Understanding sea level rise and variability
Current projections and key uncertainties

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Simulated global average temperature change

AOGCM results courtesy of PCMDI and modelling groups
Simulated thermal expansion

Sea level rise (m)

1850 1900 1950 2000
-0.02 0.00 0.02 0.04 0.06 0.08

CCSM3
CGCM3.1(T47)
CNRM-CM3
CSIRO-Mk3.0
ECHAM/MPI-OM
ECHO-G
GFDL-CM2.0
GFDL-CM2.1
GISS-AOM
GISS-EH
GISS-ER
INM-CM3.0
MIROC3.2(hires)
MIROC3.2(medres)
MRI-CGCM2.3.2
PCM
UKMO-HadCM3

AOGCM results courtesy of PCMDI and modelling groups
Krakatoa explains some of the spread

Gleckler et al. (submitted MS)
AOGCMs have a range of trends in recent decades

Antonov et al. (2005) $0.40 \pm 0.05$ mm yr$^{-1}$, AOGCMs $0.54 \pm 0.26$
AOGCMs have less variability than ocean temperature analyses
Ocean temperature variability as a function of depth

HadCM3, there is a tendency to have weak variability at depth, and overly strong variability in the surface layers, especially in the South Atlantic, South Pacific, and North Indian basins.

b. Analysis of standard deviation

Gregory et al. (2004) compared observed low-frequency temperature variability to the HadCM3 control run (natural internal variability only) by computing the standard deviation of the volume-averaged, 5-yr running mean temperature at each level from the detrended data (their Fig. 4). We will refer to this quantity as $\text{SD[Avg(T)]}$; it is shown for observed temperatures (detrended by removing the best fit line) as the broken line with triangles in Fig. B4. There is a peak in observed variability at 400 m, which neither model control run reproduced (Fig. B5, right panel).

The subsurface peak in observed $\text{SD[Avg(T)]}$ gives the impression that were a ship to occupy a station, there would be greater temperature variability measured at 400 m than above or below. This is not true, as can be seen in the global average of individual standard deviations at each point, $\text{Avg[SD(T)]}$. Generally, $\text{SD[Avg(T)]}$ because significant cancellation occurs when the volume-average temperature is taken. How much cancellation depends on the spatial coherence of temperature fluctuations, so an indication

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Pierce et al. (2006)
Simulated temperature change under scenario A1B

AOGCM results courtesy of PCMDI and modelling groups
Simulated thermal expansion under scenario A1B

AOGCM results courtesy of PCMDI and modelling groups

Model spread is due to differences in climate sensitivity and ocean heat uptake efficiency.
Geographical pattern of simulated sea level change

Colours in m AOGCM results courtesy of PCMDI and modelling groups
Simulation of glacier surface mass balance change

Glacier contribution to rate of sea level rise is calculated as

\[-\frac{1}{A_o} \sum b_i A_i \Delta T_i\]

\((A_o \text{ ocean area, } b_i, A_i, \Delta T_i \text{ mass balance sensitivity, area and temperature anomaly for region } i)\). If

\(\Delta T_i = R_i \Delta T - \theta_i\)

\((\Delta T \text{ global temperature anomaly})\), the rate can be written

\(b_g(\Delta T - \theta)\).

Zuo and Oerlemans (1997)
Gregory and Oerlemans (1998)
Global glacier contribution to sea level rise

Calculated from observed (GISTEMP) and AOGCM-simulated temperatures, compared with an observational estimate.
Global glacier mass balance as a function of $\Delta T$

- $0.15$ mm yr$^{-1}$ K$^{-1}$ calculated from GISTEMP + 0.15 K
- $0.44$ mm yr$^{-1}$ K$^{-1}$ Dyurgerov and Meier (2005)

![Graph showing the relationship between global average surface air temperature anomaly and rate of glacier mass loss](image-url)
Effect of glacier hypsometry

- **Constant area**
  - (e.g. Zuo and Oerlemans, 1997)

- **Area–volume scaling**
  - (e.g. Van de Wal and Wild, 2001)

- **Evolving hypsometry**
  - (e.g. Raper and Braithwaite, 2006)

Sea level rise vs. Time diagram with 0.5 m marker.
Simulation of ice-sheet surface mass balance change

Huybrechts et al. (2004) scaled geographical patterns of temperature and precipitation change from high-resolution climate models according to the ice-sheet area-average changes from AOGCMs. Gregory and Huybrechts (in press) repeated this with five high-resolution models. The high-resolution climate change is input to a 20-km ice-sheet mass balance calculation.

Thus we obtain ice-sheet surface mass balance perturbation (SLE) as a function of ice-sheet area-average temperature and precipitation change.
Ensemble-mean high-resolution GCM patterns

Annual precipitation change (%) (10% area-average)  Summer temperature change (K) (1 K area-average)
Precipitation rises linearly with temperature

 Antarctia temperature change (K)

 Antarctia precipitation change (%)

 cccma_cgcm3_1_t47
 ncar_pcm1
 ipsl_cm4
Warming threshold for negative surface mass balance in Greenland

![Graph showing frequency vs. warming threshold for negative surface mass balance in Greenland and the global average. The x-axis represents the warming threshold in Kelvin (K), while the y-axis represents frequency in 0.5 K bins. The graph compares the warming thresholds for Greenland and the global average, with the Greenland data represented by crosses and the global average by a dashed line with diamonds. The graph highlights the higher frequency of warming thresholds for negative surface mass balance in Greenland compared to the global average.](image-url)
Future evolution of the Greenland ice sheet

Ridley et al. (2005)
Not including any effects tending to produce rapid dynamical acceleration.
Dynamical changes in the West Antarctic ice sheet

Payne et al. (2004)
Summary

AOGCM output can be used to simulate sea level rise due to thermal expansion and land ice change.

Scenario and climate sensitivity are major uncertainties for making projections.

Uncertainties—thermal expansion

Global ocean heat uptake varies among models, reflecting differences in interior transport processes.

Geographical patterns of sea level change show substantial differences.

Simulated decadal variability of ocean heat content is smaller than in observational analyses.

Uncertainties—glaciers and ice caps

Treatment of the evolution of hypsometry and the “unperturbed” state.

Mass balance sensitivity to temperature (in general, to climate change).

Geographical patterns of temperature and precipitation change.

Role of rapid dynamical response to climate change.
Uncertainties—ice sheets

Magnitude of increase in precipitation
Geographical and seasonal pattern of change in temperature over the ice sheets
Possibility of lubrication of ice flow caused by surface runoff
Dependence of basal melting of ice shelves on ocean climate change
Vulnerability of ice shelves to surface climate change
Dynamical response of ice streams to melting at the grounding line and to removal of ice shelves
Retreat of grounding line as a feedback on dynamical change
Possibility of developing ice streams in slow-moving areas of ice sheets

Uncertainties—total

Models of the major terms (thermal expansion and glaciers) give results agreeing reasonably well with corresponding observational estimates for the 20th century—but they don’t add up to $\sim 1.5 \text{ mm yr}^{-1}$!
Simulation of historical sea level change

Gregory et al. (in press)