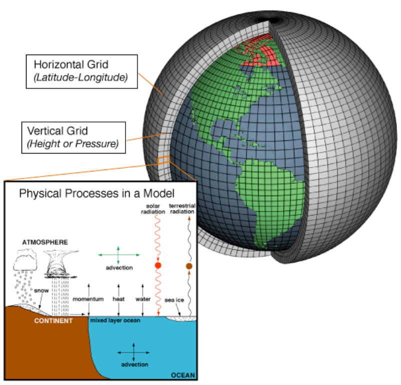
Climate Models

- What is a climate model?
- How well do they work?
  - Annual Average
  - Seasonal Cycle
  - Diurnal Cycle
  - Natural Variability
  - 20th Century Reconstructions
- What do they tell us about Glacial cycles?

Climate Models

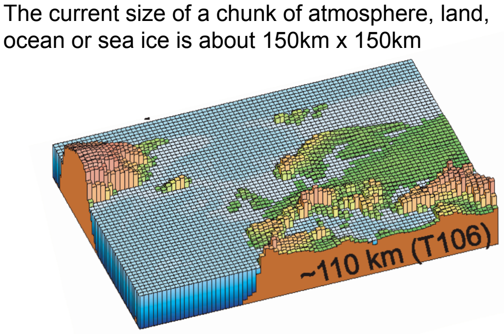
- What is a climate model?
  - Mathematical representations of the atmosphere, ocean, sea ice and land surface
  - For each component, the model is based on the laws of physics and chemistry. For example,
    - the models conserve energy, mass, momentum.The obey the laws of physics (e.g., F=ma) and chemistry
    - Radiation (solar and terrestrial) is based on detailed theory (quantum mechanics).
    - Concentrations of some gases are prescribed because they change very very slowly (N_2, O_2, Ar, CFCs, etc)
    - Other gases are sometimes prescribed and sometimes calculated by the laws of chemistry and thermodyamics
  - The equations are hopelessly complicated to solve by pen and pencil
  - The equations can't be solved at a molecular level, so the climate system is chopped up regular chunks

Climate Models



Climate Models

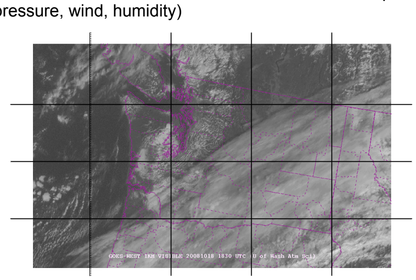
- The current size of a chunk of atmosphere, land, ocean or sea ice is about 150km x 150km



The vertical extent of a box is typically:
Atmosphere/Ocean: 80-500m   Sea Ice: 50cm   Land: 10cm

Climate Models

- The physical and chemical laws are solved in each of these chunks.
  - Within each chunk, there are things that are not explicitly modelled (e.g., clouds) but must be approximated ("parameterized") as a function of the average state of the chunk (e.g, the fraction of clouds in the chunk as a function of the chunk's temperature, pressure, wind, humidity)



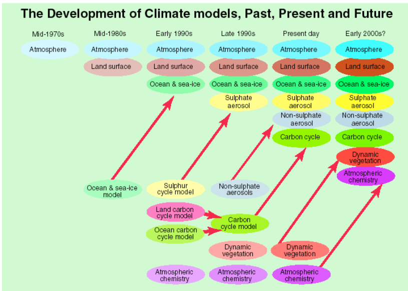
Climate Models

- Information in one chunk affects another because of *motion*
  - Wind (atmosphere)
  - Flow (ice, rivers, groundwater movement)
  - Currents (ocean)
- These calculations require enormous computer resources
  - For example, a 100 year run of a typical AR4 climate model takes

    * Six months on the world's fastest machines
    * 10,000 Gbytes of disk space (minimal output)

Climate Models

- What is a climate model
- How long have they been around?



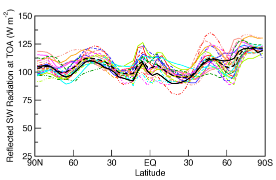
Climate Models are based on the laws of physics and chemistry, and used for ~30 years for various problems.

Climate Models

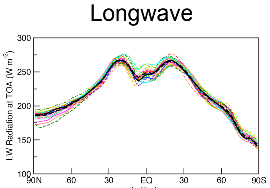
- What is a climate model?
- How long have they been around?
- How good are they?
  - Some examples from 14 of the 23 climate models used in the most recent IPCC report: Assessment Report #4 (AR4) in 2007.

Top of the Atmosphere Radiation Flux

Reflected Shortwave



Longwave



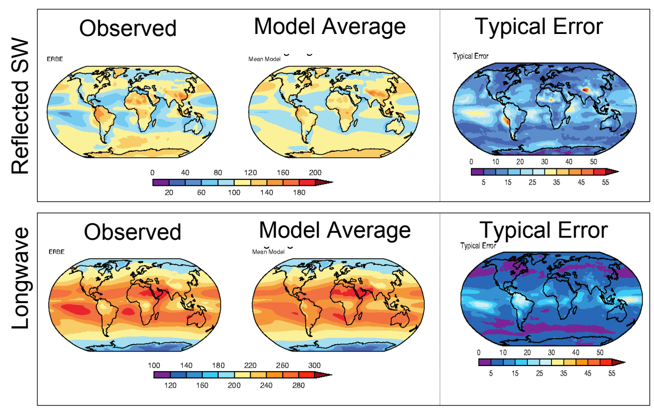
- One color line for each model
- Black solid line is observed
- Black dashed line for 'average of models'

- Error

  typically 10-15 W/m^2 (15% in reflected shortwave and 5% in outgoing longwave)

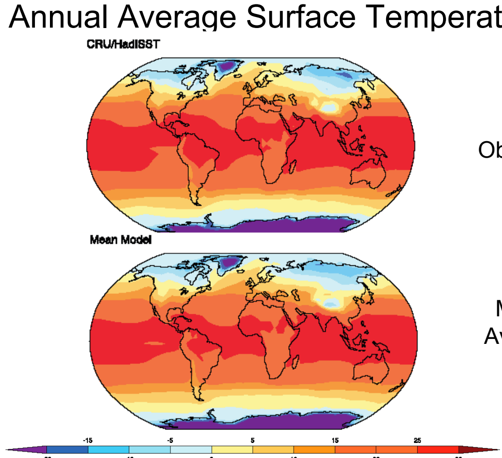
IPCC 2007

Top of the Atmosphere Radiative Flux



IPCC 2007

Annual Average Surface Temperature

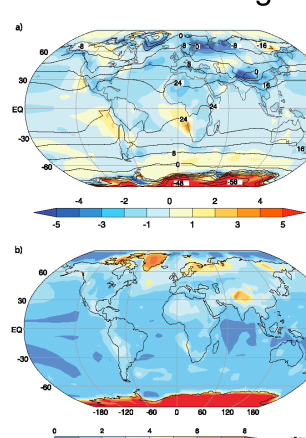


Observed

Model Average

IPCC 2007

Annual Average Surface Temperature



Contoured = Observed

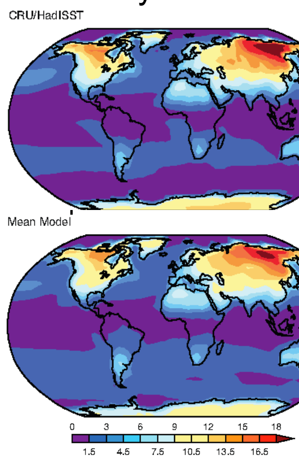
Shaded = error in 'average of the models'

Error in typical model

IPCC 2007

“Annual Cycle*” in Temperature

* Multiply by ~3



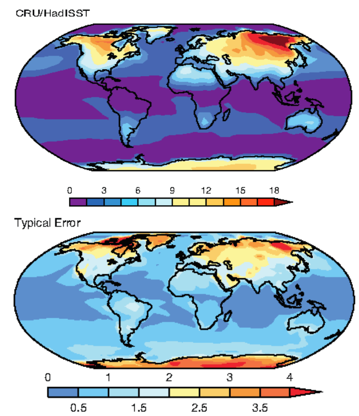
Observed

Model Average

IPCC 2007

“Annual Cycle*” in Temperature

* Multiply by ~3



Observed

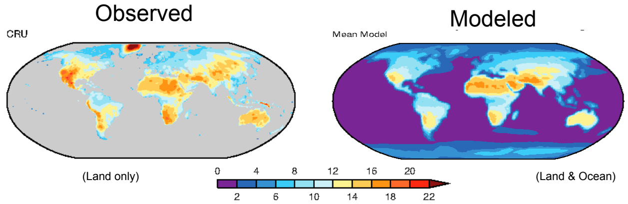
Typical Model Error

IPCC 2007

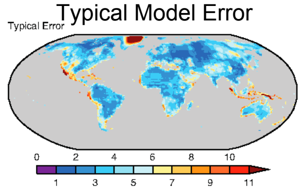
Diurnal (day-night) temperature range

Observed

Modeled

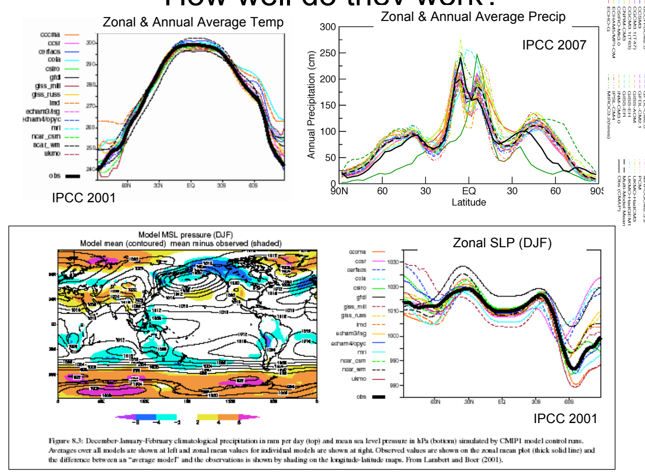


Typical Model Error



IPCC 2007

How well do they work?

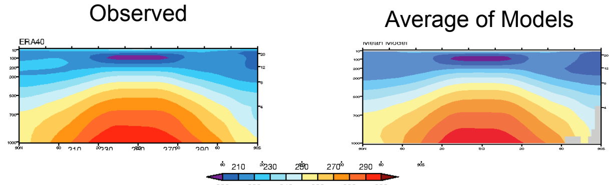


Atmospheric Temperature

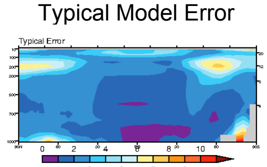
Zonal (east-west) average

Observed

Average of Models

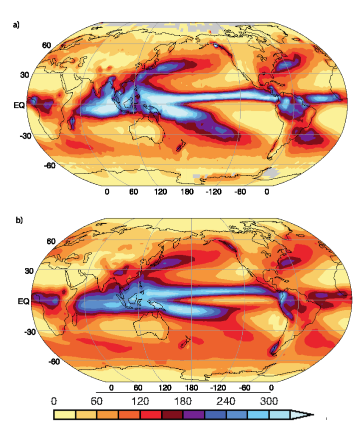


Typical Model Error



IPCC 2007

Annual Average Precipitation

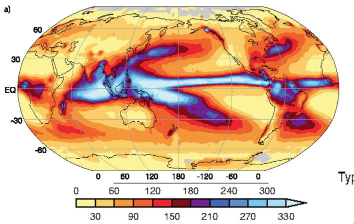


Observed (cm/year)

Average of the models

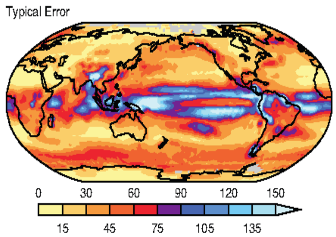
IPCC 2007

Annual Average Precipitation



Observed (cm/year)

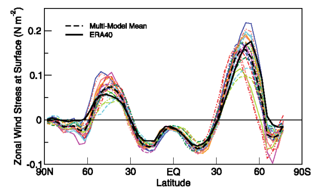
Typical Model Error



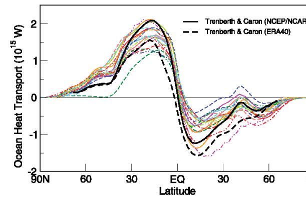
IPCC 2007

Surface Wind Stress and Ocean Heat Transport

Zonal Average Surface Wind Stress



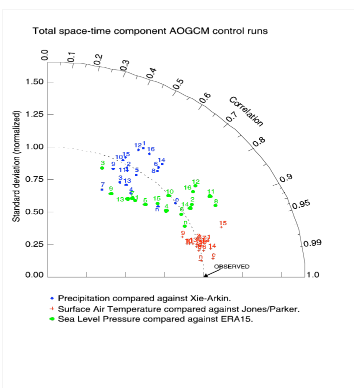
Northward Ocean Heat Transport



One color line for each model

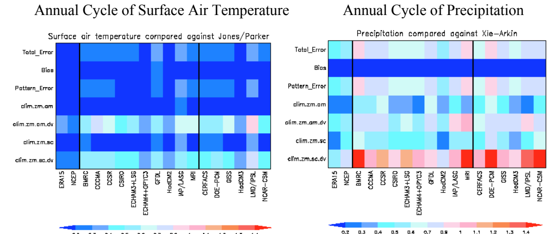
IPCC 2007

Taylor Diagram to Illustrate Error in Annual Cycle in Climate models (circa 2000)



IPCC 2001

Error depends on spatial and temporal scale and on the climate variable



Errors of surface air temperature (climatological annual cycle) simulated by CMIP2 model control runs. Shown are the total errors, the global and annual mean error ("bias"), the total r.m.s ("pattern") error, and the following components of the climatological r.m.s. error:zonal and annual mean ("clim.zm.am"); annual mean deviations from the zonal mean ("clim.zm.am.dv"), seasonal cycle of the zonal mean ("clim.zm.sc"); and seasonal cycle of deviations from the zonal mean ("clim.zm.sc.dv").

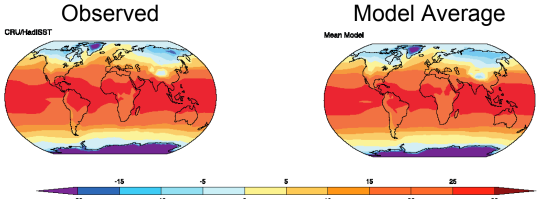
Figure 8.6: As in the Figure 8.5, for precipitation. The two left-most columns represent alternate observationally based data sets, 15-year ECMWF reanalysis ("ECMWF") and NCAR/NCEP reanalysis ("NCEP"), compared with the baseline observations (Xie and Arkin, 1996). From Covey *et al.* (2000b).

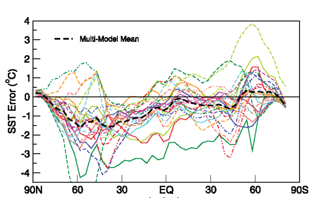
IPCC 2001

Annual Average Ocean Temperature

Observed

Model Average

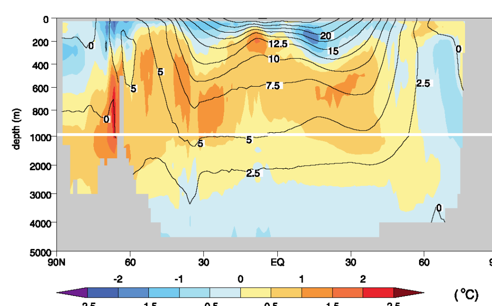




Error in zonal (east-west) averaged annual surface temperature

IPCC 2007

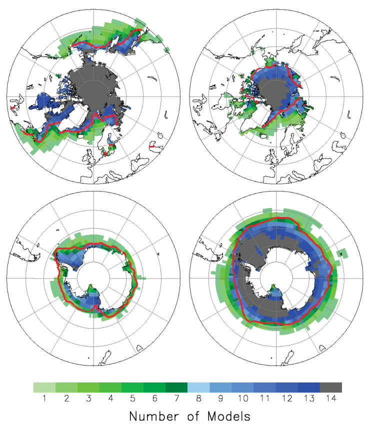
Vertical Distribution of Ocean Temperature



Contours = observed temperature
Color = error in the 'average of the models'

IPCC 2007

Sea Ice Extent



- Red line demarks the position of the 15% sea ice coverage at the end of March and September from observations
- Color is the number of models (out of 14) that have at least 15% sea ice coverage

Baseline for observations 1980-1999

Grid size for calculating sea ice coverage is 2.5 x 2.5 latitude-longitude

IPCC 2007

How well do models do snow cover?

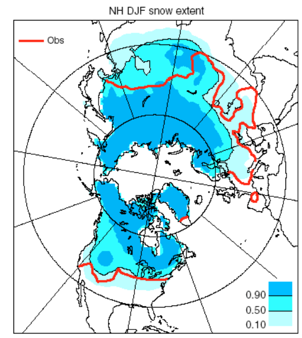


Figure 8.11: Illustration of the range of snow cover extent in CMIP1 model simulations listed in Table 8.3: Northern Hemisphere, DJF. The figure is constructed similarly to Figure 8.10 based on the prescribed 1 cm cutoff. The observed boundary is based on Foster and Davy (1988).

IPCC 2001

Climate Variability and Climate Change

1. Natural Variability
   - North Atlantic Oscillation, El Nino/Southern Oscillation

Climate Variability

2. Forced Change (natural)
   - Volcanic Eruptions (scattering particles)
   - Changes in the Solar Luminosity
3. Forced Change (human)
   - Burning of fossil fuels (increasing GH gases)
   - Burning of biomass (scattering particles)

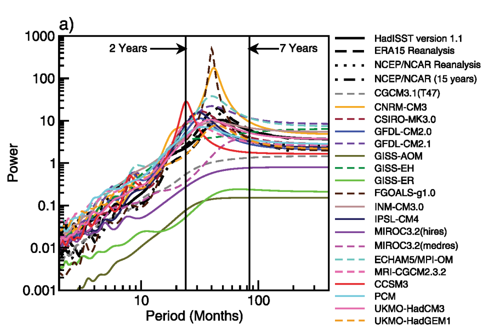
Climate Change

Natural Variability

- The models simulate reasonably well the weather on scales of > 200km.
- The models simulate reasonably well the natural patterns of variability in the atmosphere on 200-1000km scales
  – North Atlantic Oscillation, the eastern Atlantic pattern, the Pacific North American pattern, the Western Pacific pattern, etc
- The models do very poorly the ENSO phenomenon
- The models do poorly in places where topography changes markedly on scales that are smaller than the atmospheric grid (e.g., Puget Sound)
  – In these cases, useful information can be obtained by 'downscaling'

How well do they do El Nino/Southern Oscillation (ENSO)?

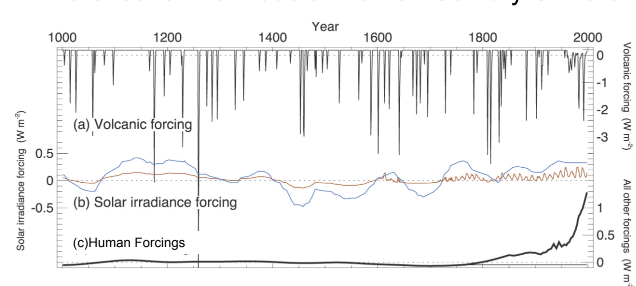
Spectrum of Nino3 Index in the Coupled Models



They are terrible.

IPCC 2007

More test of the Models: the 20th Century Climate



Aerosols from Volcanoes cool the planet

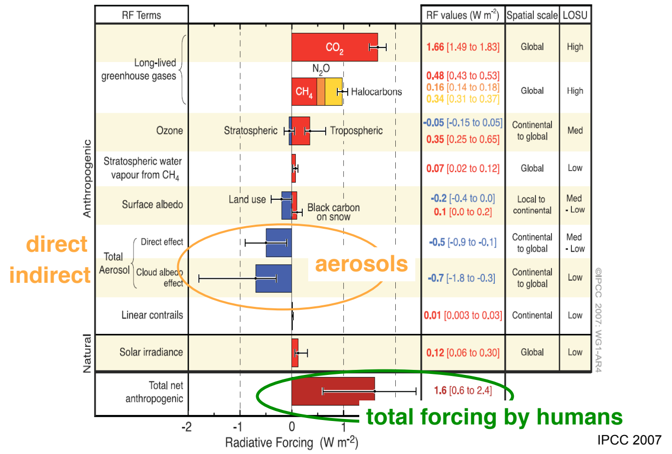
Estimate of forcing before ~1980 is *very* crude

The Sun's luminosity *(brown curve = 2007; blue curve = 2001)*

Estimates comes from: (i) extrapolating direct insolation-sunspot number relationship; (ii) modeling of the solar magnetic flux; ^{14}C and ^{10}Be measurements in trees (cosmogenic flux); (iii) observing range of luminosity in other Sun-like stars.

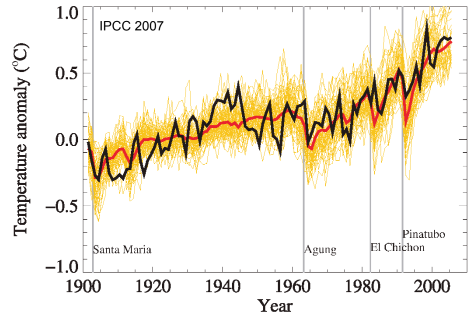
IPCC 2007 Fig 6.14

Radiative Forcing of the Climate by Humans (circa 2005)



IPCC 2007

Simulating the Global Average Temperature over the 20th Century



Each yellow line is one simulation.

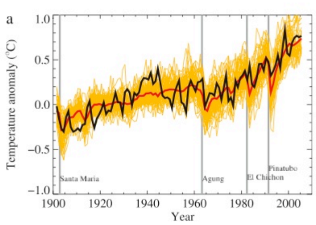
Red line = average of all 58 simulations from 14 models

Black line = observed

Simulations include natural (solar and volcanic) and human (carbon dioxide, etc) forcing

14 models were used in this figure with a total of 58 simulations

Model results with natural and human

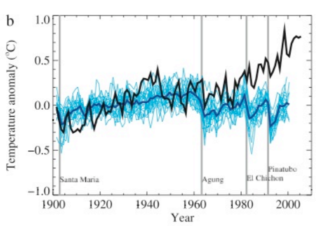


Both human and natural forcing

Each yellow line is one simulation.

Red line = average of all 58 simulations from 14 models

Black line = observed



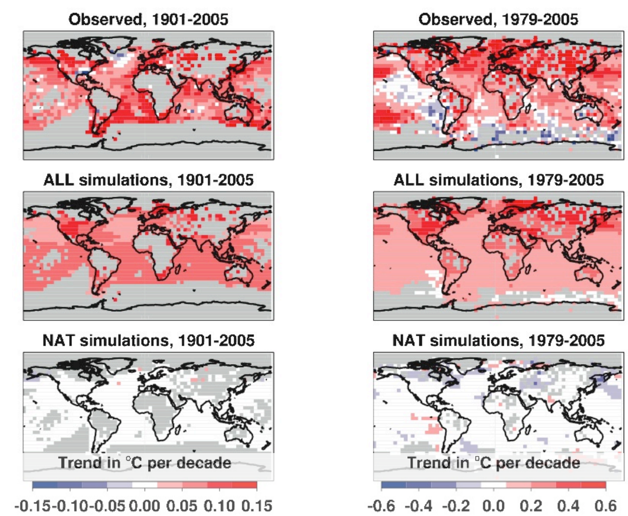
Natural forcing only

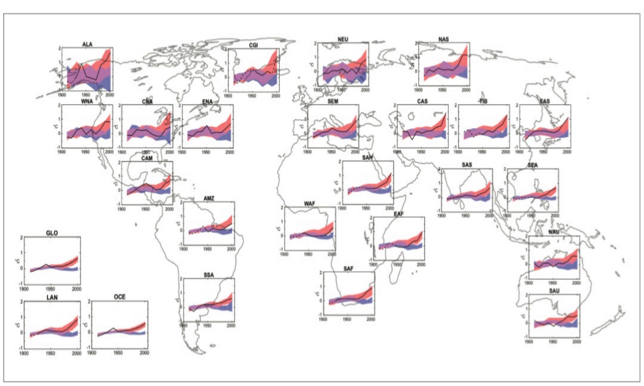
Each light blue line is one simulation.

Dark blue line = average of 19 simulations from 5 models

Black line = observed

IPCC 2007





Blue is natural forcing only   Red is all forcings

IPCC 2007

More test of the Models

- They have been used to simulate climates of the past and evaluated against the paleo (proxy) data
  - The Early Holocene: 6000 and 8500 years before present (yr BP)
    - They don't get a "green Sahara"
  - The Eocene: 65 million yr BP, when the earth was ice free and much warmer than today (by ~10-15ºC) and CO_2 levels were 2-5 times more than today.
    - Note the AR4 models used to do this systematically underestimate the warming of the Eocene
- The Last Glacial Maximum: 23,000 yr BP, the maximum extent of the most recent glacial period
    - Used to evaluate the relative contributions of changes in insolation, land ice (albedo) and carbon dioxide (180ppm vs 280ppm pre-industrial) to the climate changes.