IPCC THIRD ASSESSMENT REPORT WORKING GROUP I - SCIENCE

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KEY STATEMENT

- ***"There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities"***

Compared with the SAR:

- *"The balance of evidence suggests a discernible human influence on climate change*"

KEY FINDINGS: OBSERVATIONS

- The Earth's climate system has changed on both global and regional scales since the pre-industrial era;
- Some of these changes can be attributable to human activities;
- Global average surface temperature has risen 0.6 ± 0.2°C since 1861;
- Most of the observed warming over the last 50 years is likely due to increases in greenhouse gas concentrations as a result of human activities;
- Sea level has increased between 0.1 and 0.2 metres during the 20th century;
- It is very likely that precipitation has increased by 0.5 to 1% per decade over most mid- and high latitudes of the Northern Hemisphere continents.

KEY FINDINGS: PROJECTIONS

- CO_2 concentrations, global average surface temperature, and sea level are projected to increase under all six IPCC SREC emissions scenarios during the 21st century:
  - projected CO_2 concentration in 2100 ranges from 540 to 970 ppm, compared with 368 ppm in 2000;
  - 1.4 to 5.8°C increase in global average surface temperature;
  - 0.09 to 0.88 m rise in global mean sea level.
- An increase in climate variability (daily, seasonal, inter-annual, and decadal) and in some extreme events;
- Greenhouse gas forcing in the 21st century could set in motion large-scale, high-impact, non-linear, and potentially abrupt changes in physical and biological systems;
- There is a wide range of uncertainty associated with these events and incomplete understanding of some of the underlying processes.

CONTENTS OF THE REPORT

- Observed changes in the climate system;
- Emissions of greenhouse gases and aerosols;
- Projection of future climate;
- Attribution;
- Future work required.

Definition of confidence level

- Virtually certain: greater than 99% chance that a result is true;
- Very likely: 90-99% chance that a result is true;
- Likely: 66-90% chance that a result is true;
- Medium likelihood: 33-66% chance;
- Unlikely: 10-33% chance;
- Very unlikely: 1-10% chance;
- Exceptionally unlikely: less than 1% chance.

OBSERVED CHANGES IN THE CLIMATE SYSTEM

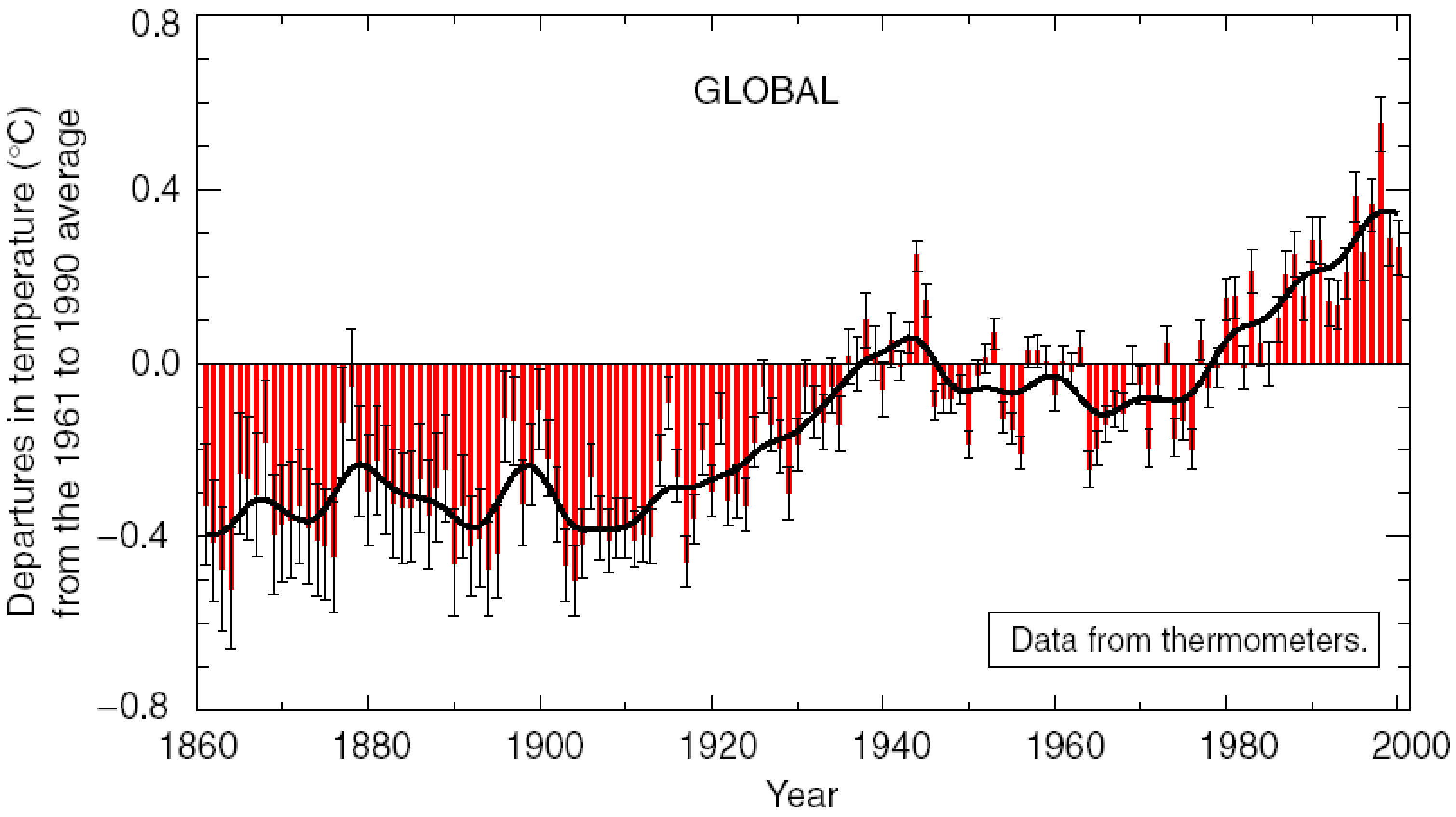
- Surface temperature;
- Sea level;
- Precipitation;
- Snow cover and ice extent;
- Other important aspects of climate;
- Aspects of climate that appear not to have changed.

Global average surface temperature

- The global average surface temperature (over land and sea) has increased by 0.6 ± 0.2°C during the 20th century;
- The increase in temperature in the 20th century is likely (66-90% chance) to have been the largest for any century during the past 1000 years;
- Globally, it is very likely (90-99% chance) that the 1990s was the warmest decade and 1998 the warmest year in the instrumental record, since 1861;
- On average, between 1950 and 1993, night-time daily minimum air temperature over land increased by about 0.2ºC per decade, while day-time daily maximum air temperatures increased by 0.1°C per decade;
- The increase in sea surface temperature between the 1950 and 1993 period is about half that of the increase of the mean land surface temperature.

Variation of the Earth's surface temperature for:

(a) the past 140 years (°C change relative to 1961 to 1990 average)



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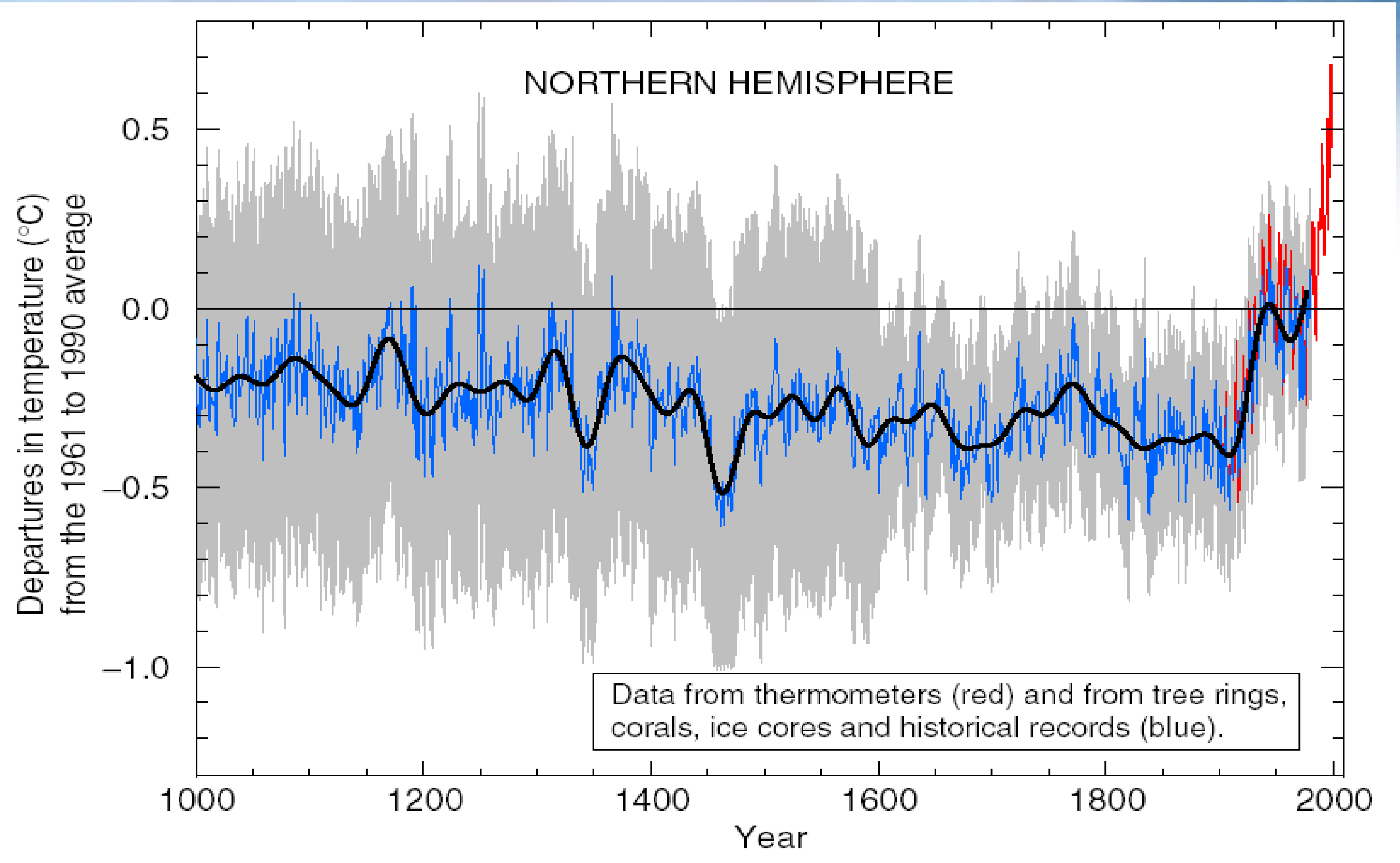
Variation of the Earth's surface temperature for:

(b) the past 1,000 years (°C change relative to 1961 to 1990 average)



Temperature in the lowest 8 kilometres of the atmosphere

- Since the late 1950s, the overall global temperature increases in the lowest 8 kilometres of the atmosphere and in surface temperature have been similar at 0.1ºC per decade;
- Since 1979:
  - global average temperature of the lowest 8 kilometres of the atmosphere has changed by +0.05 ± 0.10ºC per decade;
  - global average surface temperature has increased by +0.15 ± 0.05°C per decade;
  - the above difference occurs primarily over the tropical and sub-tropical regions;
  - this difference in warming rates is statistically significant.
- The lowest 8 kilometres of the atmosphere and the surface are influenced differently by factors such as stratospheric ozone depletion, aerosols, and El Niño phenomenon;
- Spatial sampling techniques can also explain some of the differences in trends, but these differences are not fully resolved.

Global average sea level

- Tide gauge data show that global average sea level rose between 0.1 and 0.2 metres during the 20th century;
- Global ocean heat content has increased since the late 1950s, the period for which adequate observations of sub-surface ocean temperatures have been available.

Precipitation changes in the 20th century

- It is very likely (90-99% chance) that precipitation has increased by 0.5 to 1% per decade over most mid- and high latitudes of the Northern Hemisphere continents;
- It is likely (66-90% chance) that there has been a 2 to 4% increase in the frequency of heavy precipitation events in the mid- and high latitudes of the Northern Hemisphere;
- It is likely (66-90% chance) that rainfall has increased by 0.2 to 0.3% per decade over the tropical land areas;
- It is likely (66-90% chance) that rainfall has decrease by 0.3% per decade over much of the Northern Hemisphere sub-tropical land areas;
- In contrast, no comparable systematic changes have been detected in broad latitudinal averages over the Southern Hemisphere;
- There are insufficient data to establish trends in precipitation over the oceans.

Snow cover and ice extent

- Satellite data show it is very likely (90-99% chance) that the extent of snow cover has decreased by about 10% since the late 1960s;
- Ground-based observations show it is very likely (90-99% chance) that the annual duration of lake and river ice cover has been reduced by about two weeks in the mid- and high latitudes of the Northern Hemisphere, over the 20th century;
- There has been a widespread retreat of mountain glaciers in non-polar regions during the 20th century;
- Northern Hemisphere spring and summer sea-ice extent has decreased by about 10 to 15% since the 1950s;
- It is likely (66-90% chance) that there has been a 40% decline in Arctic sea-ice thickness during late summer to early autumn and a slower decline in winter sea-ice thickness.

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Changes in other important aspects of climate

- It is likely (66-90% chance) that there has been a 2% increase in cloud cover over mid- to high latitude land areas during the 20th century;
- Since 1950 it is very likely (90-99% chance) that there has been a reduction in the frequency of extreme low temperatures, with a smaller increase in the frequency of extreme high temperatures;
- Warm episodes of the ENSO phenomenon have been more frequent, persistent and intense since the mid-1970s, compared with the previous 100 years;
- There were relatively small increases in global land areas experiencing severe drought or severe wetness;
- In some regions, such as parts of Asia and Africa, the frequency and intensity of droughts have been observed to increase in recent decades.

Important aspects of climate that appear not to have changed

- A few areas of the Earth have not warmed in recent decades, mainly over parts of the Southern Hemisphere oceans and Antarctica;
- No significant trends of Antarctic sea-ice extent are apparent since 1978, the period of reliable satellite measurements;
- Global changes in tropical and extra-tropical (mid-latitudes) storm intensity and frequency are dominated by inter-decadal to multi-decadal variations, with no significant trends evident over the 20th century;
- Conflicting analyses make it difficult to draw definitive conclusions about changes in storm activities, especially in the extra-tropics;
- No systemic changes in the frequency of tornadoes, thunder days, or hail events are evident in the limited areas analysed.

EMISSIONS OF GREENHOUSE GASES AND AEROSOLS

- Carbon dioxide
- Methane
- Nitrous oxide
- Other greenhouse gases and ozone
- Changes in Global Warming Potentials
- Radiative forcing
- Anthropogenic aerosols
- Natural factors that contribute to radiative forcing

Carbon dioxide (CO_2)

- The atmospheric concentration of CO_2 has increased by 88 ppm (31%) since 1750:
  - ie. Year 1750 = 280 ppm (approx), year 2000 = 368 ppm (approx).
- The present CO_2 concentration has not been exceeded during the past 420,000 years and likely (66-90% chance) not during the past 20 million years;
- About three-quarters of the anthropogenic emissions of CO_2 during the past 20 years is due to fossil fuel burning. The rest is predominantly due to land-use change, especially deforestation;
- The rate of increase of atmospheric CO_2 concentration has been about 1.5 ppm (0.4%) per year over the past 20 years;
- Currently the ocean and land together are taking up about half of the anthropogenic CO_2 emissions.

Methane (CH_4)

- The atmospheric concentration of methane has increased by 1060 ppb (151%) since 1750 and continues to increase:
  - ie. Year 1750 = 700 ppb (approx), year 2000 = 1760 ppb (approx).
- The present methane concentration has not been exceeded during the past 420,000 years;
- The annual growth in methane concentration slowed and became more variable in the 1990s, compared with the 1980s;
- Slightly more than half of current methane emissions are anthropogenic, eg from:
  - Use of fossil fuels;
  - Cattle and rice agriculture;
  - Landfills.

Nitrous oxide (N_2O)

- The atmospheric concentration of nitrous oxide has increased by 46 ppb (17%) since 1750 and continues to increase:
  - ie. Year 1750 = 270 ppb (approx), year 2000 = 316 ppb (approx).
- The present nitrous oxide concentration has not been exceeded during at least the past thousand years;
- About a third of current nitrous oxide emissions are anthropogenic, eg from:
  - agricultural soils;
  - cattle feed lots;
  - chemical industry.

Other greenhouse gases and ozone

- Since 1995, the atmospheric concentrations of many halocarbon gases that are both ozone-depleting and greenhouse gases (eg $CFCl_3$ and CF_2Cl_2) are either increasing more slowly or decreasing, in response to the Montreal Protocol;
- The substitutes for the above and some other synthetic compounds, e.g. Perfluorocarbons (PFCs) and Sulphur Hexafluoride (SF_6), are currently increasing;
- The total amount of ozone in the troposphere is estimated to have increased by 36% since 1750, due primarily to anthropogenic emissions of several ozone-forming gases.

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Changes in Global Warming Potentials

- Global Warming Potentials (GWPs) are an index for estimating relative global warming contributions due to atmospheric emission of a kg of a particular greenhouse gas compared to emission of a kg of carbon dioxide;
- GWPs are used to equate and add emissions of different greenhouse gases to derive a carbon dioxide equivalent (CO_2-e) value;
- The GWPs of various greenhouse gases have been changed in the TAR, eg for a 100 year time horizon:

carbon dioxide	1 (no change)	
methane	from 21	to 23
nitrous oxide	from 310	to 296
HFC-134a	1300 (no change)	
CF_4	from 6500	to 5700
C_2F_6	from 9200	to 11900
SF_6	from 23900	to 22200

Radiative forcing

- Radiative forcing is a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system, and is an index of the importance of the factor as a potential climate change mechanism. It is expressed in Watts per square metre (Wm^{-2});
- The radiative forcing due to increases of the well-mixed greenhouse gases from 1750 to 2000 is estimated to be 2.43 Wm^{-2}: 1.46 Wm^{-2} from CO_2, 0.48 from CH_4, 0.15 from N_2O, and 0.34 from halocarbons;
- The depletion of the stratospheric ozone layer is estimated to have caused a negative radiative forcing of –0.15 Wm^{-2};
- The increase of tropospheric ozone has a positive radiative forcing of 0.35 Wm^{-2}.

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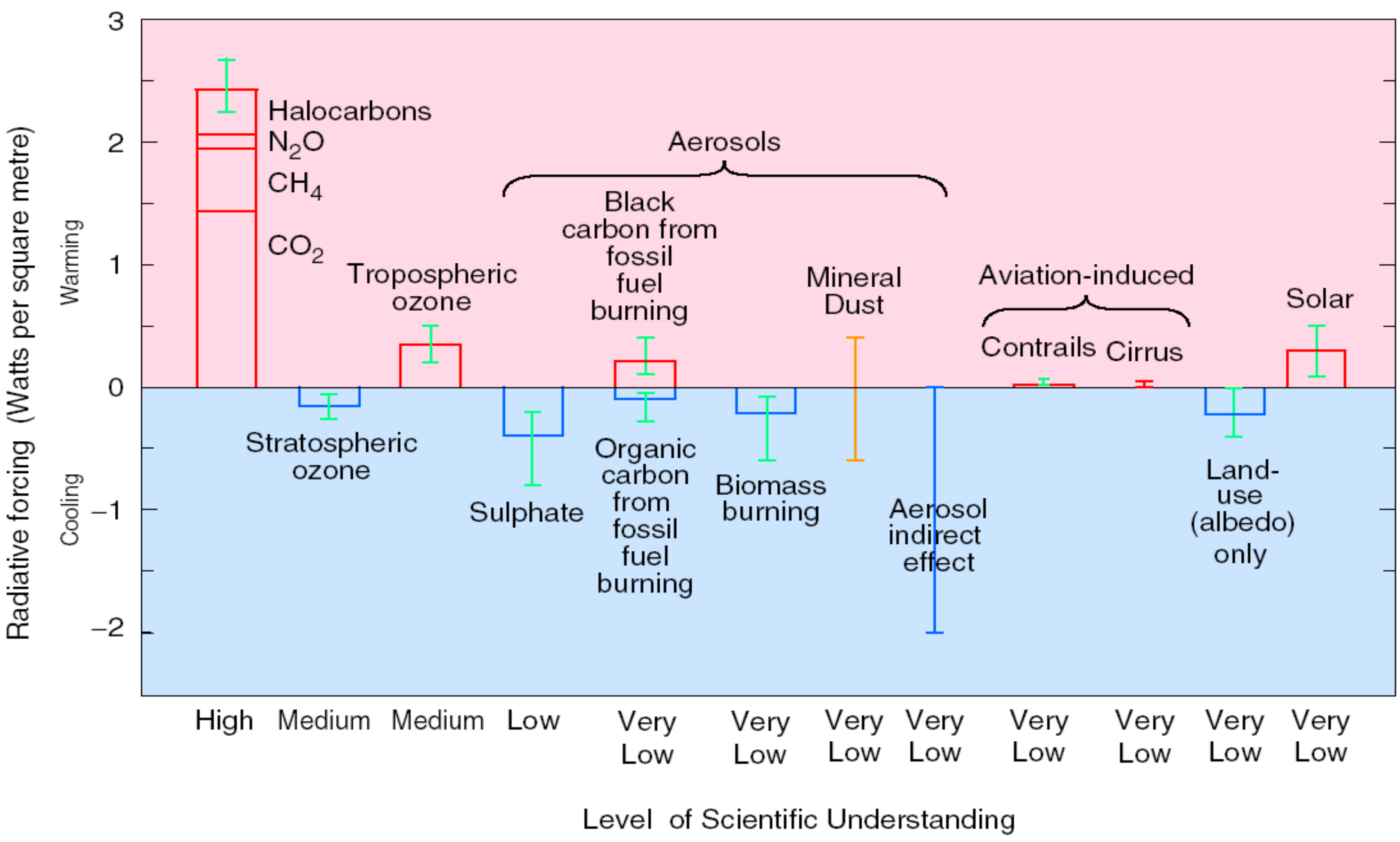
Global mean radiative forcing for year 2000, relative to 1750



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Anthropogenic Aerosols

- Anthropogenic aerosols are short-lived and mostly produce negative radiative forcing;
- The major sources of anthropogenic aerosols are fossil fuel and biomass burning. These sources are also linked to degradation of air quality and acid deposition;
- Aerosols vary considerably by region and respond quickly to changes in emissions;
- Direct radiative forcing of aerosols:
  - Sulphate: -0.4 Wm^{-2};
  - Biomass burning: -0.2 Wm^{-2};
  - Fossil fuel organic carbon: -0.1 Wm^{-2};
  - Fossil fuel black carbon: +0.2 Wm^{-2}.
- Aerosols also have an indirect radiative forcing through their effects on clouds, which is negative, but of very uncertain magnitude.

Natural factors that contribute to radiative forcing

- Radiative forcing due to changes in solar irradiance since 1750 is estimated to be about +0.3Wm^{-2}:
  - most of this occurred during the first half of the 20th century;
  - since the late 1970s, satellite instruments have observed small oscillations due to the 11-year solar cycle;
  - mechanisms for the amplification of solar effect on climate still lack a rigorous theoretical or observational basis.
- Stratospheric aerosols from explosive volcanic eruptions lead to negative forcing, which last a few years;
- The combined change in radiative forcing of the above two factors is estimated to be negative for the past two, and possibly the past four, decades.

PROJECTION OF FUTURE CLIMATE

- Emission scenarios of the Special Report on Emission Scenarios (SRES);
- Projections of greenhouse gases and aerosols;
- Radiative forcing;
- Climate parameters: temperature, sea level, precipitation, snow and ice, thermohaline circulation, El Niño, monsoons and extreme events;
- Confidence in model projections.

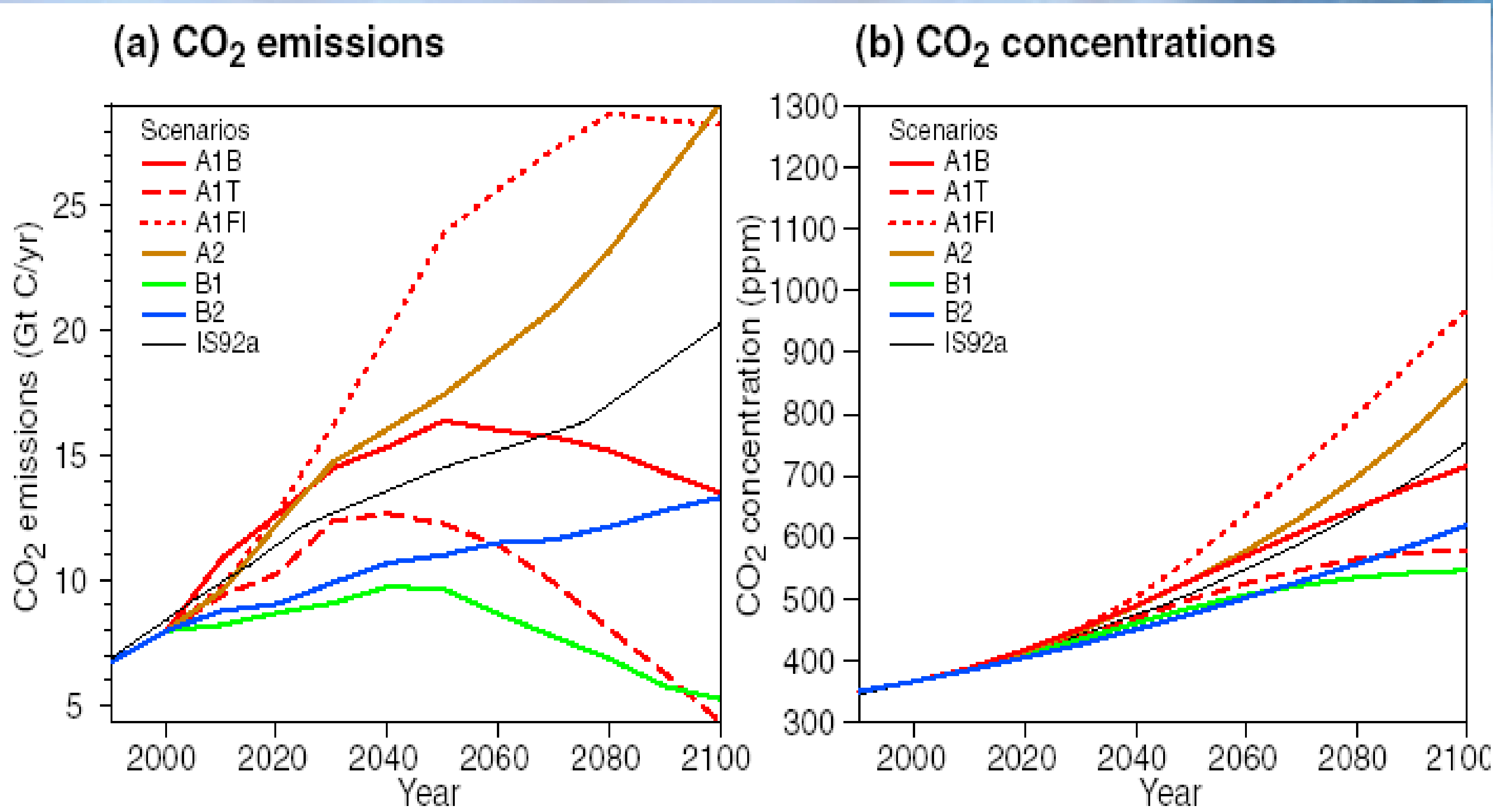
Emission scenarios of the Special Report on Emission Scenarios (SRES)

- A1: rapid economic growth, global population that peaks in mid-century and declines thereafter, rapid introduction of new and efficient technologies, and convergence and capacity building among regions. Three sub-groups:
  - A1FI, fossil intensive energy dominant;
  - A1T, non-fossil energy favoured;
  - A1B, balanced used of fossil and other energy sources.
- A2: a very heterogeneous world, self-reliance and preservation of local identities, economic development is primarily regionally oriented, technological change is fragmented and slower than other scenarios;
- B1: similar to A1, but economic structures become more a service and information economy;
- B2: emphasis on local solutions to economic, social and environmental sustainability, and oriented towards environmental protection and social equity.

Projection of carbon dioxide emissions

- Emissions of CO_2 due to fossil fuel burning are virtually certain (greater than 99% chance) to be the dominant influence on the trend in atmospheric CO_2 concentration during the 21st century;
- As the CO_2 concentration of the atmosphere increases, ocean and land will take up a decreasing fraction of anthropogenic CO_2 emissions;
- By 2100, projected atmospheric CO_2 concentrations will be in the range of 540 to 970 ppm (cf 280 ppm in 1750 and 368 ppm in 2000). These projections include the land and ocean feedbacks;
- Uncertainties cause a variation of about –10 to +30% around each scenario. Including such uncertainties, the total range is 490 to 1260 ppm;
- Changing land use could influence atmospheric CO_2 concentration.

CO_2 emissions and concentration of the 21st century



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Projection of emissions of other greenhouse gases

- Model calculations of the concentrations of the non-CO_2 greenhouse gases by 2100 vary considerably across the SRES scenarios;
- Methane will change by the amount of –190 to +1,970 ppb (present concentration 1,760 ppb);
- Nitrous oxide will change by the amount of +38 to +144 ppb (present concentration 316 ppb);
- A wide range of changes in concentrations of HFCs, PFCs and SF_6;
- Total tropospheric ozone will change by –12 to +62%. In some scenarios, such ozone would become as important a radiative forcing agent as methane.

Aerosols

- Depending on the extent of the fossil fuel use and policies to abate polluting emissions, the SRES scenarios include the possibility of either increases or decreases in anthropogenic aerosols, such as:
  - sulphate aerosols;
  - biomass aerosols;
  - black and organic carbon aerosols.
- Natural aerosols are projected to increase as a result of changes in climates; these aerosols include:
  - sea salts;
  - dust and emissions leading to the production of sulphate and carbon aerosols.

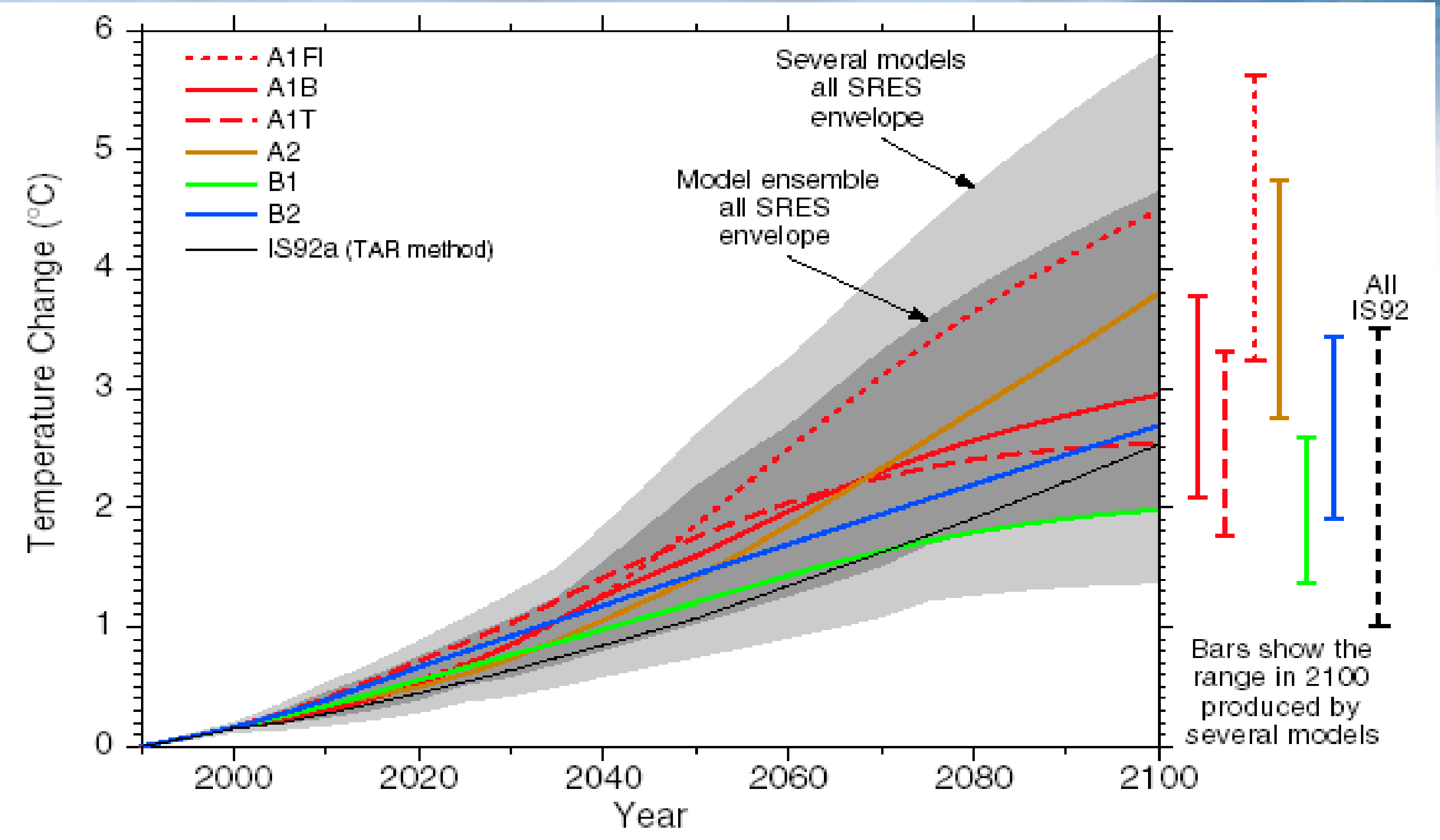
Radiative forcing over the 21st century

- Global mean radiative forcing due to greenhouse gases continues to increase through the 21st century;
- The fraction due to carbon dioxide is projected to increase from slightly more than half to about three quarters;
- The change in the direct plus indirect aerosol radiative forcing is projected to be smaller in magnitude than that of carbon dioxide.

Temperature

- Globally averaged surface temperature is projected to increase by 1.4 to 5.8ºC over the period 1990 to 2100 (cf 1.0 to 3.5ºC in the SAR);
- Anthropogenic warming is likely (66-90% chance) to lie in the range of 0.1 to 0.2ºC per decade over the next few decades;
- It is very likely (90-99% chance) that nearly all land areas will warm more rapidly than the global average, particularly those at northern high latitudes in the cold season;
- Most notable warming is in the northern regions of North America and northern and central Asia;
- The warming is less than the global mean change in south and southeast Asia in summer and in southern South America in winter;
- Trends for surface temperature to become more El Niño-like in the tropical Pacific, with the eastern tropical Pacific warming more than the western tropical Pacific.

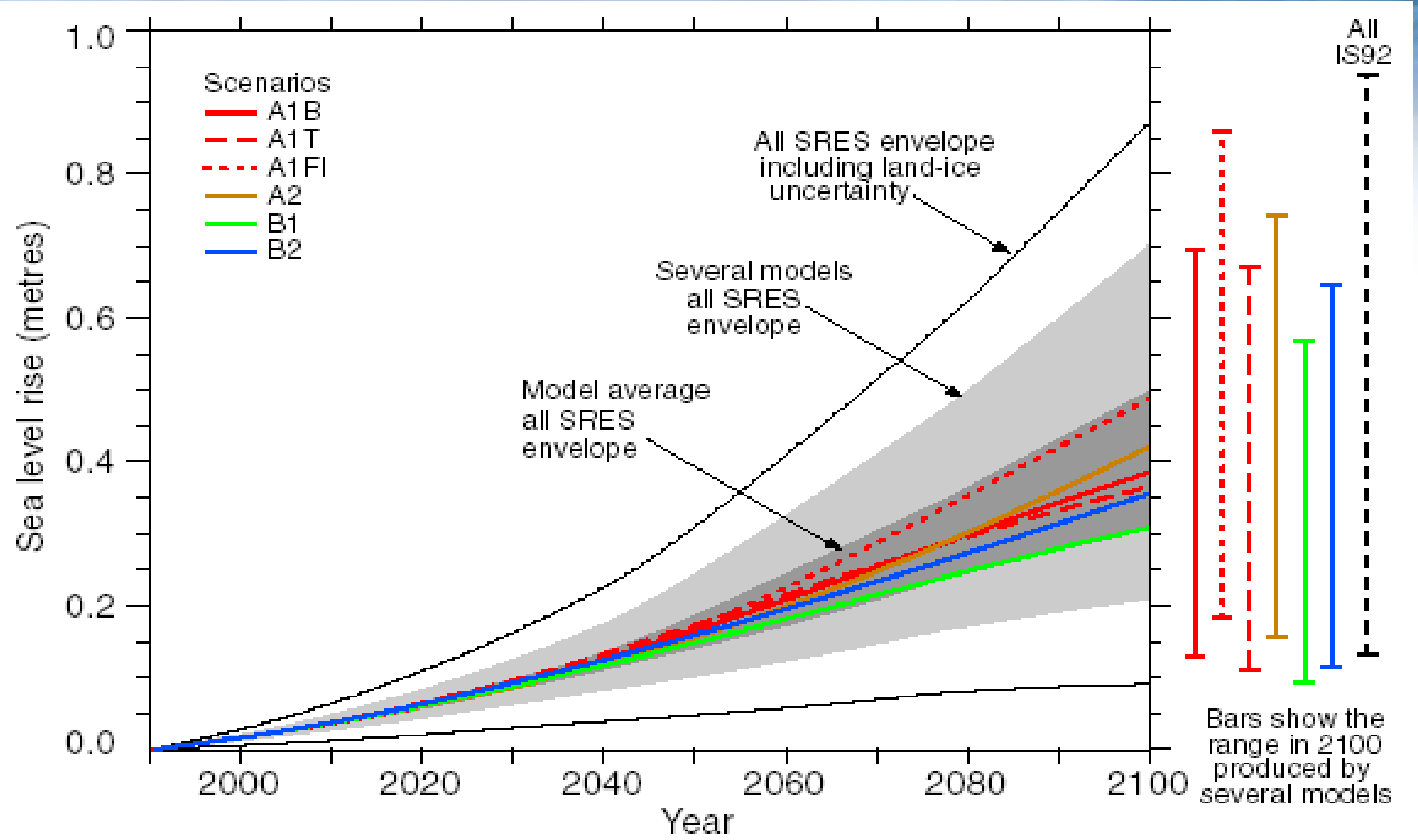
Temperature change over the 21st century



Sea level

- Sea level rise is due primary to thermal expansion and loss of mass from glaciers and ice caps;
- Global mean sea level is projected to rise by 0.09 to 0.88 metres between 1990 and 2100, for the full range of SRES scenarios;
- The range of sea level rise presented in the SAR was 0.13 to 0.94 metres based on the IS92 scenarios;
- Despite the higher temperature change projections in this assessment, the sea level projections are slightly lower, primarily due to the use of improved models, which gives a smaller contribution from glaciers and ice sheets.

Sea level rise over the 21st century



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Precipitation

- Global average water vapour concentration and precipitation are projected to increase during the 21st century;
- By the second half of the 21st century, it is likely (66-90% chance) that precipitation will have increased over northern mid- to high latitudes and Antarctica in winter;
- At low latitudes there are both regional increases and decreases over land areas;
- Larger year to year variations in precipitation are very likely (90-99% chance) over most areas where an increase in mean precipitation is projected.

Snow and ice

- Northern Hemispheric snow cover and sea-ice extent are projected to decrease further;
- Glaciers and ice caps are projected to continue their widespread retreat during the 21st century;
- The Greenland ice sheet is likely (66-90%) to lose mass because the increase in runoff will exceed the precipitation increase;
- The Antarctic ice sheet is likely (66-90% chance) to gain mass because of greater precipitation;
- Loss of grounded ice from the West Antarctic ice sheet, which may lead to substantial sea level rise, is now widely agreed to be very unlikely (1-10% chance) during the 21st century.

Thermohaline circulation

- Most models show weakening of the ocean thermohaline circulation which leads to a reduction of the heat transport into high latitudes of the Northern Hemisphere;
- However, even with such weakening, there is still a warming over Europe due to increased greenhouse gas emissions;
- The current projections do not exhibit a complete shut-down of the thermohaline circulation by 2100;
- Beyond 2100, the thermohaline circulation could completely, and possibly irreversibly, shut-down in either hemisphere if the change in radiative forcing is large enough and applied long enough.

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El Niño

- Confidence in projections of changes in future frequency, amplitude, and spatial pattern of El Niño events in the tropical Pacific is tempered by some shortcomings in how well El Niño is simulated in complex models;
- Current projections show little change or a small increase in amplitude for El Niño events over the next 100 years;
- Nonetheless, global warming is likely (66-90% chance) to lead to greater extremes of drying and heavy rainfall and increase the risk of droughts and floods that occur with El Niño events in many different regions.

Monsoons

- It is likely (66-90% chance) that warming associated with increasing greenhouse gas concentrations will cause an increase of Asian summer monsoon precipitation variability;
- Changes in monsoon mean duration and strength depend on the details of the emission scenario;
- Confidence in monsoon projections is also limited by how well the climate models simulate the detailed seasonal evolution of the monsoons.

Extreme events and confidence in projected changes

- Higher maximum temperatures and more hot days over nearly all land areas – very likely (90-99% chance);
- Higher minimum temperatures, fewer cold days and frost days over nearly all land areas – very likely (90-99% chance);
- Reduced diurnal temperature range over most land areas – very likely (90-99% chance);
- Increase of heat index over most land areas – very likely (90-99% chance);
- More intense precipitation events over many areas – very likely (90-99% chance);
- Increased summer continental drying and associated risk of drought – likely (66-90% chance);

Extreme events and confidence in projected changes (cont.)

- Increase in tropical cyclone peak wind intensities – likely (66-90% chance);
- Increase in tropical cyclone mean and peak precipitation intensities – likely (66-90% chance);
- Small scale phenomena, such as thunderstorms and tornadoes – current models cannot make confident projections.

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Long-term projections – beyond 2100

- Emissions of long-lived greenhouse gases (CO_2, N_2O, PFCs and SF_6) have a lasting effect on atmospheric composition, radiative forcing and climate;
- After greenhouse gas concentrations have stabilised, global average surface temperatures would rise at a rate of only a few tenths of a degree per century;
- Temperature increases and rising sea level from thermal expansion of the ocean will continue for hundreds of years after stabilisation of greenhouse gas concentrations;
- Ice sheets will continue to contribute to sea level rise for thousands of years after climate has been stabilised;
- Current ice dynamic models suggest that the West Antarctic ice sheets could contribute up to 3 metres to sea level rise over the next 1000 years (results strongly dependent on model assumptions).

Confidence in model projections

- Understanding of climate processes and their incorporation in climate models have improved, including: water vapour, sea-ice dynamics and ocean heat transport;
- Some models produce satisfactory simulations of current climate without the need for non-physical adjustments of heat and water fluxes at the ocean-atmosphere interface;
- Simulations that include natural and anthropogenic forcing reproduce the observed large-scale changes in surface temperature over the 20th century;
- Some aspects of model simulation of ENSO, monsoons and the North Atlantic Oscillations, as well as selected periods of past climate, have improved;

Confidence in model projections (cont.)

- Models cannot simulate some aspects of climate, eg:
  - cannot account fully for the observed trend in the surface-troposphere temperature difference since 1979;
  - there are particular uncertainties associated with clouds and their interaction with radiation and aerosols.

Attribution

There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities:

- The warming over the past 100 years is very unlikely (1-10% chance) to be due to internal variability alone;
- Reconstructions of climate data for the past 1,000 years also indicate that this warming was unusual and is unlikely (10-33% chance) to be entirely natural in origin;
- Detection and attribution studies consistently find evidence for an anthropogenic signal in the climate record of the last 35 to 50 years;
- Simulations of the response to natural forcing alone do not explain the warming in the second half of the 20th century;

Attribution (cont.)

- The warming over the last 50 years due to anthropogenic greenhouse gases can be identified despite uncertainties in forcing due to anthropogenic sulphate aerosol and natural factors (volcanoes and solar irradiance);
- The estimated rate and magnitude of warming in the models due to increasing concentrations of greenhouse gases alone are comparable with, or larger than, the observed warming;
- The best agreement between model simulation and observations over the last 140 years has been found when all the above anthropogenic and natural forcing factors are combined.

FUTURE WORK

- Further research is required to improve the ability to:
  - detect, attribute and understand climate change;
  - reduce uncertainties;
  - project future climate changes.
- In particular:
  - systematic observations and reconstructions;
  - modelling and process studies.

Systematic observations and reconstructions

- Reverse the decline of observational networks in many parts of the world;
- Sustain and expand the observational foundation for climate studies by providing accurate, long-term, consistent data;
- Implementation of a strategy for integrated global observations;
- Enhance the development of reconstructions of past climate periods;
- Improve the observations of the spatial distribution of greenhouse gases and aerosols.

Modelling and process studies

- Improve understanding of the mechanisms and factors leading to changes in radiative forcing;
- Understand and characterise the important unresolved processes and feedbacks, both physical and biogeochemical, in the climate system;
- Improve methods to quantify uncertainties of climate projections and scenarios, including long-term simulations using complex models;
- Improve the integrated hierarchy of global and regional climate models with a focus on the simulation of climate variability, regional climate changes and extreme events;
- Link more effectively models of the physical climate and the biogeochemical system, and in turn improve coupling with descriptions of human activities.