Climate forcing
Climate forcing

**External forcing** for earth’s climate includes:

- earth orbit parameters (solar distance factors)
- solar luminosity
- moon orbit
- volcanoes and other geothermal sources
- tectonics (plate motion)
- greenhouse gases (to the extent that they are not part of the climate system itself)
- land surface (likewise with respect to the climate system)
Summary for Policymakers

Anthropogenic Climate forcing

Changes in Greenhouse Gases from Ice Core and Modern Data

Figure SPM.1. Atmospheric concentrations of carbon dioxide, methane and nitrous oxide over the last 10,000 years (large panels) and since 1750 (inset panels). Measurements are shown from ice cores (symbols with different colours for different studies) and atmospheric samples (red lines). The corresponding radiative forcings are shown on the right hand axes of the large panels. {Figure 6.4}

The understanding of anthropogenic warming and cooling influences on climate has improved since the TAR, leading to very high confidence that the global average net effect of human activities since 1750 has been one of warming, with a radiative forcing of +1.6 [+0.6 to +2.4] W m\(^{-2}\) (see Figure SPM.2). {2.3., 6.5, 2.9}

Changes in Temperature, Sea Level and Northern Hemisphere Snow Cover

Figure SPM.3. Observed changes in (a) global average surface temperature, (b) global average sea level from tide gauge (blue) and satellite (red) data and (c) Northern Hemisphere snow cover for March-April. All changes are relative to corresponding averages for the period 1961–1990. Smoothed curves represent decadal average values while circles show yearly values. The shaded areas are the uncertainty intervals estimated from a comprehensive analysis of known uncertainties (a and b) and from the time series (c). {FAQ 3.1, Figure 1, Figure 4.2, Figure 5.13}

Intergovernmental Panel on Climate Change (IPCC), honored with the 2007 Nobel Peace Prize.
Observed global ocean changes that might be anthropogenic (Levitus et al. 2005)

Ocean heat uptake 0-3 km (1955-1998)

= 14.5 x 10^{22} \text{ J} \approx 0.04^\circ \text{C}

0.037^\circ \text{C}

warming

(0-3000 m)
Is there anthropogenic climate change?

- Yes (IPCC TAR)

Observed changes: basin-scale temperature
Mostly warming but some cooling (presented by H. Garcia).
Especially note cooling in high latitude Atlantic and Pacific, tropical Pacific and Indian. Not just noise.

Linear Trend of the zonally integrated heat content ($x \times 10^{18}$ J/year) for 100 m thick layers (1955/59 to 1994/98) [Levitus et al., 2005]
Observed changes: Southern Ocean
(Gille, Science 2002)

Broad warming in southern ocean at about 800 meters

Also note cooling to the north of the warm band

Accompanied by cooling in central Antarctica

This looks like the Southern Annular Mode pattern. Natural climate modes might also be forced by anthropogenic change.
Observed changes: salinity

Fifty year trends in salinity
-Durack and Wijffels, 2009
Observed changes:
Freshening of the Atlantic and Nordic Seas
(Dickson et al, Phil Trans Roy Soc 2003)
Large-scale salinity changes: fresh areas freshening and salty areas getting saltier. Suggests increase in atmospheric hydrological cycle, which would be expected in a warmer world. This can only be observed with ocean salinities rather than with trends in evaporation-precipitation since the latter data sets are very noisy.
Observed changes: Sea level rise

The reasonable agreement in recent years between the observed and simulated sea level rise is explored in greater detail in the IPCC Third Assessment Report. Regional sea level change is particularly variable, with some regions experiencing rapid rise and others falling, a fact that is not well explained by current models. The uncertainties in the simulations include the land-based water storage, which is relatively poorly known. Modelling studies suggest an upper limit for the magnitude of change in land ice, which is relatively poorly known. The sum of thermal expansion and loss of ice each account for about half of the observed sea level rise, although there is some uncertainty in the estimates.

Sea level is projected to rise at an even greater rate in this century. Sea level rose in the 20th century and is currently rising at an increased rate, after a period of little change between AD 0 and AD 1900. Coastal sea level indicators suggest that global sea level did not rise significantly from then until the late 19th century. The small discrepancy between observed sea level rise and the sum of thermal expansion and loss of ice will continue to increase as a consequence of acceleration.

Human-induced processes account for about half of the observed rise in sea level, while melting of land ice accounted for less than half. Thus, the full magnitude of the observed sea level rise during the 19th century is not satisfactorily explained by those data sets. In agreement with models, trends in sea level rise are evident in satellite data and hydrographic observations, although there is some uncertainty in the estimates.

The estimated global mean sea level rise is about 1.9 mm yr\(^{-1}\) in the instrumental record, significantly higher than the average during the previous half century. Coastal sea level indicators suggest that global sea level did not rise significantly from then until the late 19th century. As in the past, sea level could rise by several metres (Section 10.7.4) with regional sea level change varying within about ±0.15 m of the mean in a typical model projection. Thermal expansion is projected to be an even greater part of the total sea level rise in the future than in the past. The magnitude of increases in sea level could be greater for the 21st century, relative to the 1980 to 1999 mean, and has been calculated for the 21st century for the SRES A1B scenario. Estimates for the 21st century show that global average sea level rose at a rate of around 3 mm yr\(^{-1}\) for onset of sea level rise during the 19th century. The IPCC Third Assessment Report identified the sea level rise in the 20th century as the most likely cause of the changes in the mean sea level, and the global average sea level rose at a rate of around 3 mm yr\(^{-1}\) for onset of sea level rise during the 19th century. The IPCC Third Assessment Report identified the sea level rise in the 20th century as the most likely cause of the changes in the mean sea level.
Scientific uncertainty and the public

Scientific consensus on the following statement: "Human activities ... are modifying the concentration of atmospheric constituents ... that absorb or scatter radiant energy. ... [M]ost of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations"

928 abstracts, published in refereed scientific journals between 1993 and 2003, and listed in the ISI database with the keywords "climate change. Of all the papers, 75% either explicitly or implicitly accepting the consensus view; 25% dealt with methods or paleoclimate, taking no position on current anthropogenic climate change. Remarkably, none of the papers disagreed with the consensus position. [Naomi Oreskes, UCSD, Science 2004.]
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However, only 57% of Americans believe that the earth is warming, and 36% think there is warming caused by human activity. [Pew research study, October 2009]

Why???
“Uncertainties”

• While CO2 rise and overall warming are NOT in doubt, some of the specific consequences are. Why? Because they depend on details of circulation.
Sea level rise depends on circulation

The reasonable agreement in recent years between the observed and projected sea level rise provides strong evidence that human-driven climate change is responsible for the recent acceleration of the global rate of sea level rise. This observation, and similar rates have occurred in some earlier decades.

The two major causes of global sea level rise are thermal expansion of the oceans (water expands as it warms) and the loss of land-based water storage, which is relatively poorly known. Modelling results suggest an upper limit for the magnitude of change in sea level rise, while melting of land ice accounted for less than one-quarter of the observed rise. Thermal expansion contributed about one-quarter of the observed rise over the past century.

Global sea level rose by about 120 m during the several millennia that followed the end of the last ice age (approximately 21,000 years ago), and stabilised between 3,000 and 2,000 years ago. Sea level indicators suggest that global sea level did not rise significantly from then until the late 19th century. The upper limit for the magnitude of change in sea level rise is believed that on average, over the period from 1961 to 2003, sea level rise is mostly due to non-uniform changes in temperature and salinity and related to changes in the ocean circulation.

Spatial variability of the rates of sea level change is also inferred from hydrographic observations. Global mean rise, while in other regions sea level is falling. In agreement with climate models, satellite data and hydrographic observations show that sea level is not rising uniformly around the world. In some regions, rates are up to several times the mean in a typical model projection. Thermal expansion is projected to contribute more than half of the average rise, but land-based ice due to increased melting.

An important uncertainty relates to whether discharge of ice from the ice sheets will continue to increase as a consequence of acceleration of ice flow into the ocean. As in the past, sea level rise will now, as has been observed in recent years. This would increase melting of ice from the ice sheets, and add to the amount of sea level rise, but quantitative projections of how much it would add cannot be made with confidence.

During recent years (1993–2003), for which the observing period was not satisfactorily explained by those data sets, as sea level rise, while melting of land ice accounted for less than one-quarter of the observed global mean sea level rise. Estimates for onset of sea level rise during the 19th century. The small discrepancy between observed sea level rise and the sum of thermal expansion and loss of land-based ice suggests no net trend in the storage of water over land.

The satellite observation available since the early 1990s provide more accurate sea level data with nearly global coverage. This results suggest no net trend in the storage of water over land-based reservoirs, wetland drainage and deforestation).

The past and as projected for the 21st century, relative to the 1980 to 1999 mean, and has been calculated for the 21st century, for instance, global sea level reaches 0.22 to 0.44 m above 1990 levels, and is rising at about 4 mm yr$^{-1}$, significantly from then until the late 19th century. The grey shading shows estimates of the past.

Figure 1 shows the evolution of global mean sea level in the past and as projected for the 21st century for the SRES A1B scenario.
Sea level rise depends on circulation

![Graph showing sea level change over time](image1)

![Map showing geographic distribution of short-term linear trends in mean sea level](image2)

**Figure 5.15.** (a) Geographic distribution of short-term linear trends in mean sea level (mm yr\(^{-1}\)) for 1993 to 2003 based on TOPEX/Poseidon satellite altimetry (updated from Cazenave and Nerem, 2004) and (b) geographic distribution of linear trends in thermal expansion (mm yr\(^{-1}\)) for 1993 to 2003 (based on temperature data down to 700 m from Ishii et al., 2006).
“Uncertainties”

• While CO2 rise and overall warming are NOT in doubt, some of the specific consequences are. Why? Because they depend on details of circulation.
Wilkins Ice Sheet (size of Connecticut)

April 2008

April 2009

Previously weakened ice (1998)

Rest of ice shelf
(13,468 km², or 5,200 mi²)

Remaining unweakened ice

Region of disintegration

National Snow and Ice Data Center, Boulder, CO
“Abrupt” climate change?

Historical record of temperature in mid-atlantic (green) and Greenland (blue)

Pattern of ‘cold phase’

Rahmstorf, Nature, 2002
“Uncertainties”

- While CO2 rise and overall warming are NOT in doubt, some of the specific consequences are. Why? Because they depend on details of circulation.

- One of the most common consequences in the press is a slowdown of the global overturning circulation.
Turbulent mixing makes the ocean go round

- Turbulence occurs at small scales: cm to m
- Determines large scale vertical transport of heat, CO2, nutrients, etc.
- Drives meridional overturning circulation by creating potential energy.

Low Latitudes

High Latitudes

-vortex stretching
Stommel and Aarons

Turbulence occurs at small scales: cm to m

Determines large scale vertical transport of heat, CO2, nutrients, etc.

Drives meridional overturning circulation by creating potential energy.

Churn, churn, churn

How the oceans mix their waters is key to understanding future climate change. Yet scientists have a long way to go to unravel the mysteries of the deep.
Global heat transport
(Ganachaud and Wunsch, 2000)
Very simplified version of this: “Ocean Conveyor Belt”, but of course deeper circulation is more complex than this (Broecker, 1981)

Huge climate impact via meridional heat transport
Lumpkin and Speer (2007) version
North Atlantic thermohaline circulation variations - millenial time scales and abrupt climate change

What happens if melting ice makes the North Atlantic too fresh/light for deep convection?

Low Latitudes

High Latitudes
North Atlantic thermohaline circulation variations - millenial time scales and abrupt climate change

What happens if melting ice makes the North Atlantic too fresh/light for deep convection?
Is the N. Atlantic “conveyor” changing?  
e.g. Bryden et al., Nature (2005)

Bryden et al. measurements at 25°N suggested a slowdown.

Cartoon of “conveyor” and measurement arrays in place from Quadfasel (Nature, 2005)
Is the overturning circulation changing (decreasing) ??

Model data from Drijfhout & Hazeleger, 5 observations points from Bryden et al 2005
Is the N. Atlantic “conveyor” changing?

Bryden et al. measurements at 25°N suggested a slowdown. They have since withdrawn this conclusion - answer is very uncertain.
Net overturning (red) varies enormously during a single year, makes it hard to see a trend yet
MOVE (Meridional Overturning Variability Experiment):

Cost-effective concept to monitor transport of southward NADW between western boundary and Mid-Atlantic Ridge

Assumptions:

1) Balances northward thermocline transport (mass balance)

2) Little transport east of MAR (reasonable based on CFC and model data, since 2006 full-basin coverage with German mooring in east)
Internal transport rel 4700db plus boundary transport:

- Trend = +0.35 Sv/a → MOC decrease of 3Sv over measurement period
- 85% certain trend > 0
- 45 degrees of freedom
what if mixing strength changes?

In a windier world, more mixing could ‘compensate’ for changes in surface gradients, so overturning could either slow down or speed up (Schmitt et al, 2009).
“Uncertainties”

- While CO2 rise and overall warming are NOT in doubt, some of the specific consequences are. Why? Because they depend on details of circulation.

- What happens in a future climate is also somewhat uncertain. Why?
Variability in climate models

Figure SPM.5. Solid lines are multi-model global averages of surface warming (relative to 1980–1999) for the scenarios A2, A1B and B1, shown as continuations of the 20th century simulations. Shading denotes the ±1 standard deviation range of individual model annual averages. The orange line is for the experiment where concentrations were held constant at year 2000 values. The grey bars at right indicate the best estimate (solid line within each bar) and the likely range assessed for the six SRES marker scenarios. The assessment of the best estimate and likely ranges in the grey bars includes the AOGCMs in the left part of the figure, as well as results from a hierarchy of independent models and observational constraints.  {Figures 10.4 and 10.29}
Variability in climate models

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15 TAR projections were made for 2100, whereas projections in this report are for 2090–2099. The TAR would have had similar ranges to those in Table SPM.3 if it had treated the uncertainties in the same way.

16 Decreases in pH correspond to increases in acidity of a solution. See Glossary for further details.
Forcing (coupling) with no feedback

- Cause and effect: example of negative coupling
  - Volcano causes aerosols
  - Causes cooling and decrease in temperature

Feedback? None since air temperature does not change incidence of volcanoes
Positive feedbacks

- Example: ice-albedo feedback
  - Increased ice and snow cover increases albedo
    - (Positive coupling, denoted by arrow)
  - Increased albedo decreases temperature of atmos.
    - (negative coupling, denoted by circle)
  - Decreased temperature of atmos. Causes ice increase
    - (negative coupling, denoted by circle)
  - Two negatives cancel to make positive; net is positive feedback (“runaway”, unstable)

Albedo = reflectivity, scale of 0-1 with 0 = no reflection, 1 = all reflected
Albedo effect

Other model uncertainties.

- Unresolved sub-grid-scale processes: turbulence, eddies, clouds, rain.
- Don’t include much detail in shallow water, which can be particularly important for biological effects (carbon uptake, etc).
- Discretization errors ($\frac{du}{dx} \sim \frac{\Delta u}{\Delta x}$)
- Hard to represent steep/complex topography
- Physics/biology interactions (e.g. phytoplankton density controls depth of light/heat penetration)
- Iceberg calving (very nonlinear)
modeled flow in the southern ocean

![Ocean Surface Speed in NOAA/GFDL Southern Ocean Simulations](image)

**Fig. 6.** Instantaneous surface speed in 1° and 1/6° models after 40 yr. Note that the large-scale structure of the 1° model is quite similar to the 1/6° model (the currents have similar locations and have similar horizontal extents). The main difference is in the presence of intense jets and eddies in the 1/6° model.