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

[Images of Grinnell Glacier in 1938 and 2005]
Increasing global temperatures

Earth has warmed by $0.76 \pm 0.19$K since 1850.
Measurement artifacts do not affect global trends.

IPCC AR4, 2007
Atmospheric temperature and moisture

Air Temperature Trends

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

Atmospheric Moisture Trends

IPCC AR4, 2007
It is very likely that last 50 years are warmest in last 500 years.
Reductions in Arctic sea ice

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

IPCC AR4, 2007

NASA & NSIDC
Trends in land glaciers and ice

- Mass loss from glaciers since 1991 is $0.77\pm0.22$ 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 $3.1 \pm 0.7$ mm / year.
The energy budget of the Earth
Energy budget of Earth’s climate

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

![Global Heat Flows Diagram](Diagram)

<table>
<thead>
<tr>
<th>GHG</th>
<th>GH Effect (Wm⁻²)</th>
<th>GH %age</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>32</td>
<td>26</td>
</tr>
<tr>
<td>O₃</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>CH₄+N₂O</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>H₂O</td>
<td>75</td>
<td>60</td>
</tr>
</tbody>
</table>

Kiehl and Trenberth 1997
Changes in atmospheric composition

- Concentrations of greenhouse gases are highest in 650K years.
Definition of radiative forcing

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

IPCC AR4, 2007
Human-induced greenhouse forcing

- Concentrations of O\textsubscript{2} and fractions of \textsuperscript{13}C are decreasing.
- These decreases are most consistent with fossil fuel origin.
Models of aerosol radiative forcing

IPCC AR4, 2007

<table>
<thead>
<tr>
<th>Species</th>
<th>Forcing (W m(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulfate</td>
<td>(-0.4 \pm 0.2)</td>
</tr>
<tr>
<td>Fossil fuel organic carbon</td>
<td>(-0.1 \pm 0.1)</td>
</tr>
<tr>
<td>fossil-fuel black carbon</td>
<td>(+0.2 \pm 0.1)</td>
</tr>
<tr>
<td>Biomass burning</td>
<td>0.0 \pm 0.1</td>
</tr>
<tr>
<td>Nitrate</td>
<td>(-0.1 \pm 0.1)</td>
</tr>
<tr>
<td>mineral dust</td>
<td>(-0.1 \pm 0.2)</td>
</tr>
<tr>
<td>Total</td>
<td>(-0.5 \pm 0.4)</td>
</tr>
</tbody>
</table>
The Sun: a natural forcing agent

Latest solar irradiance models: 0.04% increase over 1700 - 2005.
Volcanoes: intermittent forcing agents

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

IPCC AR4, 2007
Historical radiative forcing

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

IPCC AR4, 2007
Causes of recent climate changes

- Volcanic eruptions
- Solar variability
- Human Pollution
Method for attribution: Climate models

Forcings:
- Greenhouse gases
- Manmade aerosols
- Volcanic eruptions
- Solar variability

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

**Atmosphere**
- CAM 3.0
- 1.4° x 26 levels

**Land**
- CLM2.2
- 1.4° x 10 levels

**Coupler**
- CPL 6

**Ocean**
- POP 1.4.3
- 1.0° x 40 levels

**Sea Ice**
- CSIM 4
- 1.0° x 5 levels
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.

IPCC AR4, 2007
Future evolution of the Earth’s climate
Projections for global temperatures

- Global temperatures could increase by 1.7 to 3.2K.
Projection of regional temperatures

- 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
Increased sea level and glacial melt
Climate extremes in physical climate

Change in index over 21st century for the **B1** scenario (**550 ppm CO₂ at 2100**)  
Stippled regions = all models agree on sign.

Change in index over 21st century for the **A1B** scenario (**720 ppm CO₂ at 2100**)  
Stippled regions = all models agree on sign.

Change in index over 21st century for the **A2** scenario (**850 ppm CO₂ 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
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.
First generation Earth system model

Coupler

Land

C/N Cycle Dyn. Veg. Land Use Ice Sheets

Atmosphere

Gas chem. Prognostic Aerosols Upper Atm.

Ocean

Ecosystem & BGC

Sea Ice

Climate Forcings (W/m²): 1850-2000

CO₂ CH₄ CFCs N₂O

Greenhouse Gases

Reflective Aerosols Tropospheric Ozone Black Carbon

Tropospheric Aerosols

Other Anthropogenic Forcings Volcanic Aerosols (range of decadal mean)

Forced Cloud Changes Land Cover Alter.

-0.4±0.2

Sun

(0.2, -0.5)

Hansen and Sato, 2001

Fig. 1. Estimated climate forcings; error bars are partly subjective for uncertainties.
Time scales for climate projection

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

### Characteristic time scales in the Earth system

<table>
<thead>
<tr>
<th>Process</th>
<th>Period in years</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixing of GHGs in global atmosphere</td>
<td>2 to 4</td>
<td></td>
</tr>
<tr>
<td>Time for 50% of a CO₂ pulse to disappear</td>
<td>50 to 200</td>
<td>WGI 3.4</td>
</tr>
<tr>
<td>Time for 50% of a CH₄ pulse to disappear</td>
<td>8 to 12</td>
<td>WGI 4</td>
</tr>
<tr>
<td>Air temperature to respond to CO₂ rise</td>
<td>120 to 150</td>
<td>WGI 9</td>
</tr>
<tr>
<td>Transport of heat and CO₂ to the deep ocean</td>
<td>100 to 200</td>
<td>WGI 9,11</td>
</tr>
<tr>
<td>(Up to 10,000) Sea level to respond to temp.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Up to 10,000) Ice caps to respond to temp.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acclimation of plants to high CO₂</td>
<td>1 to 100</td>
<td>WGI 3</td>
</tr>
<tr>
<td>Life of plants</td>
<td>1 to 1000</td>
<td>WGI 3, WGI 5</td>
</tr>
<tr>
<td>Decay of plant material</td>
<td>0.5 to 500</td>
<td>WGI 3</td>
</tr>
<tr>
<td>Change in energy end-use technologies</td>
<td>1 to 10</td>
<td>WGI 3,5,9</td>
</tr>
<tr>
<td>Change energy-supply technologies</td>
<td>10 to 50</td>
<td>WGI 3,5,9</td>
</tr>
<tr>
<td>Infrastructure</td>
<td>30 to 100</td>
<td>WGI 3,5,9</td>
</tr>
<tr>
<td>Social norms and governance</td>
<td>30 to 100</td>
<td>WGI 3,5,9</td>
</tr>
</tbody>
</table>
Projections for Global Surface Temperature

- 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.

Meehl et al, 2005
Transient Climate Response and Equilibrated Climate Sensitivity

- 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.

**Figure 9.20**: Comparison of CMIP2 model results for 20-year average values centred on year 70, the time of CO₂ 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*
Schema for short-range prediction

Step 1: Quantify prediction errors using hindcasting

Assimilation Phase 30 years Prediction Verification

Assimilation Phase 30 years Prediction Verification

Assimilation Phase 30 years Prediction Verification

Step 2: Ensemble prediction of near-term climate change

Assimilation Phase Climate Prediction

Step 3: Downscaling for regional and national forecasts

Climate Prediction Regional Climate Models
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?