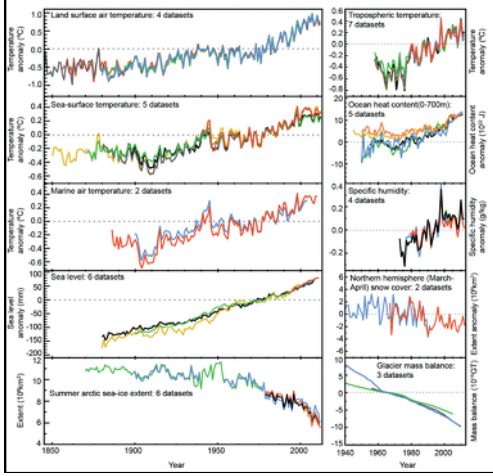
Future Climate Change

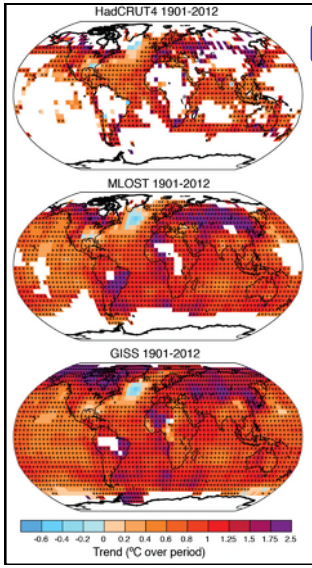
Please read IPCC
Working Group 1: 5th Assessment Report
Technical Summary
(download from class website)

Historical Trends



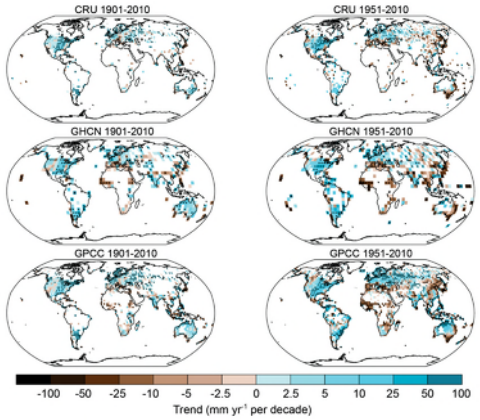
- Observed changes are large and observed in many different ways
- Warmer in air, on surface, and in ocean
- Less ice both on land and floating on sea
- Rising seas, moister air

Historical Trends



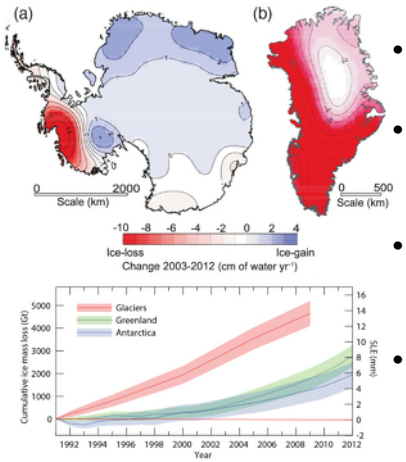
- CO_2 increased by about 33% (295 ppm in 1900, 397 ppm in 2012)
- Warming almost everywhere
- Most warming
  - on land
  - In NH
  - In Arctic
- Global average warming of about 0.8 °C (1.3 °F)
- Land warming ~ 50% more

Historical Precipitation Trends



- Warmer air evaporates more water
- Overall precipitation must therefore also increase
- Wet places get wetter, and dry places get drier

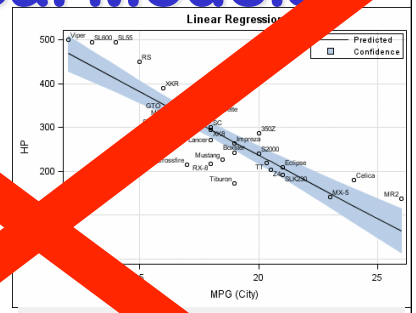
Ice Mass Loss (observed)

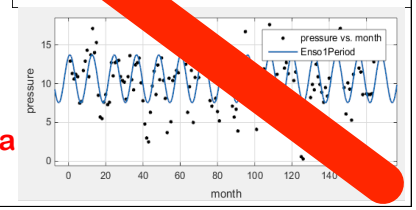


- Good data only since the 1990s (sat)
- Smaller glaciers are losing mass faster than ice sheets
- Greenland and West Antarctic Ice Sheets are losing mass
- East Antarctic Ice Sheet (much bigger) is gaining mass

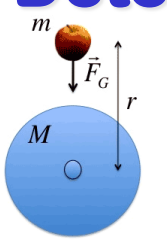
Empirical Models

- Gen[illegible]ized mathe[illegible]al formulatio[illegible]h adjustable coefficients
- Combinations of
  - polynomials
  - exponential gr[illegible] & decay
  - Periodi[illegible]es and cos[illegible]
- C[illegible]icients fit to data [illegible]g., least squares)





Deterministic Models

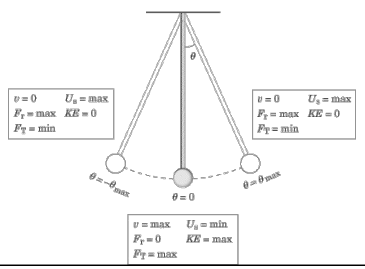


$$F = ma$$

$$\frac{GMm}{r^2} = ma$$

Then, cancelling m on both sides:

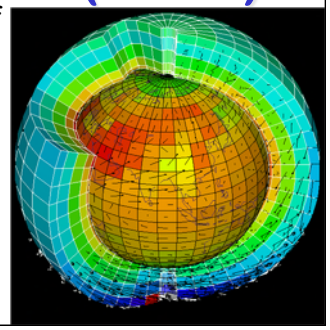
$$a = \frac{GM}{r^2} = g$$



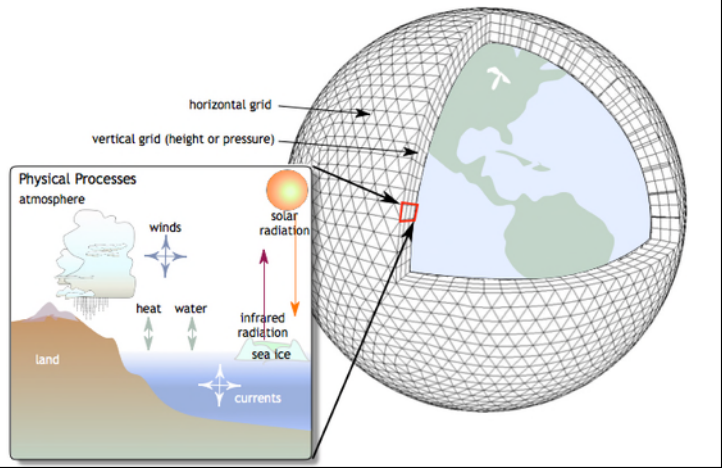
- Formulated as "cause and effect"
- Common in physics and chemistry
- Usually take the form of differential equations
- Initial & boundary-value problems
- May still have adjustable coefficients

"General Circulation Models" (GCMs)

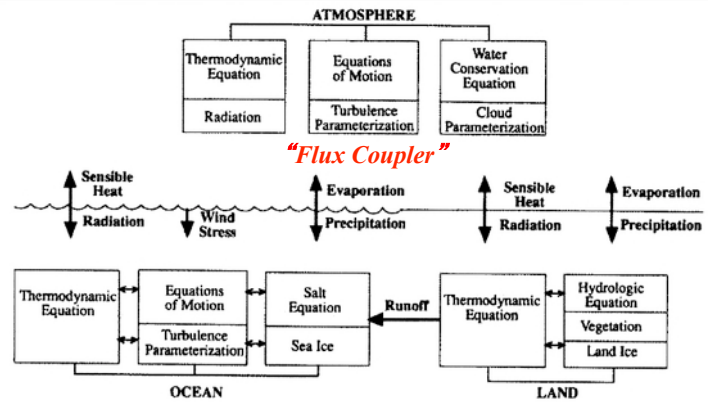
- Deterministic, not empirical
- "F = ma of a compressible fluid on a rotating sphere with radiation, thermodynamics, and phase transitions"
- Allow detailed prediction of future states at high resolution in both space and time
- Same equations:
  - Weather forecasting (initial value problem)
  - Climate simulation (boundary value problem)



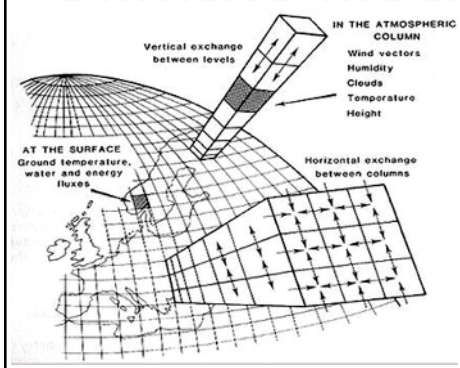
Climate Model Processes



Climate Model Structure

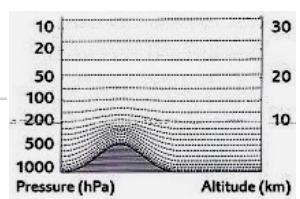


Climate Model Grids

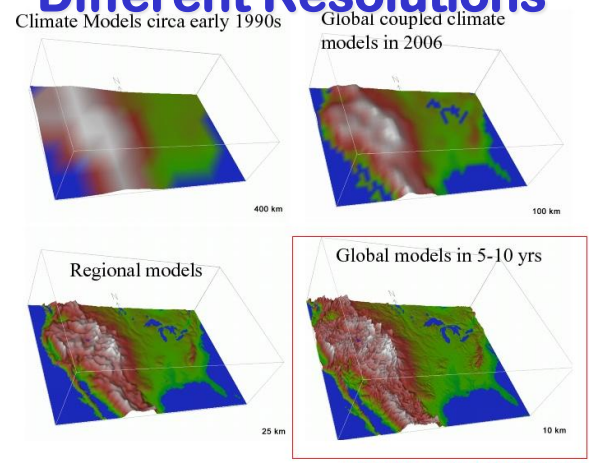


Typical climate model
$\Delta x \sim 100$ km

Typical weather forecast model
$\Delta x \sim 12$ km

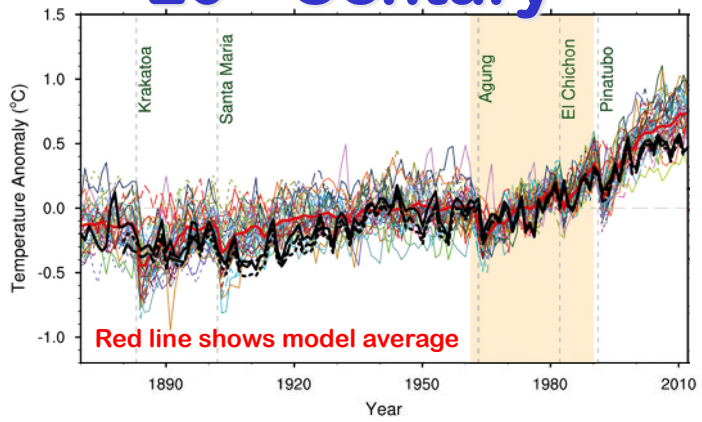


Topography at Different Resolutions



Optimistic view on model-developement

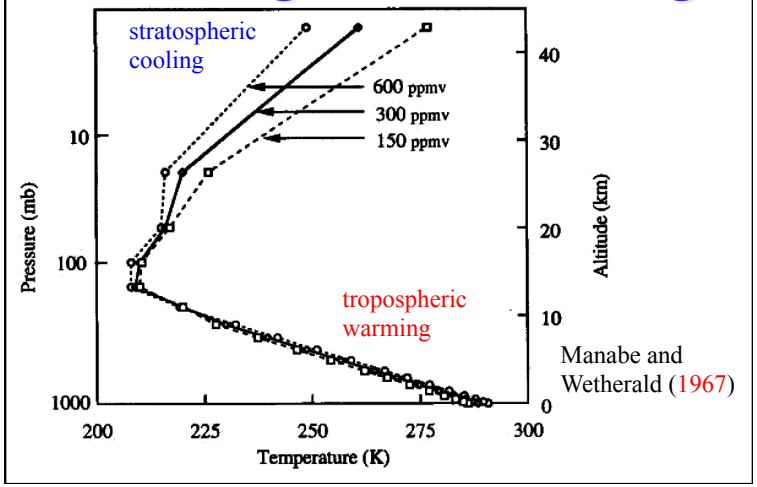
20th Century



3 observation sets
36 GCMs

Observations almost identical
Lots of model variations

Warming under Cooling



Manabe and Wetherald (1967)

Predicted Vertical Structure

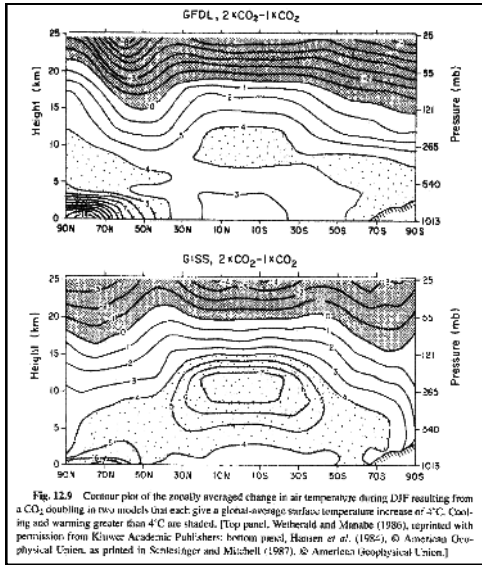
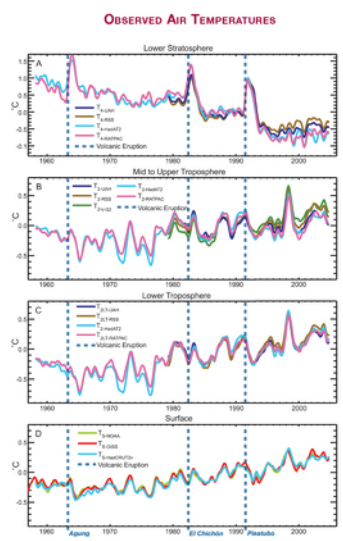
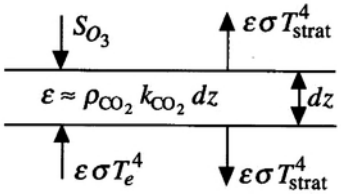


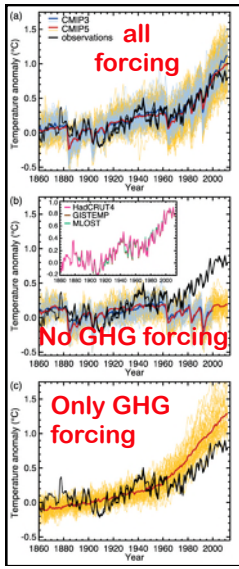
Fig. 12.9 Contour plot of the zonally averaged change in air temperature during DJF resulting from a CO_2 doubling in two models that each give a global-average surface temperature increase of 4°C. Cooling and warming greater than 4°C are shaded. [Top panel, Wetherald and Manabe (1986), reprinted with permission from Kluwer Academic Publishers; bottom panel, Hansen *et al.* (1984), © American Geophysical Union, as printed in Schlesinger and Mitchell (1987), © American Geophysical Union.]

- Greenhouse "signature" is tropospheric warming and stratospheric cooling
- Predicted in mid-1980's by climate models

Balloons, Satellites, and Surface Obs

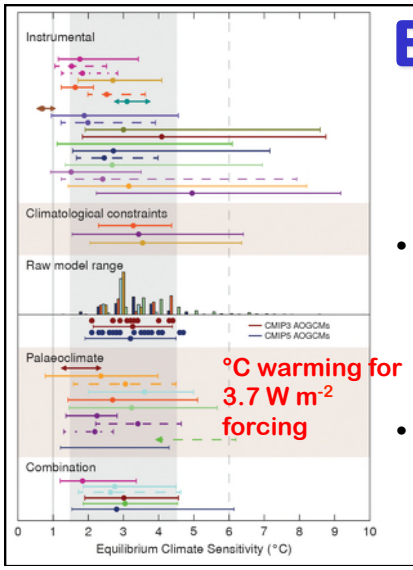






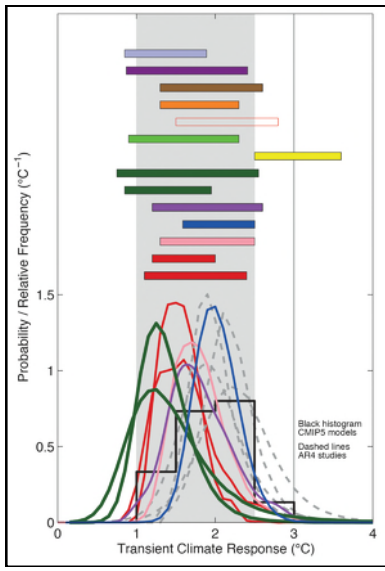
Hindcasts of 20th Century

- Models without greenhouse forcing don't predict enough warming
- Models with only greenhouse forcing predict too much warming
- Models with all forcing do a good job of predicting past climate change



Equilibrium Climate Sensitivity

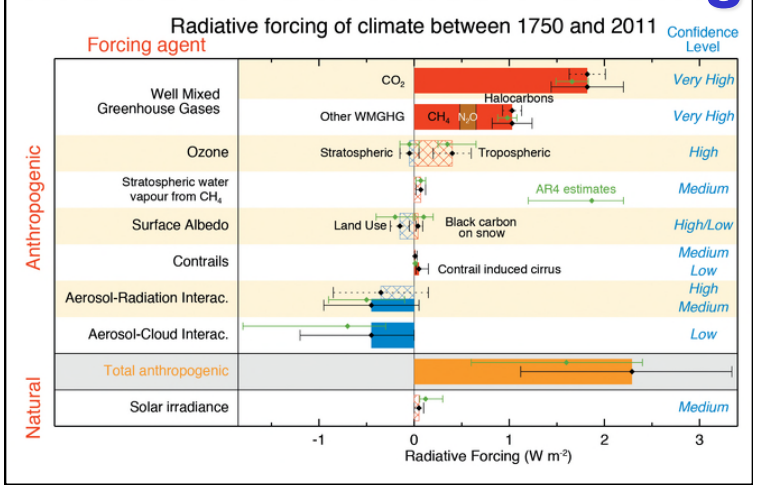
- Surface warming required to re-establish thermal equilibrium at top of atmosphere
- Many lines of paleoclimate evidence and most GCMs find about 3 °C



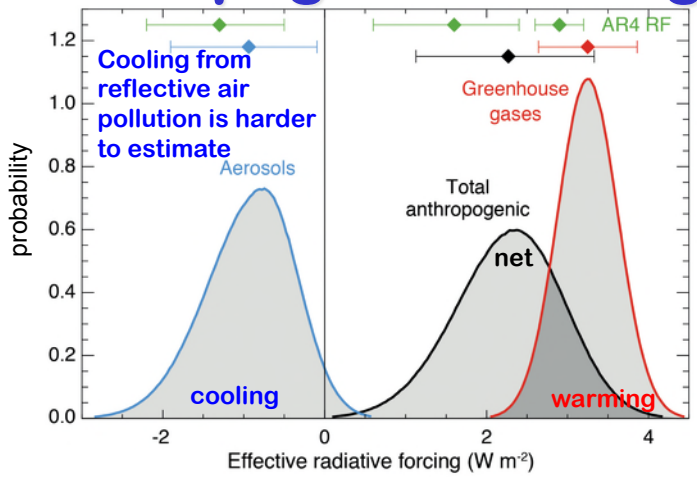
Transient Climate Response

- Warming takes a long time because much of the heat is absorbed by the oceans
- TCR is warming at time when CO_2 reaches 560 ppm
- Models and obs show TCR ~ 1 to 2.5 °C

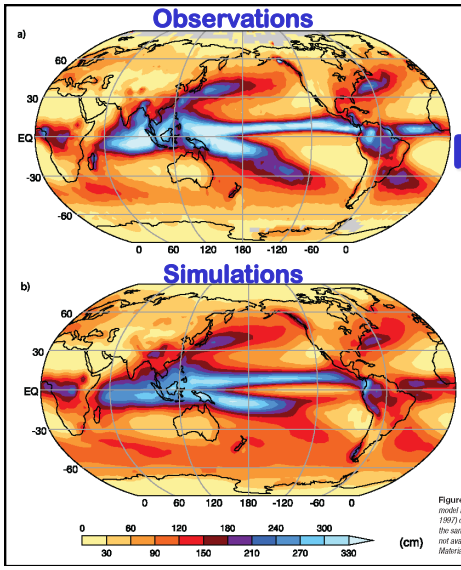
Modern Climate Forcing



Anthropogenic Forcing



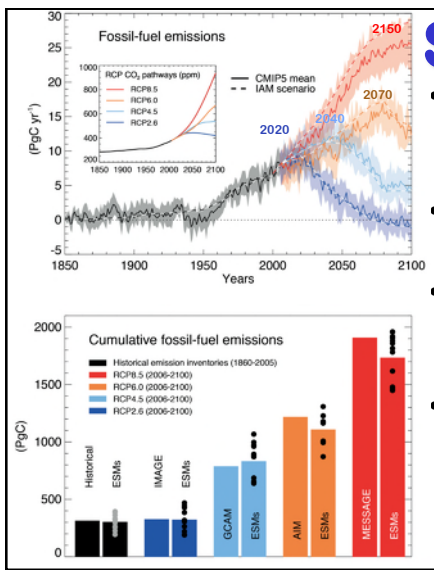
Model Evaluation: Precipitation



- General patterns and magnitudes very well simulated
- Problems with mountain ranges and some finer-scale patterns

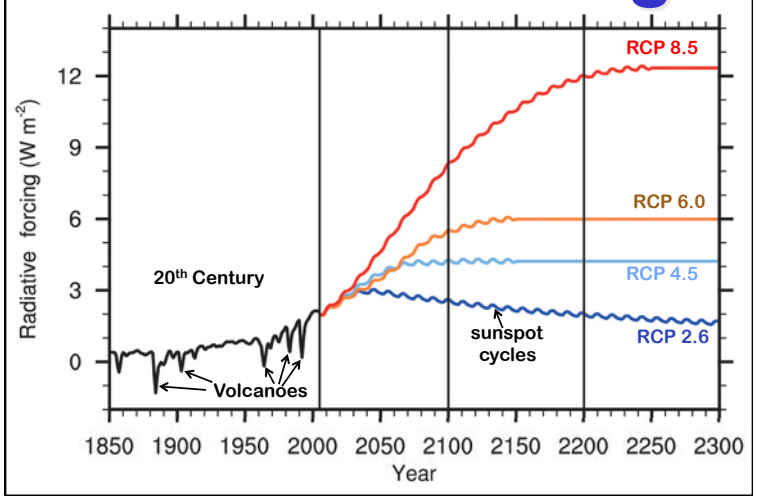
Figure 8.5. Annual mean precipitation (cm), observed (a) and simulated (b), based on the multi-model mean. The Climate Prediction Center Merged Analysis of Precipitation (CMAP; Xie and Arkin, 1997) observation-based climatology for 1980 to 1999 is shown, and the model results are for the same period in the 20th-century simulations in the MMD at PCMDI. In (a), observations were not available for the grey regions. Results for individual models can be seen in Supplementary Material, Figure S8.9.

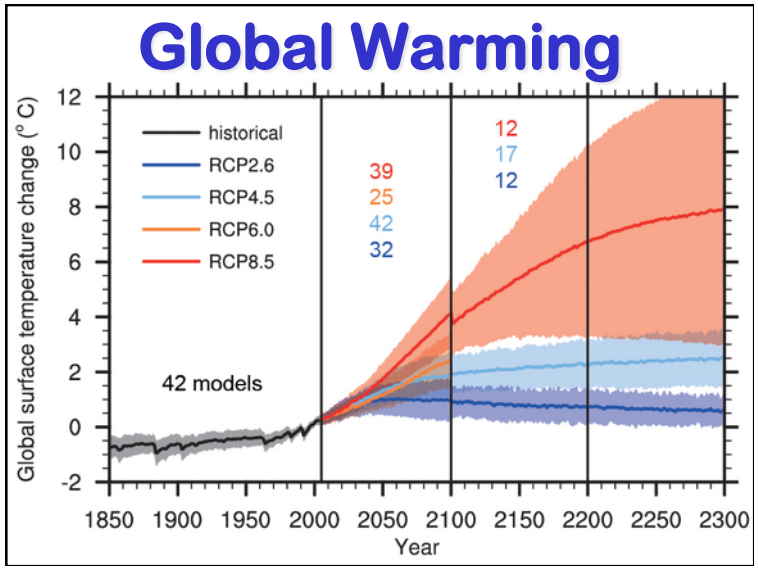
Scenarios

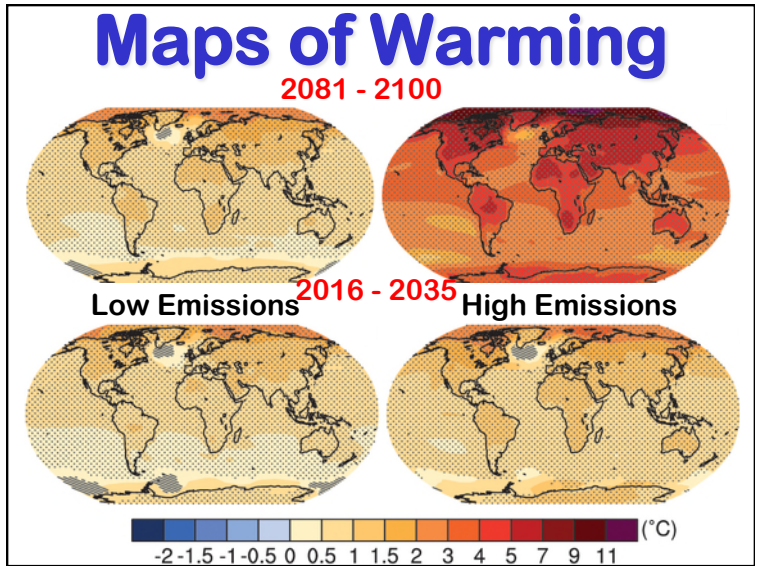


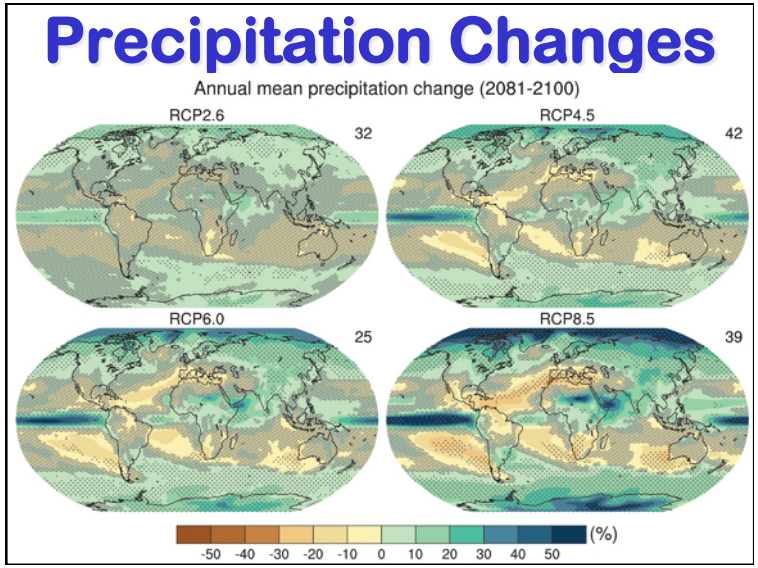
- Not predictions … "what if" experiments
- None are more or less likely
- Depends on economics and policy (politics)
- Emissions peak in
  - 2020 (RCP2.6)
  - 2040 (RCP4.5)
  - 2070 (RCP6.0)
  - 2150 (RCP8.5)

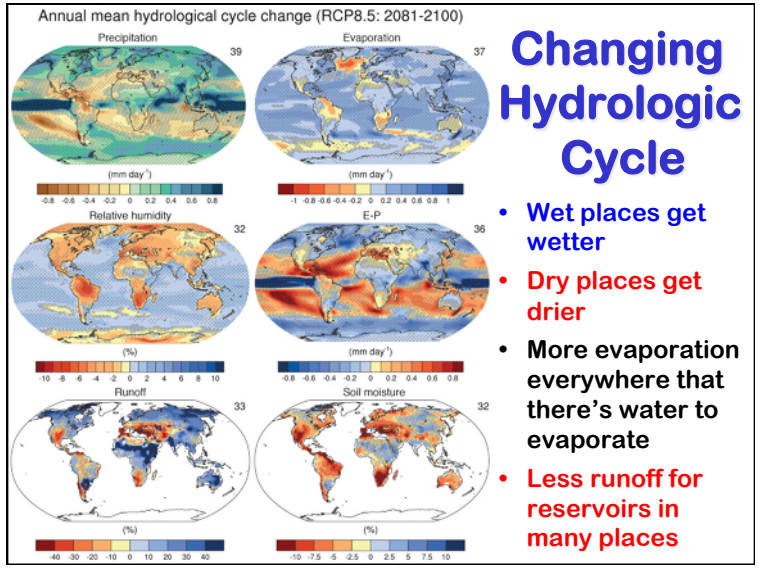
Radiative Forcing



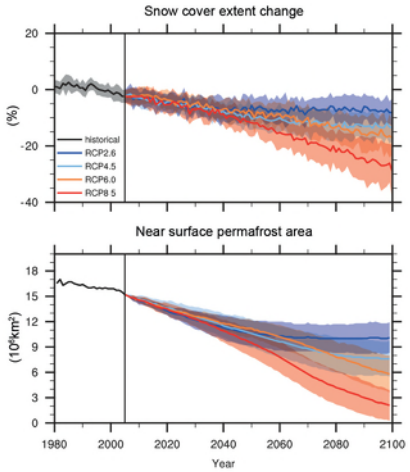

Global Warming
Global surface temperature change (° C)
12
10
8
6
4
2
0
-2
historical
RCP2.6
RCP4.5
RCP6.0
RCP8.5
39
25
42
32
12
17
12
42 models
1850 1900 1950 2000 2050 2100 2150 2200 2250 2300
Year


Maps of Warming
2081 - 2100
2016 - 2035
Low Emissions
High Emissions
(°C)
-2 -1.5 -1 -0.5 0 0.5 1 1.5 2 3 4 5 7 9 11


Precipitation Changes
Annual mean precipitation change (2081-2100)
RCP2.6
32
RCP4.5
42
RCP6.0
25
RCP8.5
39
(%)
-50 -40 -30 -20 -10 0 10 20 30 40 50

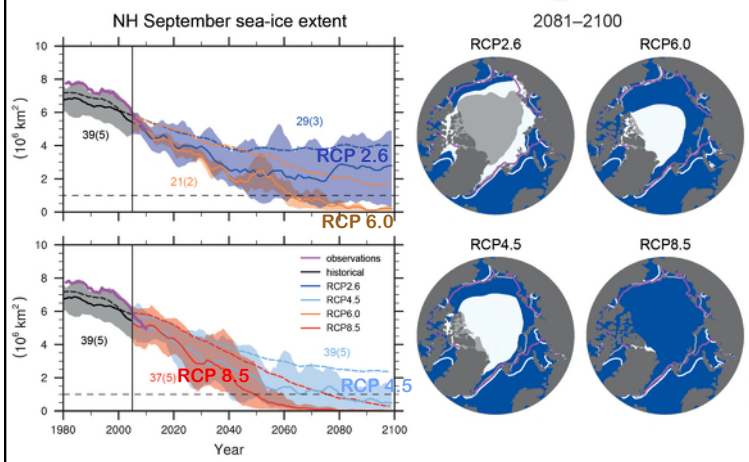

Annual mean hydrological cycle change (RCP8.5: 2081-2100)
Precipitation
39
Evaporation
37
Relative humidity
32
E-P
36
Runoff
33
Soil moisture
32
Changing Hydrologic Cycle
• Wet places get wetter
• Dry places get drier
• More evaporation everywhere that there's water to evaporate
• Less runoff for reservoirs in many places

Snow & Permafrost

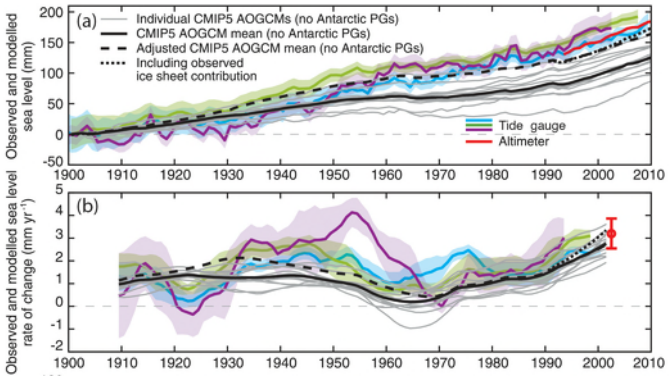


- Reduced snow and ice under all scenarios
- Reduced snow cover increases absorbed solar radiation (positive albedo feedback)
- Loss of permafrost has special risks …
  - Drainage
  - Methane and CO_2

Sea Ice Changes

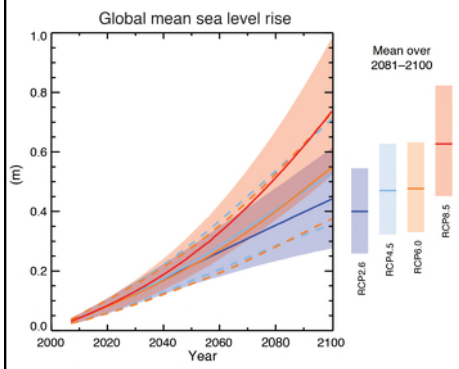


Evaluation: Sea-Level



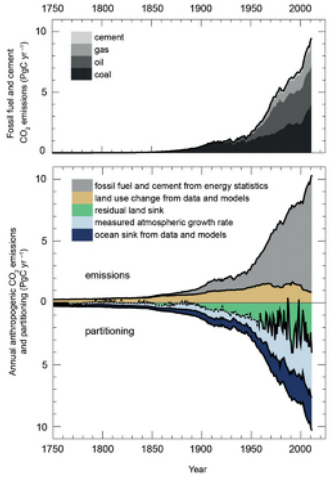
- Most models underpredict recent sea-level rise
- They completely lack ice sheet dynamics

Future Sea-Level



- All models show substantial and accelerating rise in sea-level
- Big differences depending on future emissions
- Equilibrium sea level will take many centuries

Carbon Sources and Sinks

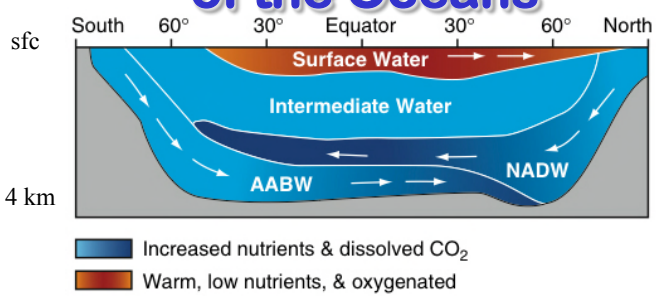


- Half the carbon from fossil fuels goes into the atmosphere
- The other half goes into land and oceans
- The land part is unexpected and unreliable
- Future of carbon sinks is harder to predict than temperatures

Where Has All the Carbon Gone?

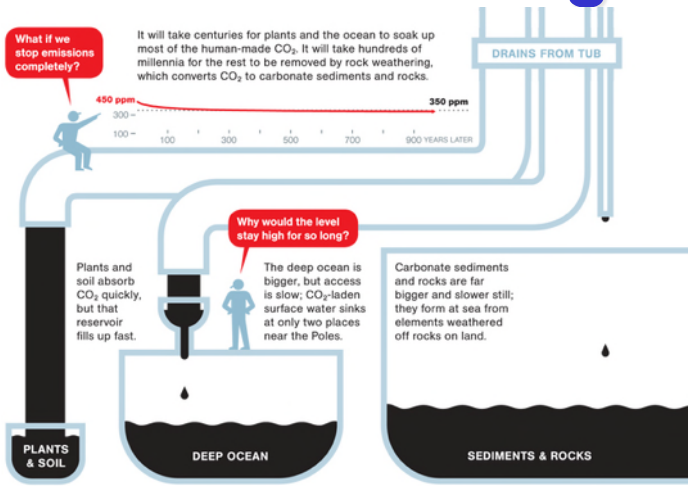
- Into the **oceans**
  - **Solubility pump** (CO_2 very soluble in cold water, but rates are limited by slow physical mixing)
  - **Biological pump** (slow "rain" of organic debris)
- Into the **land**
  - **CO_2 Fertilization** (plants eat CO2 … is more better?)
  - **Nutrient fertilization** (N-deposition and fertilizers)
  - **Land-use change** (forest regrowth, fire suppression, woody encroachment … but what about Wal-Marts?)
  - Response to **changing climate** (e.g., Boreal warming)

Vertical Structure of the Oceans

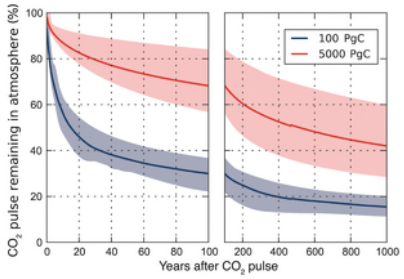


- Warm buoyant "raft" floats at surface
- Cold deep water is only "formed" at high latitudes
- Very stable, hard to mix, takes ~ 1000 years!
- Icy cold, inky black, most of the ocean doesn't know we're here yet!

Bathtub Drainage



The Long Tail



- Fossil CO_2 dissolves into the oceans
- Chemistry limits the amount the oceans can hold
- Mixing with deep oceans is very slow
- Removal of CO_2 depends on how much we add to atmosphere
- For a big pulse, 40% is still in the air after 1000 years