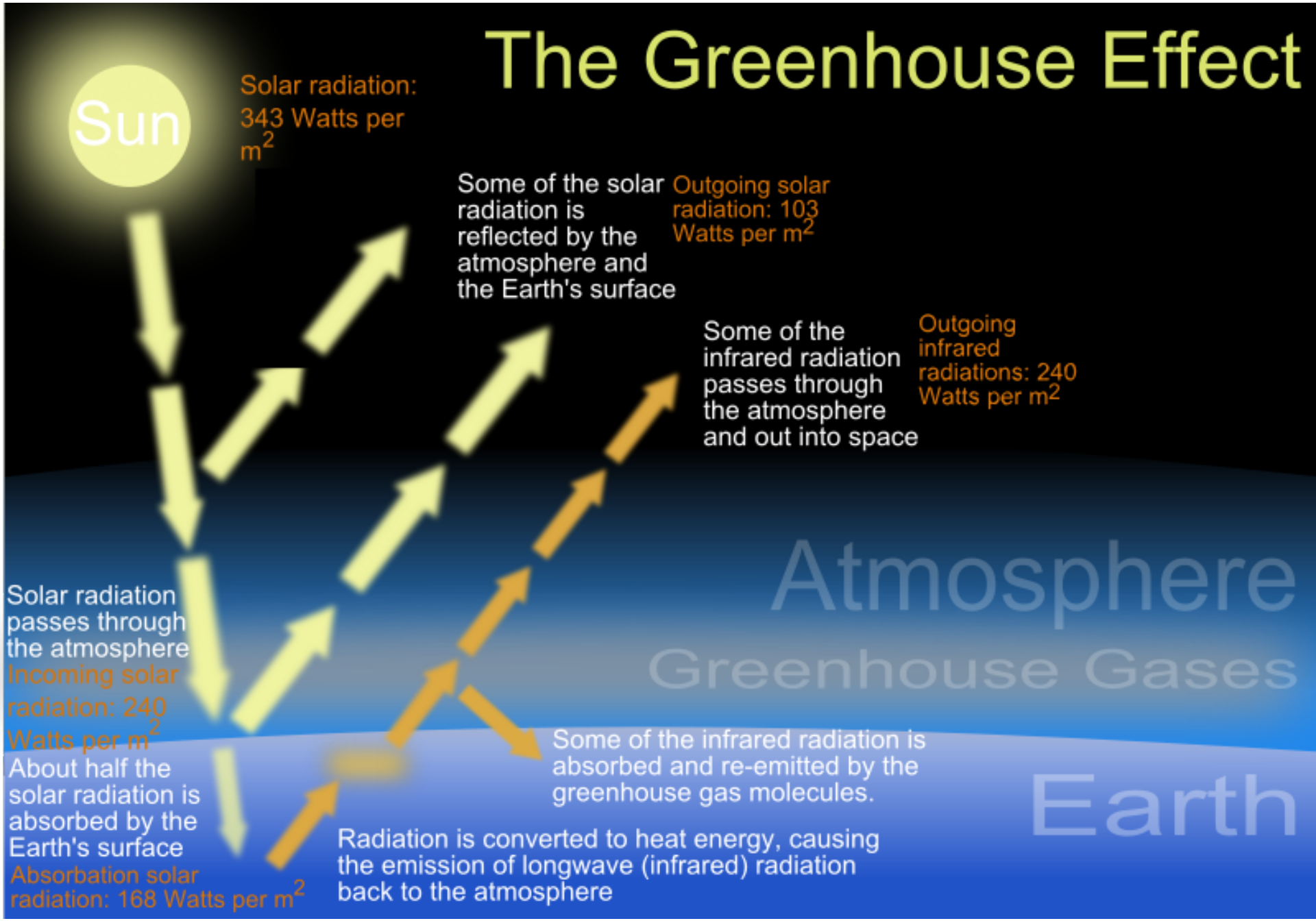
https://www.iea.org/

https://www.iea.org/stats/index.asp

https://www.iea.org/country/maps.asp

What determines Earth's temperature?

- Earth's temperature depends on the balance between energy entering and leaving.
  - When incoming energy from the sun is absorbed by the Earth system, Earth warms.
  - When the sun's energy is reflected back into space, Earth avoids warming.
  - When energy is released back into space, Earth cools.


The Greenhouse Effect
Sun
Solar radiation: 343 Watts per m2
Some of the solar radiation is reflected by the atmosphere and the Earth's surface
Outgoing solar radiation: 103 Watts per m2
Some of the infrared radiation passes through the atmosphere and out into space
Outgoing infrared radiations: 240 Watts per m2
Atmosphere
Greenhouse Gases
Solar radiation passes through the atmosphere
Incoming solar radiation: 240 Watts per m2
About half the solar radiation is absorbed by the Earth's surface
Absorbation solar radiation: 168 Watts per m2
Some of the infrared radiation is absorbed and re-emitted by the greenhouse gas molecules.
Radiation is converted to heat energy, causing the emission of longwave (infrared) radiation back to the atmosphere
Earth

Greenhouse Gases

- **Greenhouse gas =** Any gas that absorbs infrared radiation in the atmosphere. Each gas absorbs radiation at specific wavelengths as function of its structure.
- Without them, Earth's surface would be on average about 33 ºC (59 ºF) colder than at present.

Greenhouse Gases

- *Important greenhouse gases:*
  - **Carbon dioxide (CO_2)**
  - **Methane (CH_4)**
  - **Nitrous oxide (N_2O)**
  - Chlorofluorcarbons (CFCs)
  - Halogenated fluorocarbons (HCFCs)
  - Ozone (O_3)
  - Hydrofluorocarbons (HFCs)
  - Water vapor (H_2O)

Vibration Modes of Greenhouse Gas Molecules

- As the Earth cools, it emits infrared (IR) photons.
- When a greenhouse gas molecule absorbs an IR photon, the molecule gets excited to a higher vibrational energy.
- When the molecule returns to a more stable vibrational energy, it emits an IR photon in a random direction.
- Some of the remitted photons return to Earth.

http://www2.ess.ucla.edu/~schauble/MoleculeHTML/CO2_html/CO2_page.html

http://www2.ess.ucla.edu/~schauble/MoleculeHTML/H2O_html/H2O_page.html

http://www2.ess.ucla.edu/~schauble/MoleculeHTML/N2O_html/N2O_page.html

http://www2.ess.ucla.edu/~schauble/MoleculeHTML/CH4_html/CH4_page.html

http://www2.ess.ucla.edu/~schauble/MoleculeHTML/CHClF2_html/CHClF2_page.html

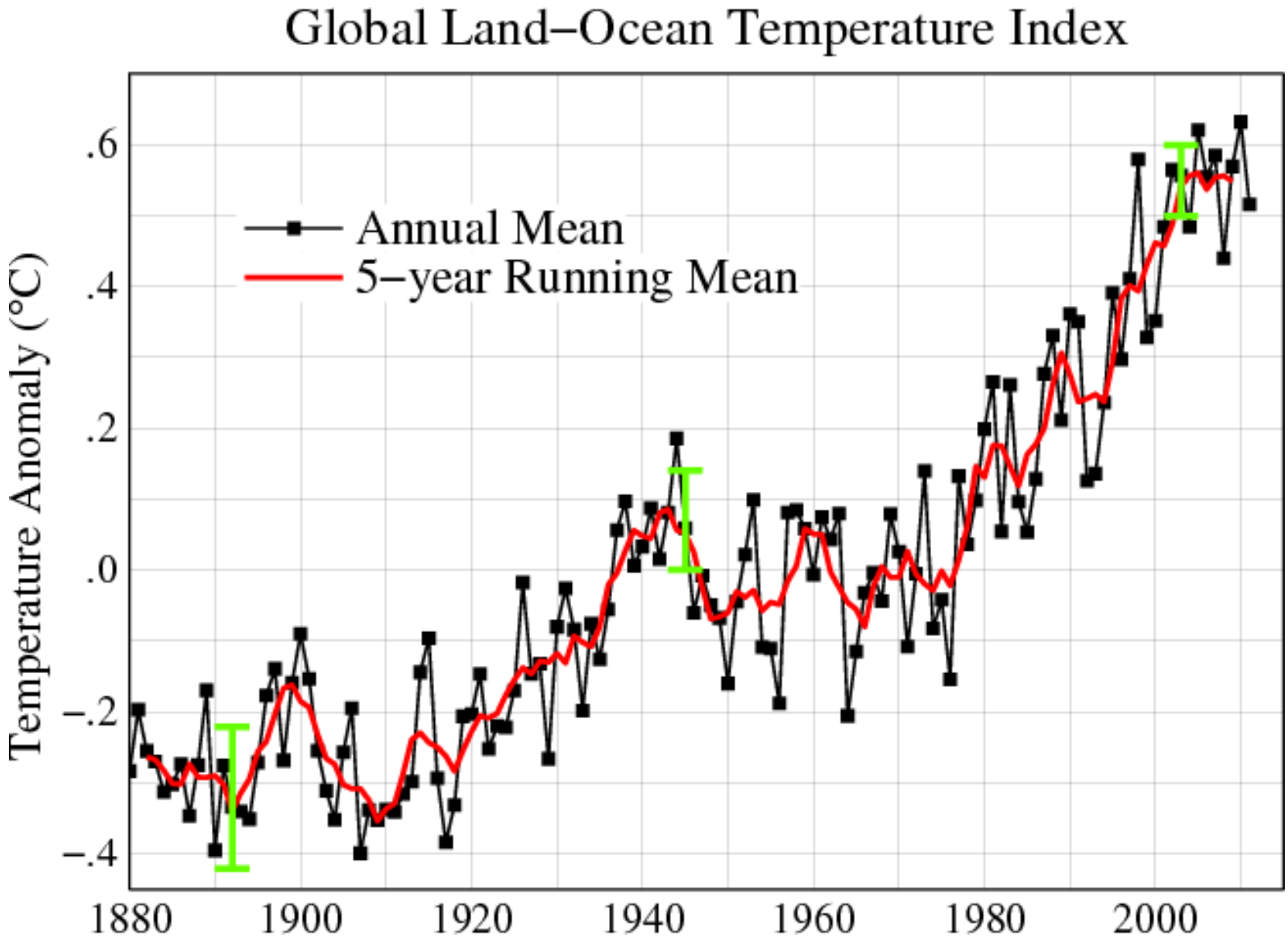
http://www.explainingclimatechange.ca/Climate%20Change/swf/irwindows/IRwindows2.swf

Climate Change

- Earth's average temperature has risen by about 1 ºC (1.4 ºF) over the past century, with about 2/3 of this since 1980.
- Projected to rise another 1 to 6 ºC (2 to 11.5 ºF) over the next hundred years.

http://www.explainingclimatechange.ca/

Temperature Variation from 1880-present



http://www.explainingclimatechange.ca/Climate%20Change/swf/videos/historical%20_temp.swf

Ways to Change Radiation Balance

- Three fundamental ways to change the radiation balance of the Earth:
  - by changing the incoming solar radiation due to changes in Earth's orbit or changes in the Sun,
  - changing the fraction of solar radiation that is reflected (called albedo) by changes in cloud cover, atmospheric particles, vegetation, or amount of water in the ice form,
  - by altering the infrared radiation from Earth back towards space by changing greenhouse gas concentrations.

Climate Change

- Small changes in the average temperature lead to large and potentially dangerous shifts in climate and weather. For example,
  - Changes in rainfall, resulting in more floods, droughts, or intense rain, as well as more frequent and severe heat waves.
  - Oceans are warming and becoming more acidic, ice caps are melting, and sea levels are rising.

http://www.explainingclimatechange.ca/

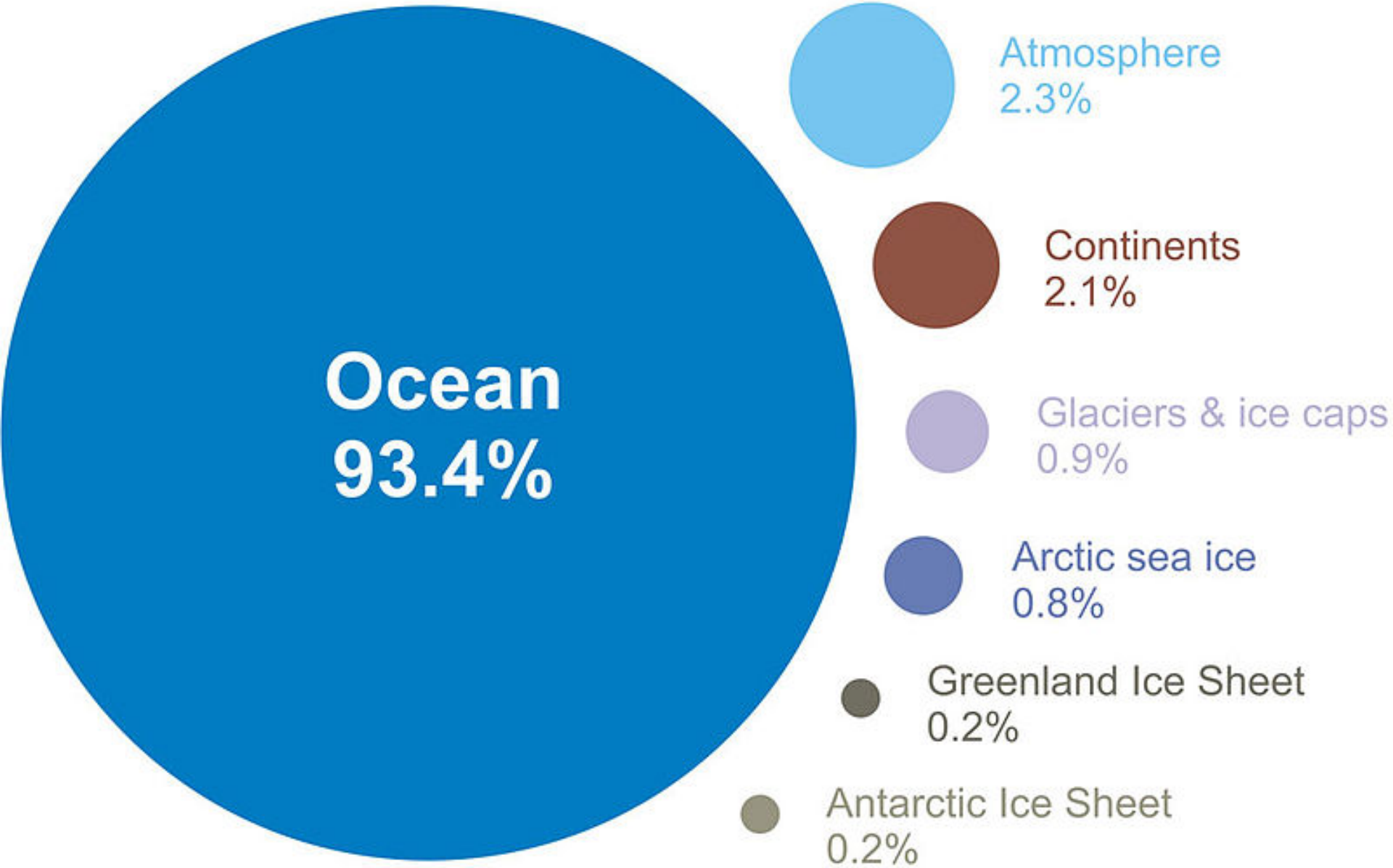
Climate vs. Weather

- **Weather** = the conditions of the atmosphere over a short period of time and typically for a local area.
  - Familiar examples of weather characteristics include the daily temperature, humidity, or the amount of precipitation produced by a storm.
  - Weather also includes severe weather conditions such as hurricanes, tornadoes, and blizzards.
  - Because of the dynamic nature of the atmosphere, it is not possible to predict weather conditions in a specific location months or years in advance.

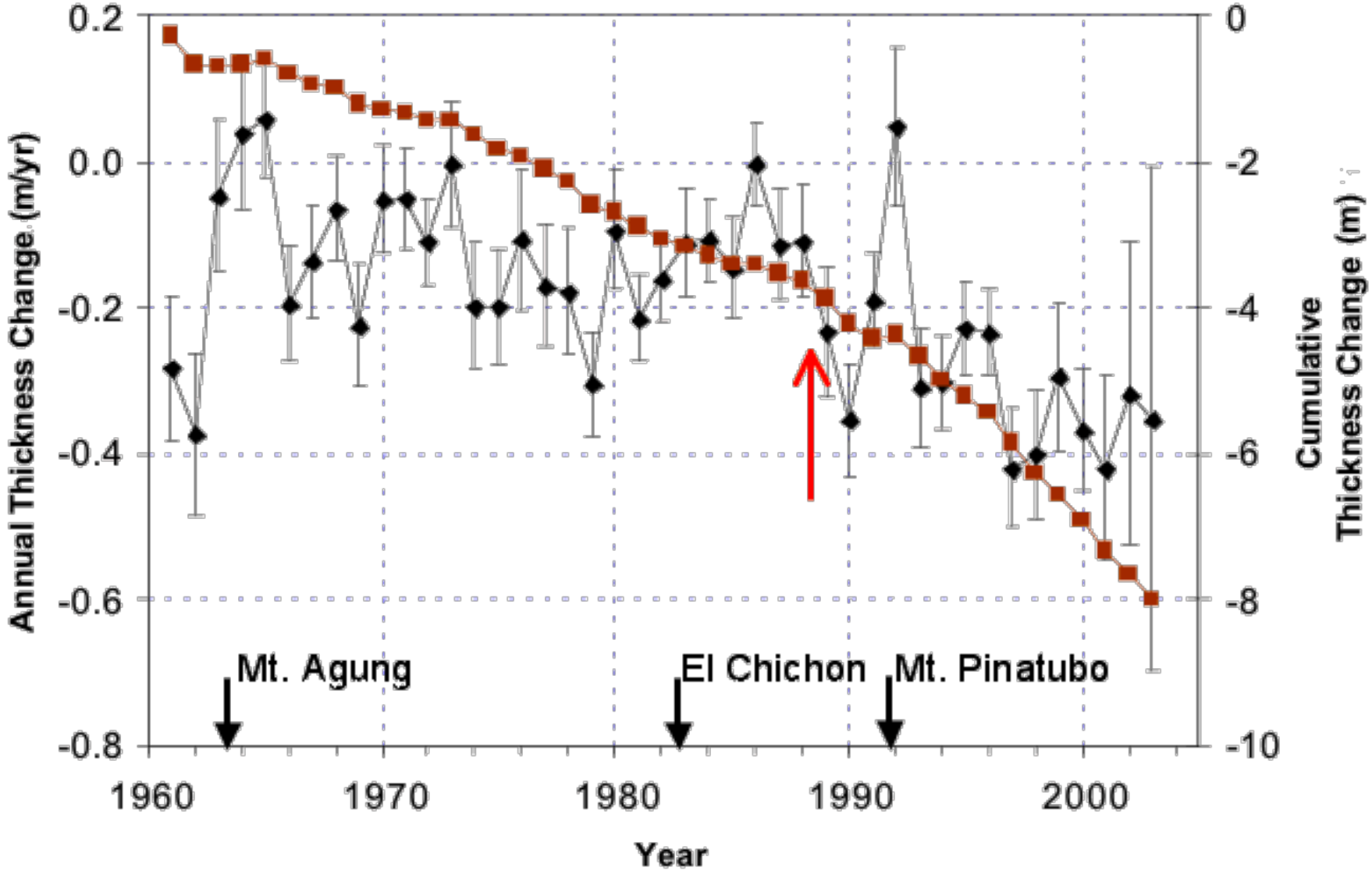
Climate vs. Weather

- **Climate** = the behavior of the atmosphere over a longer period of time and usually for a large area.
  - Climate is typically defined based on 30-year averages of weather.
  - Climate represents our expectations for the weather.
  - Scientists can compare recent and long-term observations of the climate to detect the influence of greenhouse gases on climate conditions.

Where is global warming going?

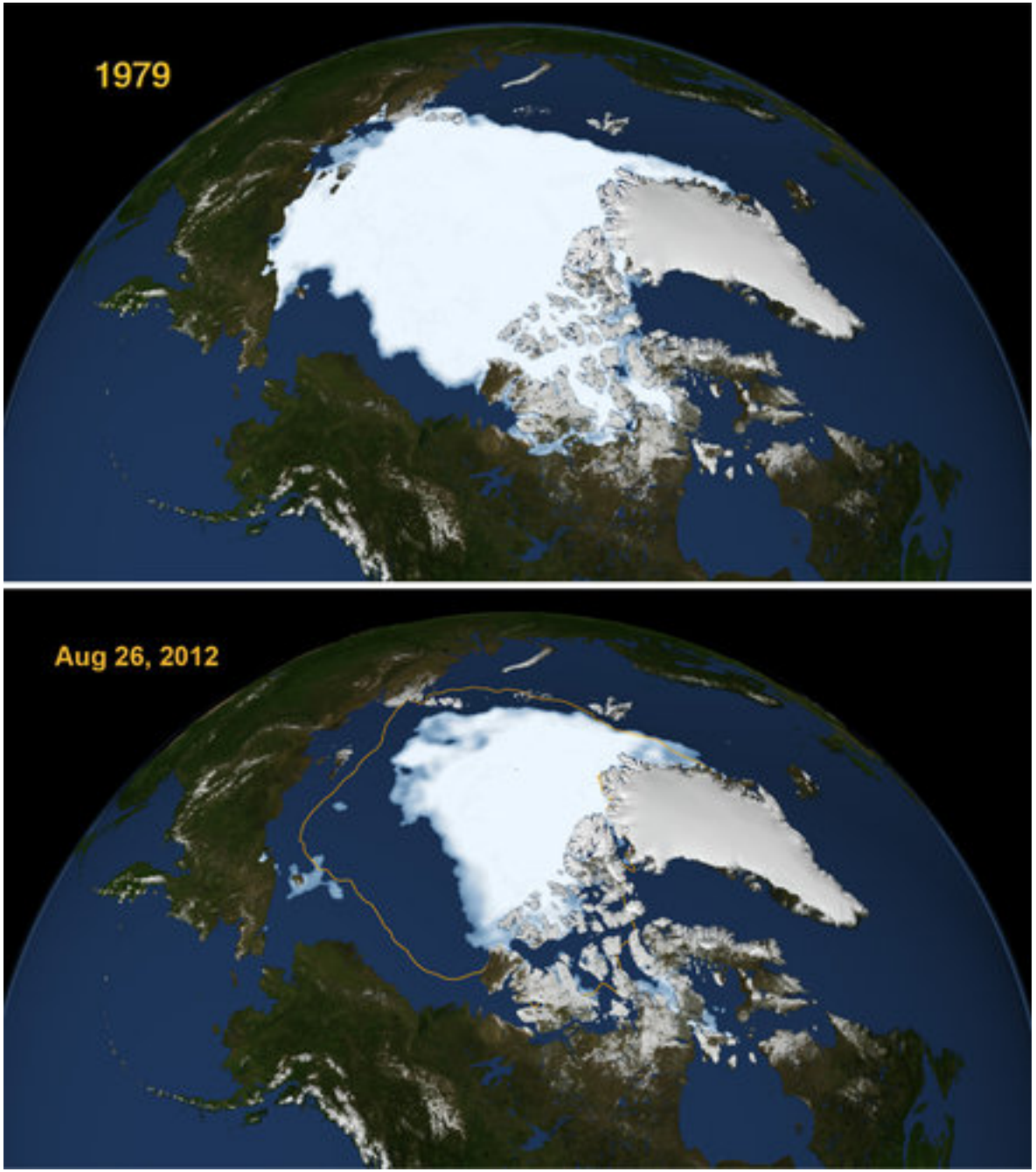


Effect on Glaciers



https://nsidc.org/glims/glaciermelt

https://climate.nasa.gov/climate_resources/4/graphic-dramatic-glacier-melt/

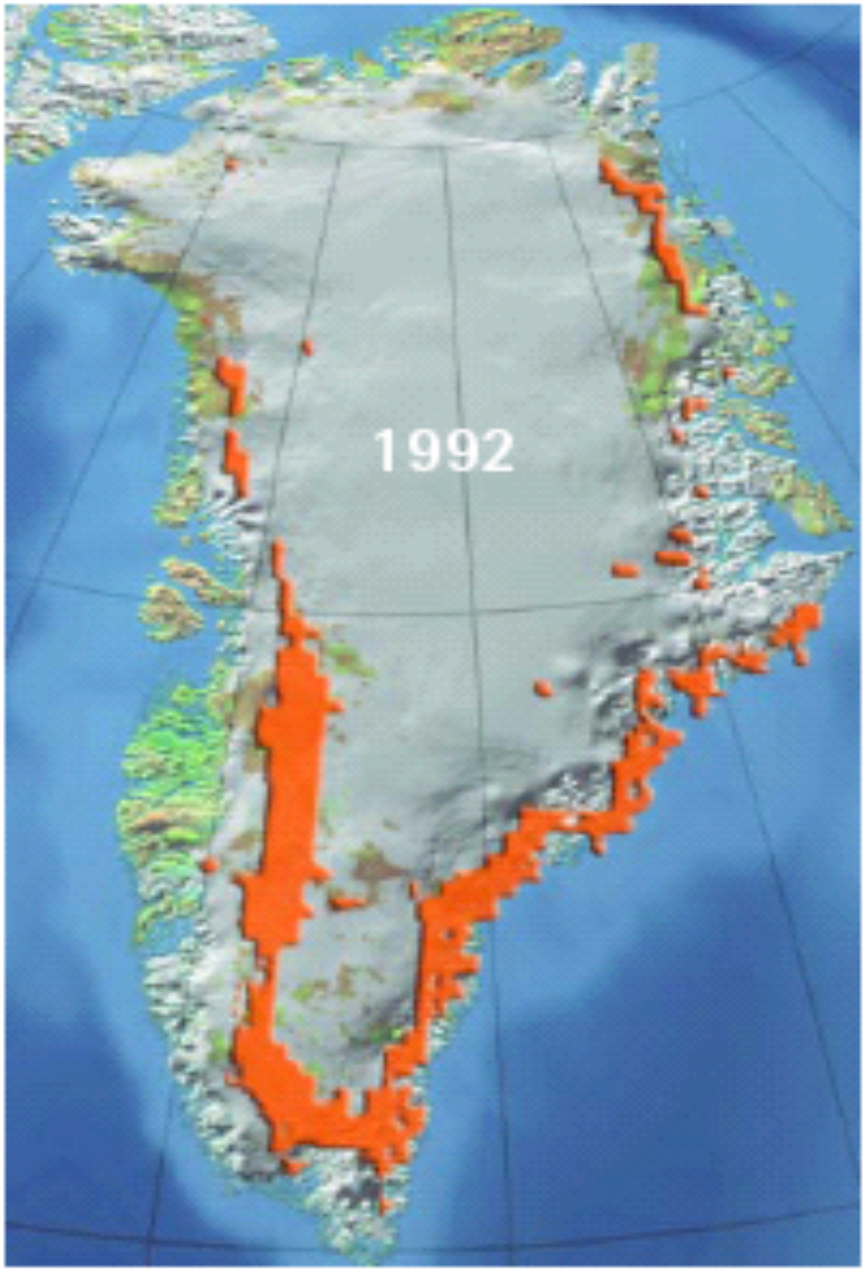


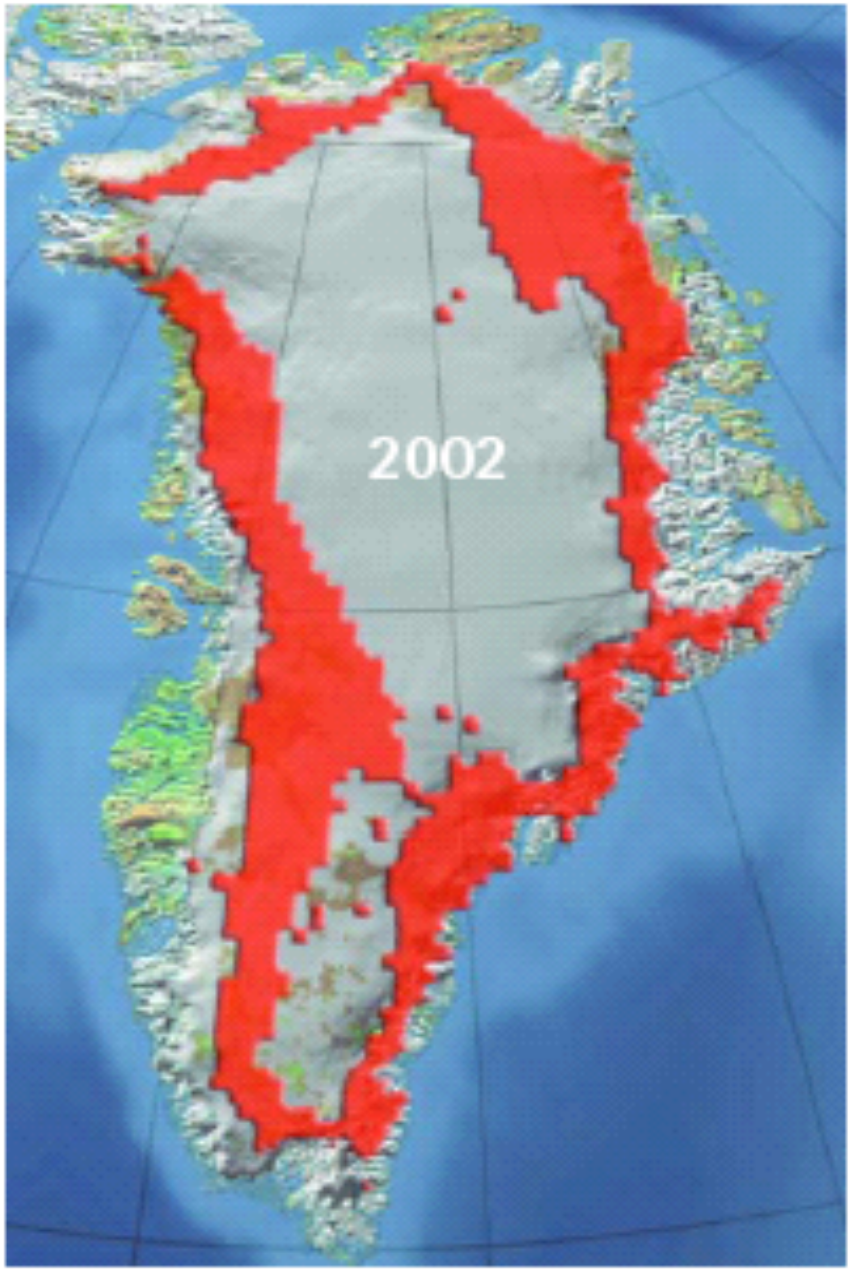
NASA photograph

Shrinking Polar Ice

Extent of Arctic summer ice in 1979 (top satellite image) and in August 2012 (lower satellite image).

Extent of ice melt in Greenland, 1992 and 2002





Arctic Climate Impact Assessment 2004

Why care about climate?

Climate governs:

- Distribution & abundance of species
- Productivity of farms, forests, & fisheries
- Geography of disease
- Livability of cities in summer
- Damages from storms, floods, wildfires
- Property losses from sea-level rise
- Expenditures on engineered environments

Feedback Loops

- One example of a feedback loop involves ice and liquid water.
  - Increased temperature melts more ice.
  - Liquid water absorbs more radiation from the sun than ice, which reflects more radiation back into space.
  - This increases the temperature of Earth and melts more ice.
  - Etc.

Land Use Changes

- Forests store more carbon than agricultural land.
- Agricultural land reflects more radiation back into space.

The Climate Change Story Line

Human Activities →

More GHG Emissions and Land Use Changes →

Change in Atmospheric GHG Concentrations →

Change in Average Surface Temperature →

Direct & Indirect Feedbacks →

Direct & Indirect Biogeophysical Impacts →

Societal Impacts →

Policy Response?

- Change in GHG Emissions? (**Mitigation**)
- Adapting to Changes? (**Adaptation**)
- Suffering the Consequences? (**Suffering**)

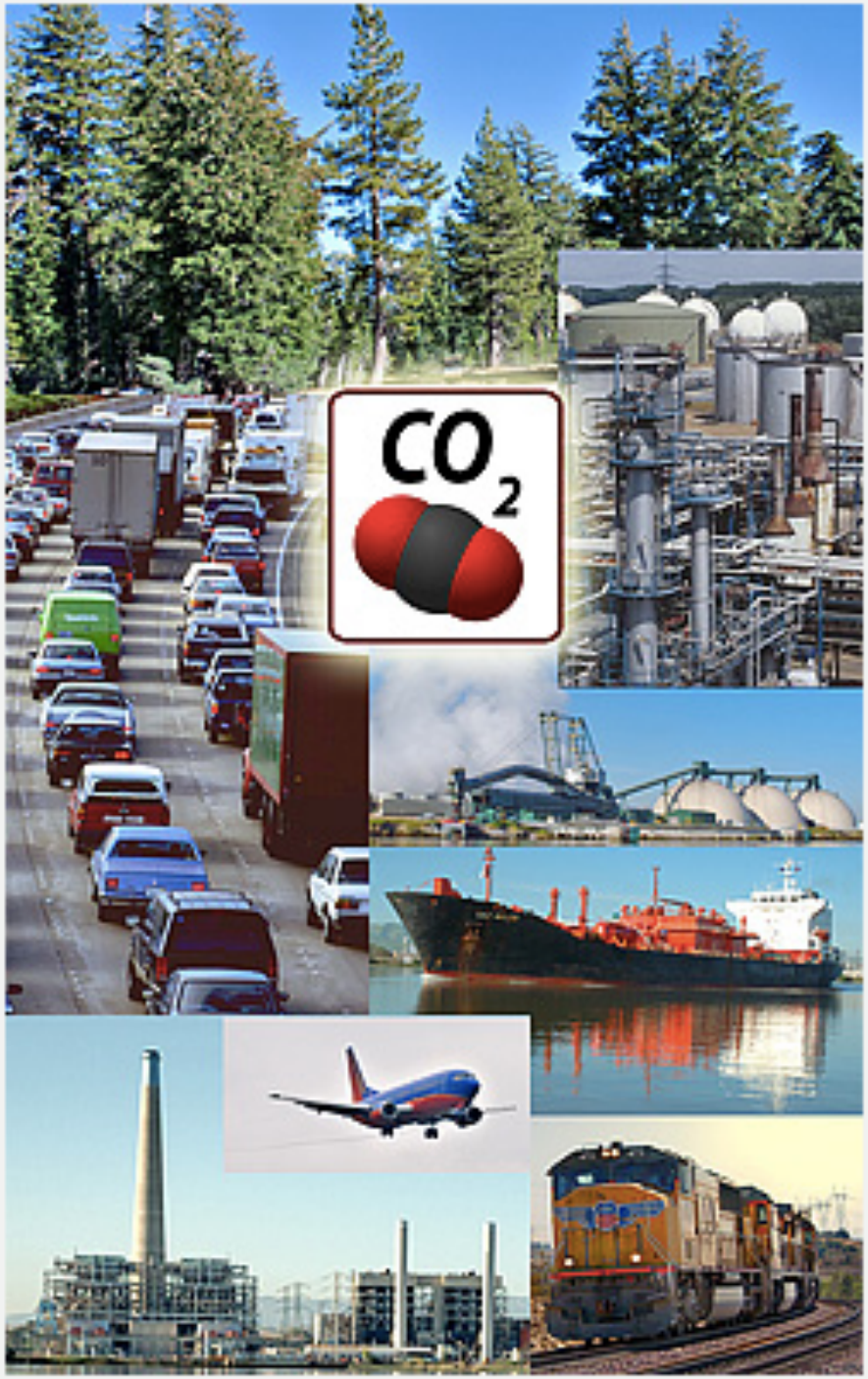
GHG Atmospheric Lifetimes and Global Warming Potential

- Each GHG has its own atmospheric residence time, governed by the sinks that remove it from the atmosphere.
- The global warming potential (GWP) of each GHG is measured relative to CO_2. GWP combines the GHG's efficiency at trapping IR radiation with its residence time in the atmosphere.
- Example: Over a 100-year period, a molecule of CH_4 contributes as much effect on climate change as 25 molecules of CO_2.

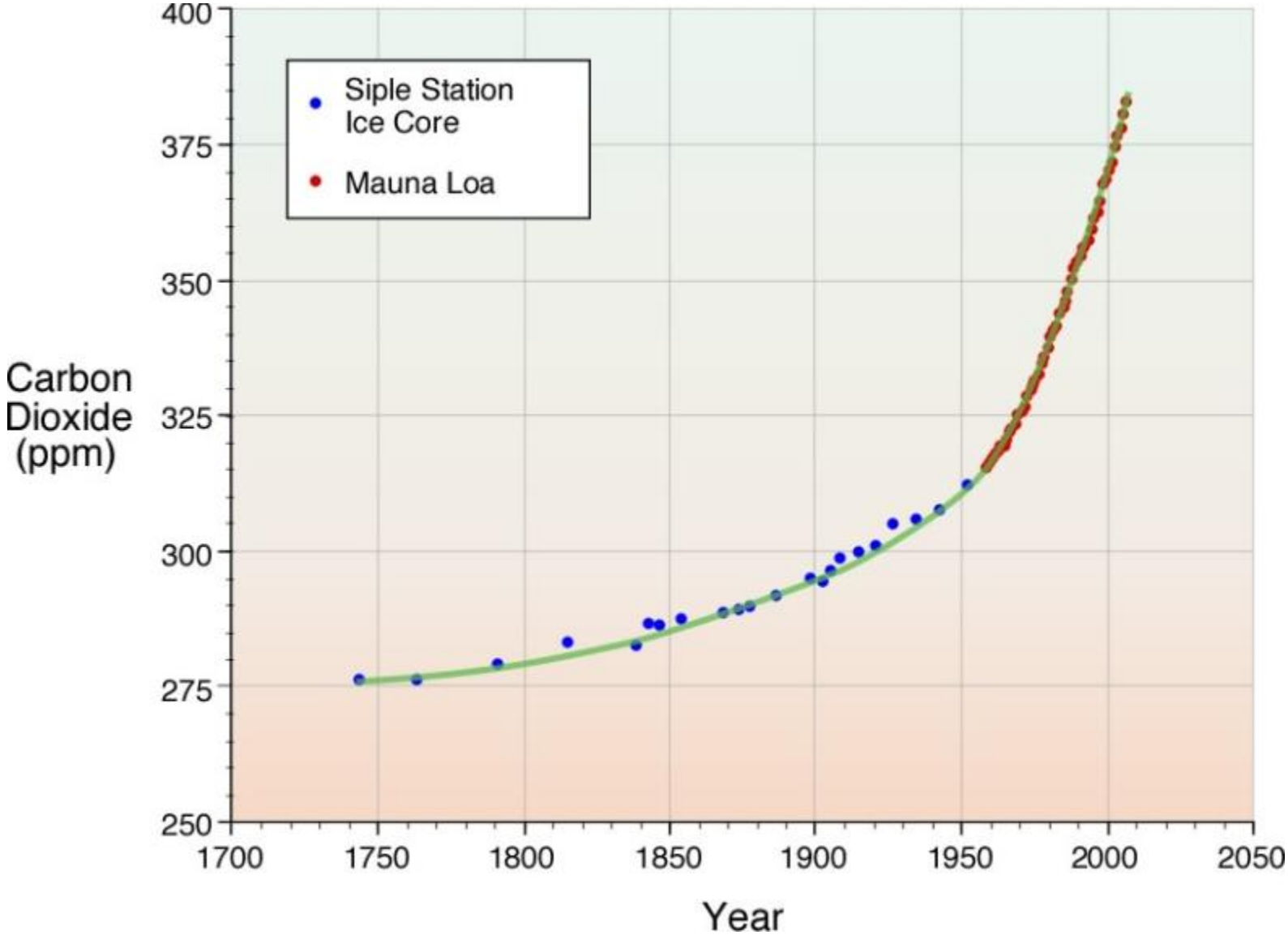
Global Warming Potential (GWP) = radiative impact of a GHG per molecule relative to impact of CO_2, taking into account its radiative properties and atmospheric lifetime

Atmospheric lifetime and GWP relative to CO_2 at different time horizon for various greenhouse gases.

Gas name	Chemical formula	Lifetime (years)	Global warming potential (GWP) for given time horizon		
			20-yr	100-yr	500-yr
Carbon dioxide	CO_2	See above	1	1	1
Methane	CH_4	12	72	25	7.6
Nitrous oxide	N_2O	114	289	298	153
CFC-12	CCl_2F_2	100	11,000	10,900	5 200
HCFC-22	$CHClF_2$	12	5160	1810	549
Tetrafluoromethane	CF_4	50,000	5210	7390	11,200
Hexafluoroethane	C_2F_6	10,000	8630	12,200	18,200
Sulphur hexafluoride	SF_6	3200	16,300	22,800	32,600
Nitrogen trifluoride	NF_3	740	12,300	17,200	20,700

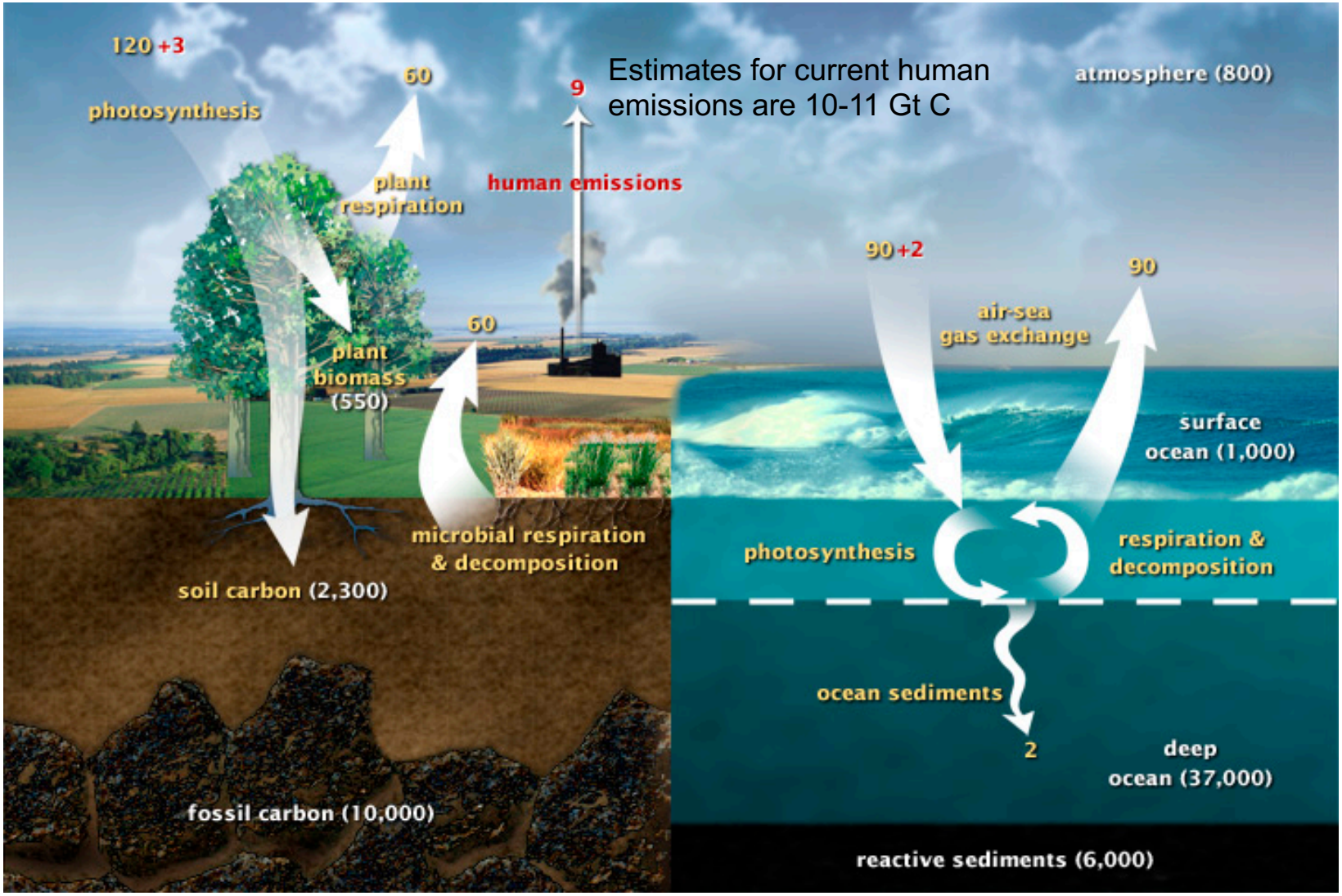

CO_2

CO_2 Concentrations



http://www.eoearth.org/article/Greenhouse_gas

Fast Carbon Cycle



The movement of carbon between land, atmosphere, and oceans in billions of tons of carbon per year. Yellow numbers are natural fluxes, red are human contributions in Gt of carbon per year. White numbers indicate stored carbon.

Role of Humans in the CO_2 Increases

- About 65% of anthropogenic CO_2 to atmosphere is from combustion of fossil fuels.
- Remaining 35% from deforestation and the conversion of prairie, woodland, and forested ecosystems primarily into less productive agricultural systems.
- Natural ecosystems can store 20 to 100 times more carbon dioxide per unit area than agricultural systems.

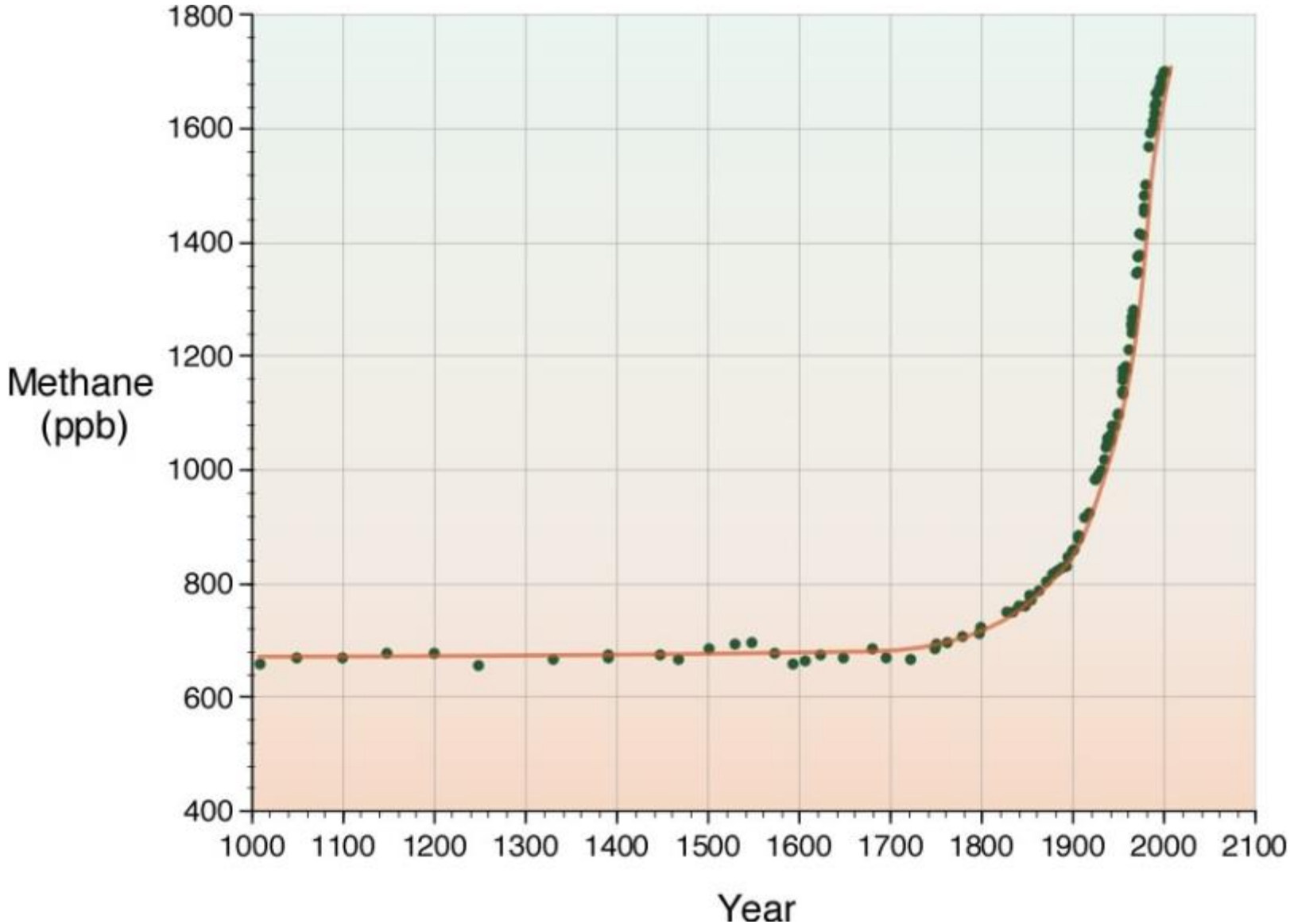
http://www.eoearth.org/article/Greenhouse_gas

Role of Humans in the CO_2 Increases

- The main human sources of CO_2 – deforestation and fossil-fuel burning – are quite well quantified. The observed CO_2 build-up in the atmosphere matches these human inputs, after subtraction of estimated rates of uptake in the oceans and northern forests.
- The ice-core data show that atmospheric CO_2 has not been above 300 ppm in the last 400,000 years (it's over 400 ppm today) and that natural fluctuations in atmospheric CO_2 over the past 10,000 years have been only ± 10 ppm (compared to the over 100 ppm increase since the start of the Industrial Revolution).
- Carbon-14 analysis of tree rings back to 1800 confirms the fossil-fuel contribution to the atmospheric CO_2 burden in the last 200 years.


CH4

Methane Concentrations 1000-2000 AD



http://www.eoearth.org/article/Greenhouse_gas

Naturally Occurring Methane

- Naturally occurring methane is mainly produced by the process of methanogenesis, a multistep process is used by microorganisms as an energy source. The net reaction is:

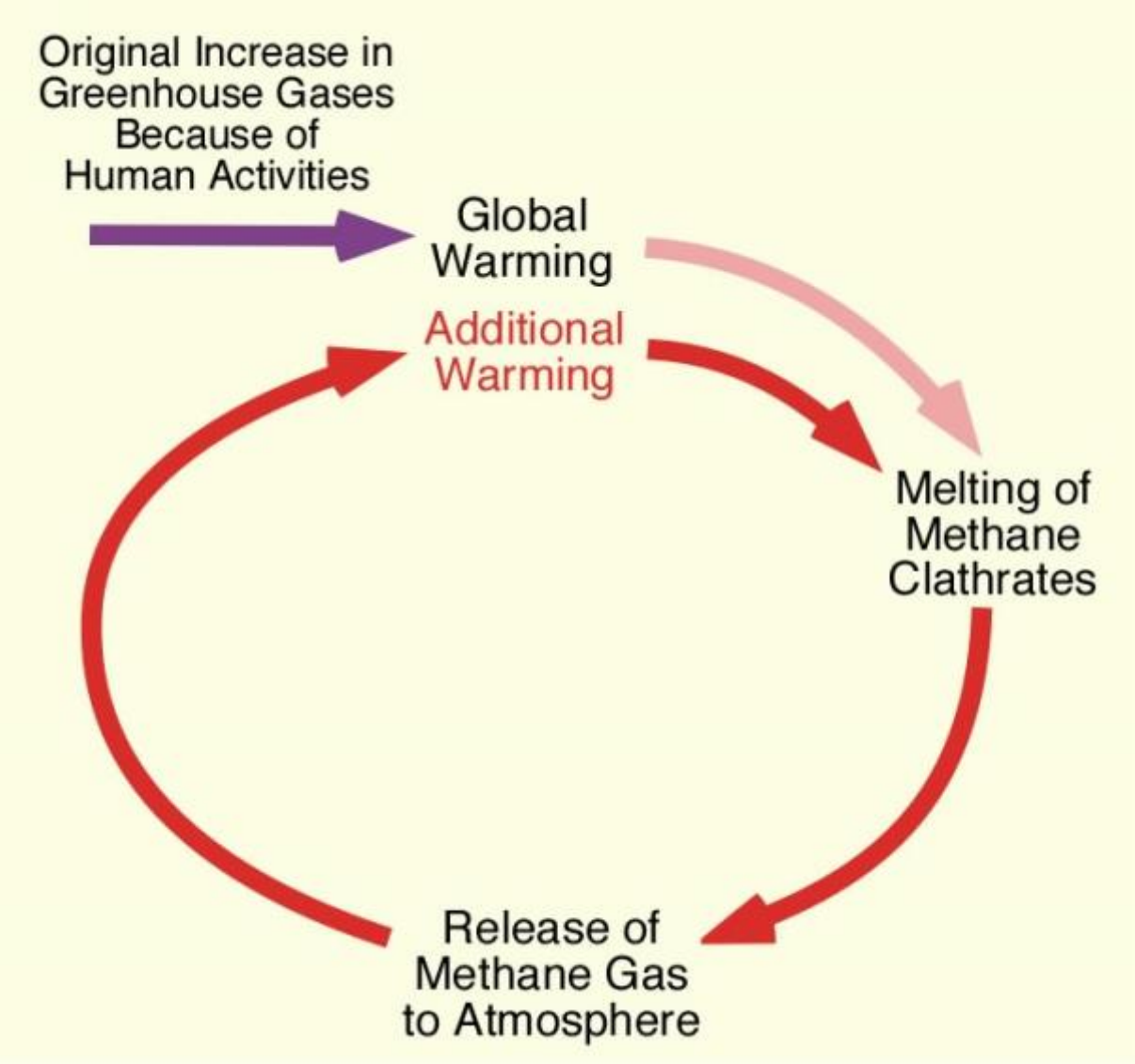
$$CO_2 + 8\ H^+ + 8\ e^- \rightarrow CH_4 + 2\ H_2O$$

- Methanogenesis is a form of anaerobic respiration used by organisms that occupy landfill, ruminants (e.g., cattle), and the guts of termites.

Atmospheric Methane Sources

- Biogenic sources (>70% of total)
  - Wetlands
  - Rice agriculture
  - Livestock
  - Landfills
  - Biomass burning
  - Forests
  - Oceans
  - Termites
- Non-biogenic sources
  - Emissions from natural gas, petroleum and coal mining and burning
  - Waste treatment
  - Geological sources (methane clathrates in ocean and permafrost)
  - Fossil CH_4 from natural gas seepage
  - Geothermal/volcanic CH_4

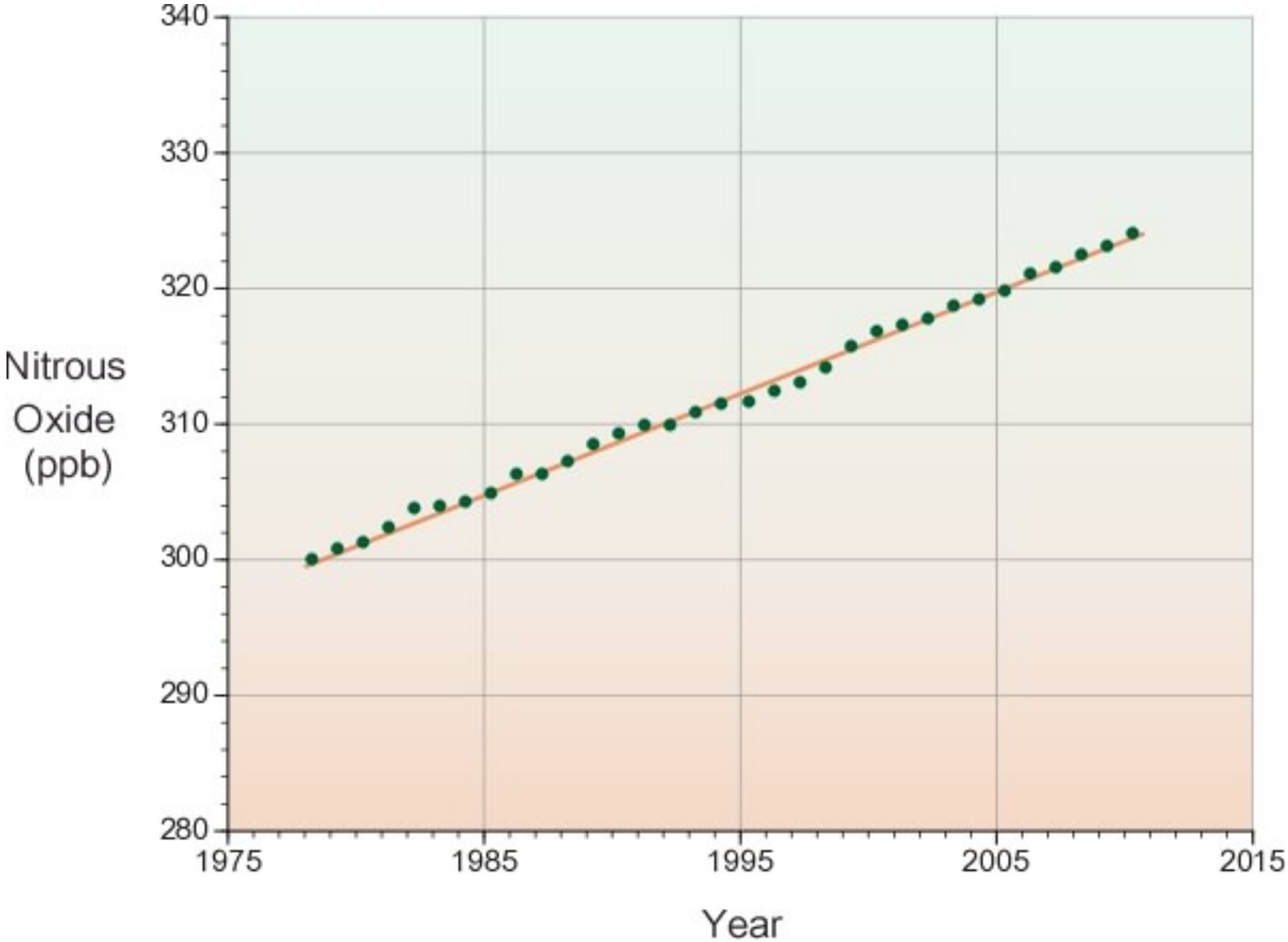
Feedback Example



http://www.eoearth.org/article/Greenhouse_gas


N_2O

N_2O Concentrations



http://www.eoearth.org/article/Greenhouse_gas

Role of Humans in the N_2O Increases

- The average concentration of nitrous oxide in the atmosphere is now increasing at a rate of 0.2 to 0.3% per year.
- Sources for the increase of nitrous oxide in the atmosphere include land-use conversion, fossil fuel combustion, biomass burning, and soil fertilization.
  - Most of the nitrous oxide added to the atmosphere each year due to human activities comes from agricultural soils, where nitrogen-rich fertilizer and manure is converted to nitrous oxide by soil bacteria. Nitrous oxide is also released into the atmosphere when fossil fuels and biomass are burned.

http://www.eoearth.org/article/Greenhouse_gas

What could change the Earth's energy balance and change the Earth's temperature?

- Changes in solar input
  - Sun's output
  - Earth's position and orientation
  - Cosmic dust
- Changes in transparency of atmosphere to incoming shortwave energy
  - Clouds
  - Dust, ash, soot
  - O_3
- Changes in transparency of atmosphere to outgoing long wave radiant energy
  - Clouds
  - Greenhouse gases (H_2O, CO_2, CH_4, N_2O, O_3)

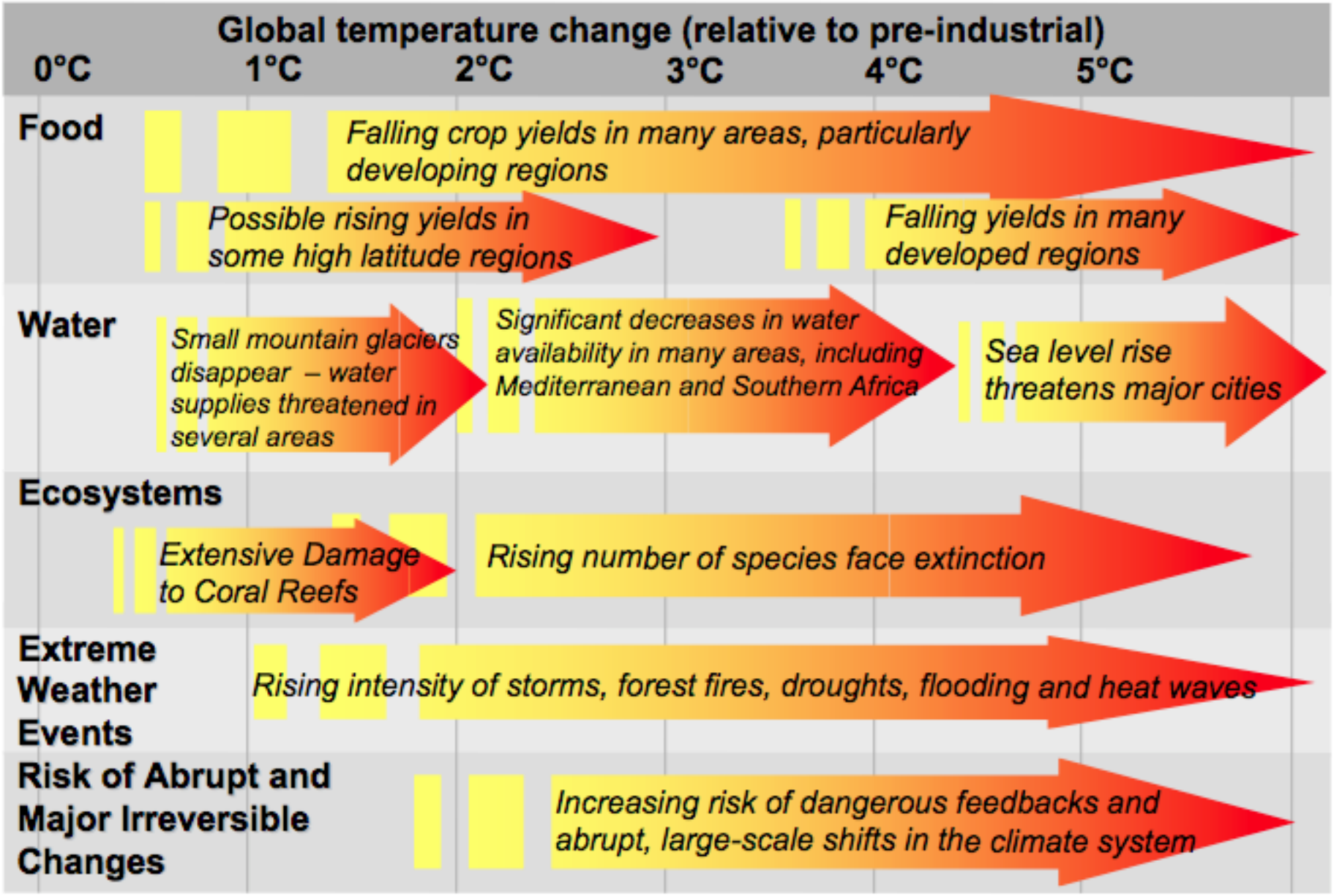
Do other factors explain the temperature rise?

http://www.bloomberg.com/graphics/2015-whats-warming-the-world/

Some Examples of Climate Change Impacts

- Biodiversity
- Coral Reefs
- Disease vectors
- Extreme Weather
- Sea level rise
- Water supplies
- Wildfires

Projected impacts of climate change



2015 Paris Climate Change Agreement

http://www.nytimes.com/interactive/2015/11/23/world/carbon-pledges.html

http://www.nytimes.com/interactive/2015/12/12/world/paris-climate-change-deal-explainer.html

https://www.nytimes.com/interactive/2017/11/06/climate/world-emissions-goals-far-off-course.html

Ocean Impacts of Anthropogenic Climate Change

- Decreased ocean productivity,
- Altered food web dynamics,
- Reduced abundance of habitat-forming species,
- Shifting species distributions,
- A greater incidence of disease.

O Hoegh-Guldberg, J F Bruno
Science 2010;328:1523-1528

Effect of CO_2 Absorption in Ocean

- *Oceans have absorbed approximately one-third of the carbon dioxide produced by human activities.*
- *The absorption of anthropogenic CO_2 has acidified the surface layers of the ocean, with a steady decrease of 0.02 pH units per decade over the past 30 years and an overall decrease since the pre-industrial period of 0.1 pH units.*
- *Although these increases appear small in terms of pH, they are associated with a substantial decline in the concentration of carbonate ions.*

O Hoegh-Guldberg, J F Bruno Science 2010;328:1523-1528

What can we do?

- Eat lower on the food chain, less meat and more fruits and vegetables.
- Waste less food and encourage businesses to sell imperfect produce.
  - Food production worldwide produces about 18% of the carbon dioxide emissions.
  - About 1/3 of the food produced worldwide goes uneaten.
- Walk or bicycle for trips under a mile or two.
  - The average car produces about 411 grams (almost a pound) of carbon dioxide per mile.

What can we do?

- If you can afford it…
  - Insulate your home
  - Solar panels for electricity
  - Drive a hybrid or any high mpg car
  - LED light bulbs
- Fly less
- ***Encourage your elected representatives to take action.***

Meat and Climate Change

- *The global livestock industry produces more greenhouse gas emissions than all cars, planes, trains and ships combined.*
- *The recent landmark report from the Intergovernmental Panel on Climate Change found that dietary change can "substantially lower" emissions.*
- *Two recent peer-reviewed studies calculated that, without severe cuts in this trend* [to more meat consumption*], agricultural emissions will take up the entire world's carbon budget by 2050, with livestock a major contributor. This would mean every other sector, including energy, industry and transport, would have to be zero carbon, which is described as "impossible".*

http://www.theguardian.com/environment/2014/dec/03/eating-less-meat-curb-climate-change