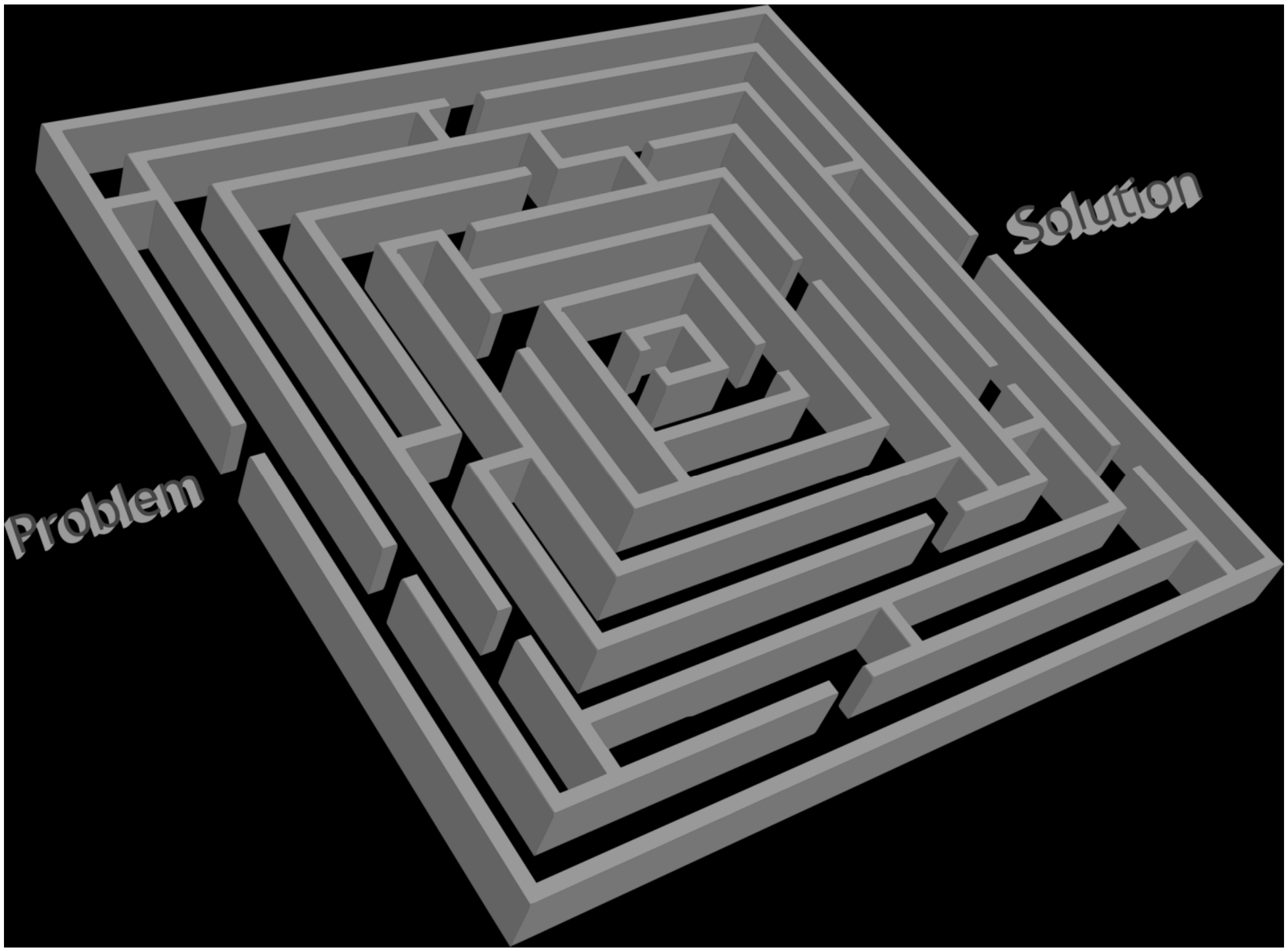
Climate Change

…a review

Climate Change

Climate Change

Climate Change



Climate Change

- How will it affect me
- What do we know
  - Sun-Earth-Atmosphere
  - Hydrosphere-Cryosphere
  - Balance
- How does it work
- History
- Corrections *(…or how best to "fix" the mess we've made)*
- Resources

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How will it affect me?

- Small changes in climate result in large changes in habitat
  - During the last ice age, Northeast United States was covered by 3000 ft of ice
    …and the temperature was only 5 - 9°F cooler!
  - Glaciers are shrinking
  - Plant and animal ranges are shifting
  - Precipitation patterns are changing
  - Sea level is rising
  - Heat waves are more intense
  - Hurricanes are more intense
  - Frost-free and growing seasons are longer
  - Ice is disappearing from the Arctic and will likely become ice-free
  - Fresh water sources are shifting

…just as it has since the Earth became a planet!

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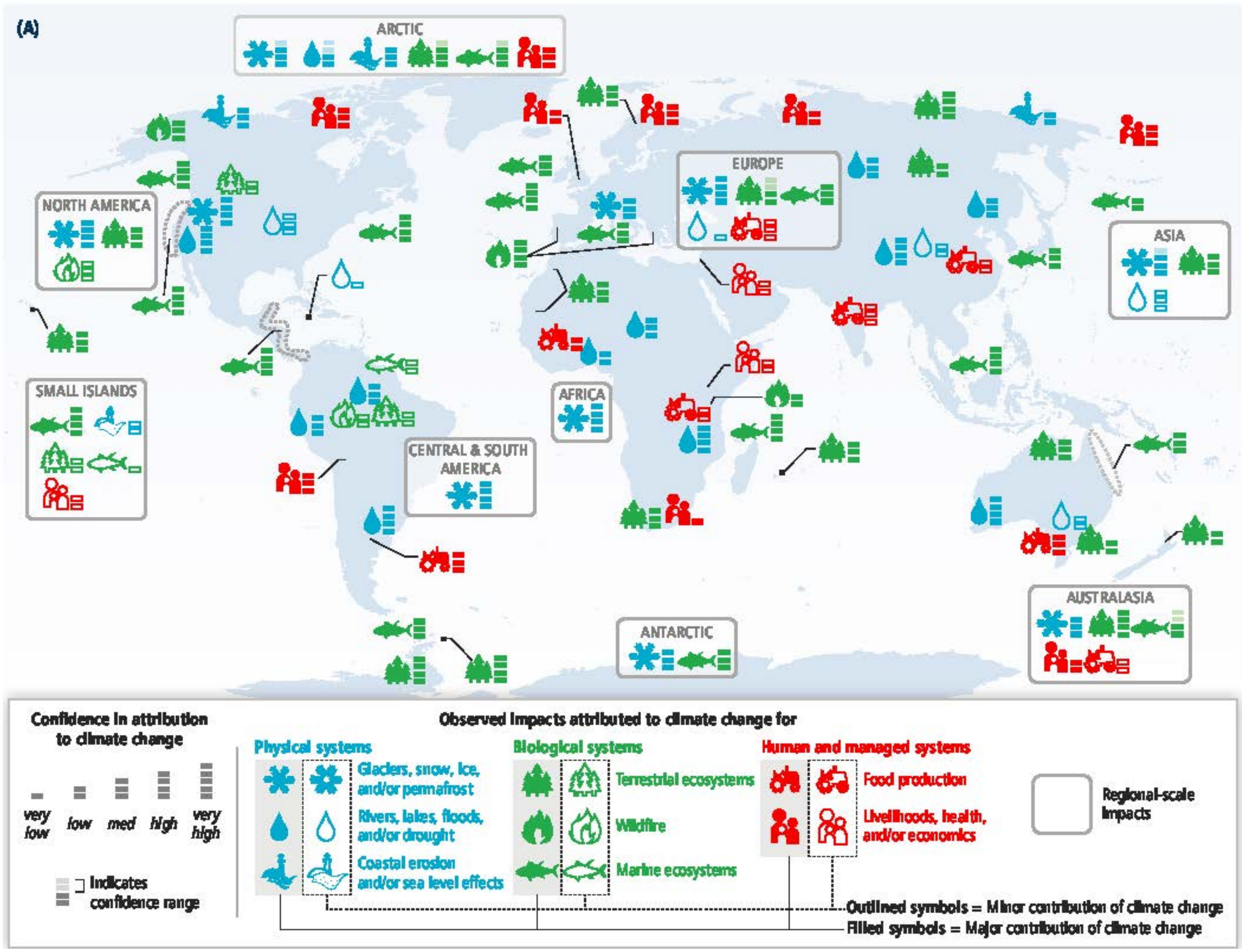

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- Climate is the state of the Earth's habitable environment consisting of the following components and their interactions
  - **Atmosphere**—a fast responding medium which surrounds us and immediately affects our condition
  - **Hydrosphere**—oceans and all reservoirs of water in liquid form. These are the main source of moisture for precipitation. The hydrosphere exchanges gases and particulates with the atmosphere
  - **Land masses**—affect the flow of atmosphere and oceans through their topography, vegetation cover, roughness, hydrological cycle, radiative properties (solids, liquids, gases) picked up by the wind or ejected from the earth's interior (volcanoes)
  - **Cryosphere**—the ice component of the climate system both on land in on the ocean's surface. The cryosphere plays a significant role in the Earth's radiation balance
  - **Biota**—all forms of life that through respiration and other activities affect the composition and physical properties of air and water

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- The energy that drives the climate system comes from our Sun
  - The Sun's energy reaching the earth is partially absorbed by different parts of the climate system
  - Absorbed energy is converted to heat
  - This energy is uneven in both space and time giving rise to seasonal variation

- Sun's energy
  - The Sun is a thermonuclear fusion reaction that converts hydrogen into helium.
  - Estimated temperature of the Sun's surface is 9,900°F and transfers heat energy via radiation
  - Solar radiation wavelength band is 0.2 to 2 micrometers (µm)

- Radiation heat transfer
  - Unlike conduction and convection, radiation heat transfer is independent of matter
  - All bodies emit radiation. The wavelength / spectrum of radiation are determined only by the body's temperature
  - Energy flux drops as the square of distance from the radiating body

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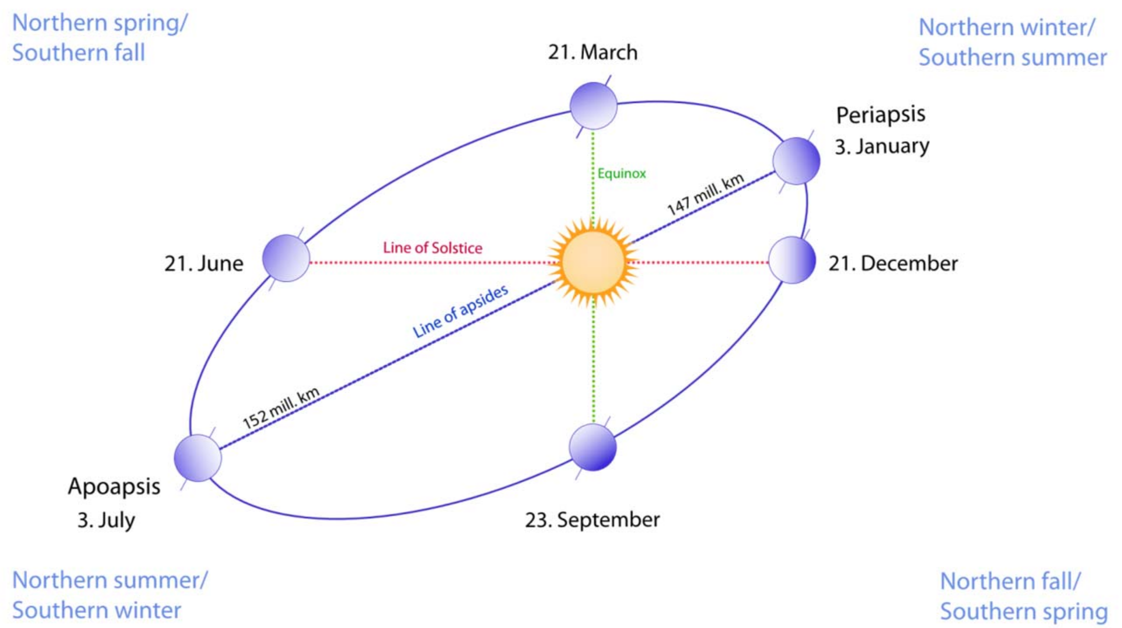
- Earth's orbit
  - The Earth's orbit around the Sun is elliptical with the sun at one foci of the ellipse. The time-of-year (season) for perihelion changes with a period of 21,000 years



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What about Earth sending energy into space?

- Earth's reflectivity = albedo = an average of 0.3
- Radiative equilibrium is when incoming and outgoing radiation are equal
- Stefan-Boltzman
  - Heat absorbed by Earth = $(1 - a)nR^2S_O$
    - $a = albedo$
    - $R = Earth's\ radius$
    - S_O= *solar constant*
  - Heat radiated from Earth =$(4\pi R^2)\sigma T^4$
    - $\sigma = Stefan - Boltzman\ constant$
    - $T = absolute\ temperature$
  - Earth's temperature
    - $T_e = \left[\frac{(1-Aa)S_O}{4\sigma}\right]^{0.25}$
    - which equals -18°C vs measured average surface temperature of 15°C
    - The difference? Greenhouse effect!

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- Earth's temperature
  - $T_e = \left[\frac{(1-Aa)S_O}{4\sigma}\right]^{1/4}$
  - ***which equals -18°C vs measured average surface temperature of 15°C***
  - The difference? Greenhouse effect!

…and we thought the greenhouse effect was a bad thing!

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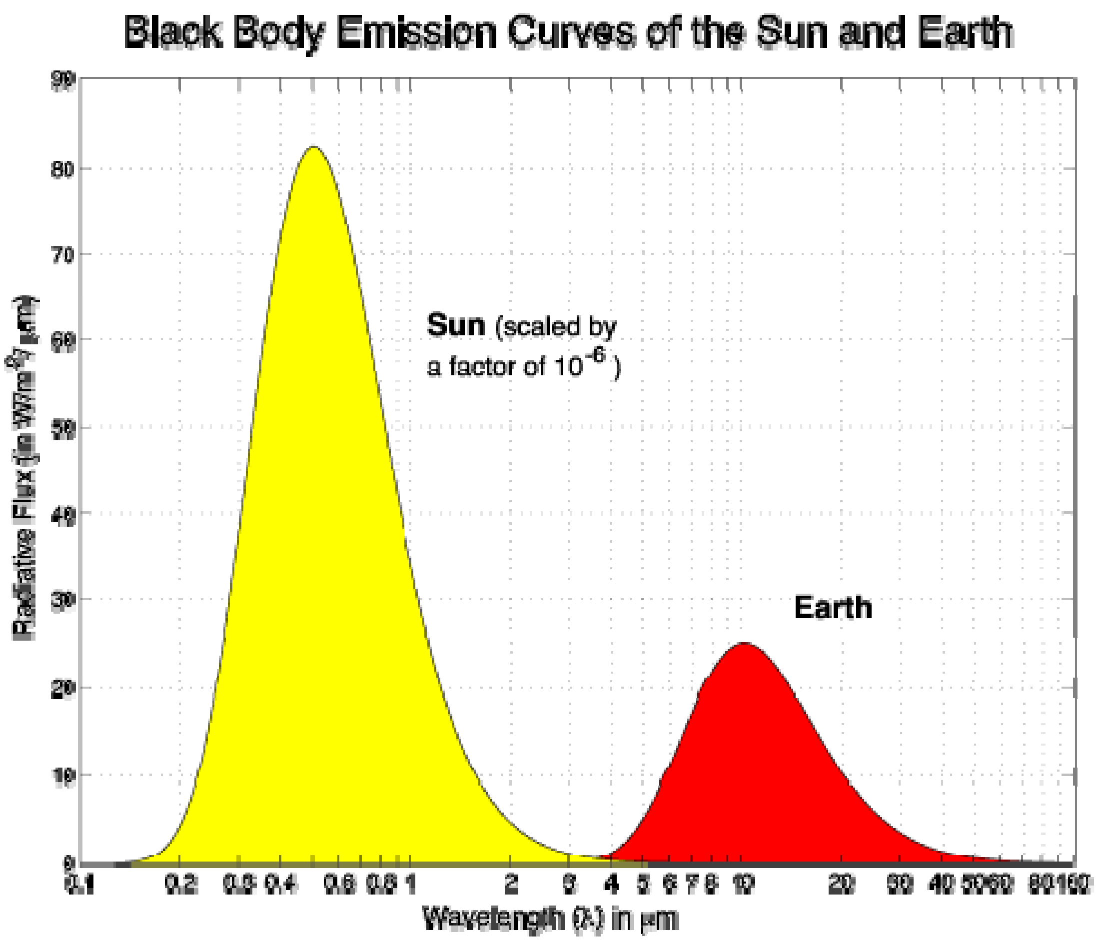

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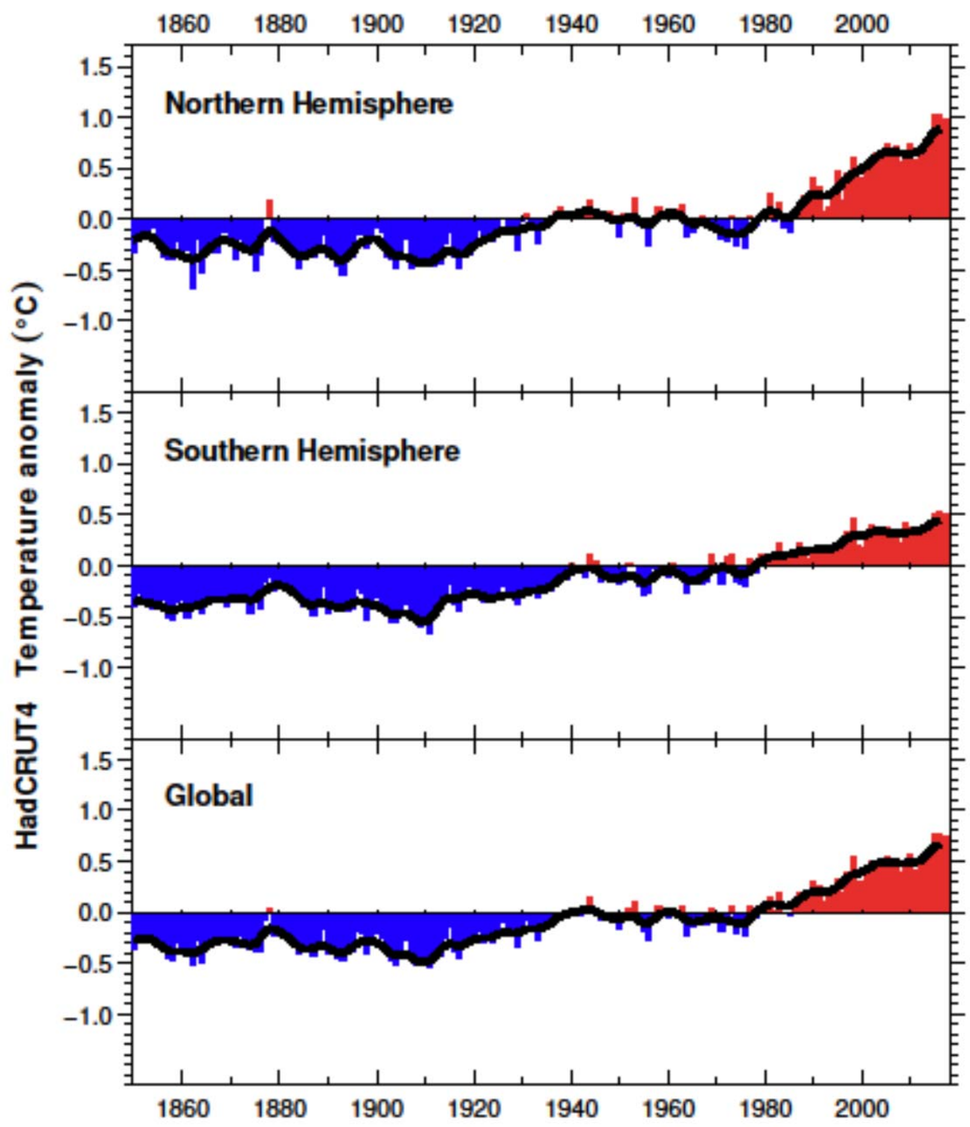

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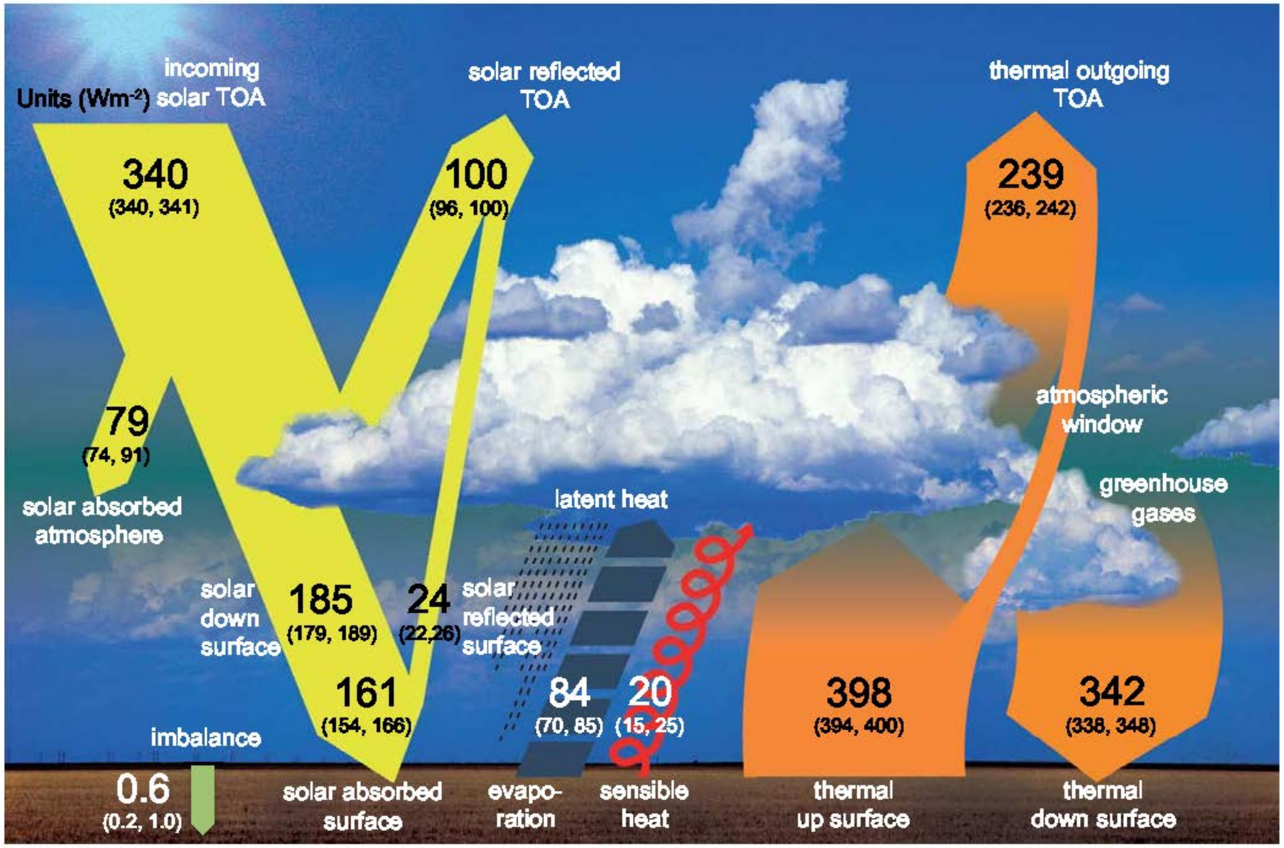

Figure 2.11: | Global mean energy budget under present-day climate conditions. Numbers state magnitudes of the individual energy fluxes in W m^{-2}, adjusted within their uncertainty ranges to close the energy budgets. Numbers in parentheses attached to the energy fluxes cover the range of values in line with observational constraints. (Adapted from Wild et al., 2013.)

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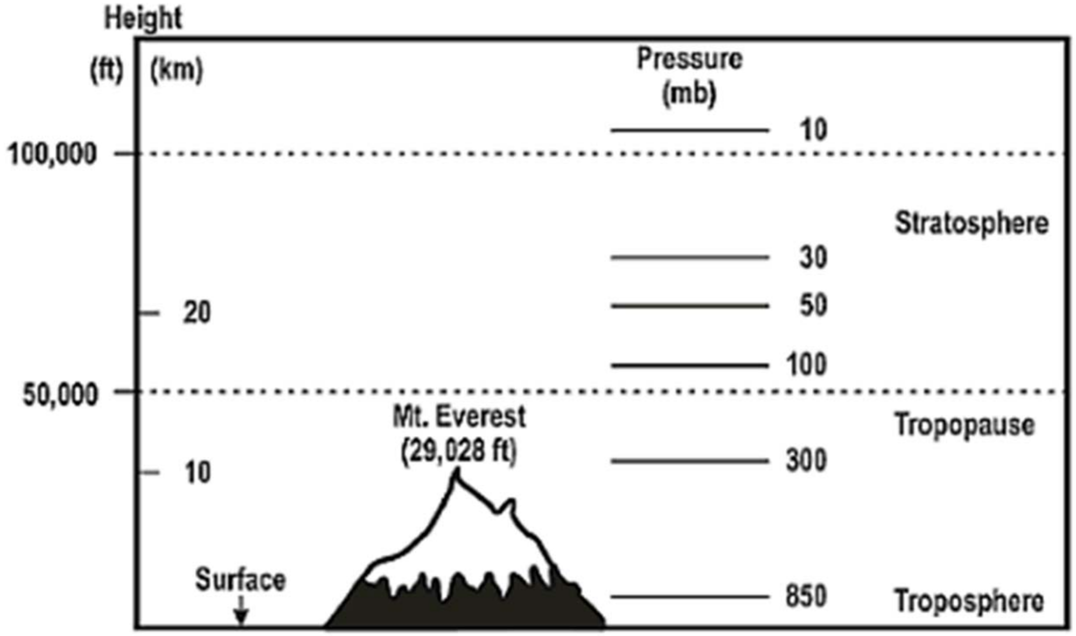

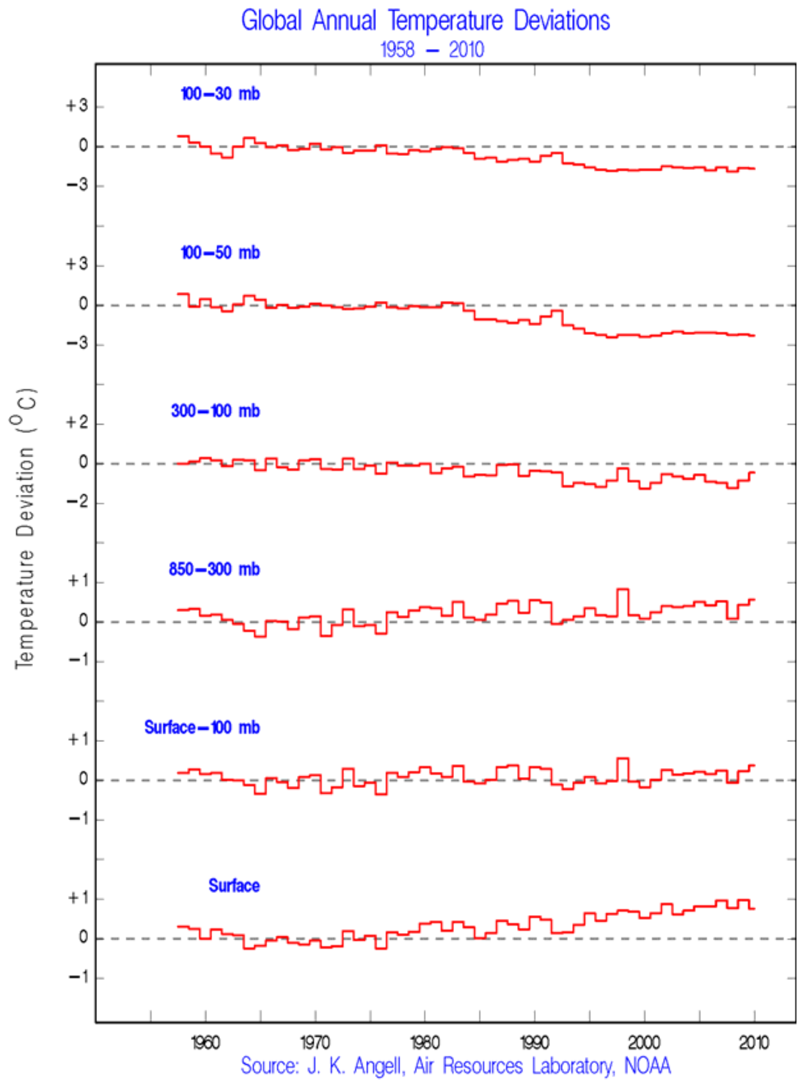

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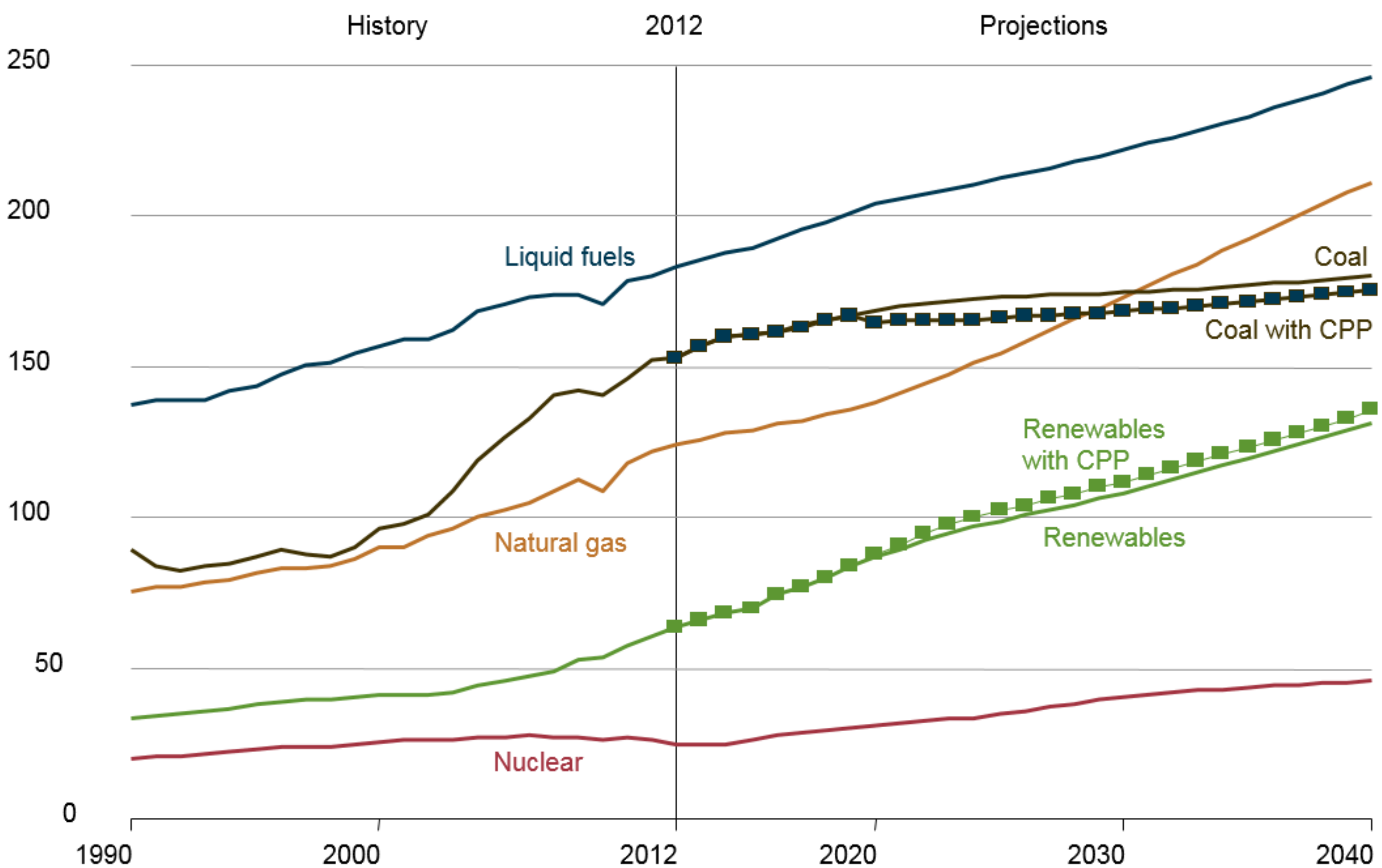
Figure ES-2. Total world energy consumption by energy source, 1990-2040

quadrillion Btu



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- Let's do some math:
  - 450 quads of energy produced via hydrocarbons per year
  - 145 lbs CO_2 per MMBTU hydrocarbon combusted
  - = 66 trillion lbs CO_2 emitted per year (…and 11 trillion lbs H2O!)
  - = 30 billion metric tons per year (*if all that's combusted stays in the atmosphere!!)*
  - $5.15\ x\ 10^{18}$ total kg in the atmosphere = 5.8 ppmw increase in CO_2 per year
  - = 3.8 ppmv increase in CO_2 per year

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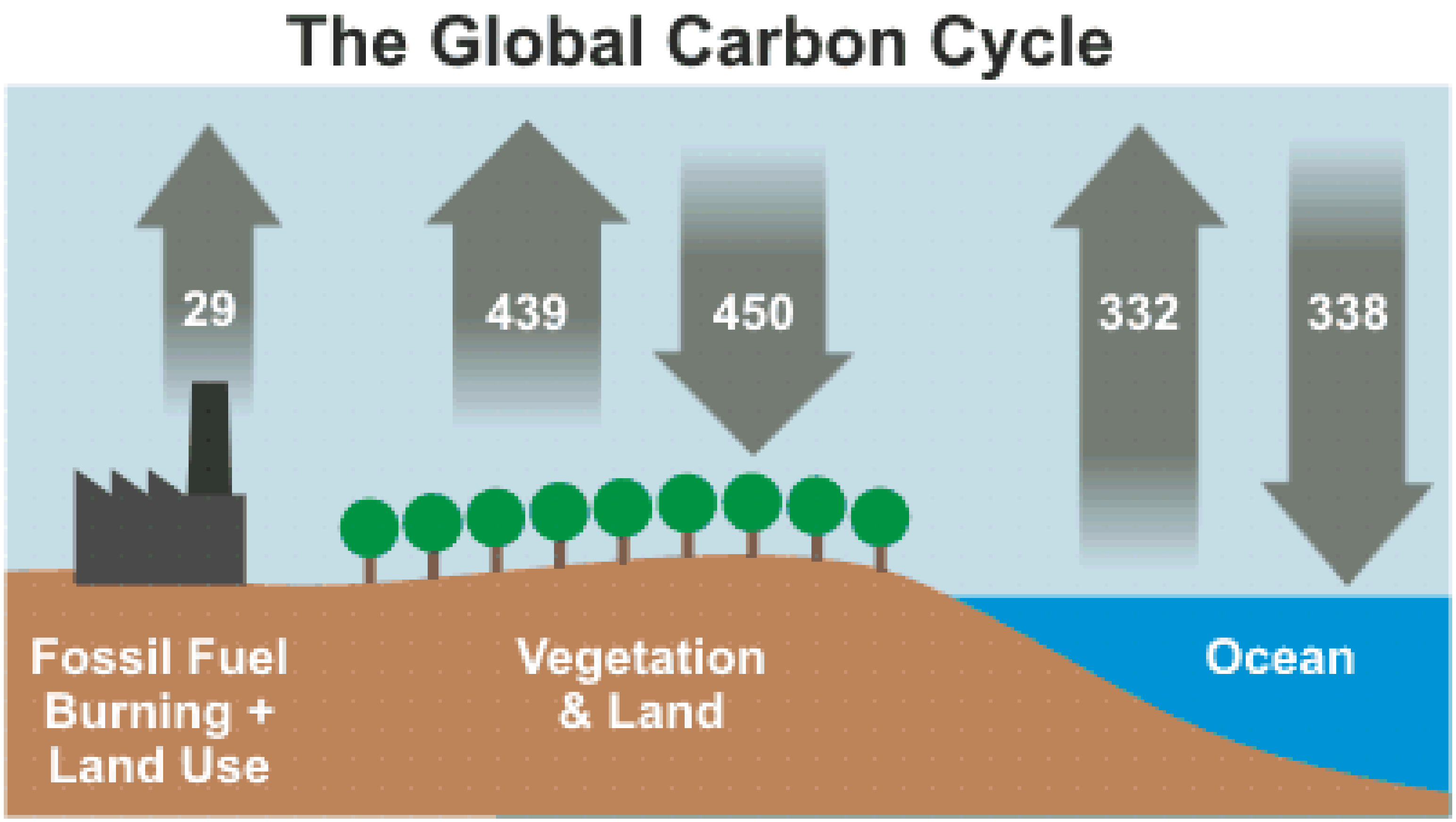

- *Figure 1: Global carbon cycle. Numbers represent flux of carbon dioxide in gigatons (Source: Figure 7.3, IPCC AR4).*

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- Why are we picking on CO_2?

Greenhouse Gas	Summer Fluxes 1998	(W/m^2) 1999	Past
CFC11 all	0.15	0.11	0.15
CFC12 all	0.29	0.24	0.27
HNO_3	0.075	0.063	0.066
CH_4	1.16	0.60	1.08
N_2O	1.14	0.64	0.89
O_3	2.57	2.47	2.61
H_2O	178	256	251
CO_2	10.5	10.5	10.5
Total			

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- That's a thumbnail of information about energy transfer between the sun, earth, and atmosphere
- …and a useful tool to evaluating local conditions is: Temperature evaluation tool (URL here)

  …with instructions: Temperature evaluation tool instructions

- …but wait, there's more, what about the ocean and polar ice?...

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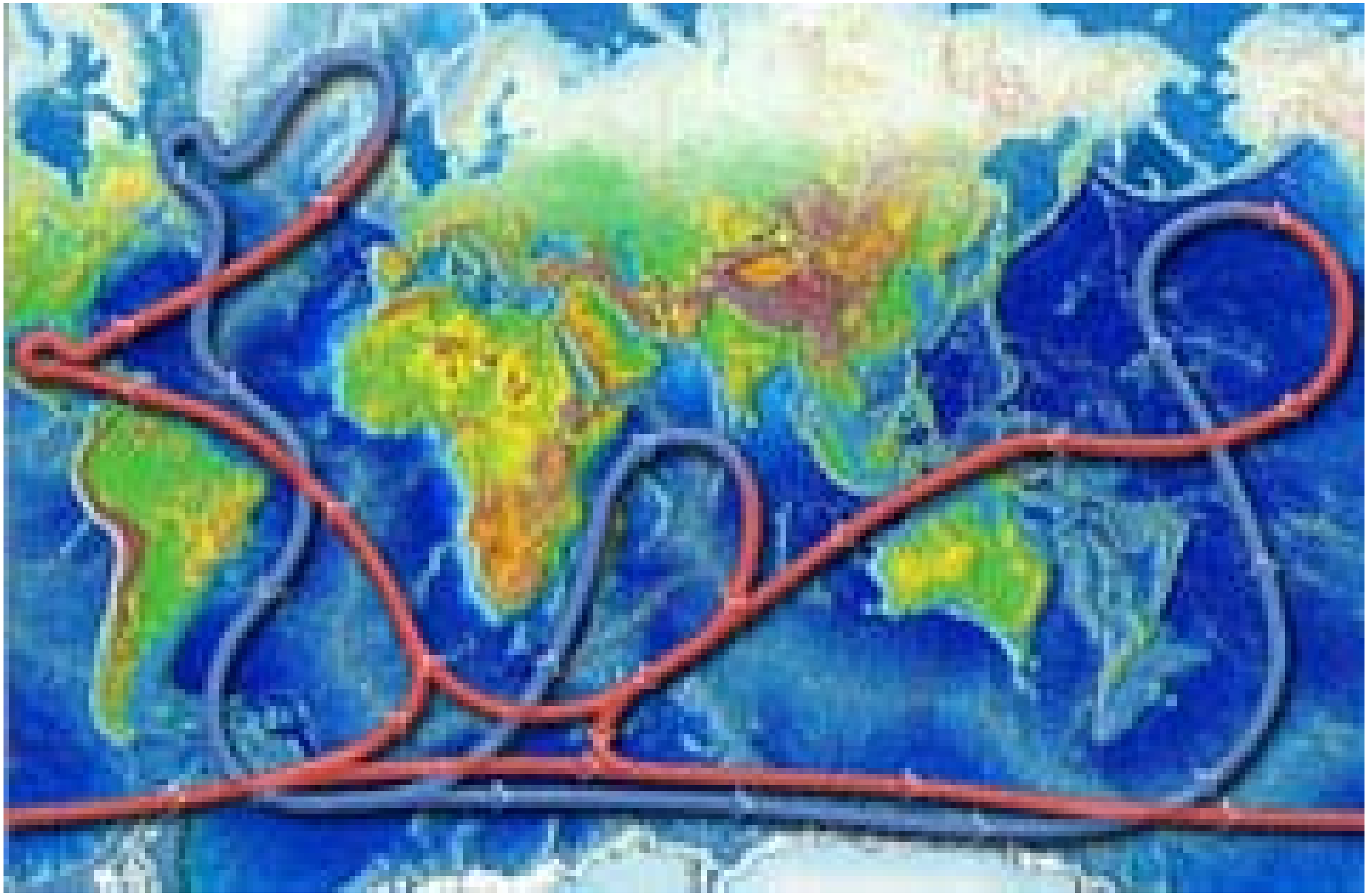

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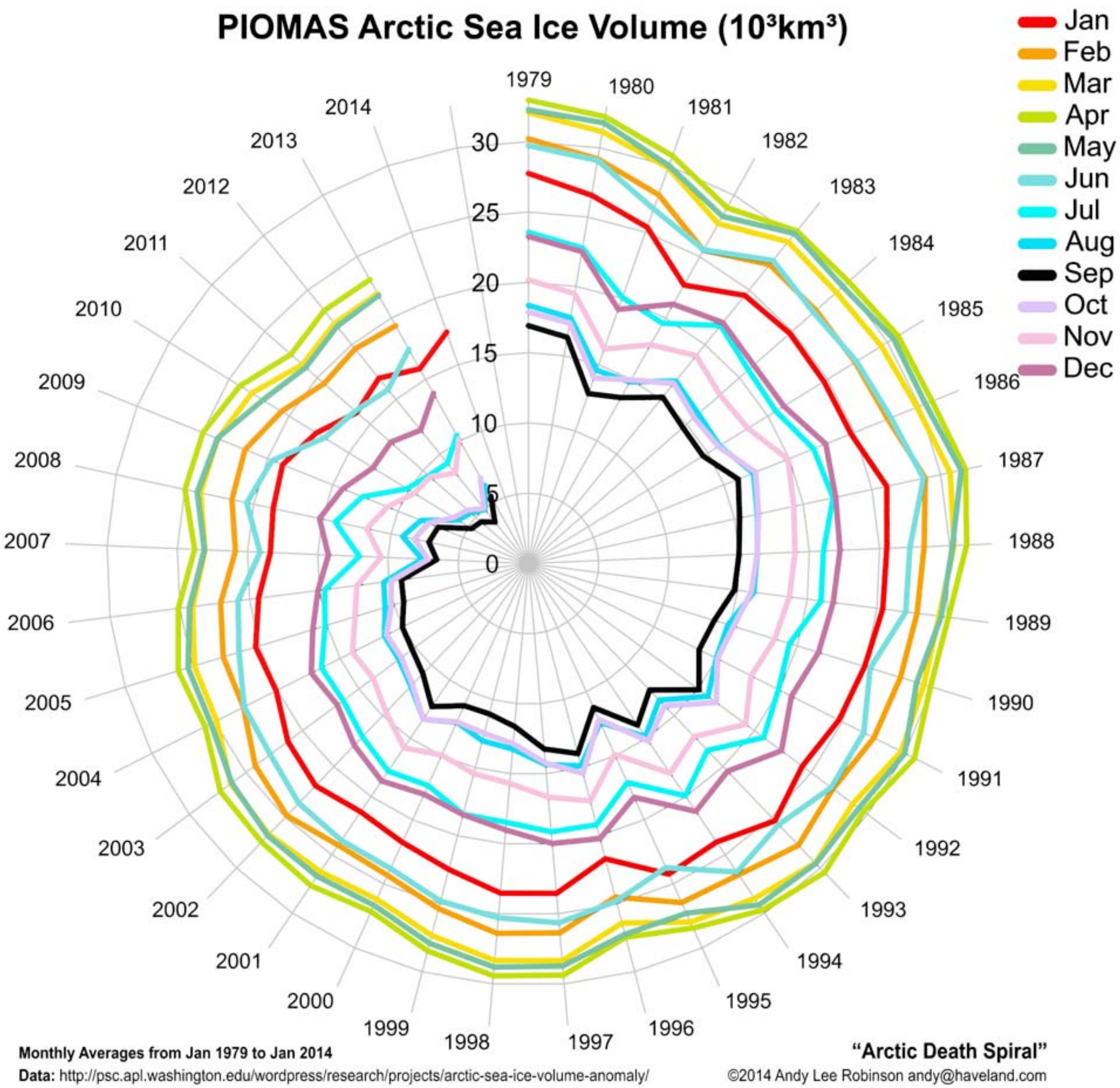

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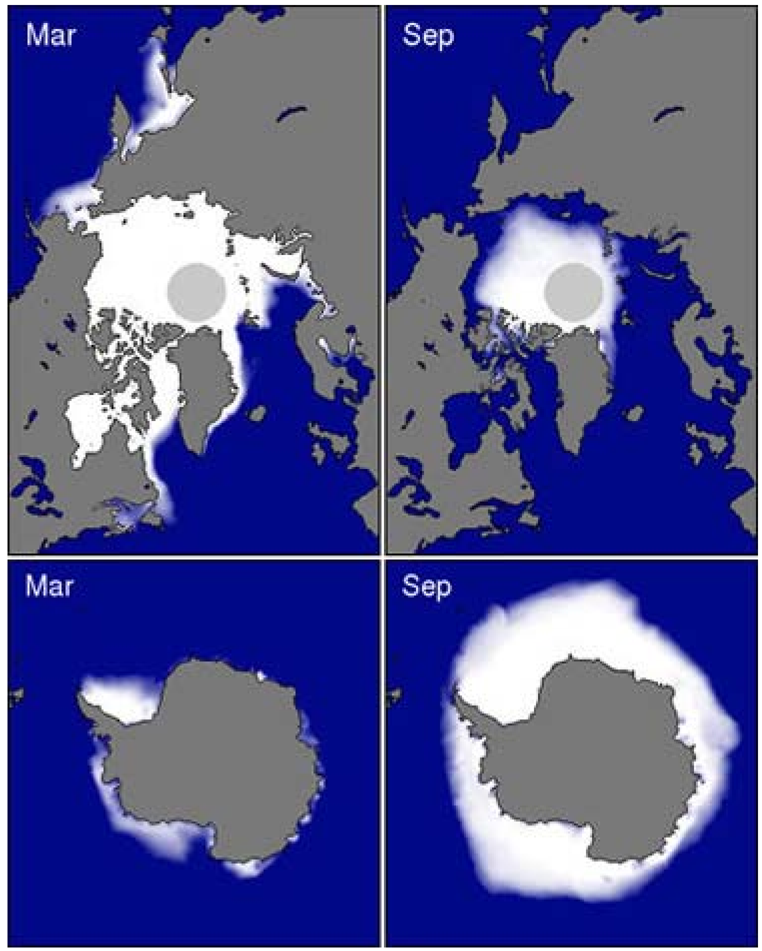

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[Polar Ice Animations from NSIDC]

(URL here)

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Summary of differences between Arctic and Antarctic sea ice characteristics		
	Arctic	**Antarctic**
Average Maximum Areal Extent	15,600,000 km^2 (6,000,000 mi^2)	18,800,000 km^2 (7,260,000 mi^2)
Average Minimum Areal Extent	6,500,000 km^2 (2,510,000 mi^2)	3,100,000 km^2 (1,200,000 mi^2)
Typical Thickness	~ 2 m (6 ft)	~ 1 m (3 ft)
Geographic Distribution	Asymmetric	Symmetric
Snow Thickness	Thinner	Thicker
Trend, 1979-2008	Significant decrease of 4.4% (~520,000 km^2; 201,000 mi^2) per decade	Small increase of 1.8% (~219,000 km^2; 85,000 mi^2) per decade

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- And that’s a brief overview of how the oceans and polar ice caps play a role in climate change.
- …now let’s take a look at history….

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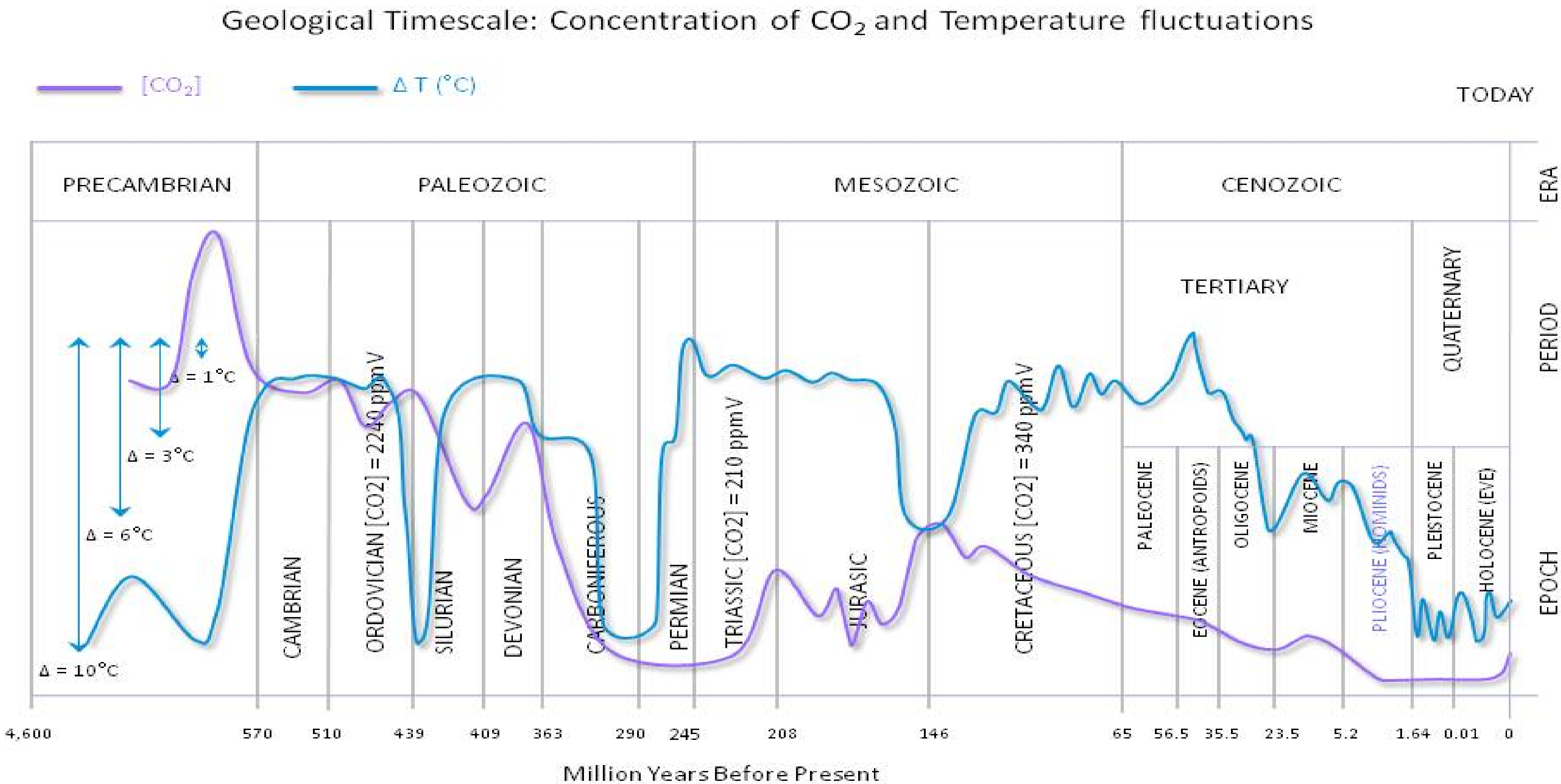

1- *Analysis of the Temperature Oscillations in Geological Eras* by Dr. C. R. Scotese © *2002*. 2- Ruddiman, W. F. 2001. *Earth's Climate: past and future*. W. H. Freeman & Sons. New York, NY. 3- Mark Pagani *et all*. *Marked Decline in Atmospheric Carbon Dioxide Concentrations During the Paleocene*. Science; Vol. 309, No. 5734; pp. 600-603. 22 July 2005. *Conclusion and Interpretation* by Nasif Nahle ©2005, 2007. *Corrected on 07 July 2008 (CO2: Ordovician Period).*

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- History—providing perspective through the ages.
- So what are “we” doing about all this….

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- The state of measuring and modeling climate change was a mess until we woke up—call it mid 80's
- Temperature measurements that filled data bases were located near HVAC exhausts, near parking lots, on roof-tops. The denier literature is filled with examples of poor data collection
- In 1999, NOAA began constructing USCRN stations to provide accurate climate data
- Modeling was in a similar state of development. A paper was written in 1999 describing how glaciers could grow if the atmospheric CO_2 levels were 10 times current levels—the answer was "YES"

  "Late Ordovician glaciation under high atmospheric CO_2: A coupled model analysis" Poussart, Weaver, Barnes School of Earth and Ocian Sciences, University of Victoria, Victoria, British Columbia, Canada

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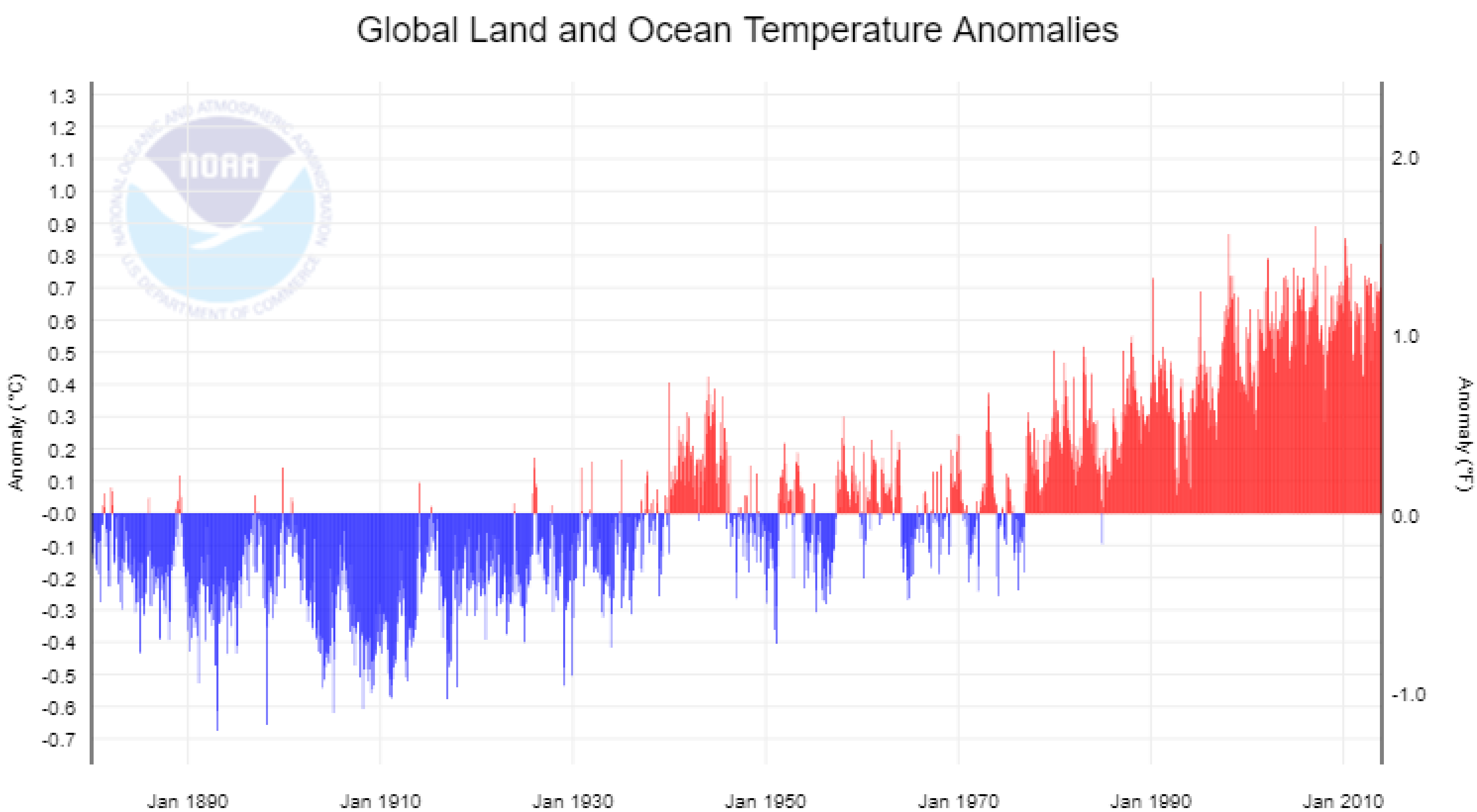

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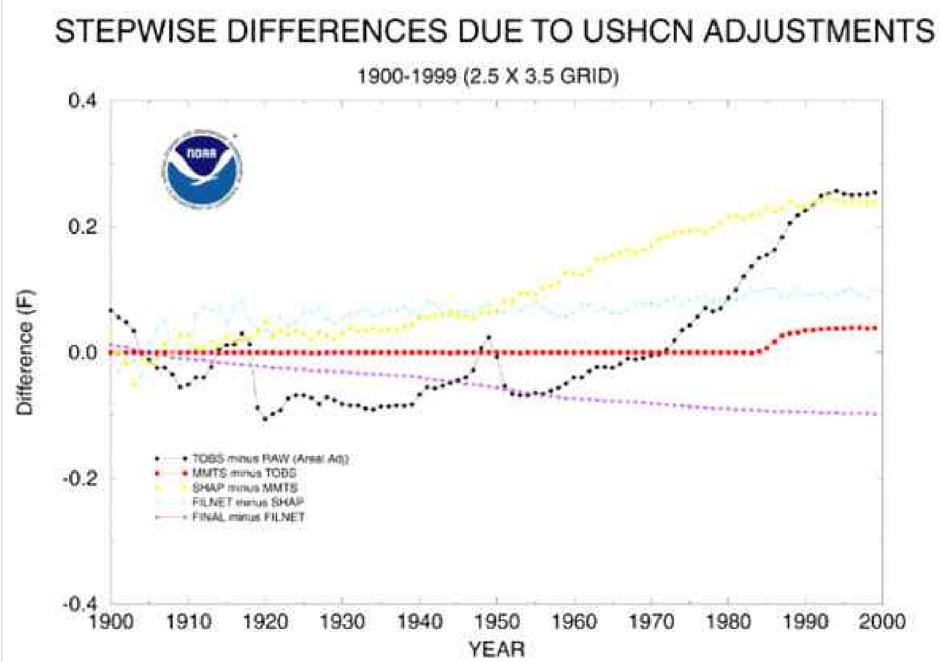

- Black line is a time of observation adjustment, adding about 0.3C since 1940
- Light Blue line is a missing data adjustment that does not affect the data much since 1940
- Red line is an adjustment for measurement technologies, adding about 0.05C since 1940
- Yellow line is station location quality adjustment, adding about 0.2C since 1940
- Purple line is an urban heat island adjustment, subtracting about 0.05C since 1950.

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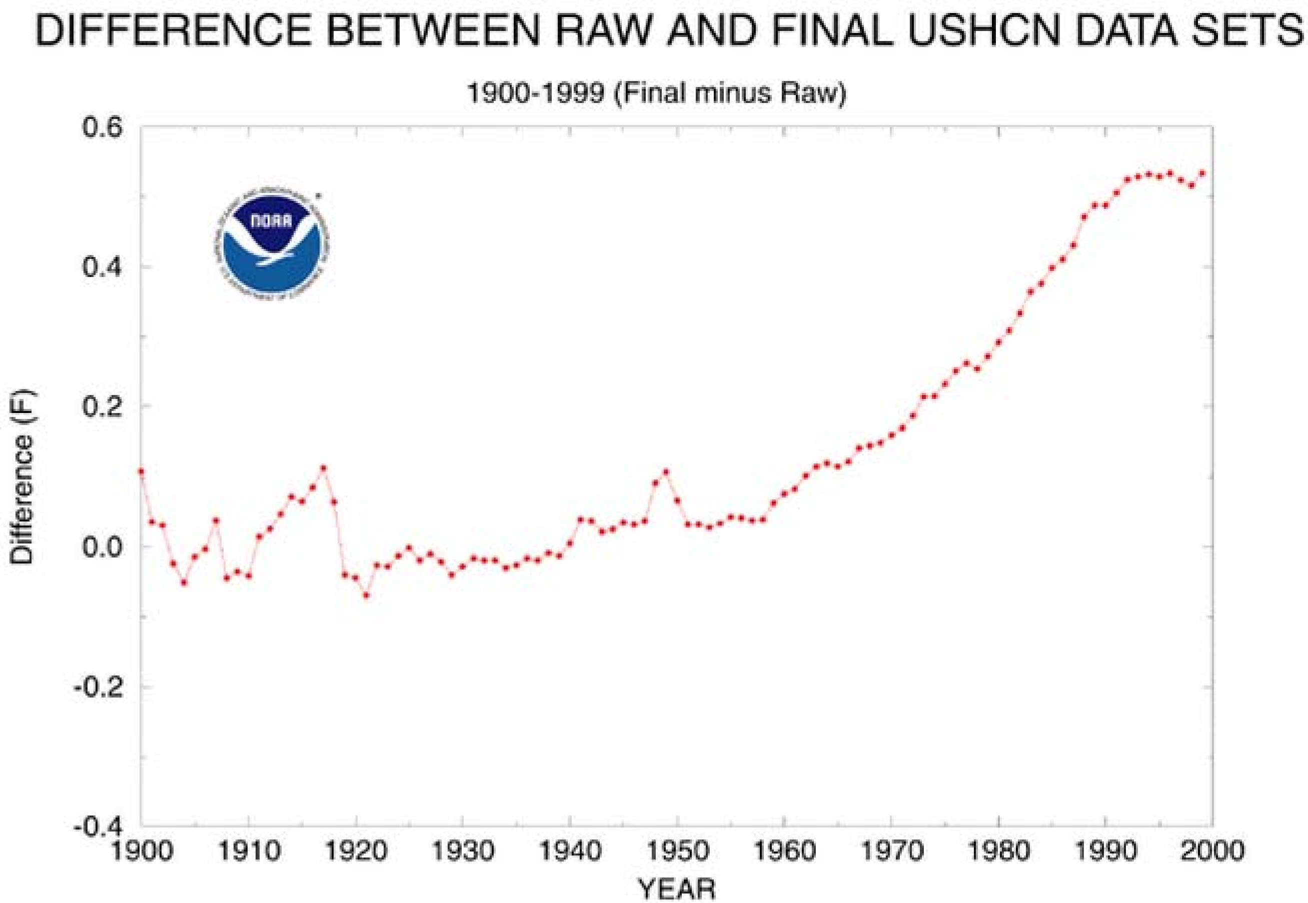

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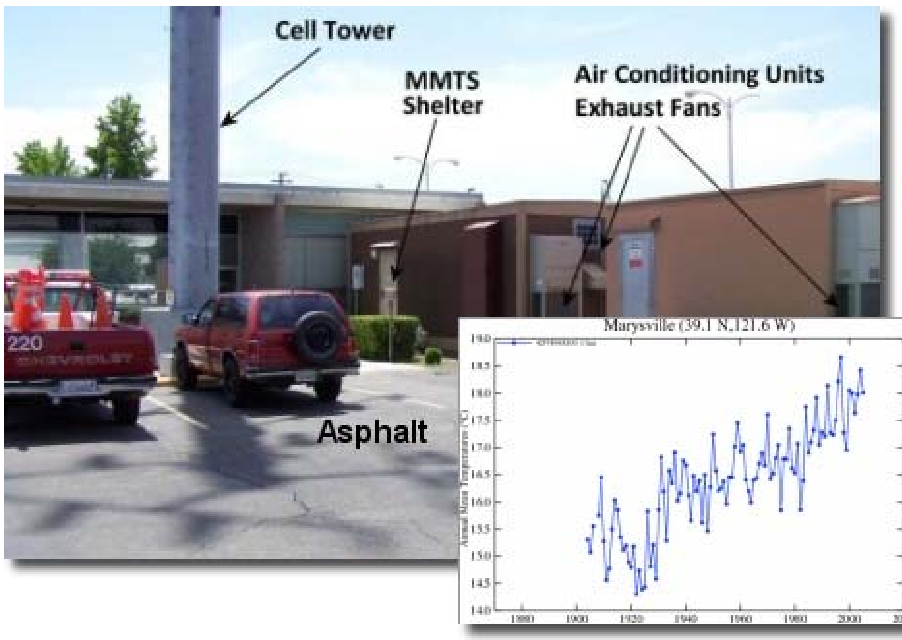

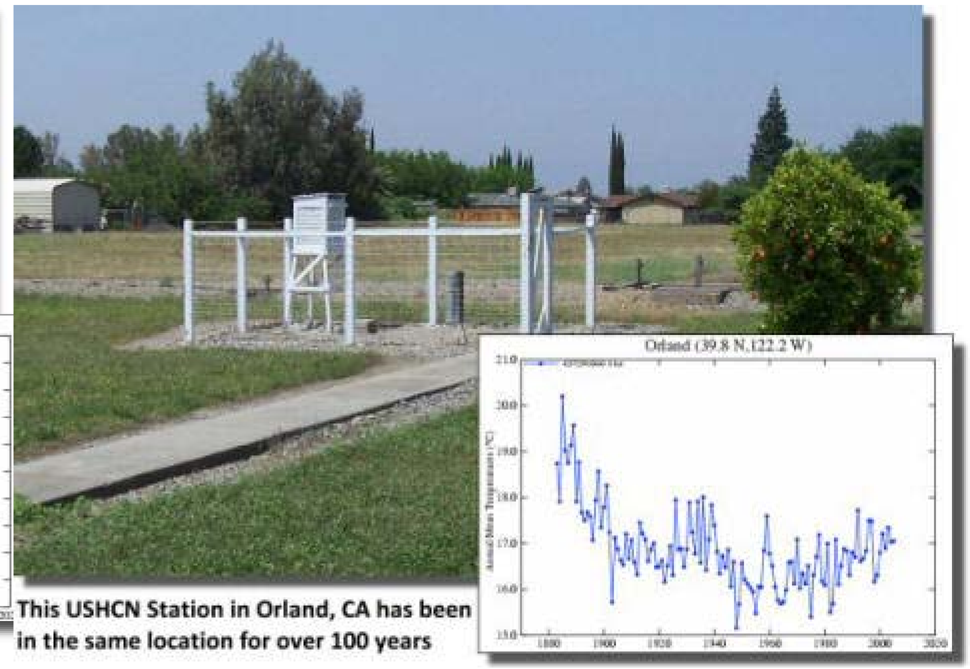

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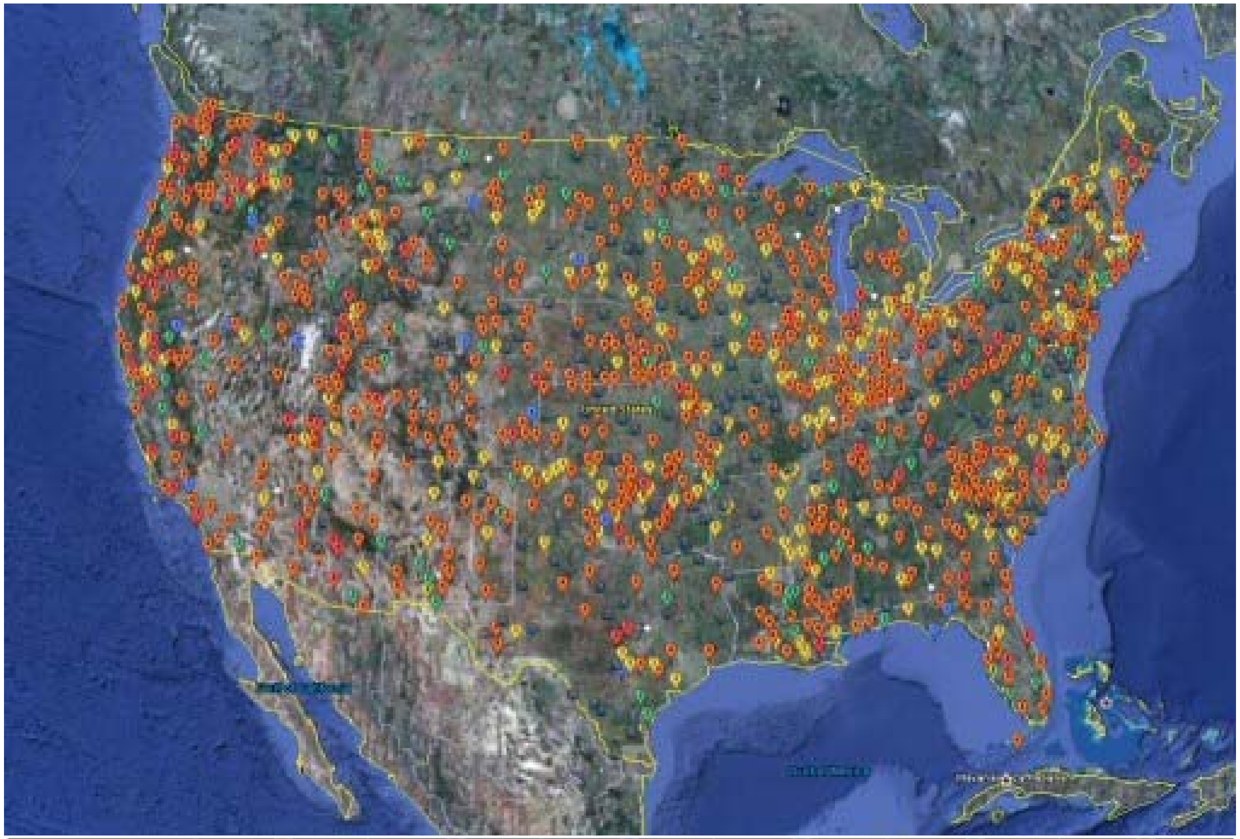

CRN Rating key	1	2	3	4	5	
Estimated Error in °C (per NOAA)	Error ≤1°C	Error ≤1°C	Error ≥1°C	Error ≥2°C	Error ≥5°C	Unrated
Quality	Best	Good	Fair	Poor	Worst	Closed

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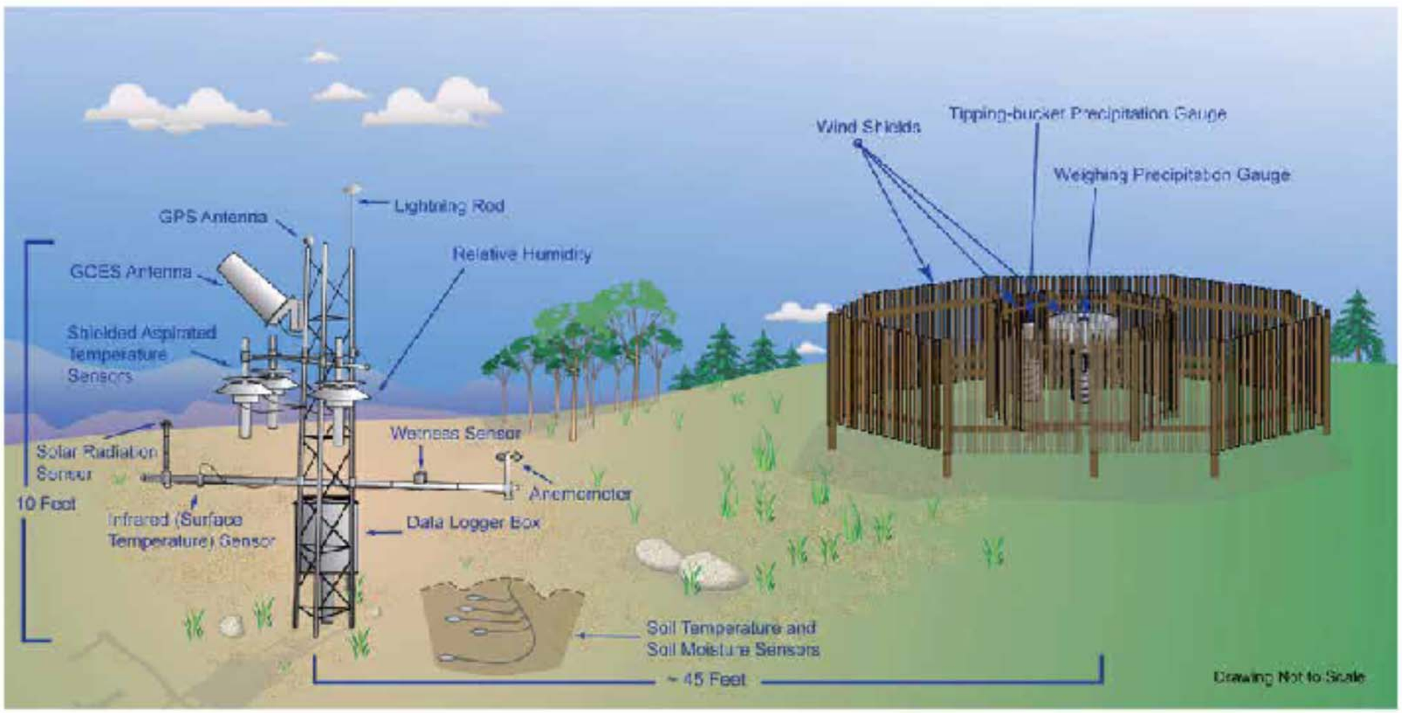
US Climate Reference Network

Instruments at a Typical USCRN Station



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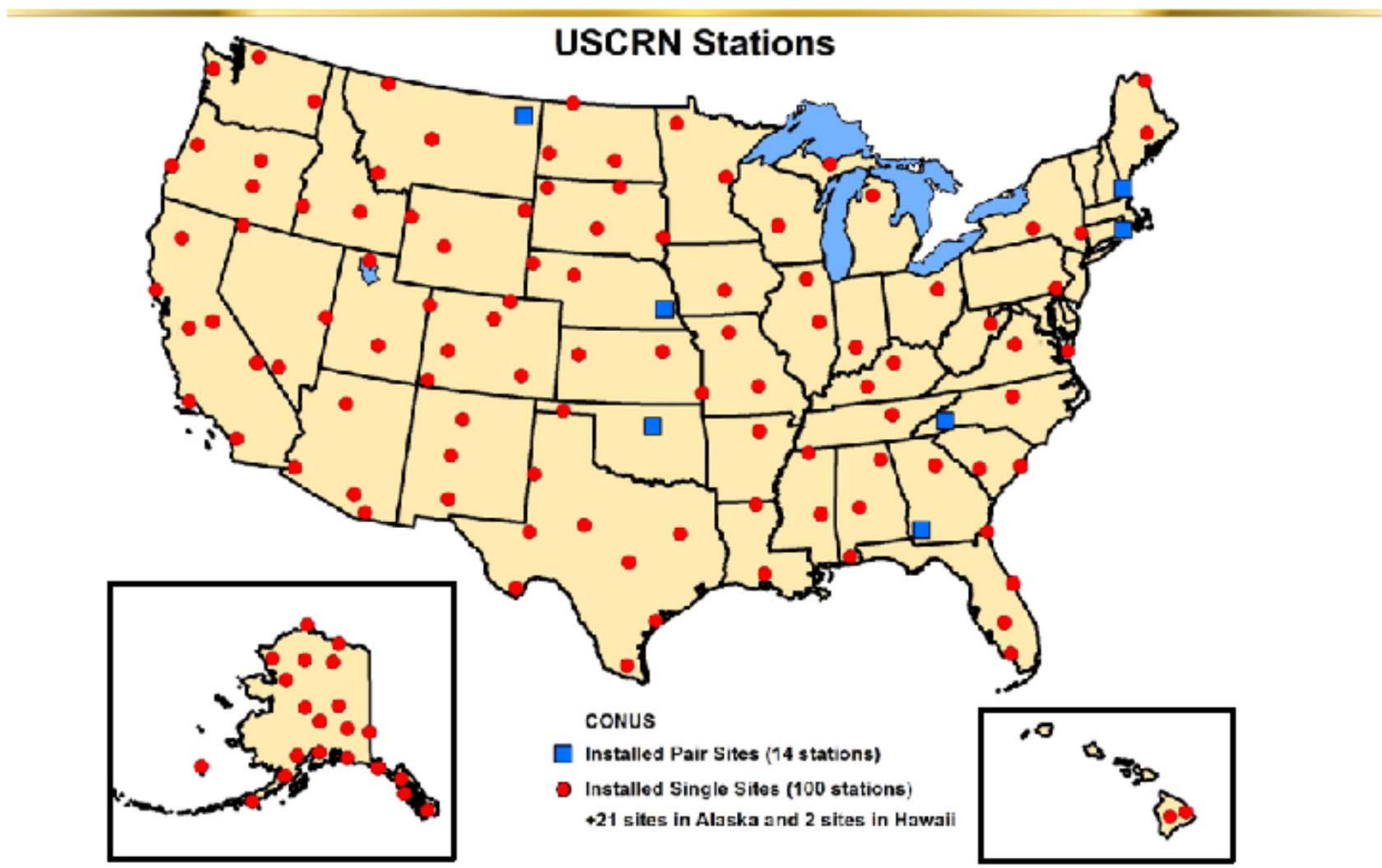
US Climate Reference Network



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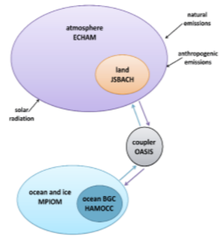
US Climate Reference Network

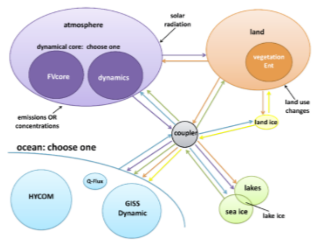
TX Palestine 6 WNW

[a]Software Engineering Lab, Department of Computer Science, University of Toronto

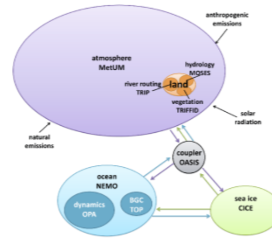
COSMOS 1.2.1
Max-Planck-Institut für Meteorologie, Germany



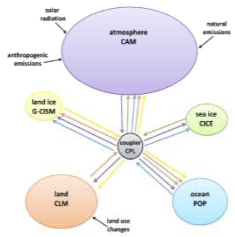
Model E October 11, 2011 revision
NASA Goddard Institute for Space Studies, USA



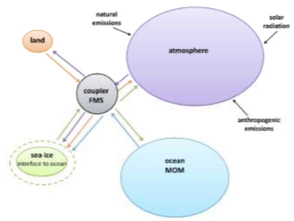
HadGEM3
Met Office, UK



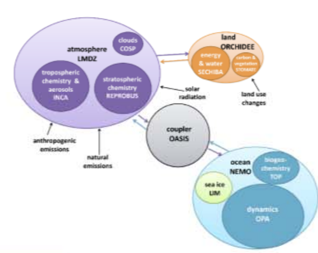
CESM 1.0.3
National Center for Atmospheric Research, USA



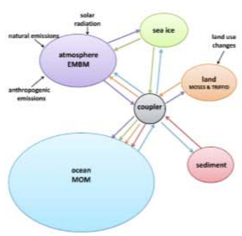
GFDL Climate Model 2.1 (coupled to MOM 4.1)
Geophysical Fluid Dynamics Laboratory, USA



IPSL Climate Model 5A
Institut Pierre Simon Laplace, France



UVic Earth System Climate Model 2.9
University of Victoria, Canada



Key to Diagrams

Each component of the climate system has been assigned a colour:
atmosphere ocean land sea ice land ice sediment

Model code for a component is represented with a bubble. Fluxes are represented with arrows, in a colour showing where they originated.

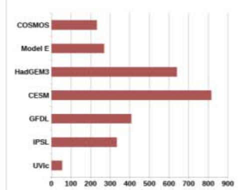
Couplers are grey. Components can pass fluxes either directly to each other or through the coupler.

The area of a bubble represents the size of its code base, relative to other components in the same model.

A smaller bubble within a larger one represents a small, highly encapsulated model of a system (eg clouds) that is used by the component.

Radiative forcings are passed to components with plain arrows.

Size (thousands of lines of code)



Generated using David A. Wheeler's "SLOCCount".

Introduction

It has become common to compare and contrast the output of multiple global climate models (GCMs), such as in the Climate Model Intercomparison Project Phase 5 (CMIP5). However, intercomparisons of the software architecture of GCMs are almost nonexistent. In this qualitative study of seven GCMs from Canada, the United States and Europe, we attempted to fill this gap in research. By examining the model source code, reading documentation, and interviewing developers, we created diagrams of software structure and compared metrics such as encapsulation, coupler design, and complexity.

Component-Based Software Engineering

A global climate model is really a *collection* of models (components), each representing a major realm of the climate system, such as the atmosphere or the land surface. They are highly encapsulated, for stand-alone use as well as a mix-and-match approach that facilitates code sharing between institutions.

This strategy, known as component-based software engineering (CBSE), pools resources to create high-quality components that are used by many GCMs. For example,

- **UVic** uses a modified version of GFDL's ocean model, MOM.
- **HadGEM3** and **CESM** both use CICE, a sea ice model developed a third institution (Los Alamos).

Contrary to CBSE goals, there is no universal interface for climate models, so components need to be modified when they are passed between institutions. Furthermore, the right to edit the *master* copy of a component's source code is generally restricted to the development team at the hosting institution. As a result, many different branches of the software develop.

A drawback to CBSE is the fact that, in the real world, components of the climate system are not encapsulated. For example, how does one represent the relationship between sea ice and the ocean? Many different strategies exist:

- **CESM**: sea ice and ocean are completely separate components.
- **IPSL**: sea ice is a sub-component of the ocean.
- **GFDL**: sea ice is an interface to the ocean. All fluxes to and from the ocean must pass through the sea ice region, even if no ice is actually present.

Acknowledgements

Gavin Schmidt (NASA GISS); Tim Johns (Met Office); Gary Strand (NCAR); Arnaud Caubel, Marie-Alice Foujols, and Anne Cozic (IPSL); Reinhard Budich (MPI); and Michael Eby (University of Victoria) answered questions about their work developing GCMs and helped to verify our observations. Additionally, Michael Eby from the University of Victoria was instrumental in improving the diagram design.

This project was funded by NSERC and the Centre for Global Change Science at the University of Toronto.

The Coupling Process

Since the climate system is highly interconnected, a CBSE approach requires code to tie the components together - interpolating fluxes between grids and controlling interactions between components. These tasks are performed by the coupler. While all GCMs contain some form of coupler, the extent to which it is used varies widely:

- **CESM**: Every interaction is managed by the coupler.
- **IPSL**: Only the atmosphere and the ocean are connected to the coupler. The land component is directly called by the atmosphere.
- **HadGEM3**: all components are connected to the coupler, but ocean-ice fluxes are passed directly, since NEMO and CICE have similar grids.

A CBSE approach has even affected coupling. OASIS, a coupler used by many models (including COSMOS, HadGEM3, and IPSL) is built to handle any number and any type of components, as well as the flux fields within.

Complexity and Focus

A simple line count of GCM source code serves as a reasonable proxy for relative complexity. A model that represents many processes will generally have a larger code base than one that represents only a few. Between models, complexity varies widely. Within models, the bulk of a GCM's complexity is often concentrated in a single component, due to the origin of the model and the institution's goals:

- **HadGEM3**: atmosphere-centric. It grew out of the atmospheric model MetUM, which is also used for weather forecasting, requiring high atmospheric complexity.
- **UVic**: ocean-centric. It began as a branch of MOM, and kept the combination of a complex ocean and a simple atmosphere due to its speed and suitability to very long simulations.
- **CESM**: atmosphere-centric, but land is catching up, having even surpassed the ocean. It is embracing the "Earth System Model" frontier of terrestrial complexity, particularly feedbacks in the carbon cycle.

Conclusions

While every GCM we studied shares a common basic design, a wide range of structural diversity exists in areas such as coupler structure, relative complexity between components, and levels of component encapsulation. This diversity can complicate model development, particularly when components are passed between institutions. However, the range of design choices is arguably beneficial for model output, as it inadvertently produces the software engineering equivalent of perturbed physics (although not in a systematic manner).

Additionally, architectural differences may provide new insights into variability and spread between model results. By examining software variations, as well as scientific variations, we can better understand discrepancies in GCM output.

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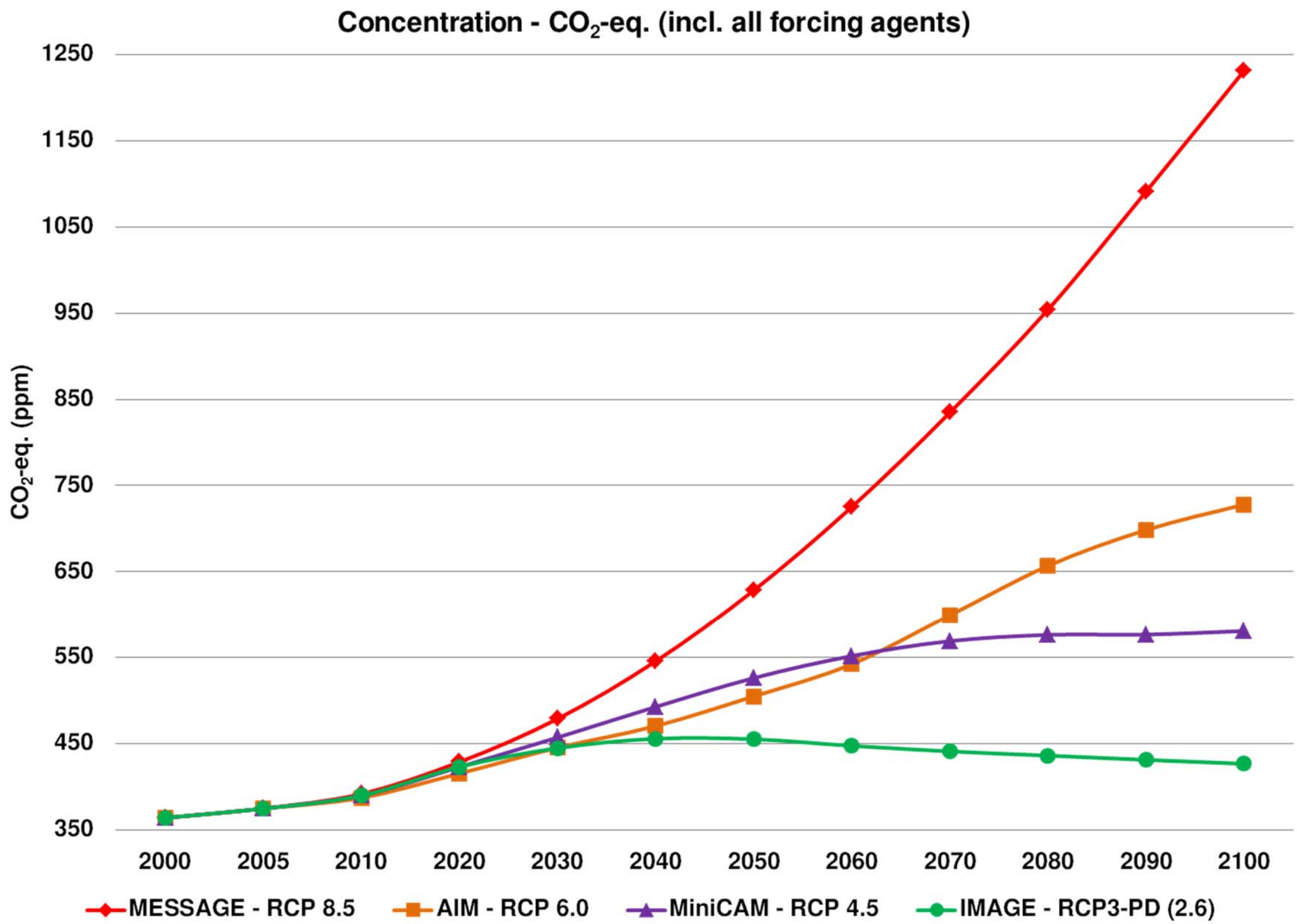

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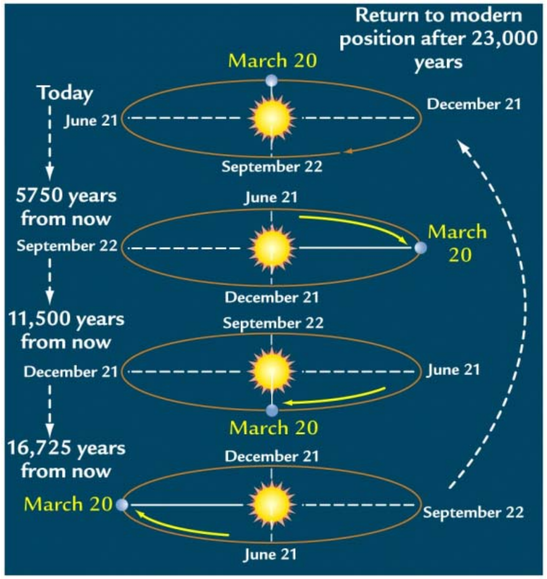
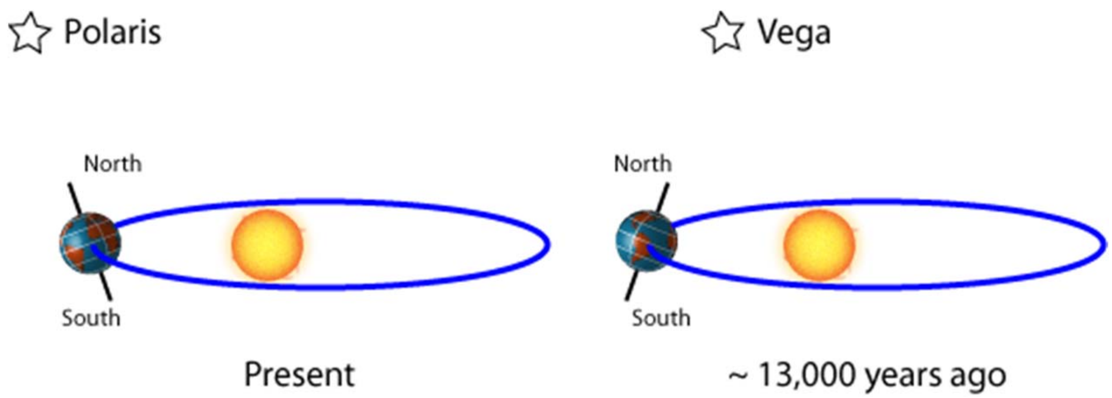
Conclusions?

- The Sun heats the Earth. The Earth re-radiates some heat
- Greenhouse gases keep sufficient heat so that biota thrive
- We are now taking better climate measurements
- Small changes in climate parameters often leverage into large changes
- What about Makinkovitch cycles?





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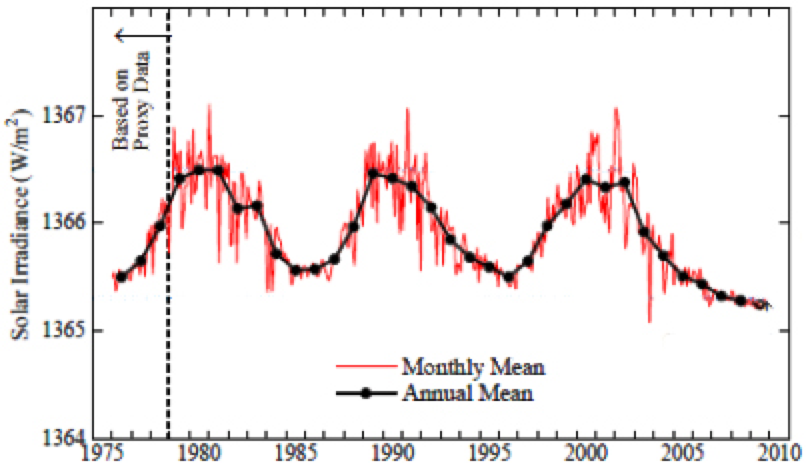
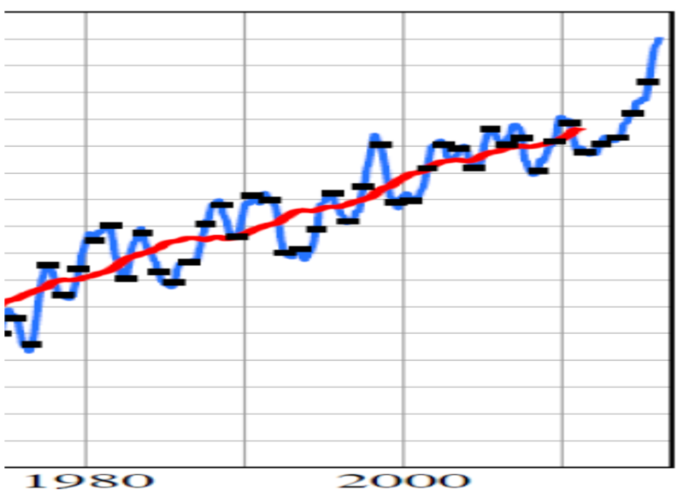
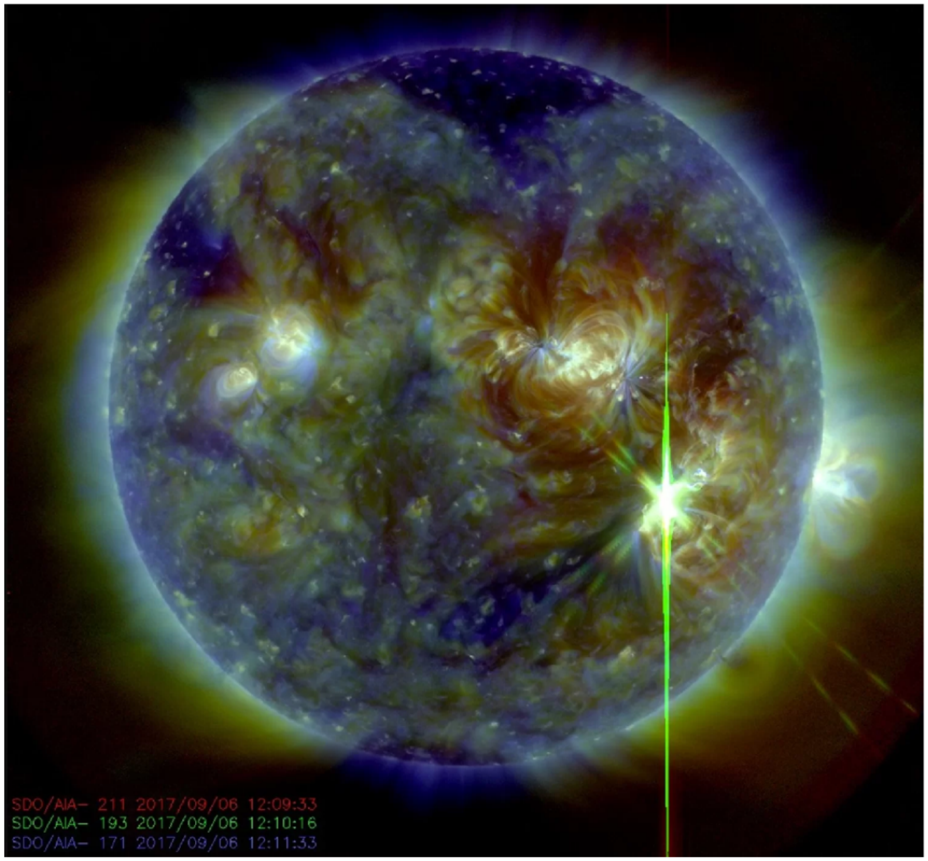
- What about sunspots?







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- References:

  - Intergovernmental Panel on Climate Change
  - NOAA
  - NASA
  - American Institute of Physics
  - AIChE Engage

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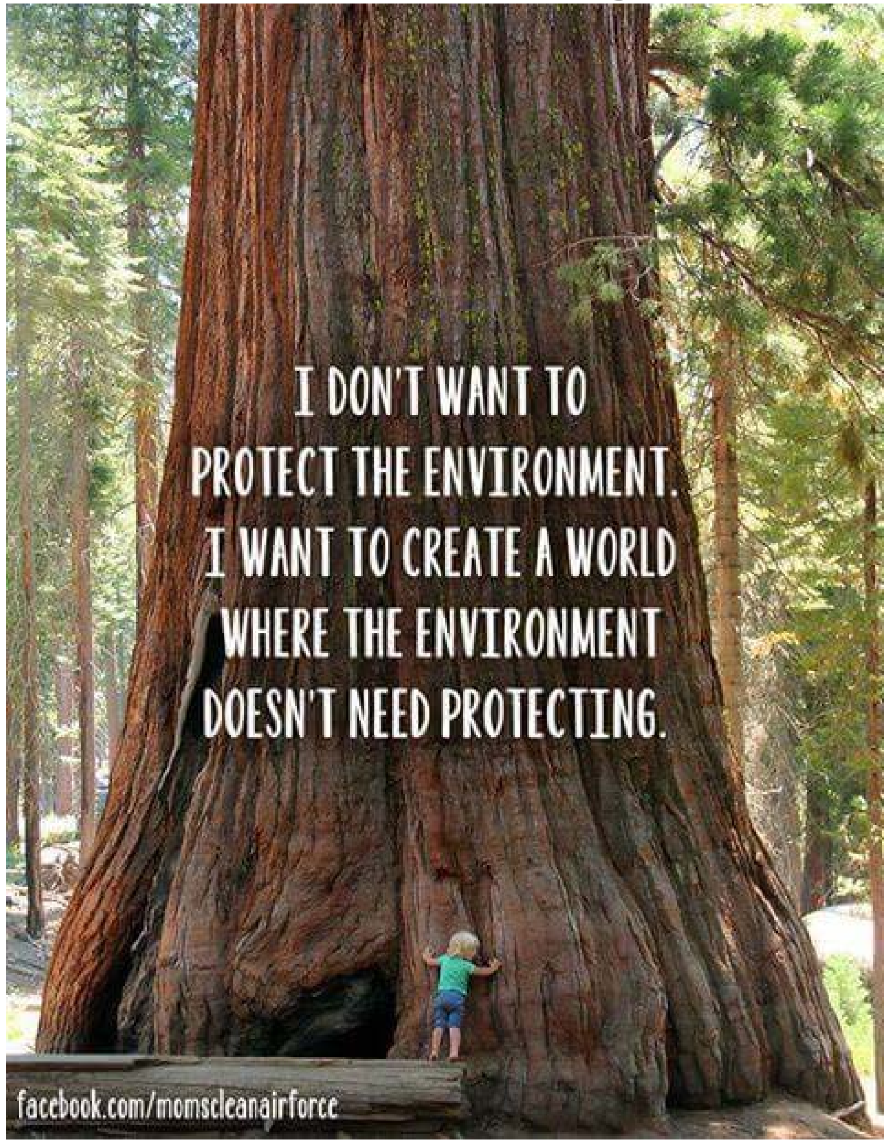

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- What do we think collectively?
  - Is climate change occurring?
  - Do we know why?
  - Are human activities part of the cause for climate change?
  - What must we do to prepare our heirs and humanity for these changes?