WEDNESDAY: global weather and climate

Climate Change: Past, Present, Future

- Ice ages, climate change of the recent past
- How is climate prediction different from weather prediction?
- Why it's simpler than you think
- What is a (computer) climate model?
- Future climate predictions, uncertainties

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Weather ↔ Climate

"*Weather* tells you what to wear, *Climate* tells you what clothes to buy"

✗ Weather: the condition at a specific location at a specific time

✗ Climate: the average conditions and their variability (includes extremes); the statistics of weather

✗ Climate is an "envelope of possibilities" within which the weather bounces around

✗ Weather depends very sensitively on the evolution of the system from one moment to the next ("initial conditions")

✗ Climate is determined by the properties of the Earth system itself ("boundary conditions")

Weather ↔ Climate

✗ Today's sunset: 8:32 pm

✗ Today's 5-day forecast: 95 / 61 F

✗ July Long-Term Climatology: 85 F / 56 F

✗ June 2013: average temperature 70.4 F (5th warmest in 125 year record), minimum: 41 F (on 2 June), maximum: 97 F (on 27/28 June)

✗ Weather: minutes to weeks, ~ the time scale to which a specific event may be forecast

✗ Climate: seasonal, annual, decadal, centurial, millennial, ...

Climate & Climate Change

- Climate is the accumulation of daily and seasonal weather events over a long period of time (climate is the statistics of weather)
- Climate can change on various time-scales: millions of years, thousands of years, hundreds of years, decades
- Climate can change in response to different factors:
  - Natural
  - Anthropogenic

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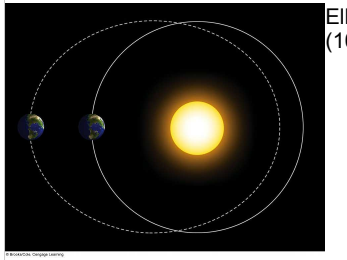
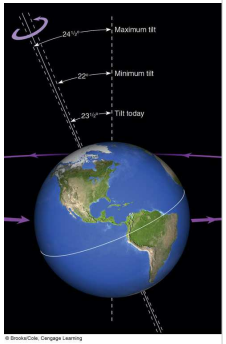
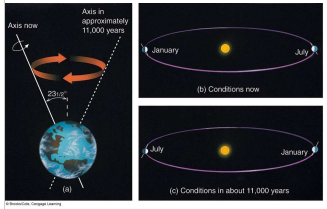
Milankovitch Theory (Ice Ages)



Ellipticity of Orbit (100,000 years)



Changes in Tilt (41,000 years)



Precession (23,000 years)

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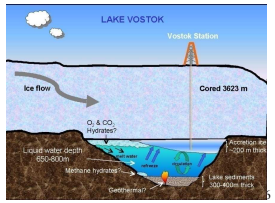
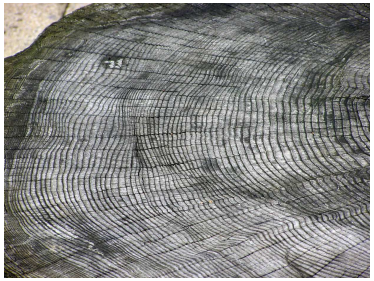
How to obtain data of past climates?
Ice Core Proxies

- Drilling long cores into the ice at places like Antarctica and Greenland:
  - Atmospheric gas concentrations
  - Temperatures through oxygen isotope data (O^{18}/O^{16})
  - Sulfur concentrations from volcanoes and dust
  - Biological activity
- Some cores go back ~800,000 years



Courtesy Montana State University

How to obtain data of past climates?
Tree Ring Proxies



- Width and density of growth rings can give info about temperature and precipitation in different years
- Has been used to derive climate for past 10,000 years combining live and dead trees (e.g. Bristlecone Pines)

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How to obtain data of past climates?
Ocean/Lake Sediment Core Proxies

Courtesy Lamont/Doherty Earth Observatory

- A ~million years of sediments can be obtained from bottom of the ocean
- Isotopic ratios of calcium carbonate shells within these sediments give information about ocean temperature

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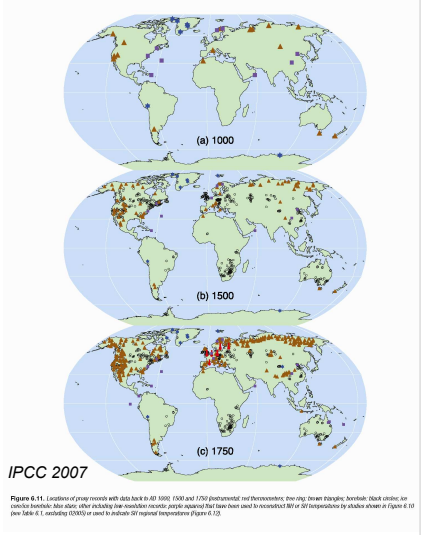
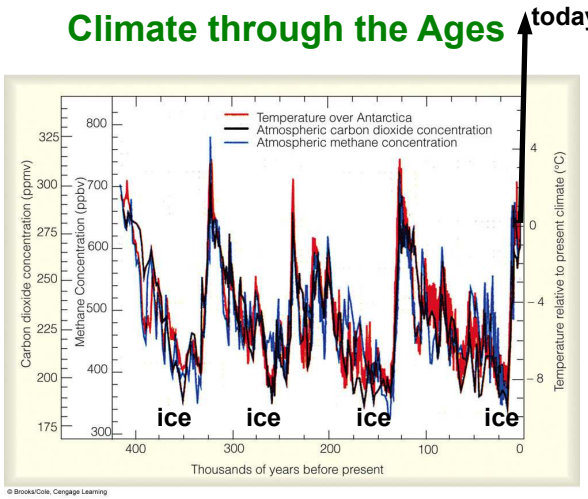
Number of Climate Proxy Measurements significantly decreases into the Past!

- Number of climate reconstruction data is much less for 1500 and even less for 1000 compared to 1750
- Much of the data comes from the NH – hard to infer global behavior



Climate through the Ages



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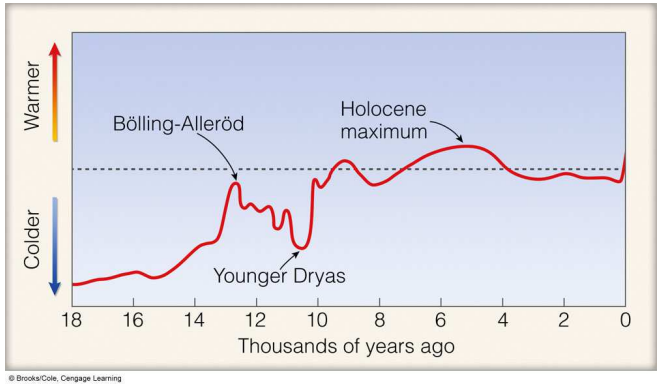
Climate through the Ages



- Last ice age was near its peak 18,000 years ago
- Since then general warming (except Younger Dryas)

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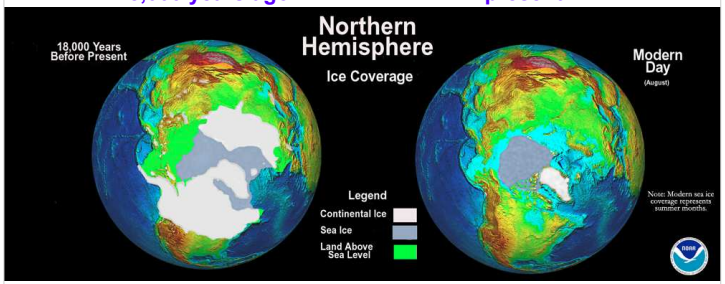
Ice Cover during the Last Ice Age

18,000 years ago present



- Recent N. American glaciers at maximum 18,000 years ago
  - Places like Chicago under ice all year
  - Sea level 125 m lower
  - Bering land bridge allowed Asia/N. American migration

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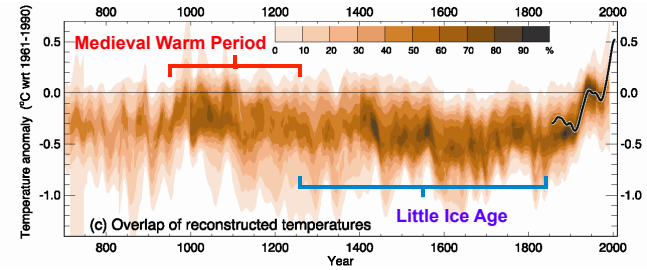
Reconstructed Temperature (last 1,300 years), from IPCC 2007



- Temperature relative to present, plotted as agreement between different reconstructions (e.g. from tree rings)
- Thermometer record available over past 150 years: solid line
- Relatively warm period 950–1250 (Medieval Warm Period)
- Relatively cold period 1250–1850 (Little Ice Age)

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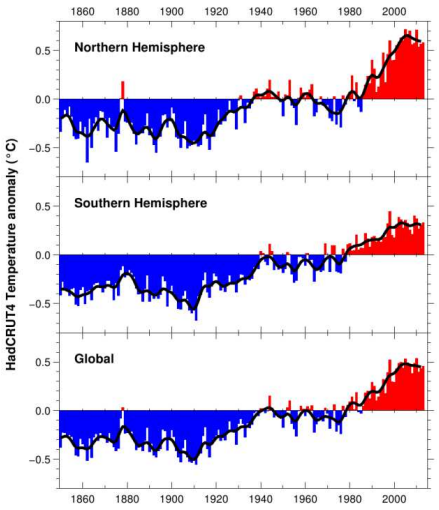

Up-to-date temperature record for the industrial era (1850 – now)

This is relative to the 1961–1990 average.

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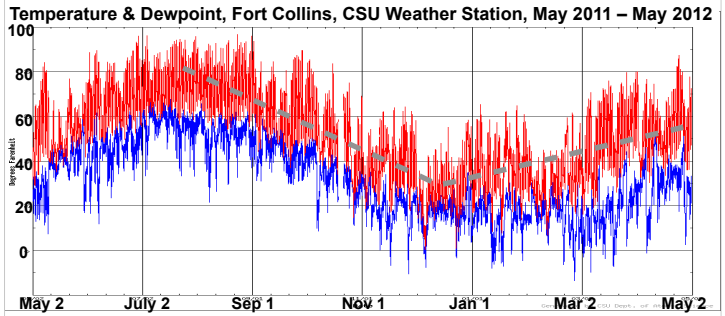
http://www.cru.uea.ac.uk/cru/data/temperature/

Cautionary Note: Do Not Overinterpret every Wiggle in the Plot!



- We are sure that July will be warmer than January due to increasing solar insolation, even though there's lots of natural variability along the way (mostly related to weather patterns)
- Individual warm or cold spells do not necessarily indicate a trend!

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Can we attribute the recent observed temperature changes to anthropogenic (human) forcing?

- To answer this scientists look at (amongst other things):
  - Basic physics
  - vertical/horizontal patterns of temperature changes
  - Oceanic temperature / heat content changes, sea level changes
  - Sea ice and glacier retreat
  - Climate model response to imposed greenhouse gas forcing

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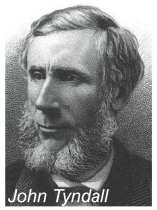
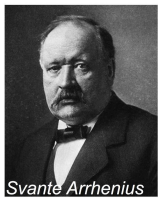
Basic Physics & Common Sense
Why it's simpler than you think


Joseph Fourier


John Tyndall

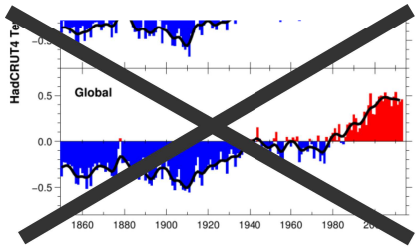
- Fourier in the 1820's first describes the atmospheric greenhouse effect
- Tyndall in the 1850's first measures the radiative properties of atmospheric greenhouse gases (H_2O, CO_2, ...)


Svante Arrhenius

- Arrhenius in the 1890's: doubling CO_2 would add 4 watts to every square meter of the surface of the Earth, 24/7
- Doing that would make the surface warmer (Arrhenius in 1906: $2 \times CO_2 \rightarrow 2.1\ C = 3.8\ F$ warming)

A Common Myth

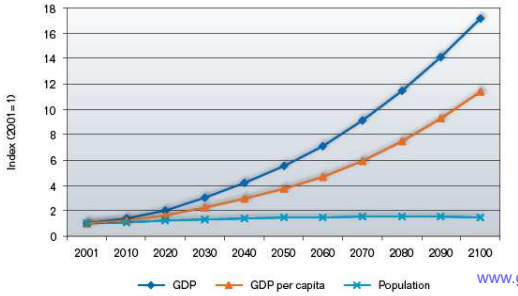
"People are worried about climate change because it's been getting warmer lately"



WRONG! We're concerned because we know that when we add energy to things, they warm up!

We're also concerned because if you strongly perturb a complicated system, it often reacts in irreversible & complicated ways.

Population growth is not the driver of future climate!



UN Reference Scenarios

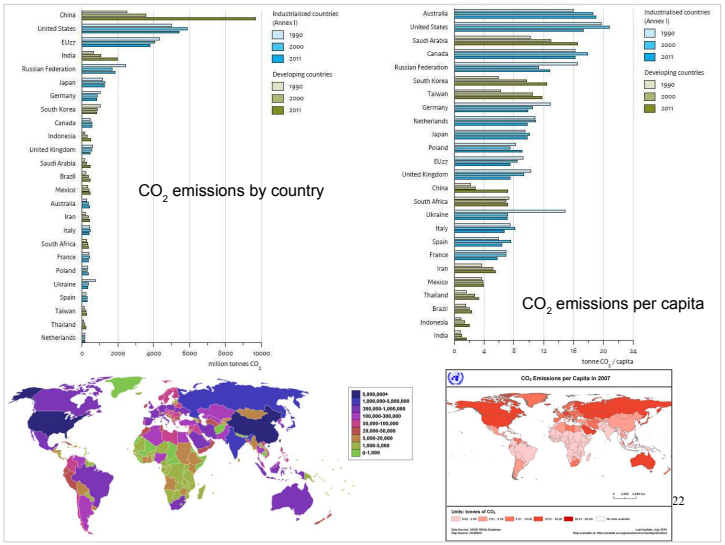
www.garnautreview.org.au

- Population to grow by 40% in 100 years
- Global **economy to grow by 1600%**

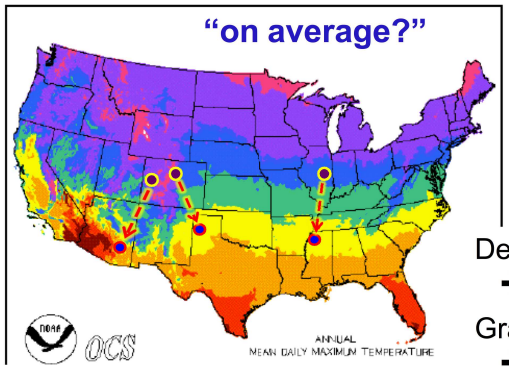
(assumes 2.8% annual GDP growth)

Shanghai, China 1990

Shanghai, China 2012



Where is it 10°F Warmer



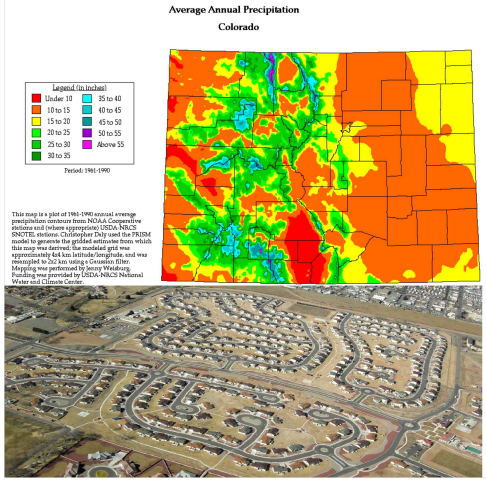
Water? ***Crops?***
Real Estate? ***Health?***

Denver
➔ Amarillo

Grand Junction
➔ Tucson

Illinois
➔ Mississippi

A Region On the Edge



Much of the region already receives only marginal precipitation

Just enough snow to support forests and reservoirs

Just enough irrigation water to support farming

Just enough water to support 5.1 million people

Anthropogenic Climate Variability and Change

Various resources at the Intergovernmental Panel on Climate Change (IPCC) Website:

http://www.ipcc.ch/ipccreports/ar4-wg1.htm

Note: there will be a new report coming out ~early 2014

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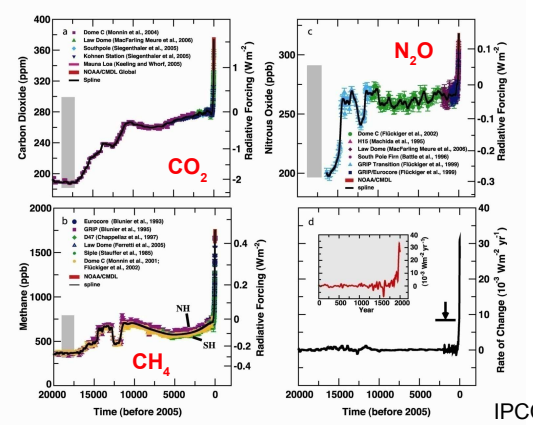
Concentrations of most GHGs have been increasing in the modern age



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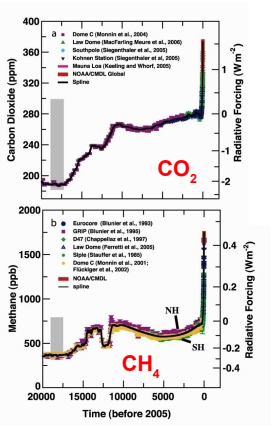
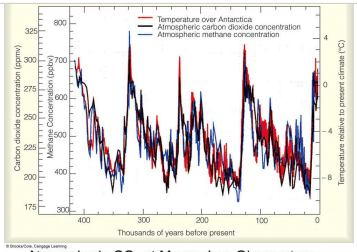
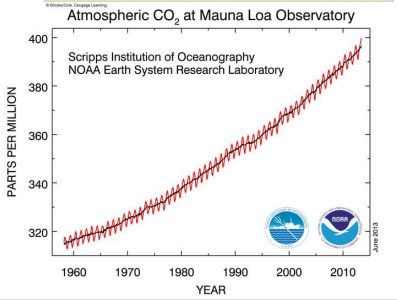
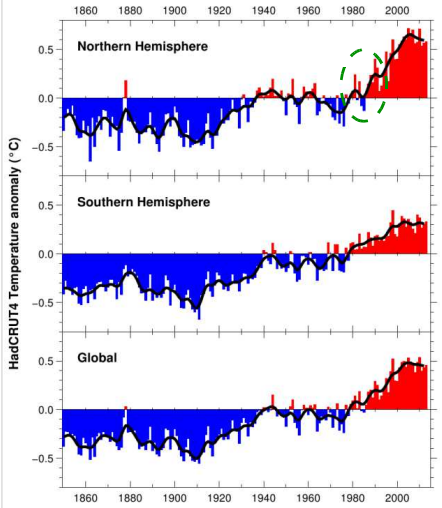
IPCC, 2007



IPCC, 2007







Up-to-date temperature record for the industrial era (1850 – now)

This is relative to the 1961–1990 average.

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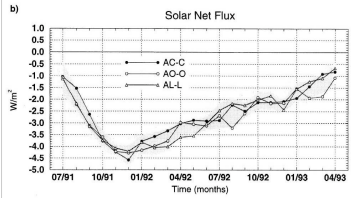
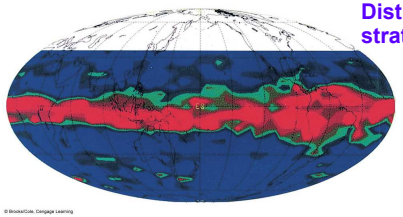
Volcanoes



- Volcanoes emit sulfur dioxide that become aerosols (airborne solids) in the stratosphere → reflect sunlight, increase earth's albedo reducing the solar radiation absorbed by the climate system
- For example, lower-left: globally-averaged reduction in absorbed solar radiation after Mt. Pinatubo eruption in summer 1991
- Some are advocating man-made stratospheric injections of aerosols to mitigate anthropogenic climate warming

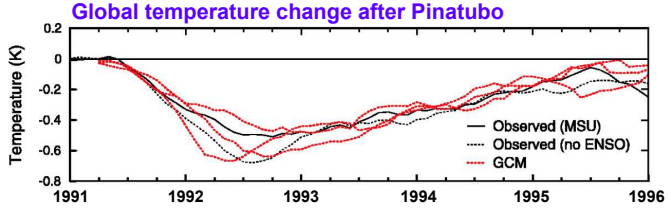
Volcanoes



Distribution of Mt. Pinatubo stratospheric forcing

- Reduction in solar radiation due to Mt. Pinatubo led to a cooling of the globally-averaged temperature ~ 0.5-0.7 C

Global temperature change after Pinatubo



Feedbacks

- *A process that changes the sensitivity of the climate response to an external forcing*
- **Positive feedback:** increase the magnitude of the response to the forcing
  - Ice/albedo feedback
  - Water vapor feedback
  - Ocean carbon cycle feedbacks
- **Negative feedback:** decrease the magnitude of the response to the forcing
  - Stefan-Boltzmann feedback (i.e. warmer Earth emits more radiation out to space)

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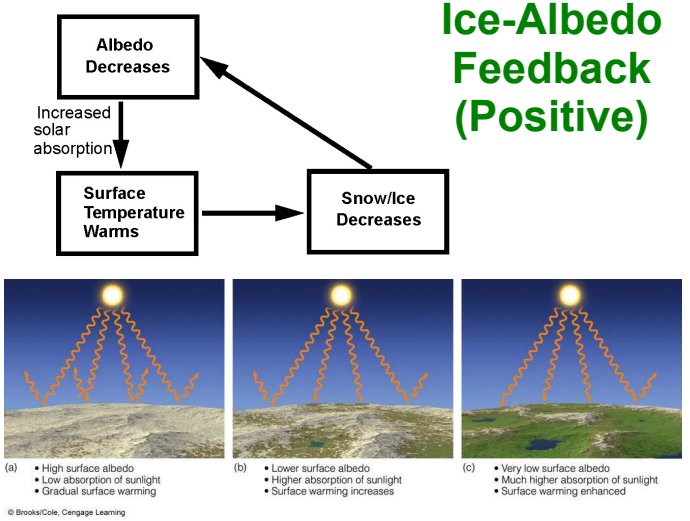
Ice-Albedo Feedback (Positive)



Water Vapor Feedback (Positive)

- Most important feedback in the climate system
- (recall that water vapor is a powerful greenhouse gas)
- As climate warms saturation vapor pressure increases – warm air tends to contain more water vapor
- As water vapor increases its radiative effects warm the climate more
- As the climate warms further air tends to contain even more water vapor, and so on ...
- This feedback loop is true as long as relative humidity is roughly constant (which seems to be roughly the case in observations and climate models)

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Stefan-Boltzmann Feedback (Negative)

- Recall the total possible rate of radiation emission by an object is given by: $E = \sigma T^4$
- Hence, a warmer earth will emit more radiation to space, eventually stabilizing the climate system and capping the rise in temperature
- Likewise, a cooler earth will emit less radiation to space

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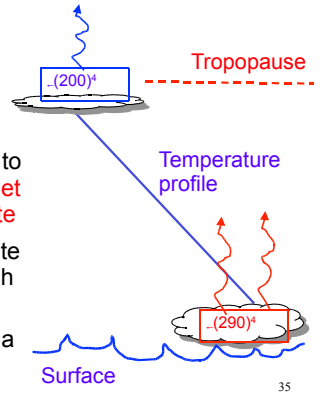
Cloud Feedback

- Effect of clouds on climate: thick vs thin, high vs low
- High, very thin clouds warm the climate (let most sunlight through, emit at low temperature)
- Low, thick clouds cool the climate (emit a lot of terrestrial radiation, reflect a lot of solar radiation)
- Recall: in the net clouds contribute to Earth's albedo, i.e. clouds have a net cooling influence on average climate
- Cloud *feedback* in a warming climate depends on relative changes of high vs low clouds
- Currently, clouds are thought to be a slight positive feedback, but big uncertainties



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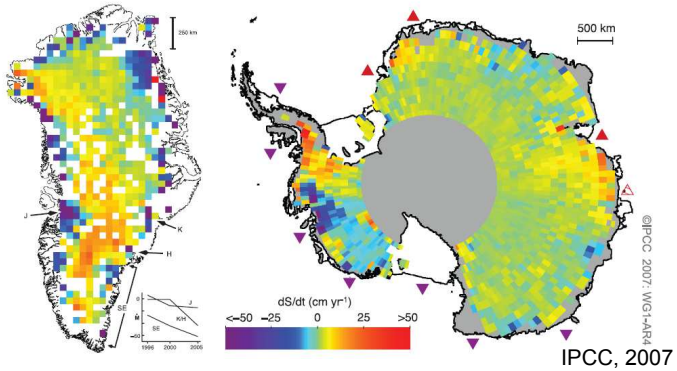
Ice Sheet Retreat



IPCC, 2007

Greenland and Antarctica have been loosing mass, mostly at the fringes of the land masses, contribute ~ 1 mm/yr to sea level rise

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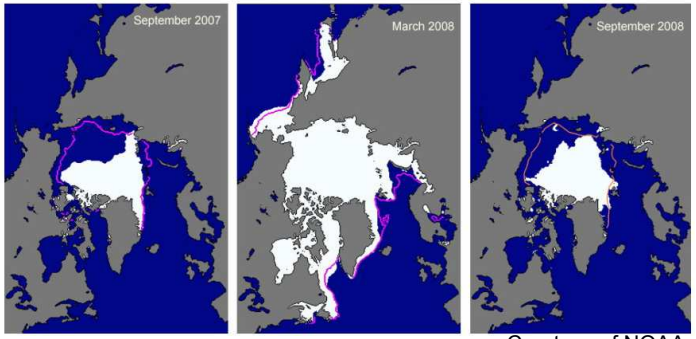
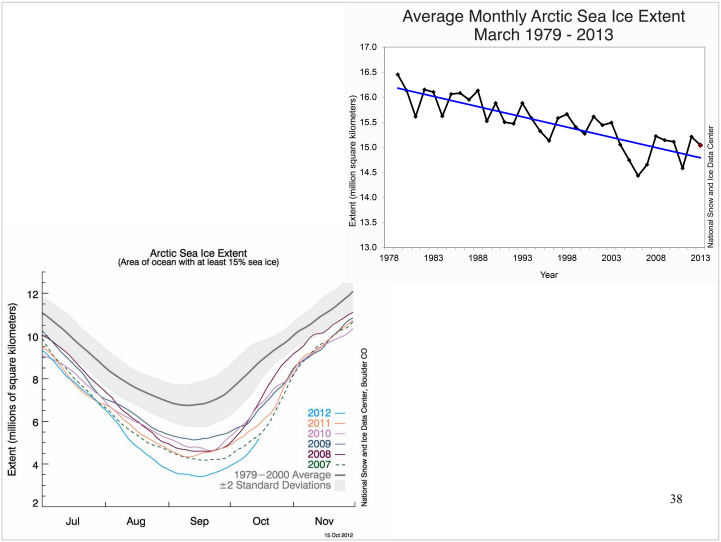
Sea Ice Extent



Courtesy of NOAA

Summer minimum sea ice extent in the Arctic has been a record low in 2007, shipping lanes through the arctic have been open! 37



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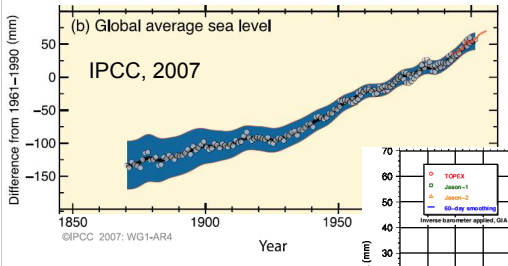
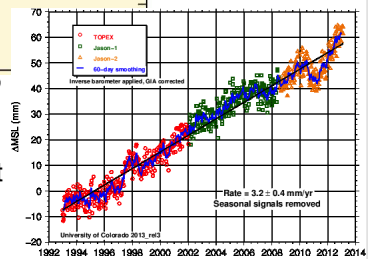
Sea Level Rise





- Sea level has gone up about 20 cm since the late 1800's
- Currently at about 3 mm/yr
- Approximately equal contributions from thermal expansion (warmer temperatures) and melting of ice

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Computer Climate Modeling

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Different CO_2 concentrations in Radiative-Convective Equilibrium Model: Change in surface temperature when going from 300 to 600 ppmv CO_2 is ≈ 2.4 C ≈ 4.3 F.

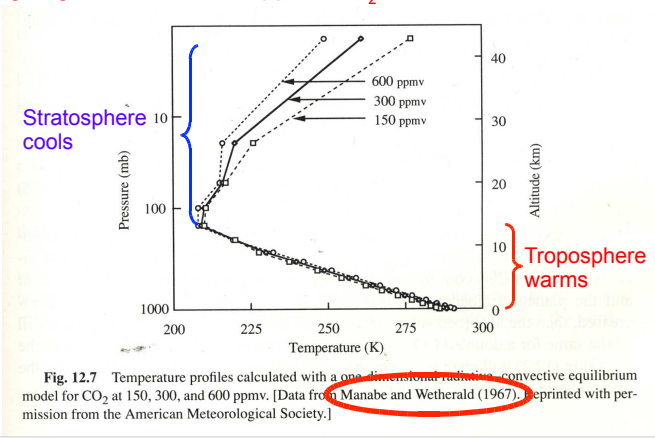
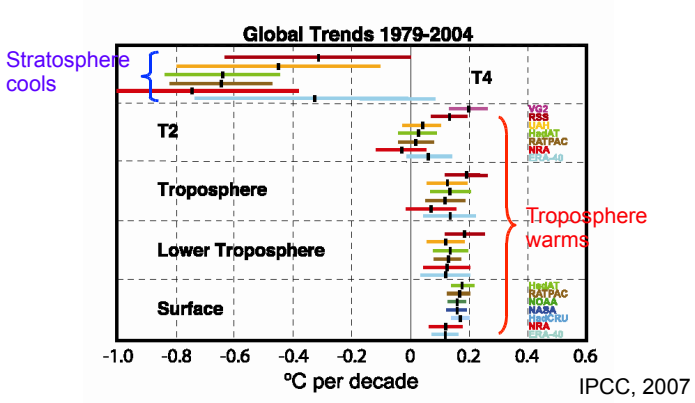


Fig. 12.7 Temperature profiles calculated with a one-dimensional radiative–convective equilibrium model for CO_2 at 150, 300, and 600 ppmv. [Data from Manabe and Wetherald (1967). Reprinted with permission from the American Meteorological Society.]

Observed Vertical Trend Structure



IPCC, 2007

These temperature trends are consistent with what one would expect due to greenhouse gas forcing.

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Force "full-blown" climate model with past radiative perturbations → what is the response?

- Greenhouse Gases
- Volcanoes
- Solar variations
- Land use changes
- Aerosols
- Ozone changes

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What is a Climate Model?

Basically, a set of equations that represent the atmosphere, ocean, sea ice, land surface, and land ice. E.g. for the atmospheric component:

Wind $\frac{\partial \mathbf{v}}{\partial t} = -\mathbf{v}\cdot\nabla\mathbf{v} - \omega\frac{\partial \mathbf{v}}{\partial p} + f\mathbf{k}\times\mathbf{v} - \nabla\Phi + \mathbf{D}_M$

Temperature $\frac{\partial T}{\partial t} = -\mathbf{v}\cdot\nabla T + \omega\left(\frac{\kappa T}{p} - \frac{\partial T}{\partial p}\right) + \frac{\tilde{Q}_{rad}}{c_p} + \frac{\tilde{Q}_{con}}{c_p} + D_H$

Water Vapor $\frac{\partial q}{\partial t} = -\mathbf{v}\cdot\nabla q - \omega\frac{\partial q}{\partial p} + E - C + D_q$

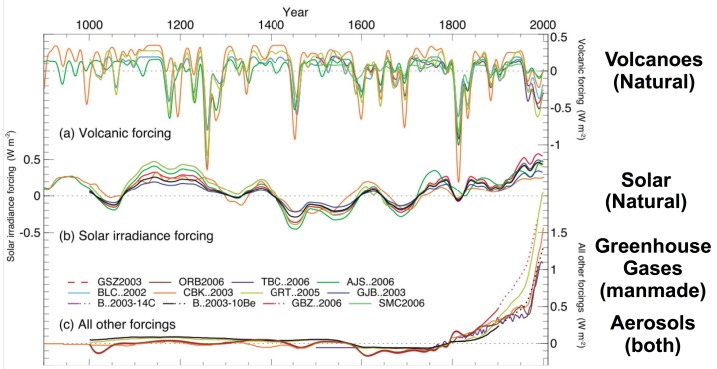
Mass Conservation $\frac{\partial \omega}{\partial p} = -\nabla\cdot\mathbf{v}$

Hydrostatic Balance $\frac{\partial \Phi}{\partial p} = -\frac{RT}{p}$,

from Trenberth (1992)

These quantities represent the effects of clouds, radiation, evaporation, friction on the atmosphere. They cannot be calculated directly (below model scale) and need to be estimated/parametrized.

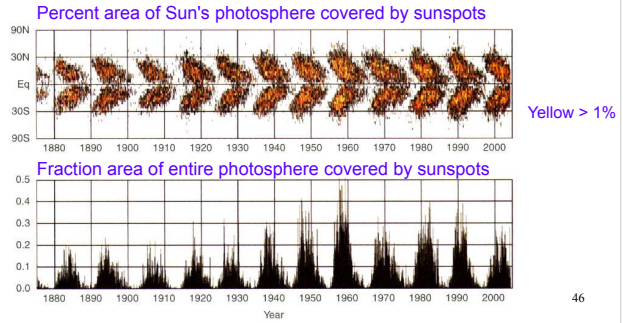
Past Radiative Forcing

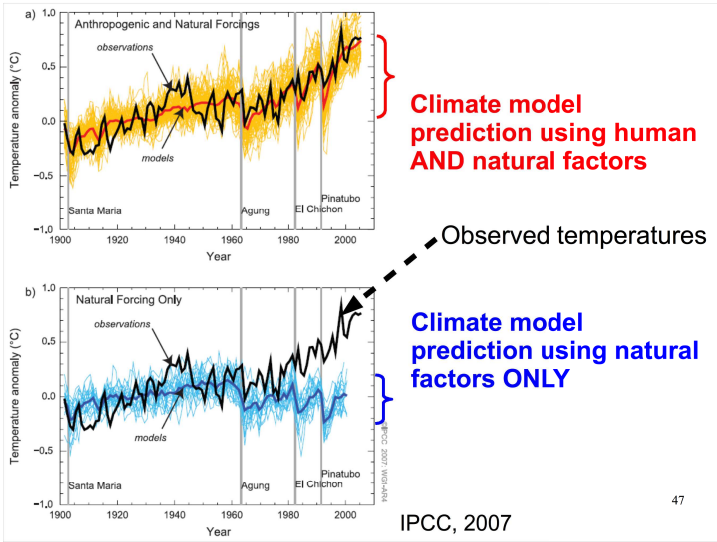


IPCC, 2007

Solar Variability

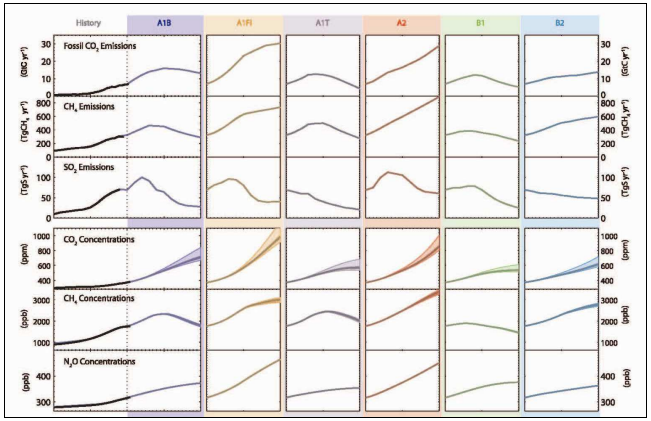
- The Sun's output is not exactly constant at 1366 W/m^2 – it does show some modest variation in time
- 11-year cycle in output, corresponding to variations in sunspots (large number of spots = high output)





IPCC, 2007

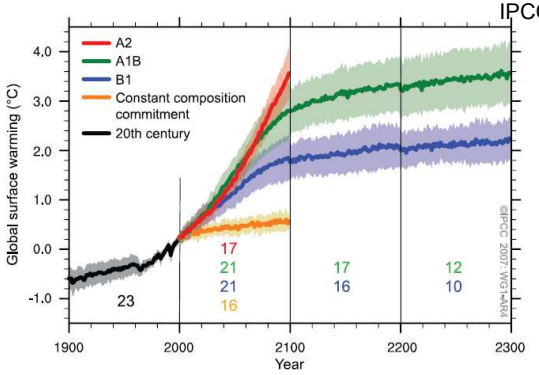
Future greenhouse gas emissions



IPCC, 2007

Future trends from Climate Models

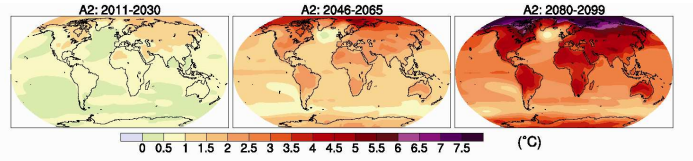
IPCC, 2007



Depending on the scenario, anywhere from 2–4 C for globally averaged warming in the year 2100. This warming will likely not be uniformly distributed.

Future trends from Climate Models

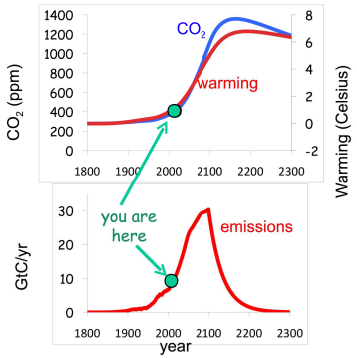
IPCC, 2007



- Warming is greatest in high latitudes, least in the tropics. This is for one of the higher end scenarios.
- Notice North Atlantic melting of ice on Greenland is expected to freshen the North Atlantic, slowing down the thermohaline circulation and the transport of warm water into the North Atlantic

The Long Tail

- If China and India industrialize with coal …
- CO_2 will rise to **4 times preindustrial**
- Extra CO_2 will remain for **millennia** after coal is gone



We Know for Sure

- CO_2 molecules absorb & re-emit thermal radiation (John Tyndall, 1859)
- Doubling the number of CO_2 molecules would add 4 W m^{-2} to the Earth 24/7 (Svante Arrhenius, 1896)
- If China and India industrialize with coal, CO_2 will approach ~400% of its preindustrial level by 2100
- Additional CO_2 will continue adding heat to Earth for thousands of years

What We're Not So Sure About

- **By precisely how much** the climate will change, especially locally
- How climate varies on **relatively short time-scales** (years to a couple of decades)
- The economic, political, and social **consequences** of these changes
- **What to do** about all of this

Solutions

- To provide a decent standard of living for billions of people on Earth …
- … we must generate huge amounts of energy without releasing CO_2.
- This is definitely possible (as an engineering task) …
- … but currently expensive and politically difficult.
- Can't do it by "tinkering around the edges."
- Requires profound changes to energy and economics

Imagine it's 1800, and you're in charge …

Somebody presents you with a grand idea for transforming the world's economy:

- ✓ Dig 10 billion tons of carbon out of the ground every year
- ✓ Build a system of pipelines, supertankers, railroads, highways, and trucks to deliver it to every street corner on the planet
- ✓ Build millions of cars every year, and millions of miles of roads to drive them on
- ✓ Generate and pipe enough electricity to every house to power lights & stereos & plasma TVs

… "and here's the itemized bill …"

Choose Your Future

- Some people think:
  - "Our modern lifestyle is only possible because it is subsidized by cheap fossil fuel. If we ever stop burning coal we'll freeze in the dark!"
- I prefer:
  - "Our well-being depends on creativity, innovation, and hard work. Our ingenuity puts us in a position to invent energy technologies for the 21st Century before we run out of oil."