The Future of the Earth's Climate: Frontiers in Forecasting

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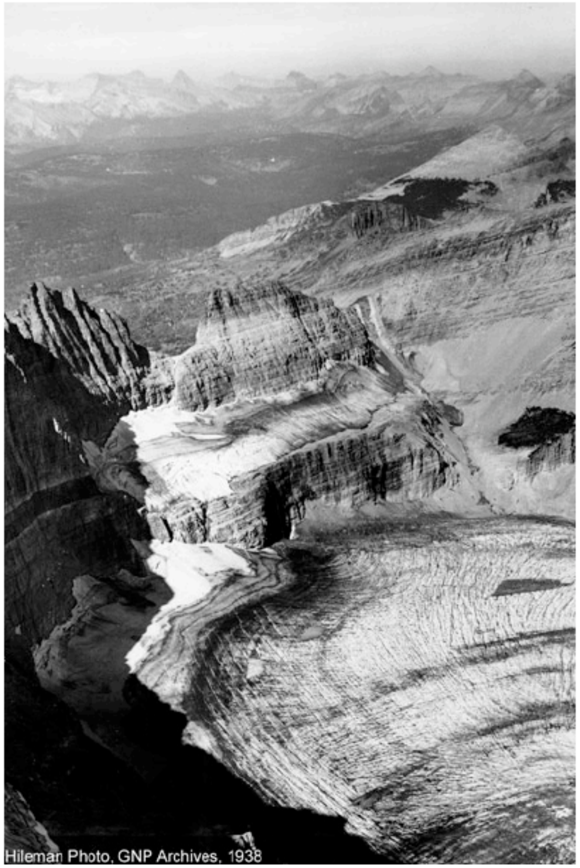
Key climate questions

- How has the physical climate changed in the recent past?
- How has the energy budget of the planet changed?
- Are recent changes natural or human-induced?
- What are the possible futures of the Earth's climate?
- What are the key uncertainties in impacts and mitigation?

Evidence for physical climate change

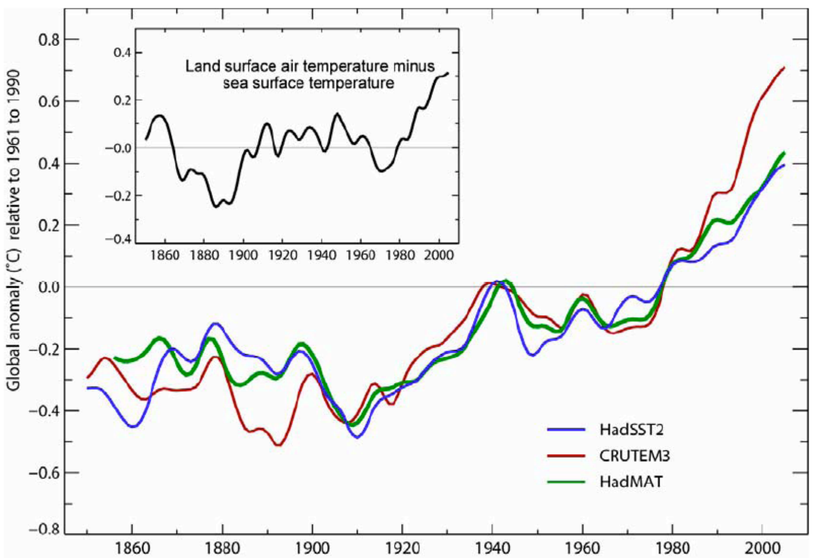
Grinnell Glacier, Montana, 1938



Grinnell Glacier, Montana, 2005

Increasing global temperatures

Global Temperatures



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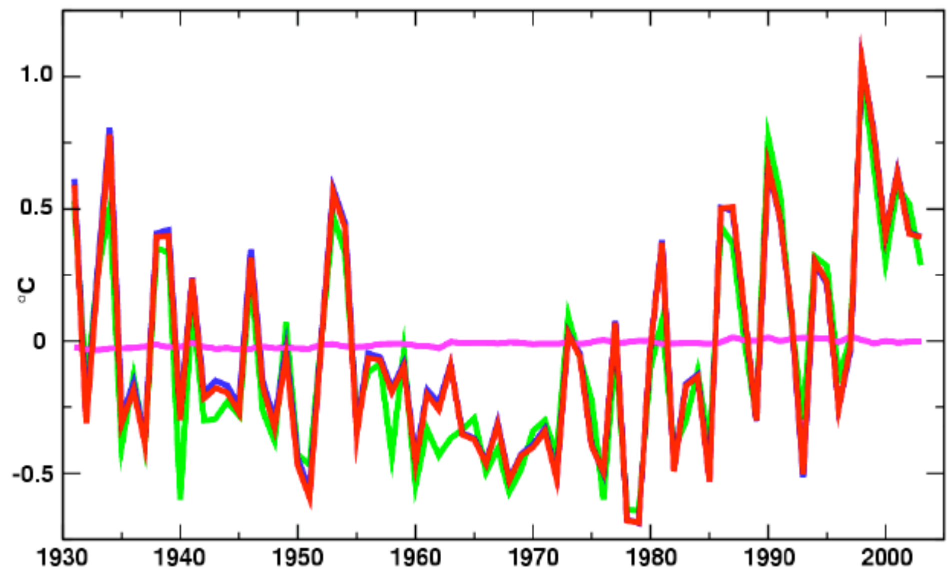
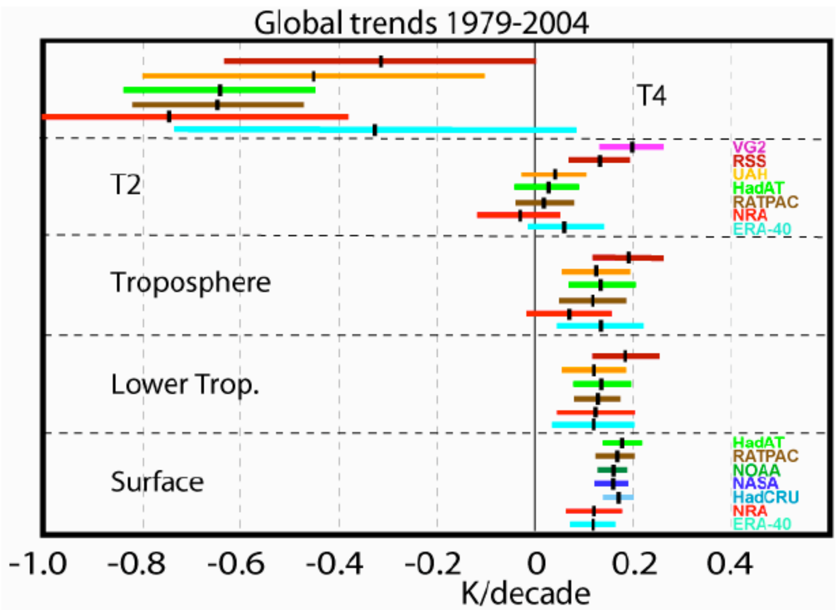
Urban Heat Island Effect



• Earth has warmed by 0.76 ± 0.19K since 1850.
• Measurement artifacts do not affect global trends.

Atmospheric temperature and moisture

Air Temperature Trends



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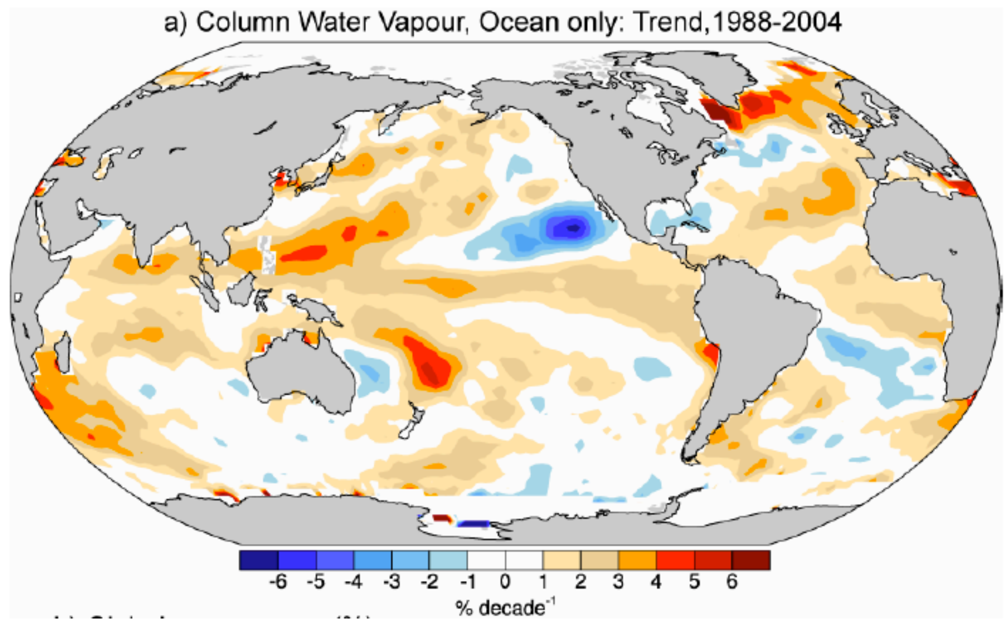
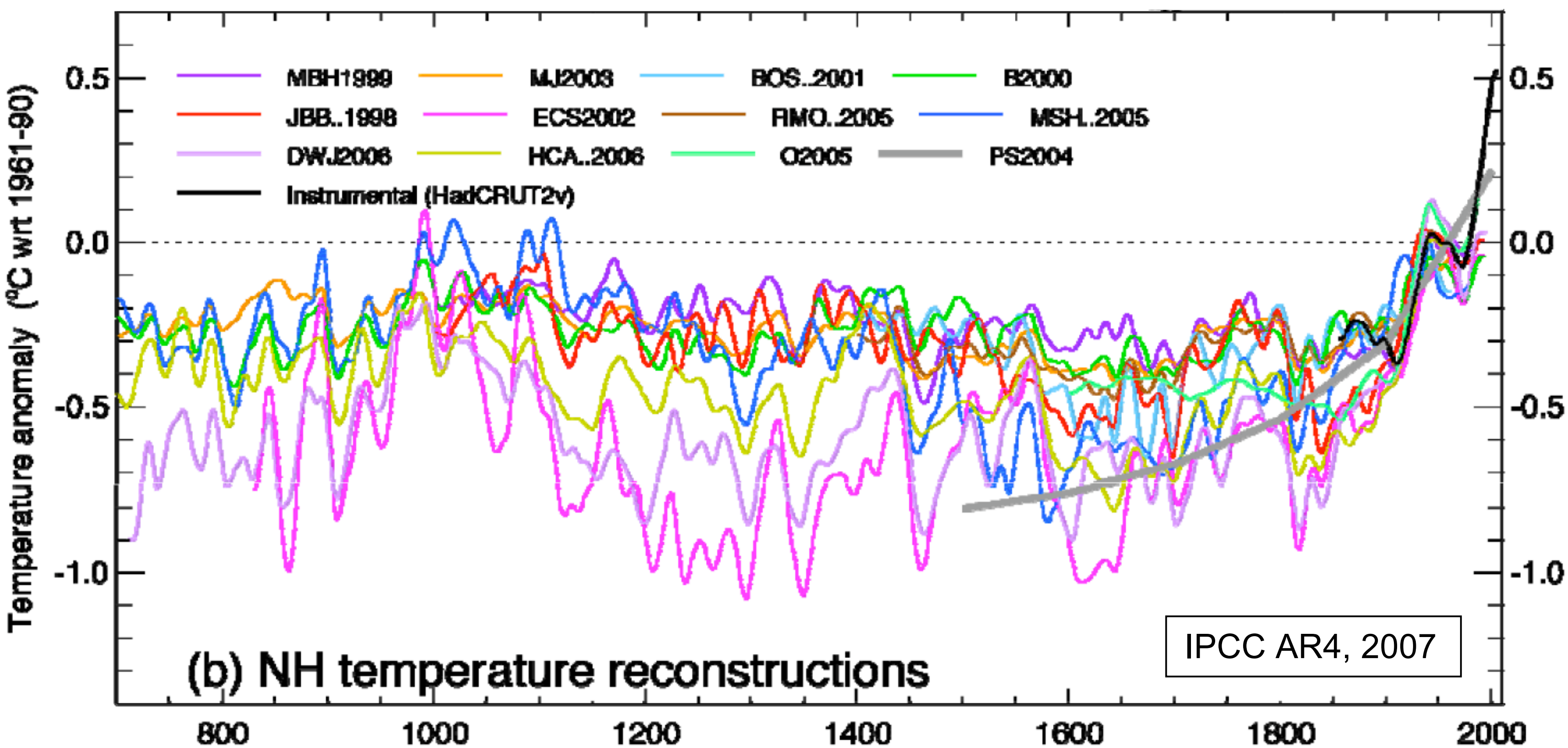
Atmospheric Moisture Trends



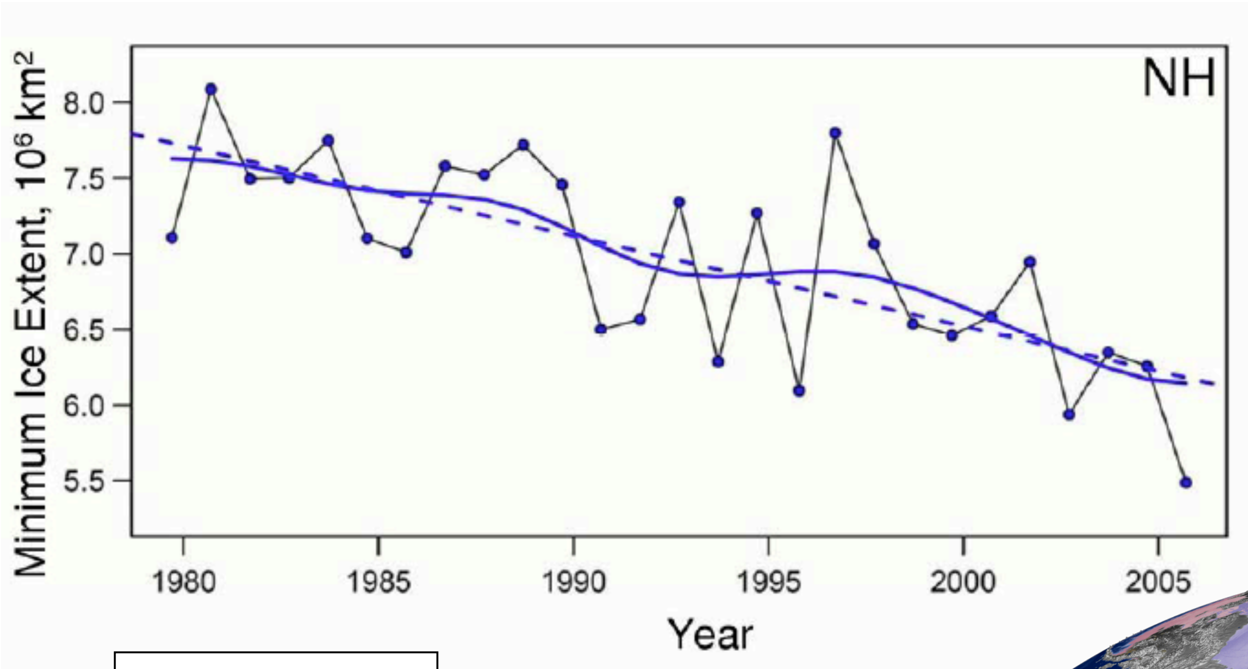
- Troposphere is warming by 0.16K to 0.18K per decade.
- Tropospheric humidity is increasing by 1.2%/decade.

Climatic context of warming



• It is very likely that last 50 years are warmest in last 500 years.

Reductions in Arctic sea ice



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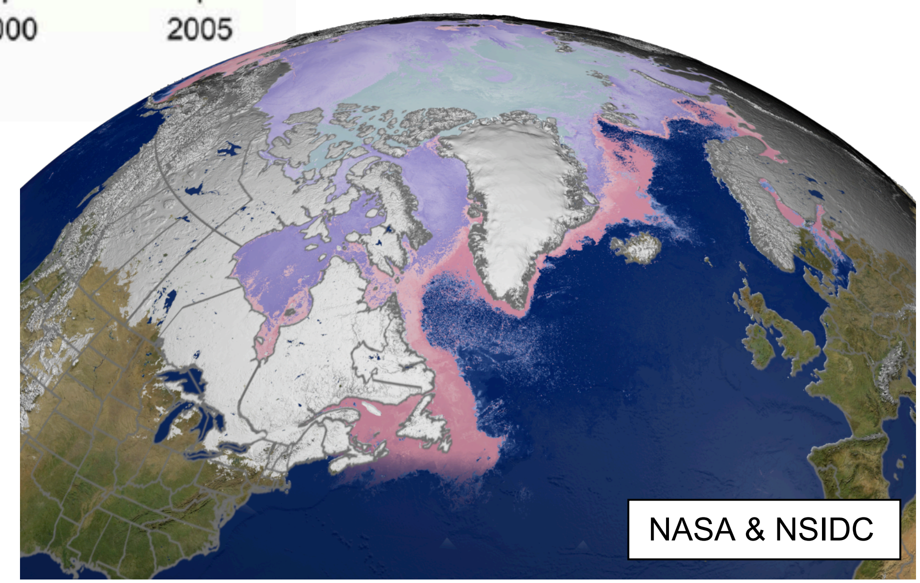
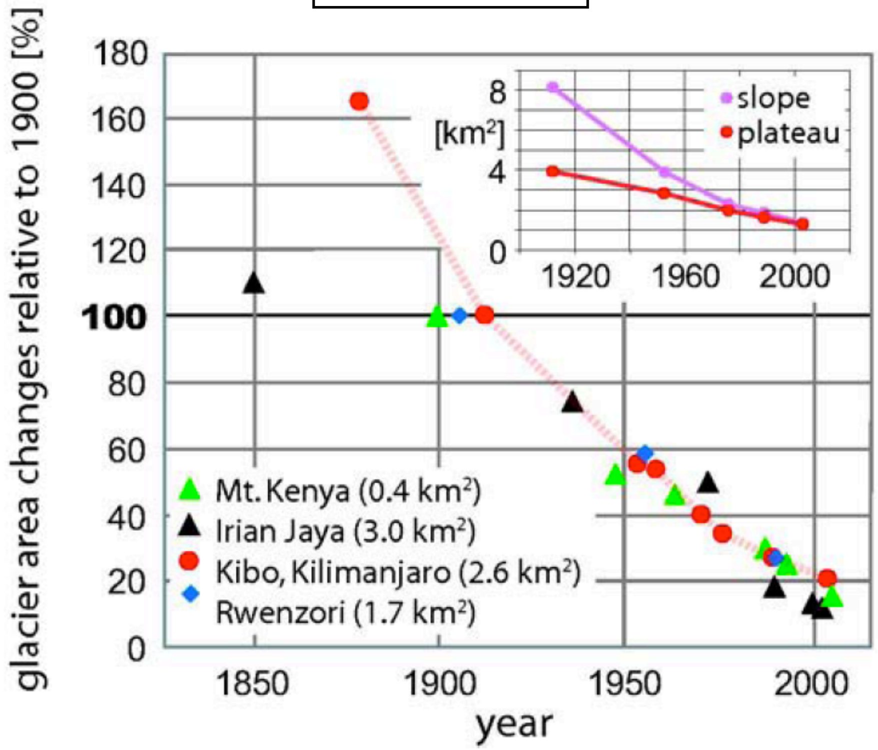
- Arctic summer sea ice extent is shrinking at 7.4±2.4% per decade.



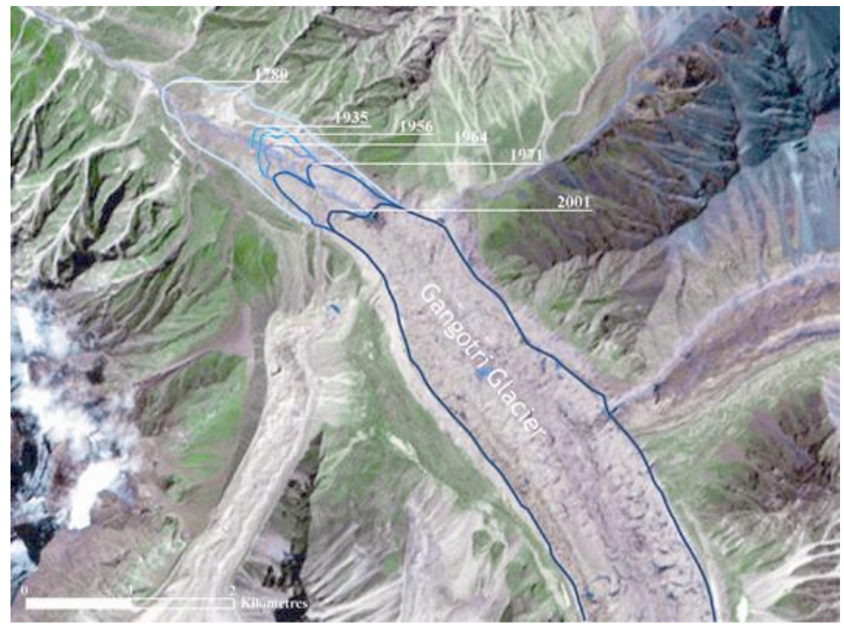
NASA & NSIDC

Trends in land glaciers and ice

Glacial Area



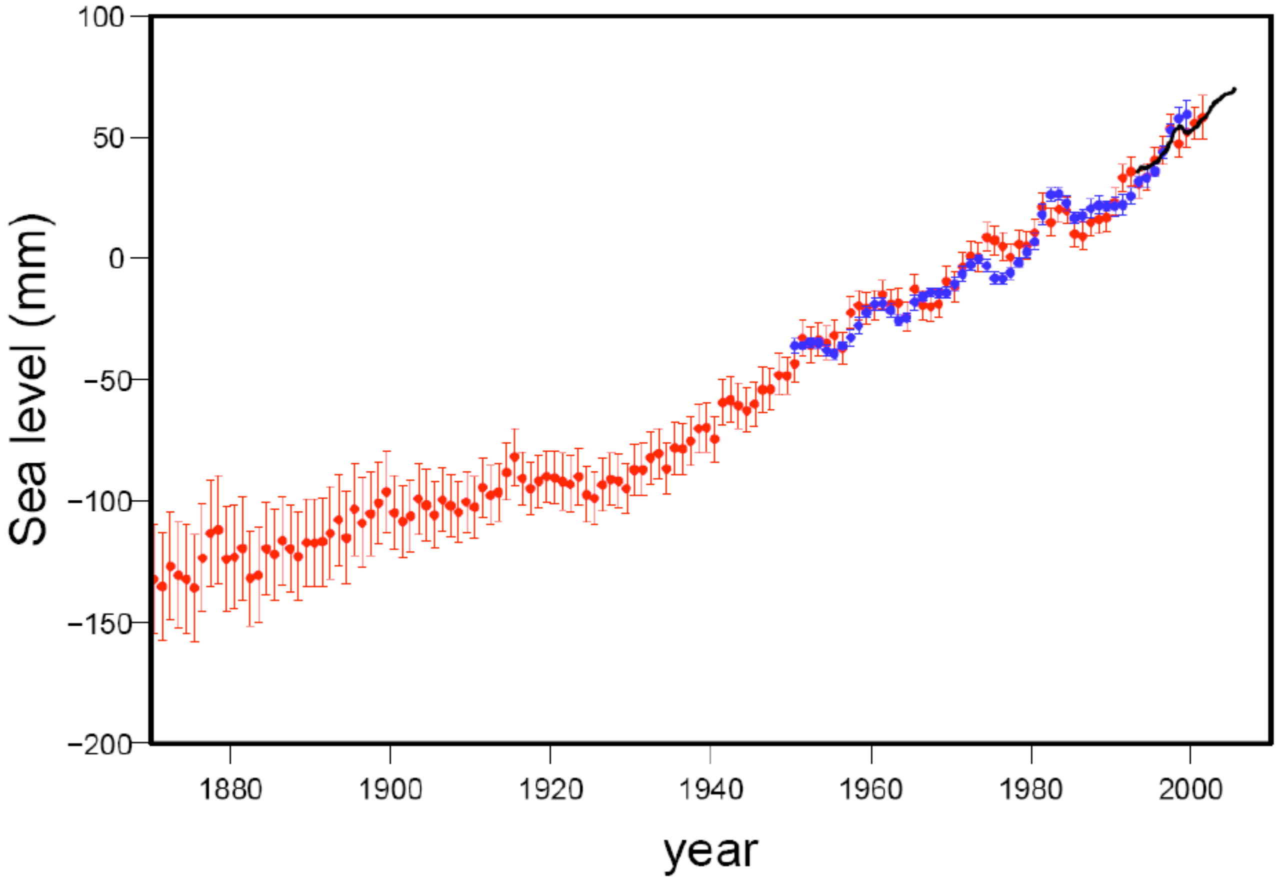
Gangotri Glacier, Northern India

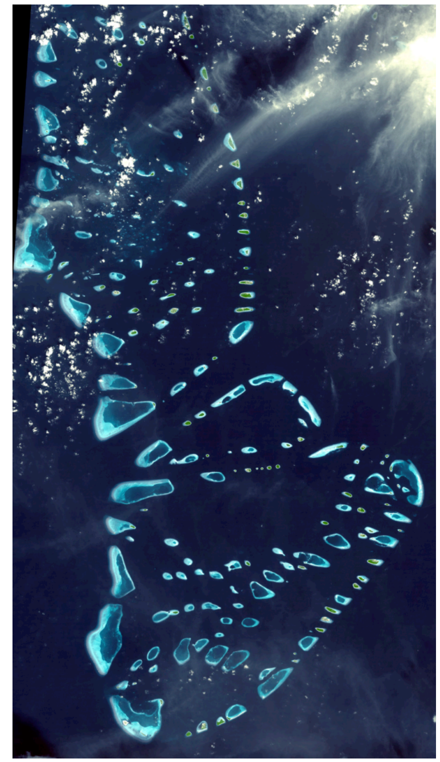


- Mass loss from glaciers since 1991 is 0.77±0.22 mm/year SLE.
- This accounts for approximately 1/4 of the observed sea-level rise.

Increases in sea level

Maldives Atoll

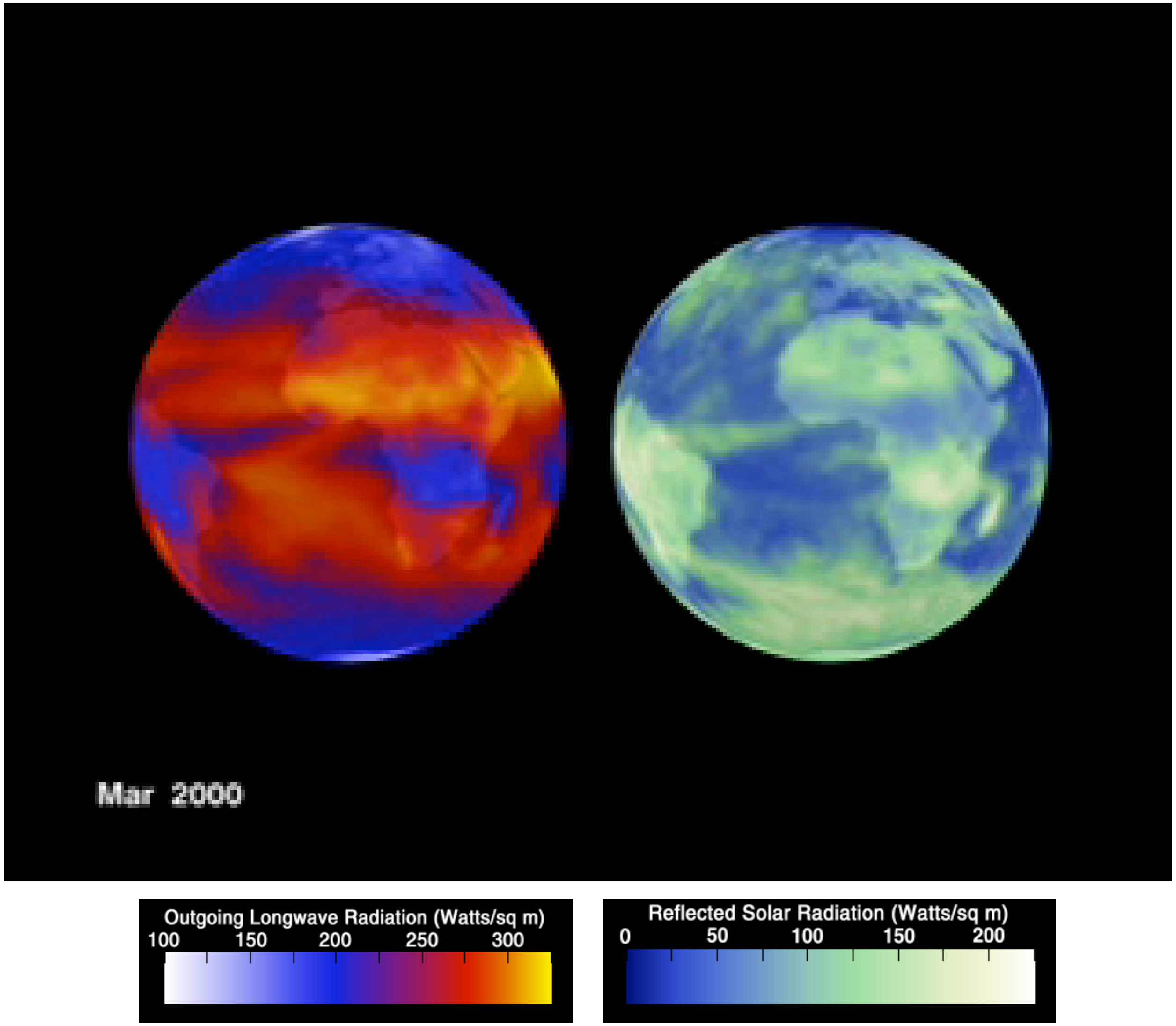




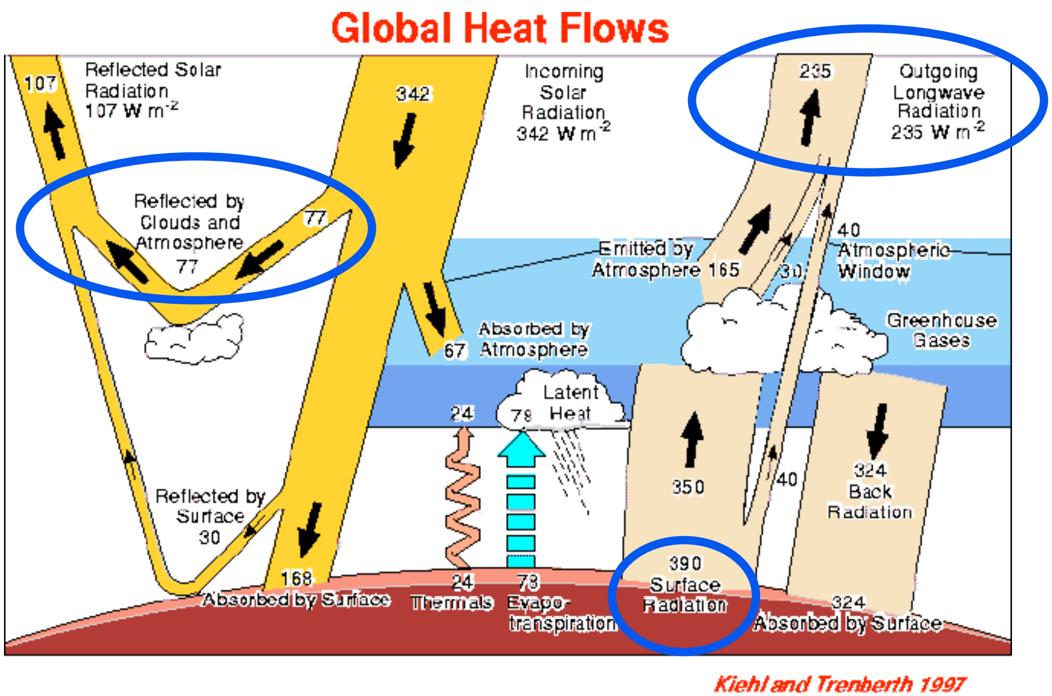
- Elevation: 1.8m
- Population: 370K

- Sea level during 1993-2003 increased by 3.1±0.7 mm / year.

The energy budget of the Earth



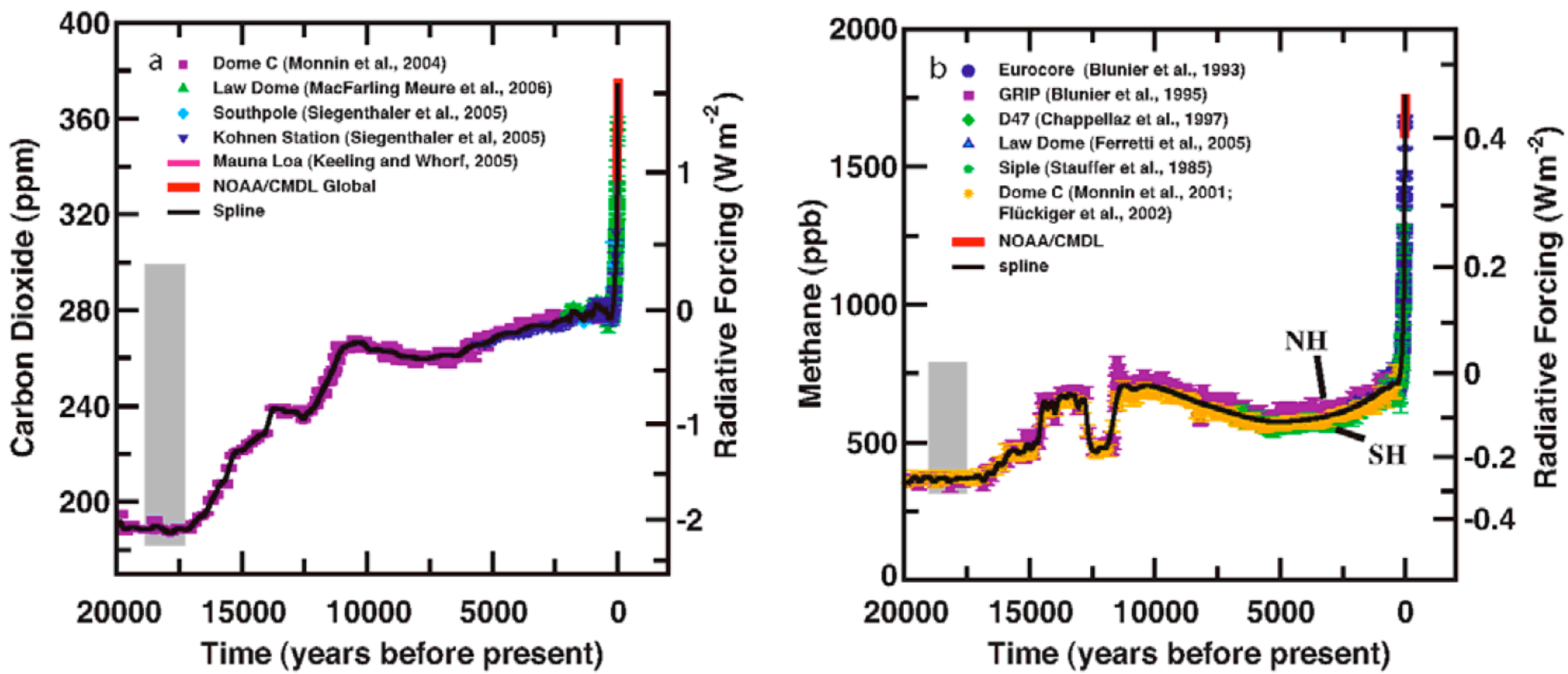
Energy budget of Earth's climate



GHG	GH Effect (Wm^{-2})	GH %age
CO_2	32	26
O_3	10	8
CH_4+N_2O	8	6
H_2O	*75*	*60*

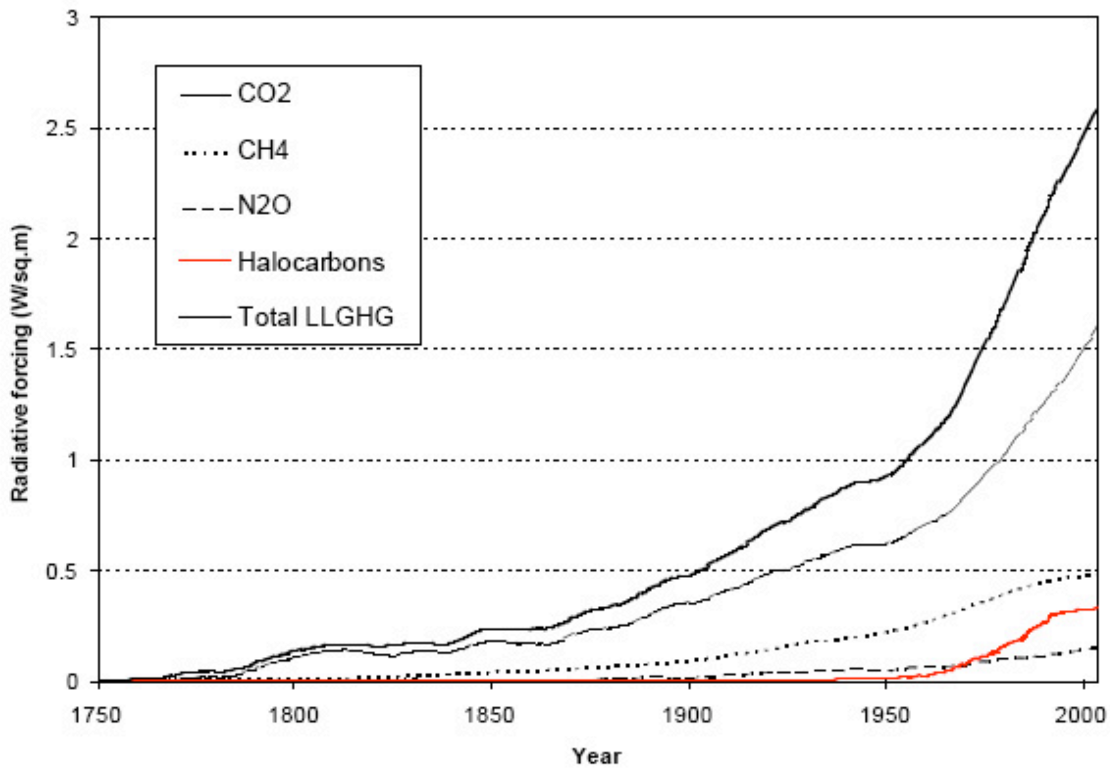
- Imbalance in Earth's energy budget drives climate change.
- Changes in greenhouse effect or albedo can cause imbalance.

Changes in atmospheric composition



• Concentrations of greenhouse gases are highest in 650K years.

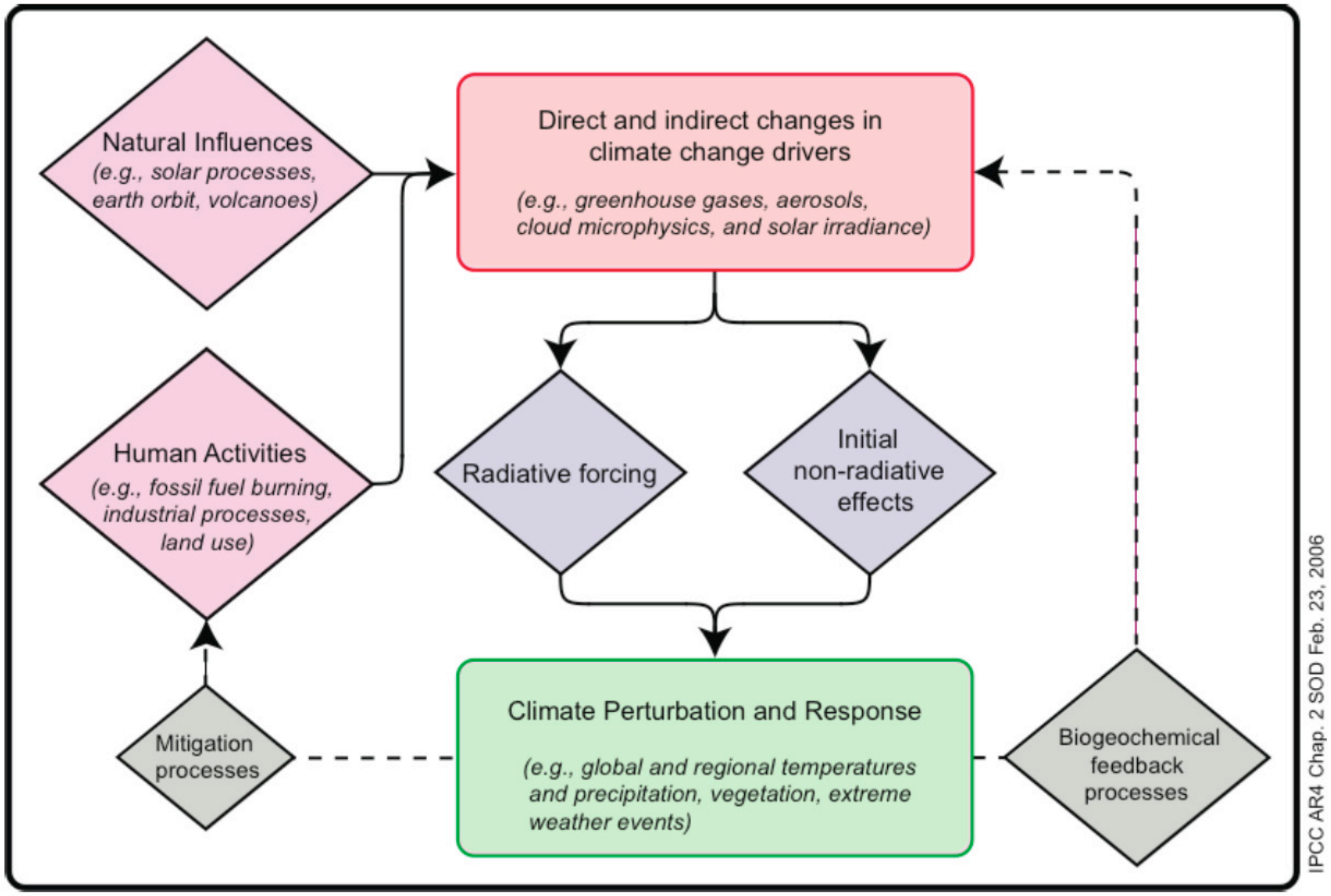
Definition of radiative forcing



IPCC AR4, 2007

Radiative forcing is an "externally imposed perturbation in the radiative energy budget of the Earth's climate system." (IPCC TAR)

Interactions in the Earth system



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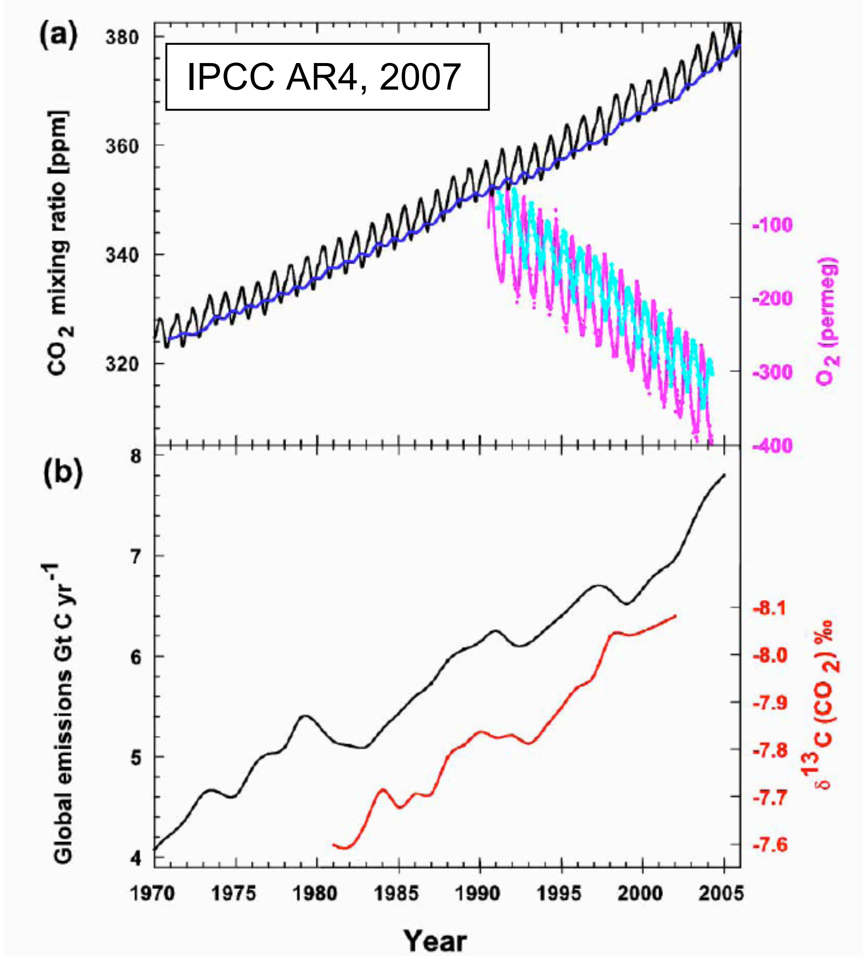
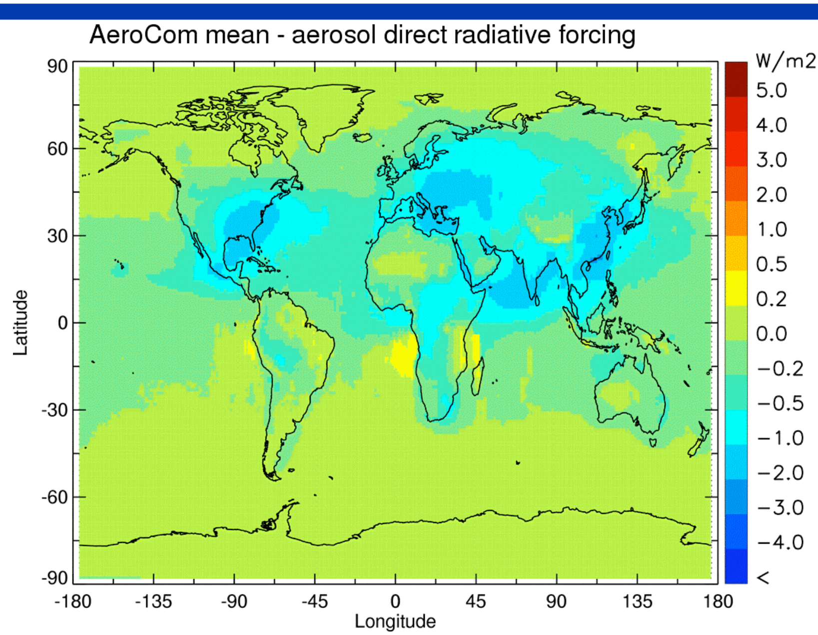
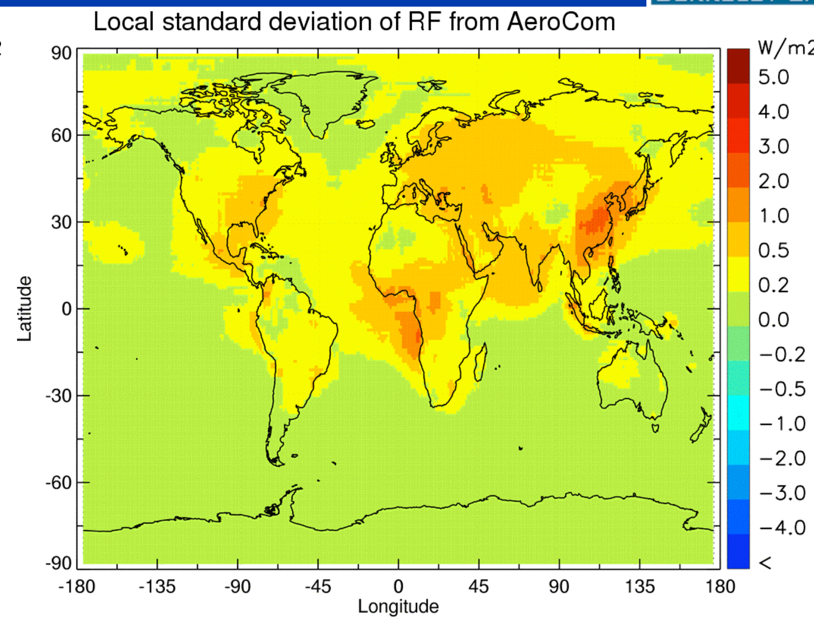
Human-induced greenhouse forcing



- Concentrations of O_2 and fractions of ^{13}C are decreasing.
- These decreases are most consistent with fossil fuel origin.

Models of aerosol radiative forcing

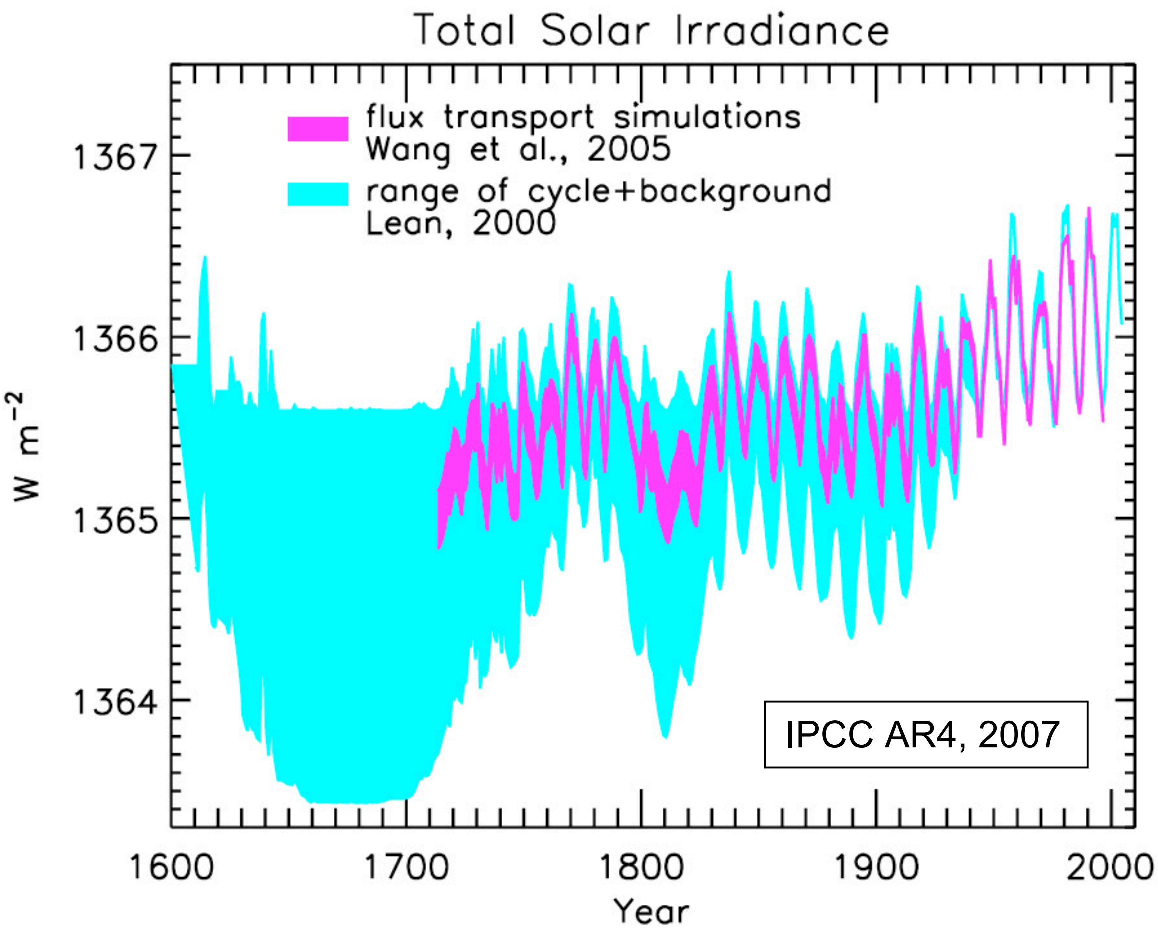




IPCC AR4, 2007

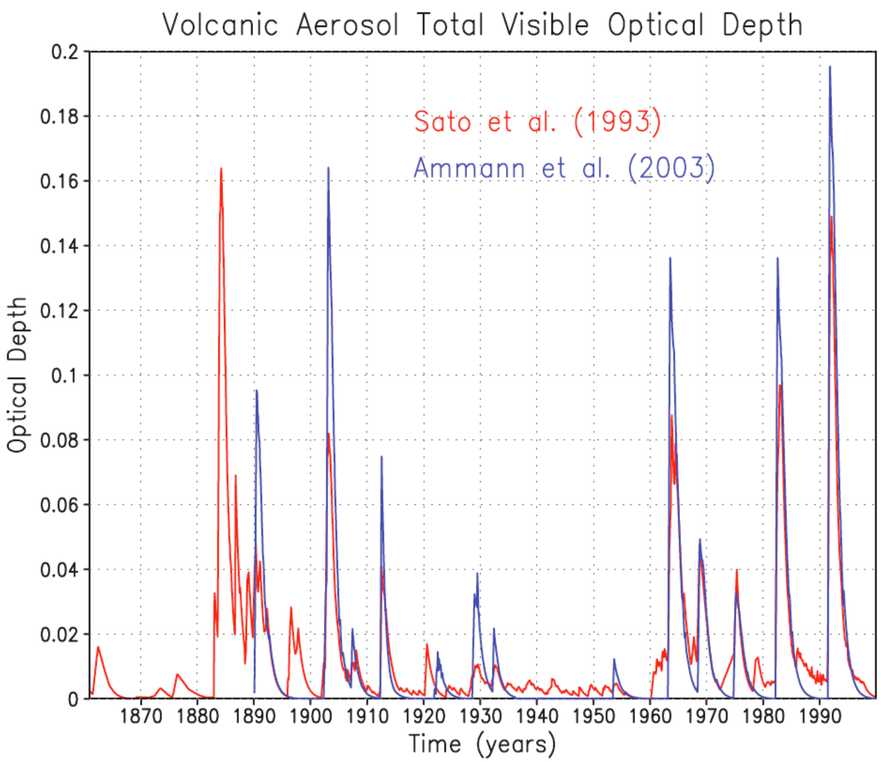
Species	**Forcing** (W m^{-2})
Sulfate	**–0.4 ± 0.2**
Fossil fuel organic carbon	**–0.1 ± 0.1**
fossil-fuel black carbon	**+0.2 ± 0.1**
Biomass burning	**0.0 ± 0.1**
Nitrate	**–0.1 ± 0.1**
mineral dust	**–0.1 ± 0.2**
Total	–0.5 ± 0.4

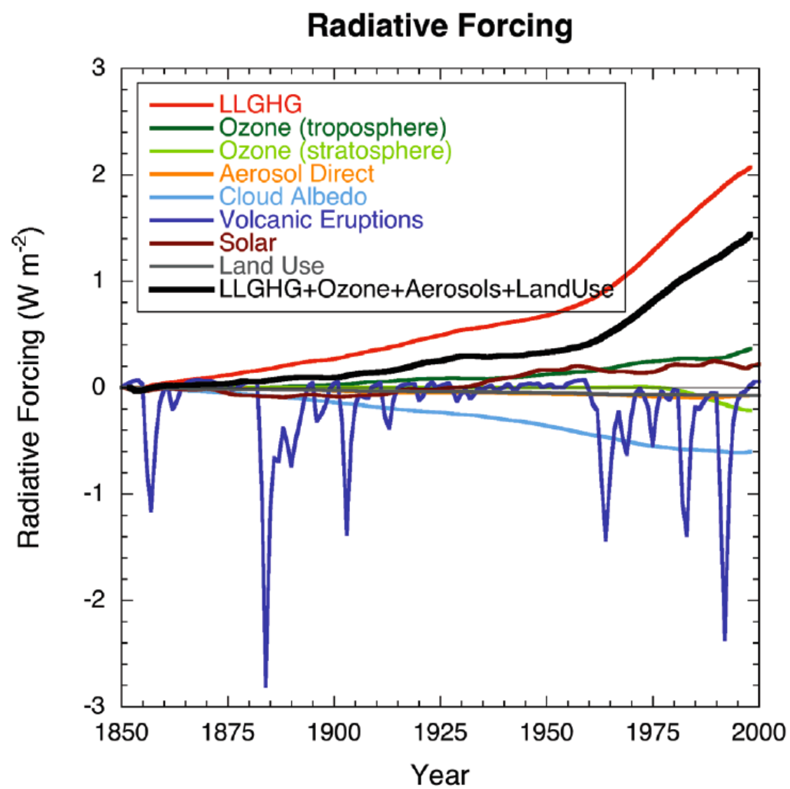
The Sun: a natural forcing agent



Latest solar irradiance models:
0.04% increase over 1700 - 2005.

Volcanoes: intermittent forcing agents

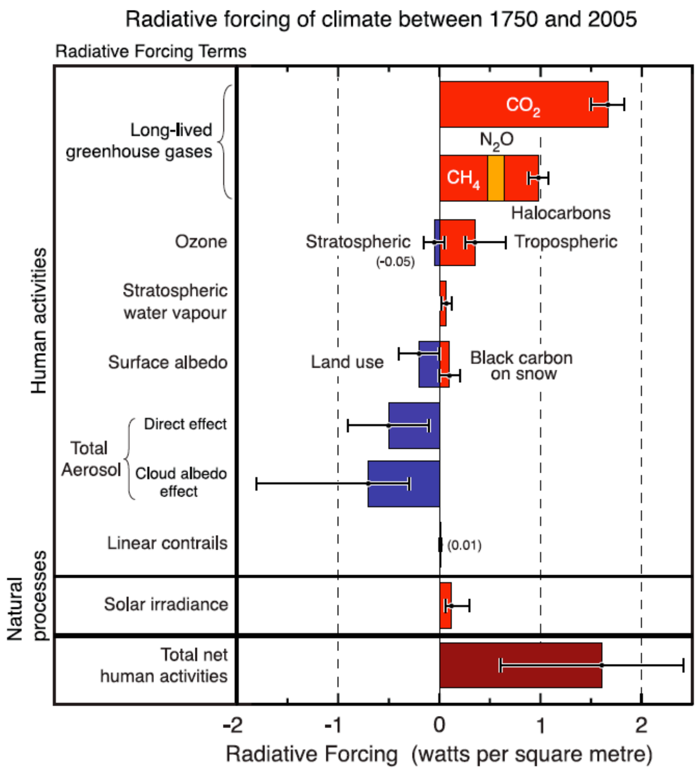


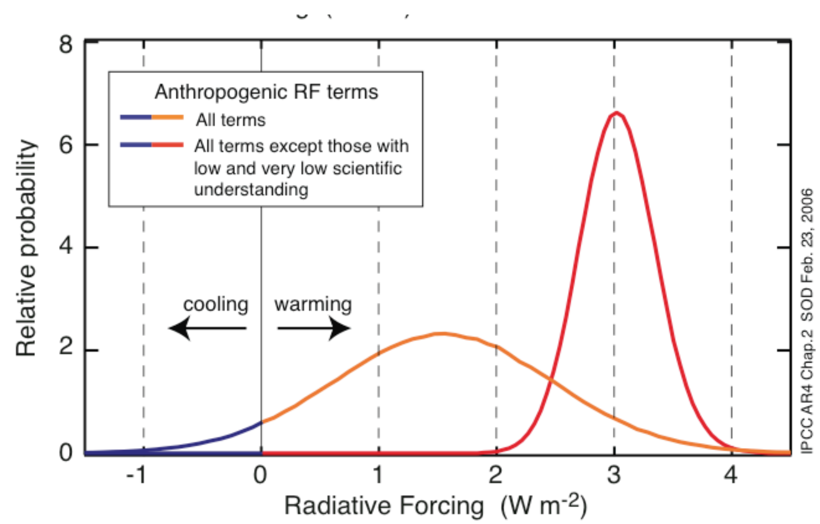


IPCC AR4, 2007

- Largest recent volcanic forcing = -3 Wm^{-2}
- Forcing prior to 1980 highly uncertain.

Historical radiative forcing



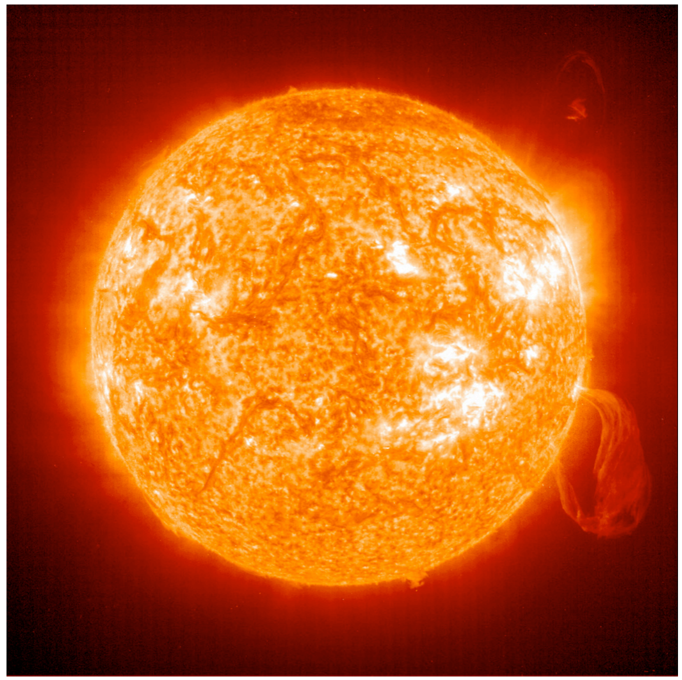


IPCC AR4, 2007

- Probability that historical forcing > 0 is very likely (90%+).
- However, confidence in short-lived agents is still low at best.

Causes of recent climate changes

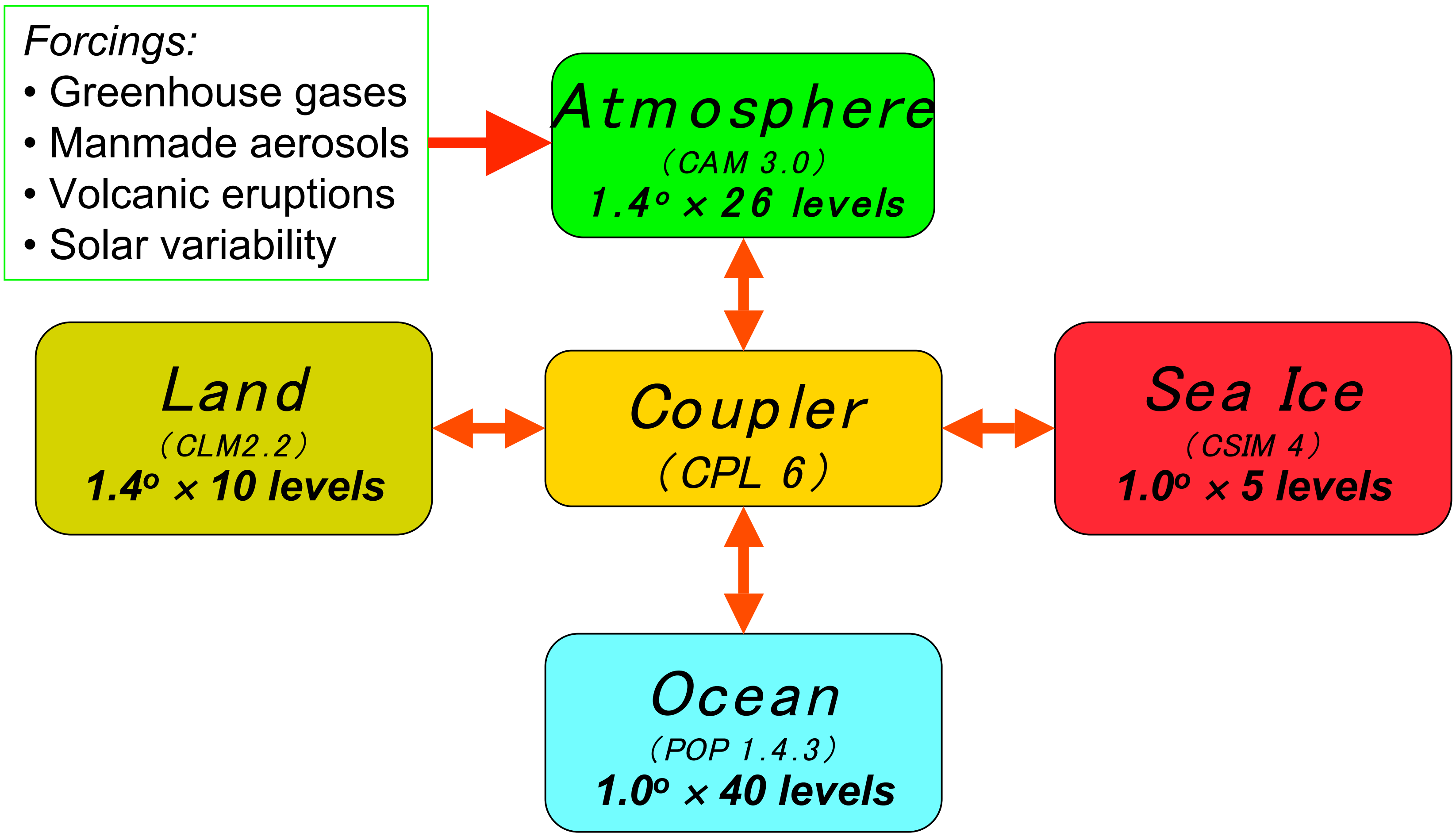
Volcanic eruptions



Solar variability

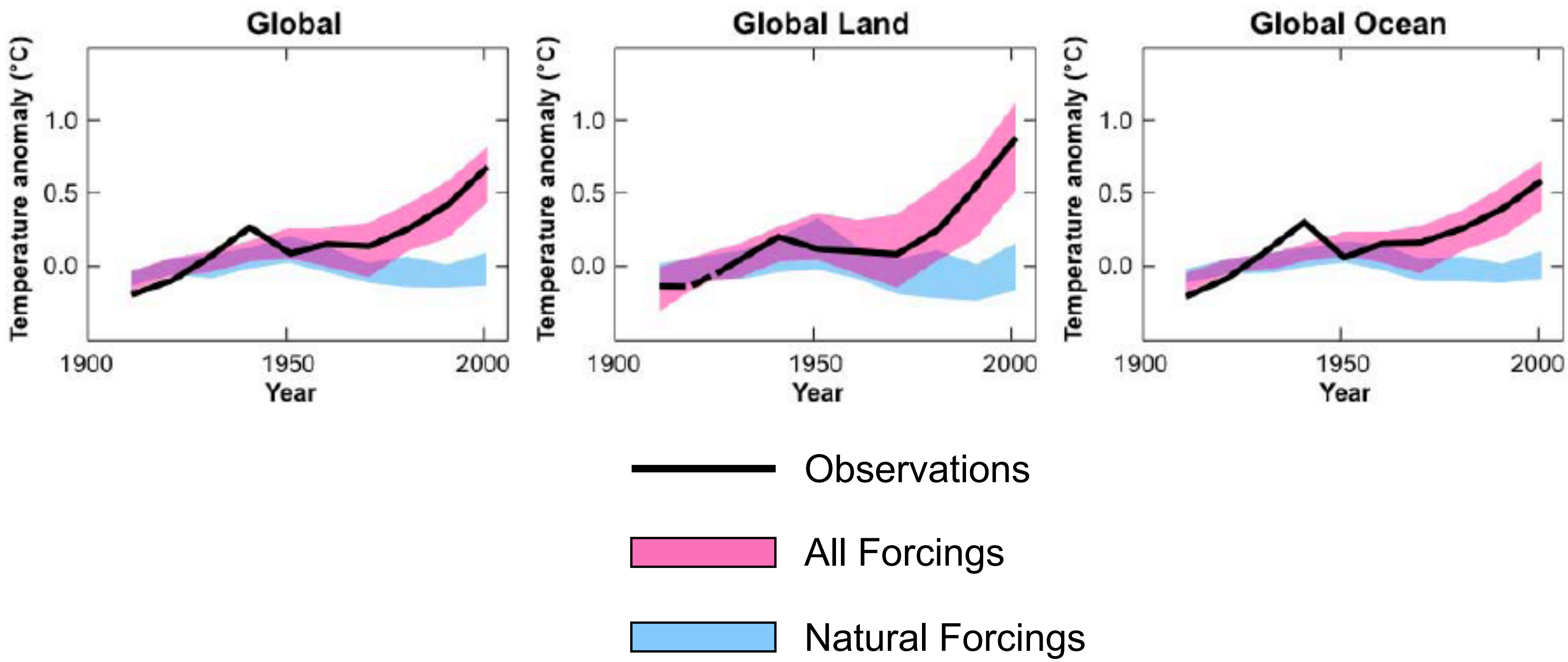
Human Pollution

Method for attribution: Climate models



CCSM3 Model: http://www.ccsm.ucar.edu

Attribution of past climate change



- Models with only natural forcings do not match observations.
- It is very likely (>90%) humans are cause of recent warming.

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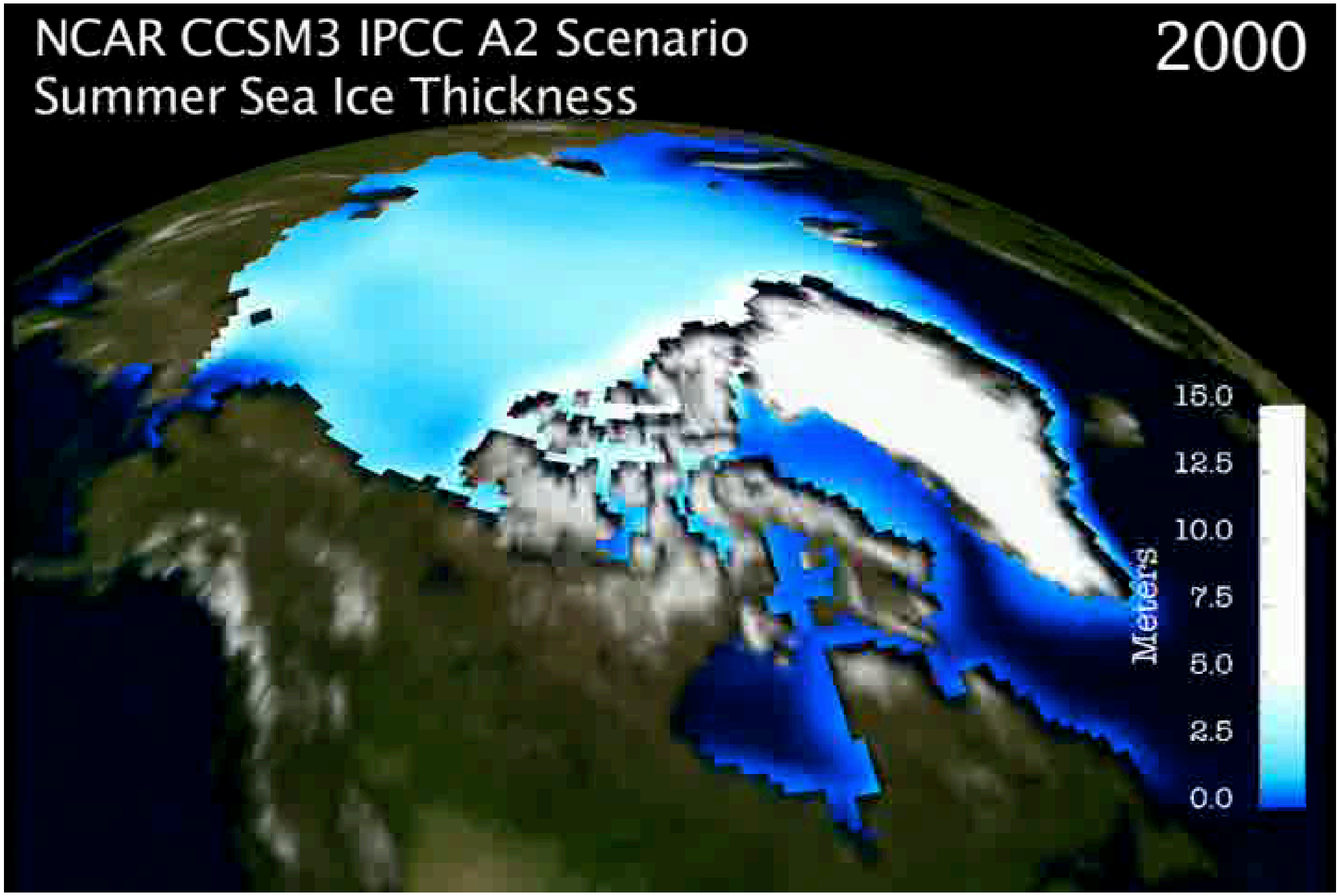
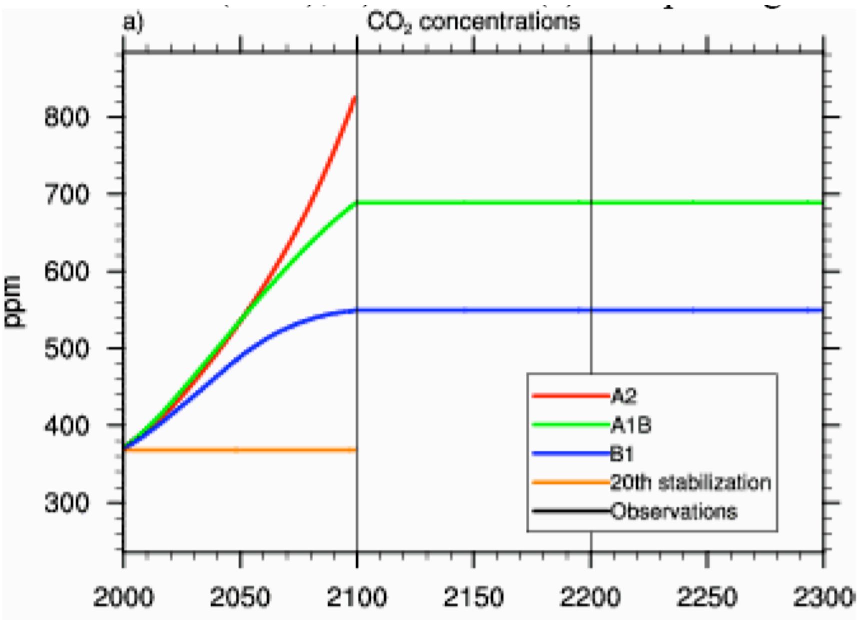
Future evolution of the Earth's climate

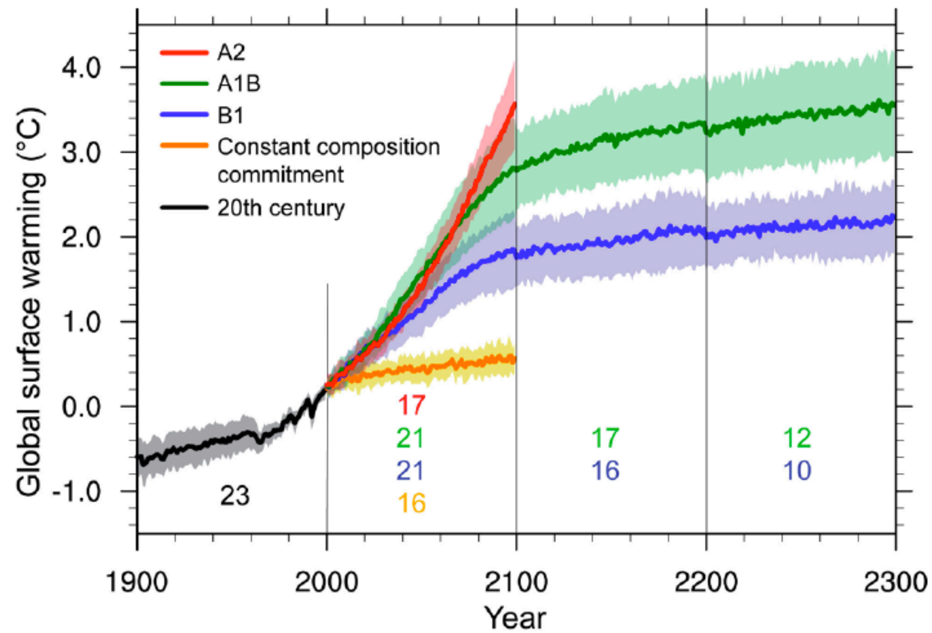


Projections for global temperatures

Emissions Scenarios

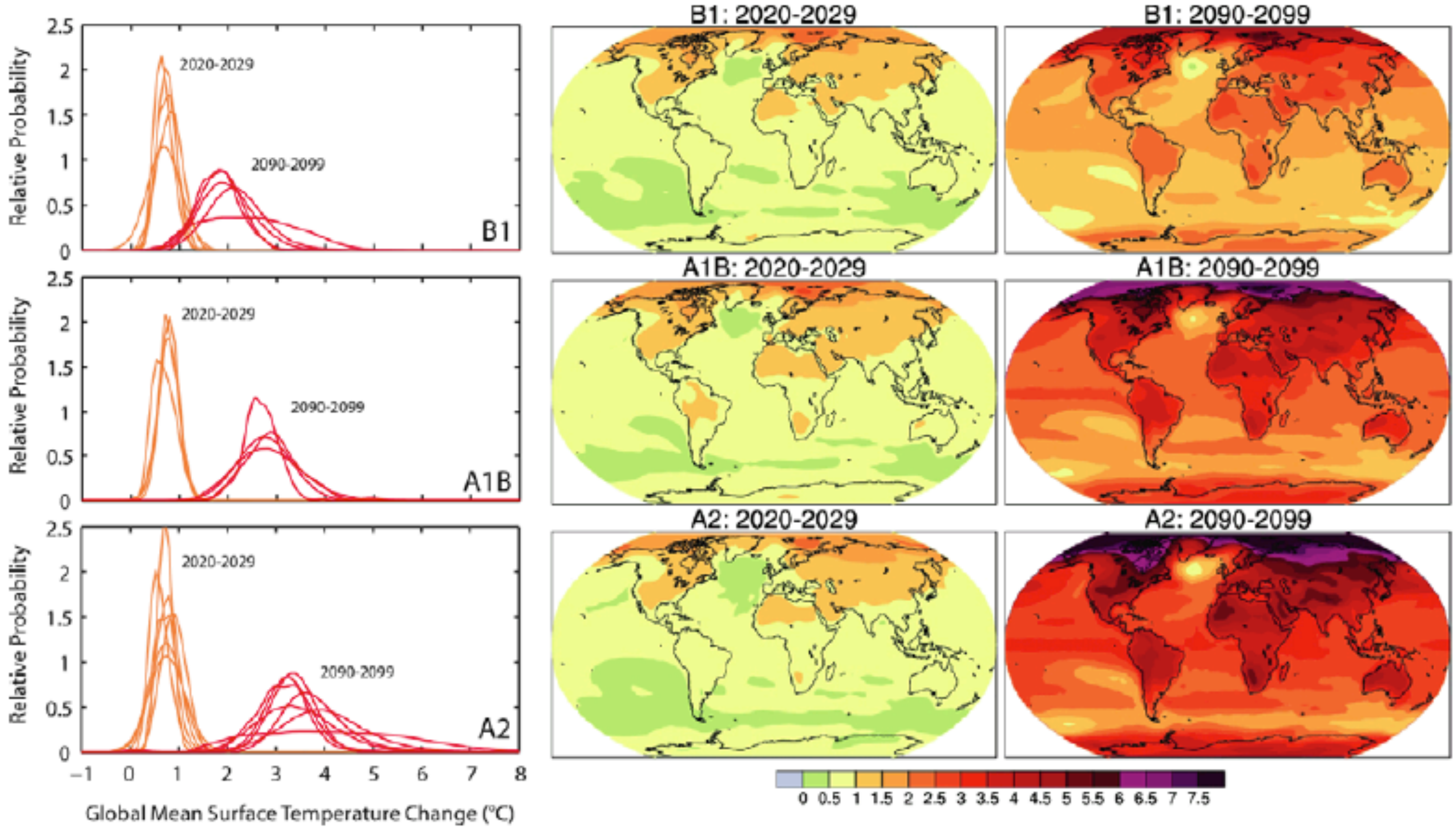


Global Temperature Projections



• Global temperatures could increase by 1.7 to 3.2K.

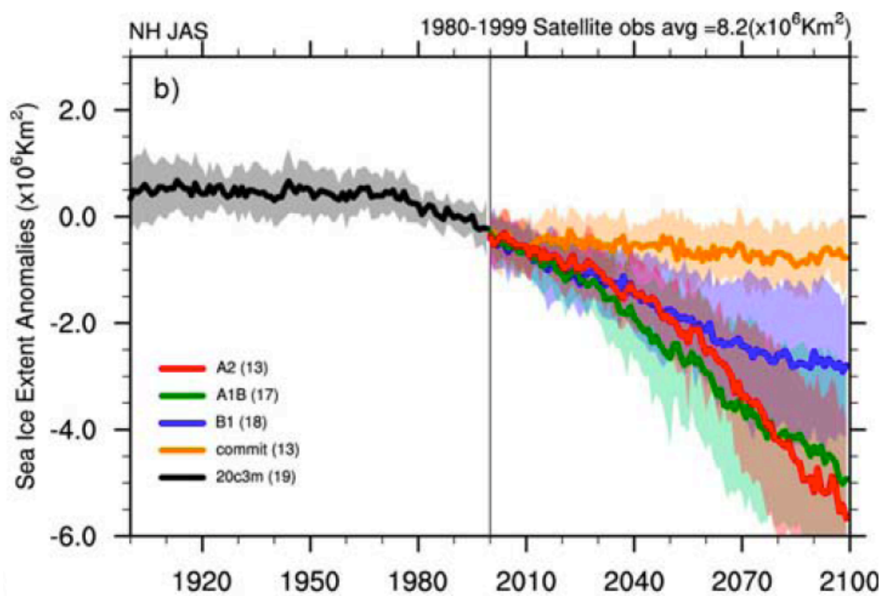
Projection of regional temperatures



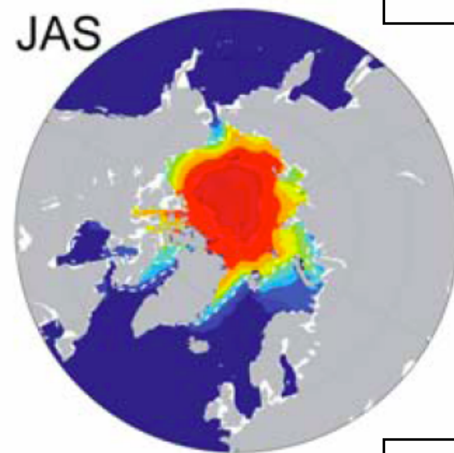
IPCC AR4, 2007

- Roughly 2/3 of warming by 2030 is from historical changes.
- Uncertainties at 2100 are from physics and emissions.

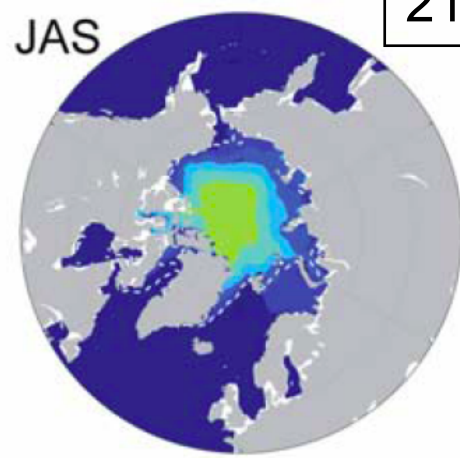
Further reductions in Arctic sea ice



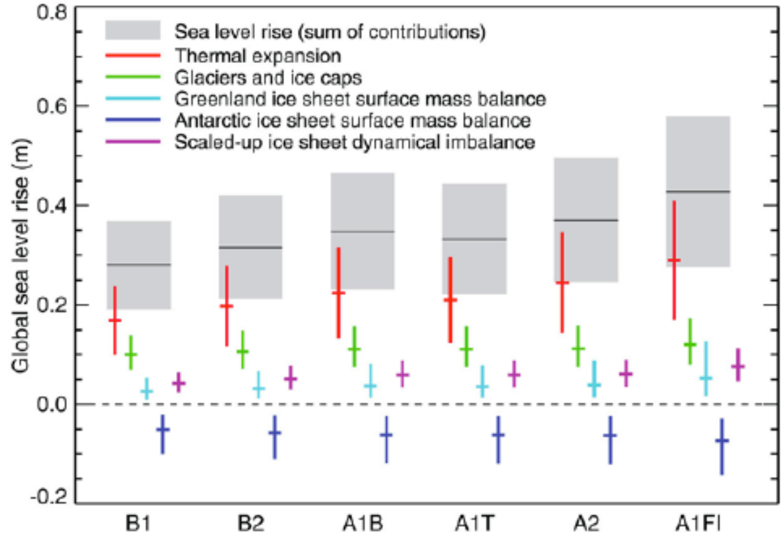
2000

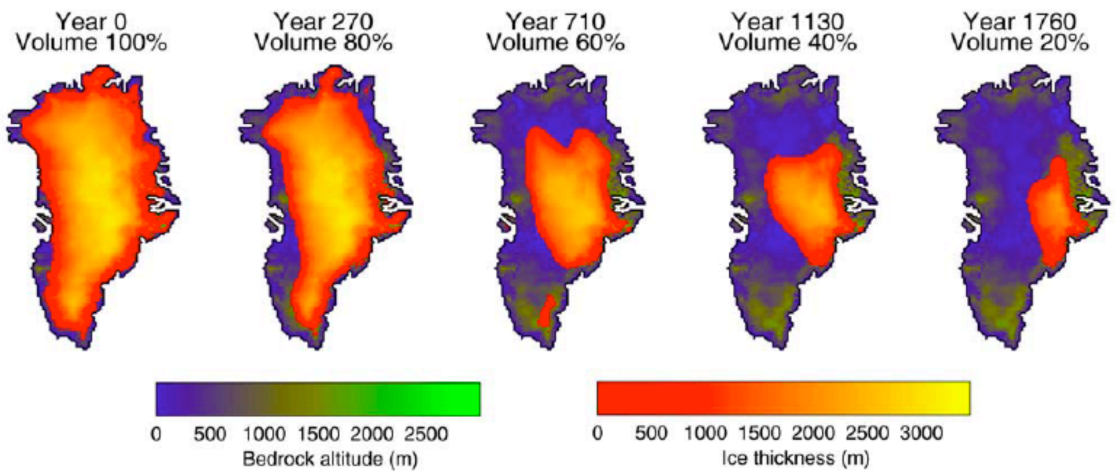


2100

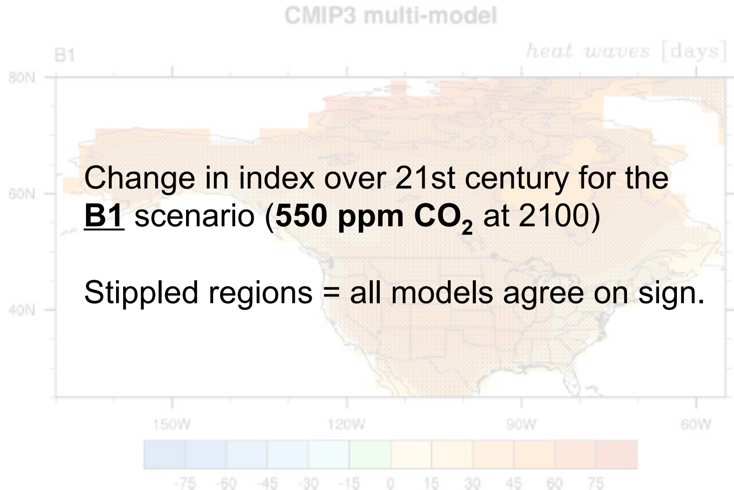


Increased sea level and glacial melt



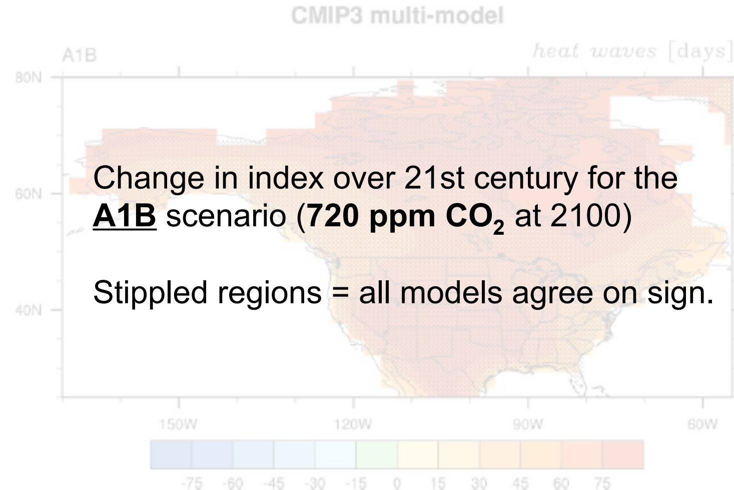


Climate extremes in physical climate



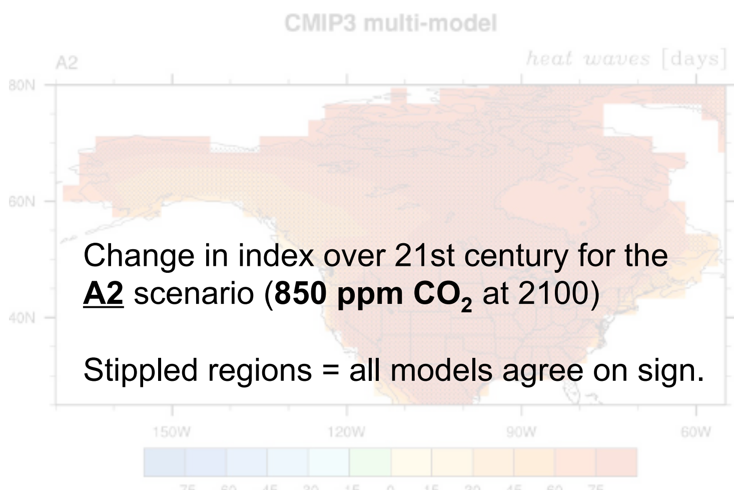
Change in index over 21st century for the **B1** scenario (**550 ppm CO_2** at 2100)

Stippled regions = all models agree on sign.



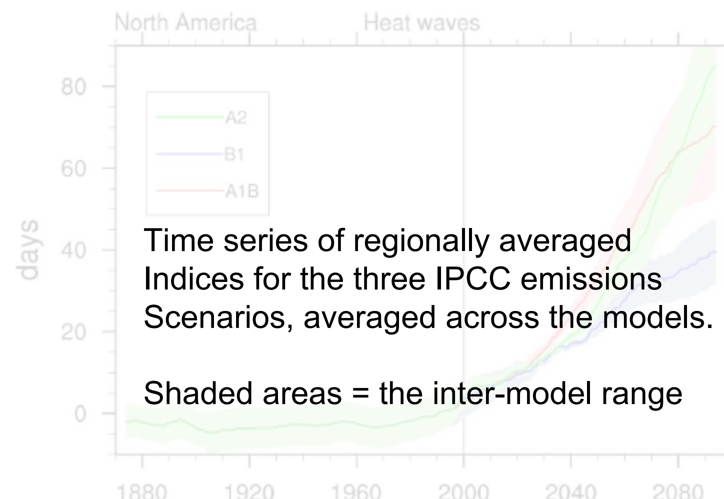
Change in index over 21st century for the **A1B** scenario (**720 ppm CO_2** at 2100)

Stippled regions = all models agree on sign.



Change in index over 21st century for the **A2** scenario (**850 ppm CO_2** at 2100)

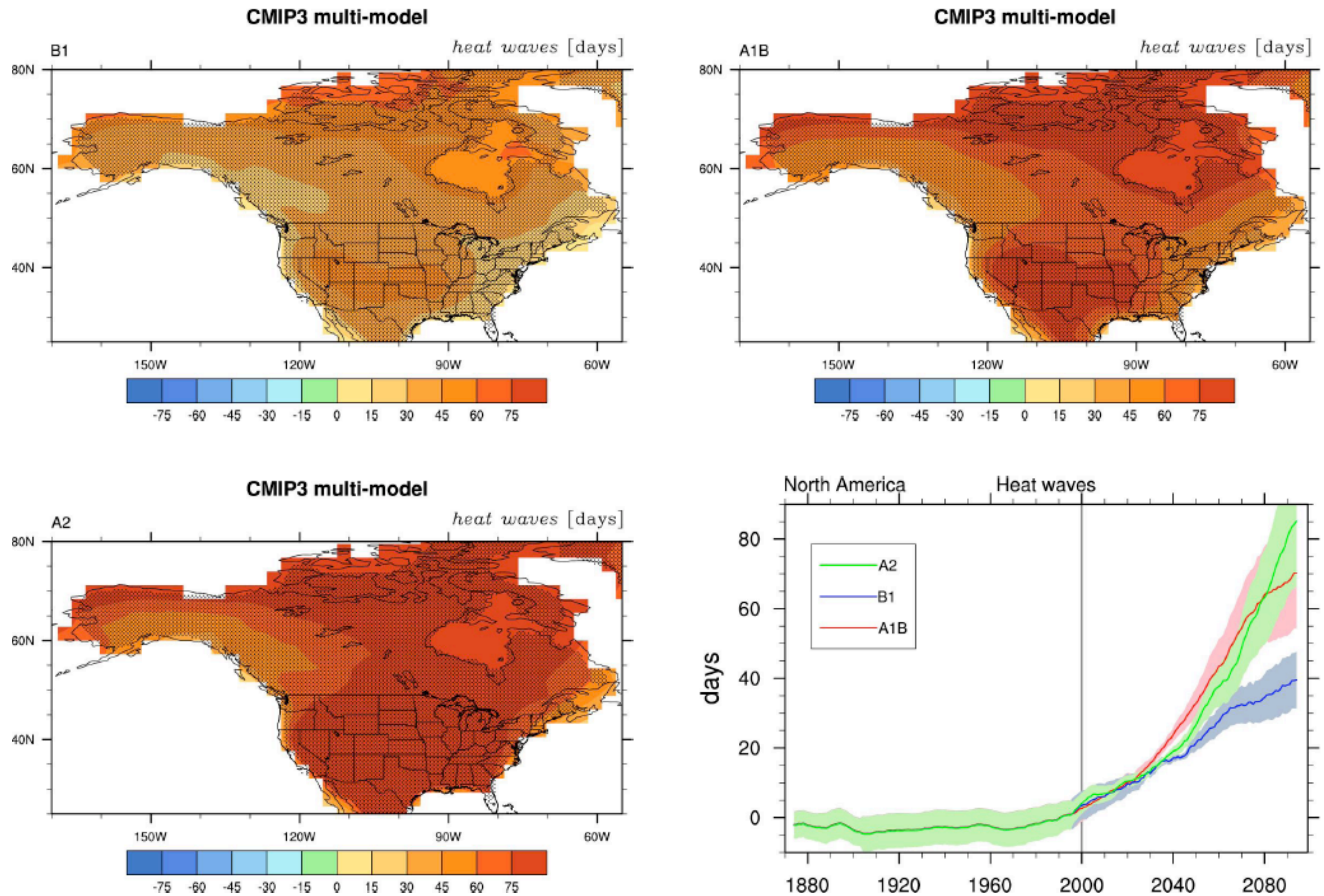
Stippled regions = all models agree on sign.



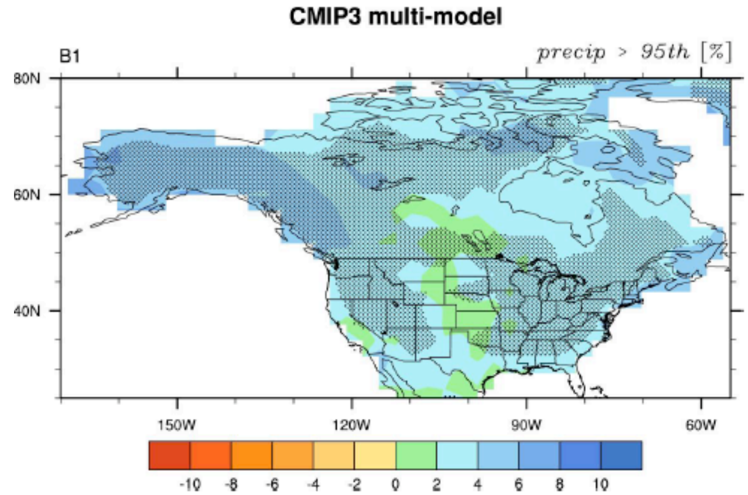
Time series of regionally averaged Indices for the three IPCC emissions Scenarios, averaged across the models.

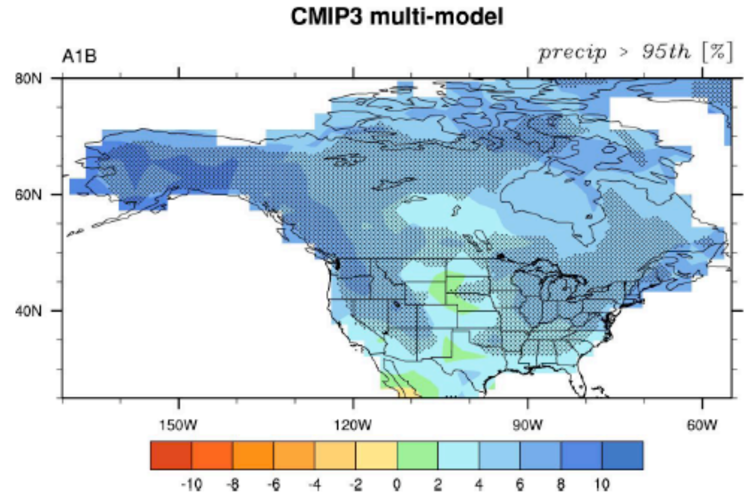
Shaded areas = the inter-model range

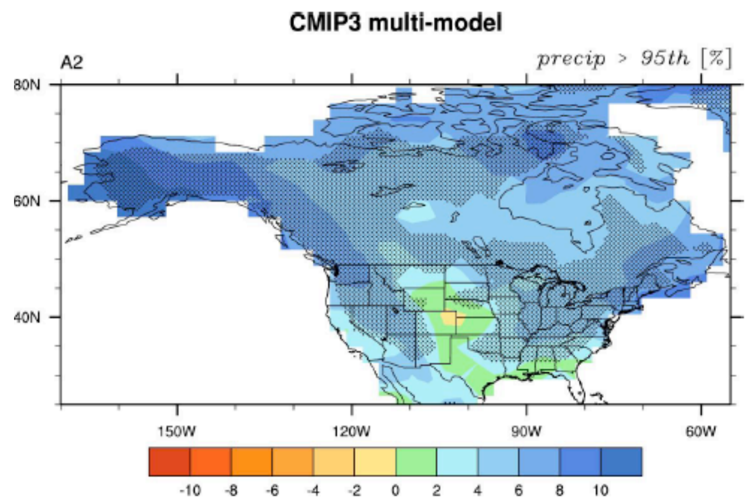
Heat wave duration: 5 days > 5K

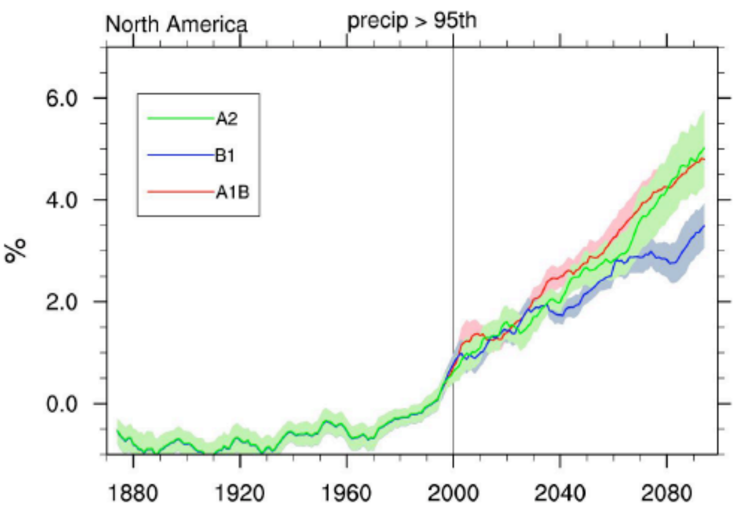


Precipitation fraction > 95th percentile

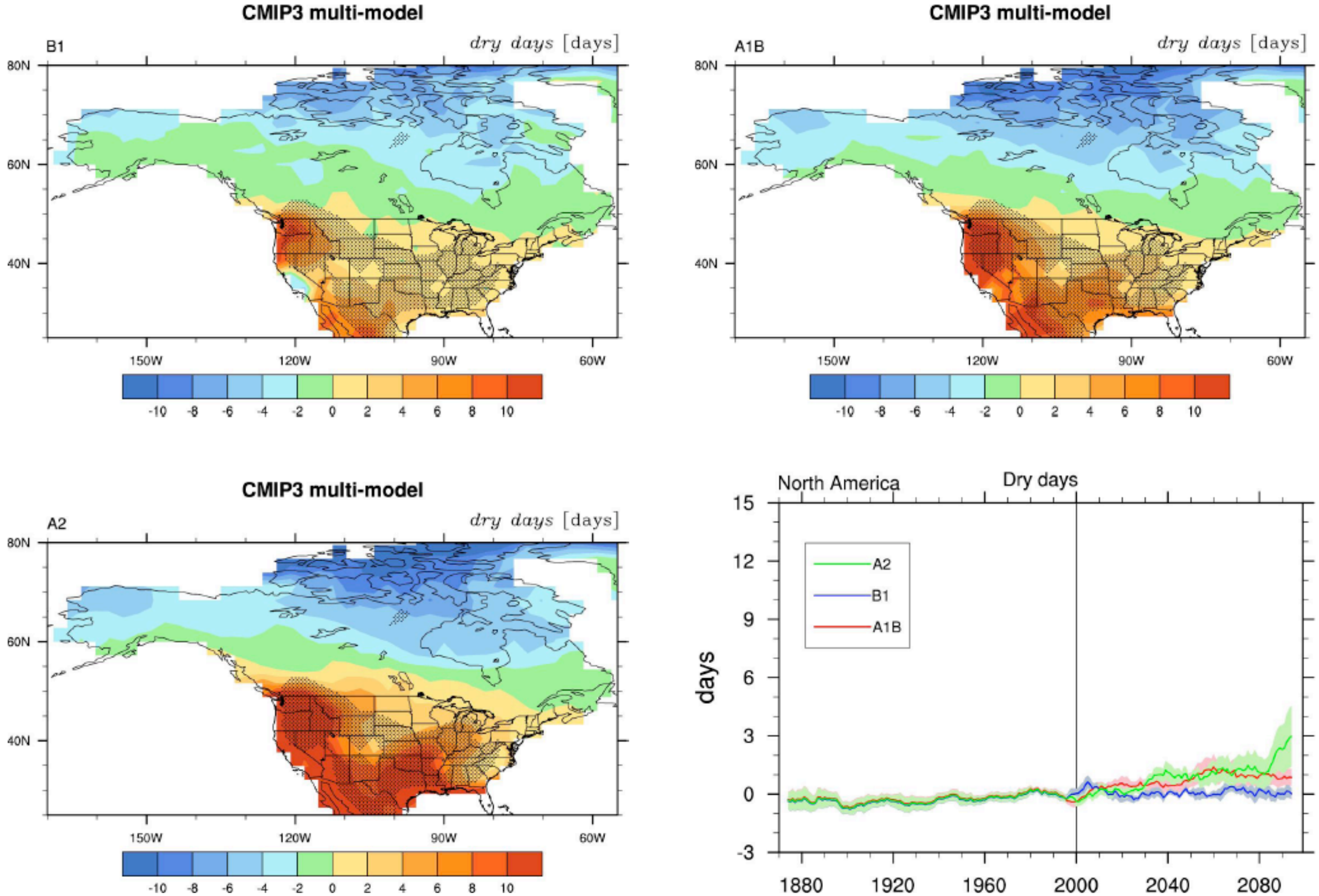








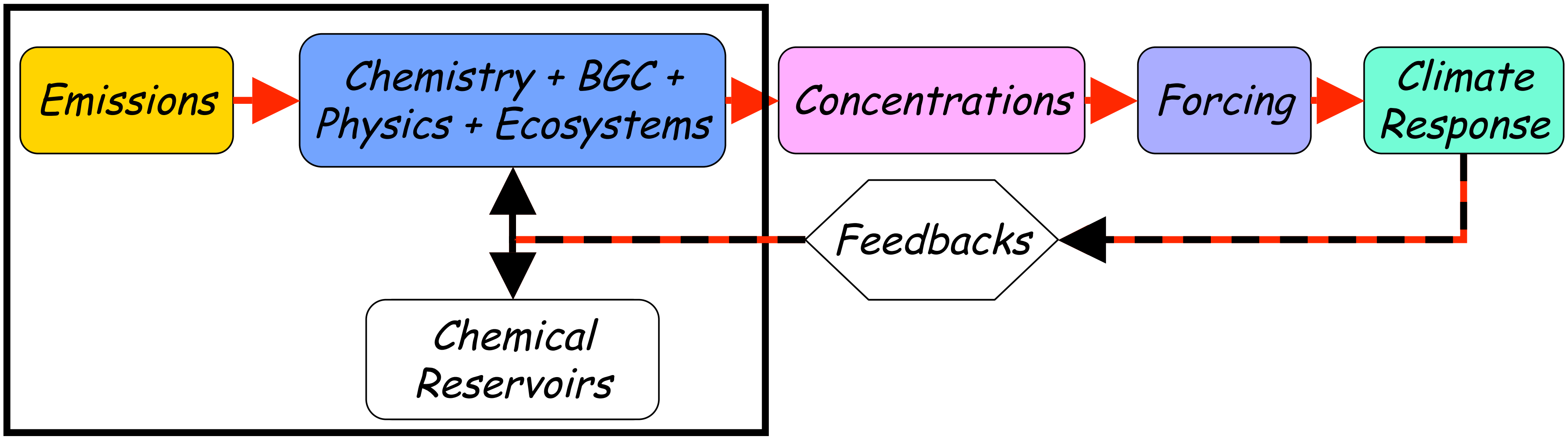
Consecutive dry days: rain < 1 mm



Future research in science, impacts, and adaptation

Sea level rise in Washington from:
- 38 cm sea-level rise
- Category II hurricane

Simulating the climate system

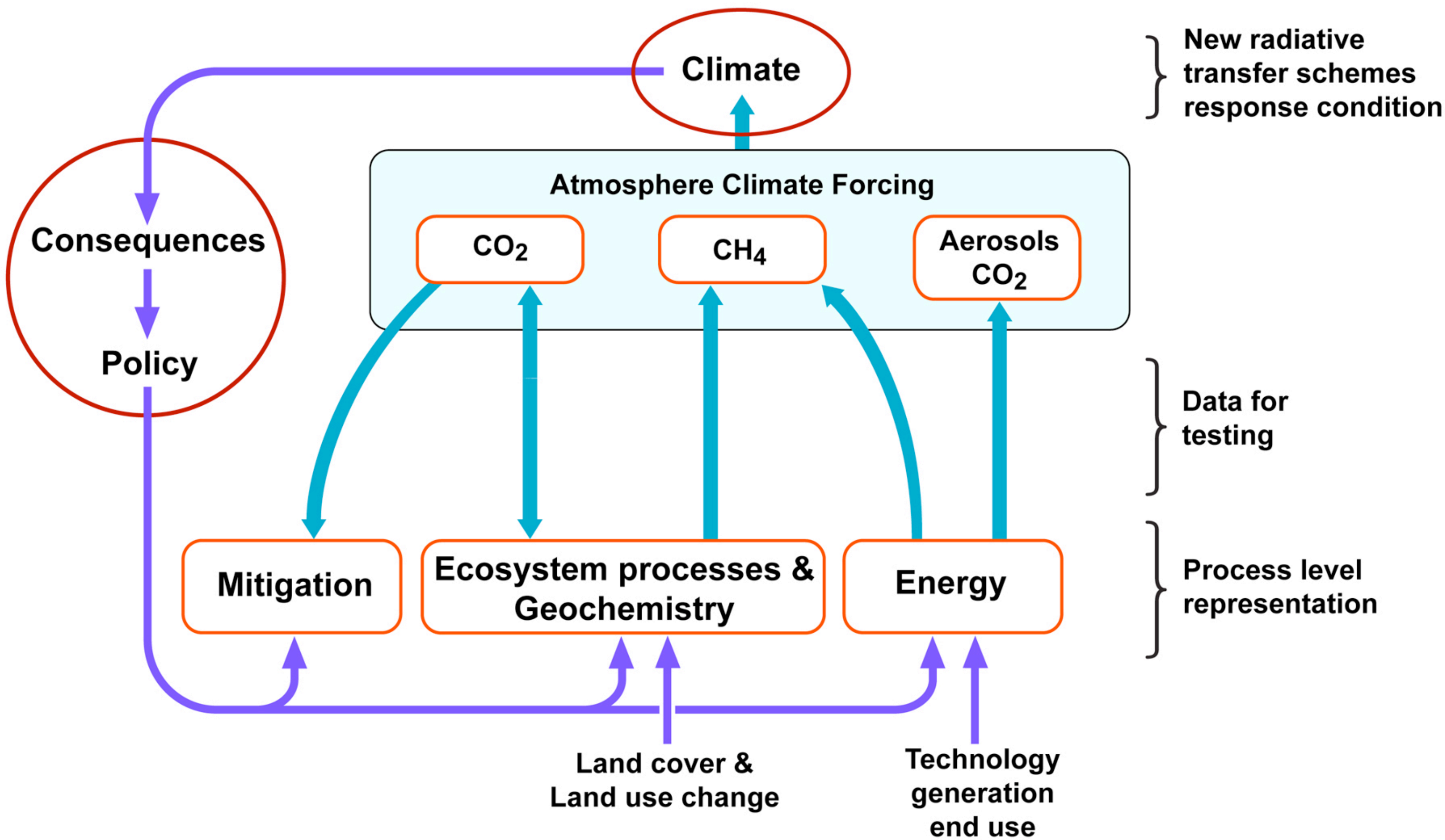


- In the past, we have generally used offline models to predict concentrations and read these into models.

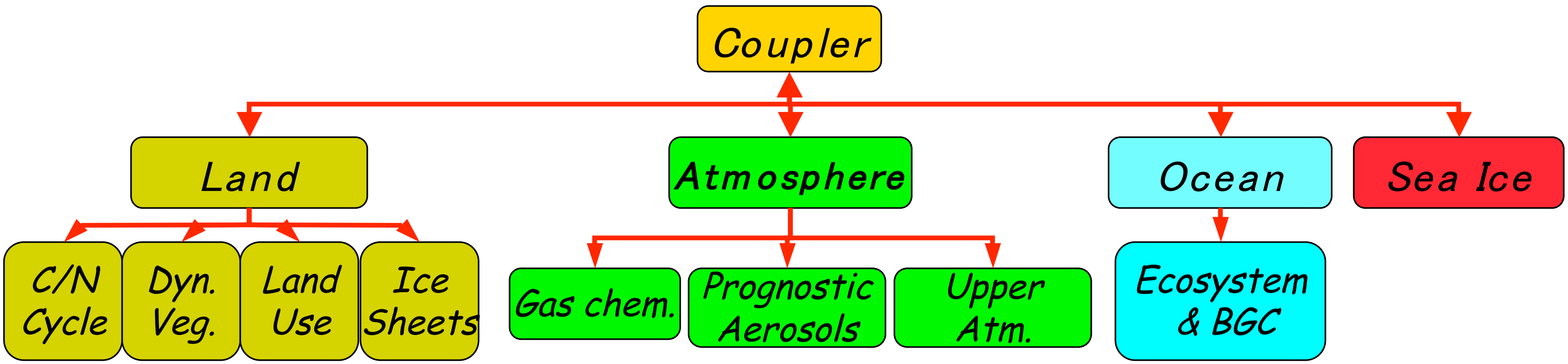
- This approach is simple to implement, but
  - It cuts the feedback loops.
  - It eliminates the chemical reservoirs.

- The next generation of models will include these interactions.

Our Plans:
Center for Integrated Earth System Modeling



First generation Earth system model



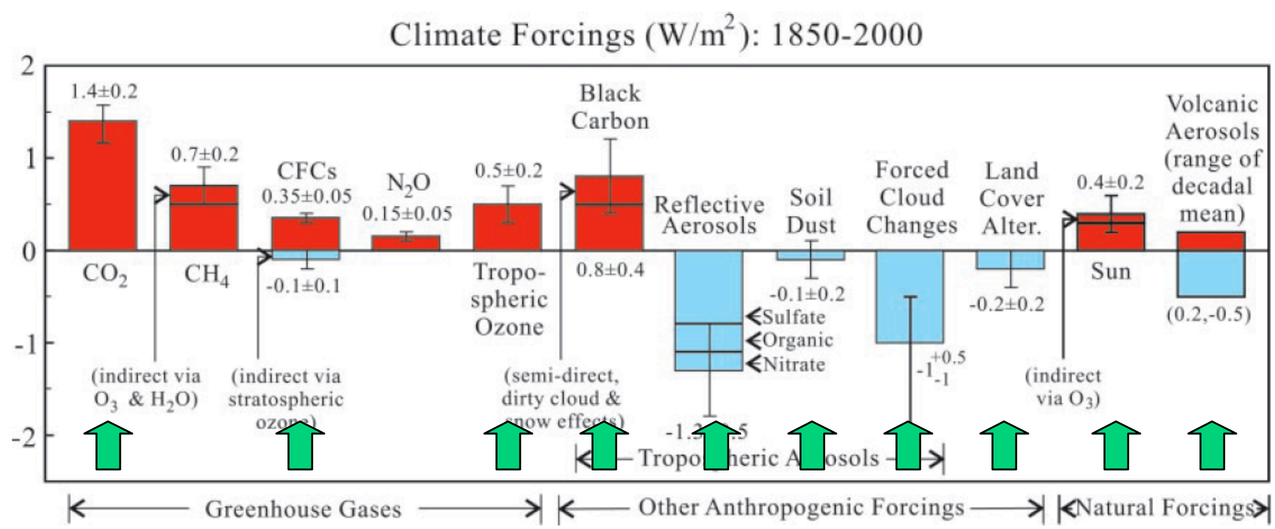
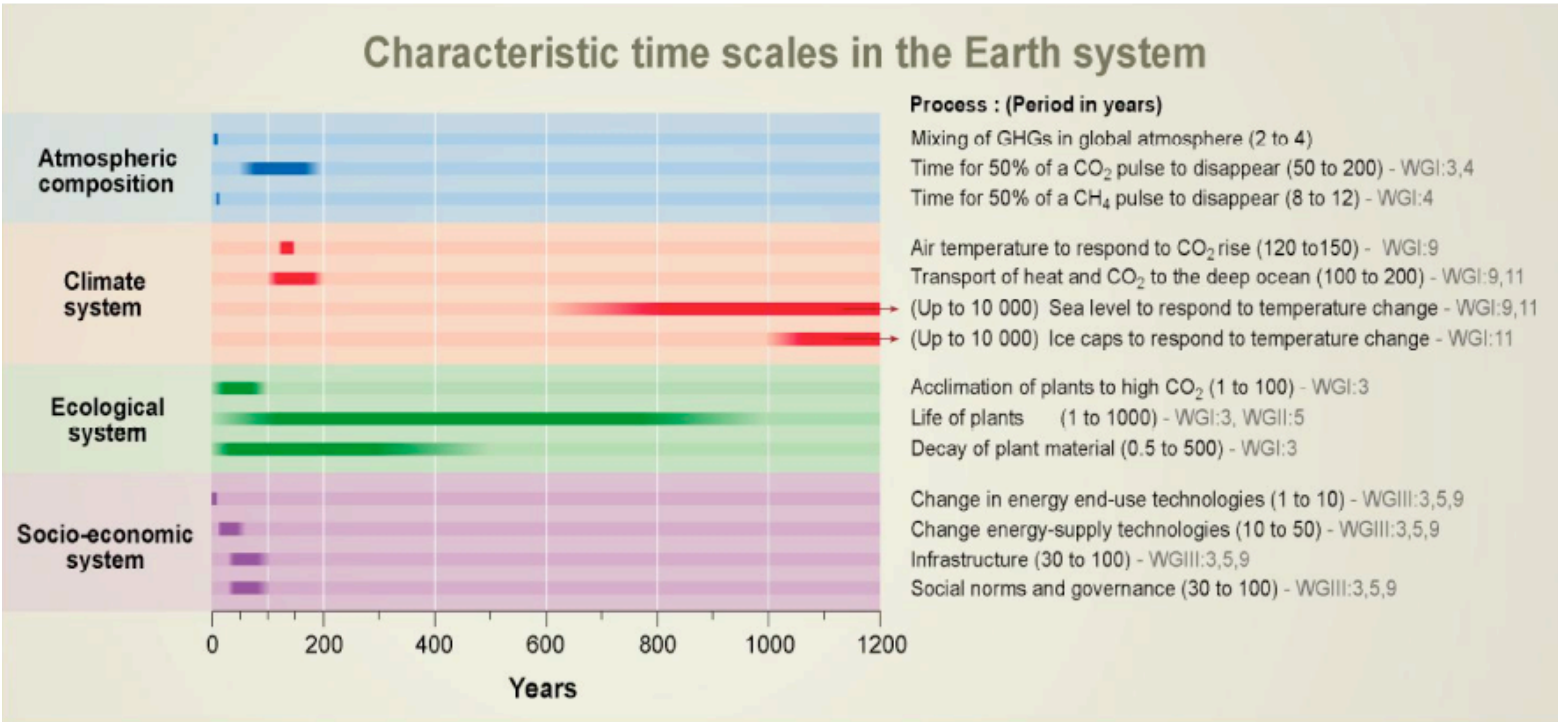


Fig. 1. Estimated climate forcings; error bars are partly subjective 1σ uncertainties.

Hansen and Sato, 2001

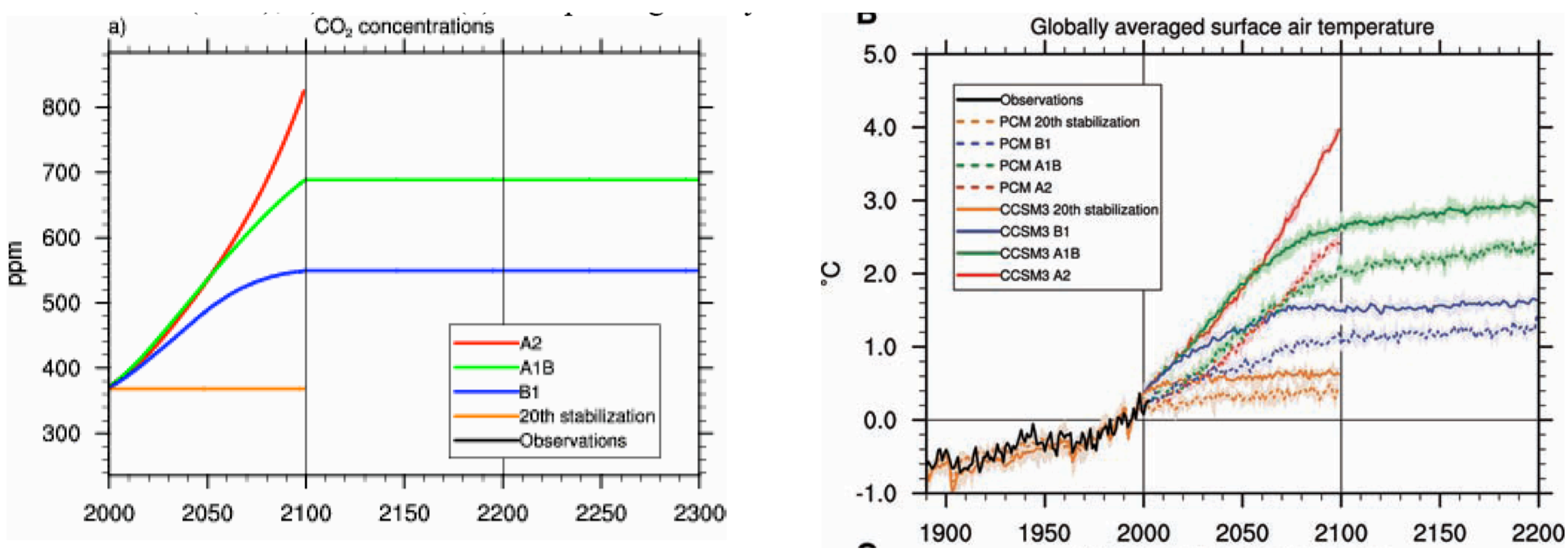
Time scales for climate projection



IPCC TAR, 2001

- Traditional assessments treat centennial time scales for composition and climate response.
- The time scales relevant for adaptation of infrastructure and agrisystems are decadal.

Projections for Global Surface Temperature



Meehl et al, 2005

- Between 50 to 70% of warming in 2050 relative to pre-industrial periods Is “committed”.
- Therefore the short-range predictions are relatively insensitive to socioeconomic scenarios.

Transient Climate Response and Equilibrated Climate Sensitivity

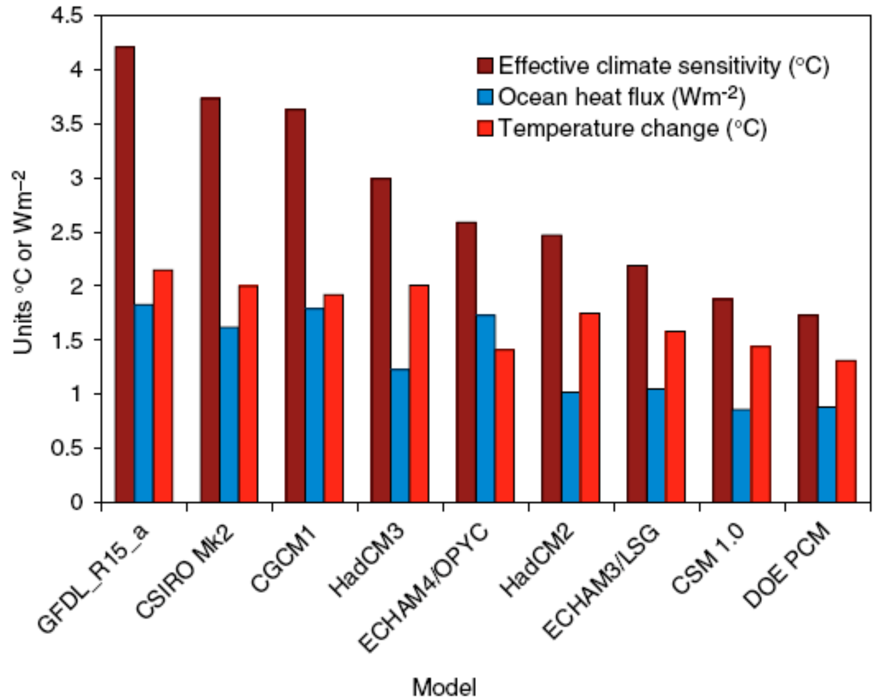
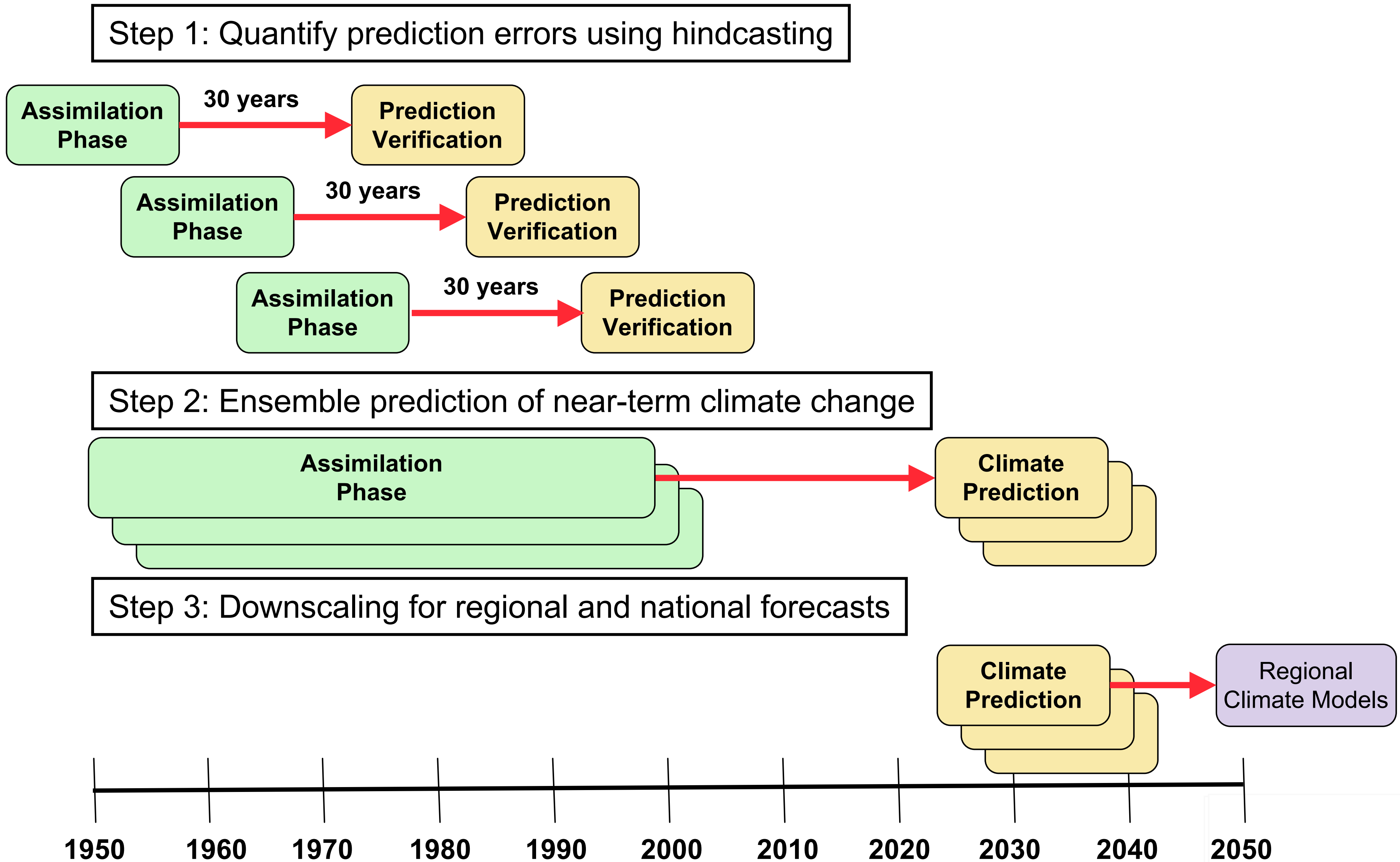


Figure 9.20: Comparison of CMIP2 model results for 20-year average values centred on year 70, the time of CO_2 doubling. Values are shown for the effective climate sensitivity, the net heat flux across the ocean surface multiplied by the ocean fraction and the global mean temperature change (TCR).

IPCC TAR, 2001

- The range of transient response is 3X smaller than the equilibrated sensitivity.
- Therefore the multi-model set of short-term predictions should be more consistent.

Schema for short-range prediction



Conclusions - Scientific Objectives

- How do natural and anthropogenic factors influence past, present, and future climate?
- How does the hydrological and ecological cycles respond to these influences?
- How will natural systems amplify or reduce human influences on climate?
- What are optimal (and sub-optimal) methods for adapting to and mitigating climate change?