Climate change

Scientific basis
October 2015

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Compiled by the A.T. Kearney Energy Transition Institute

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About the FactBook – Climate Change

This FactBook was prepared ahead of the COP 21 meeting held in Paris in December 2015. It document aims to make accessible to a wide audience the key scientific aspects of climate change. The report defines the core scientific concepts relating to climate change and presents evidence for past and recent changes in the Earth's climate. It also collates peer-reviewed content covering the attribution of observed changes, the projections made by the most recent climate models, and their potential consequences.

About the A.T. Kearney Energy Transition Institute

The A.T. Kearney Energy Transition Institute is a nonprofit organization. It provides leading insights on global trends in energy transition, technologies, and strategic implications for private sector businesses and public sector institutions. The Institute is dedicated to combining objective technological insights with economical perspectives to define the consequences and opportunities for decision makers in a rapidly changing energy landscape. The independence of the Institute fosters unbiased primary insights and the ability to co-create new ideas with interested sponsors and relevant stakeholders.

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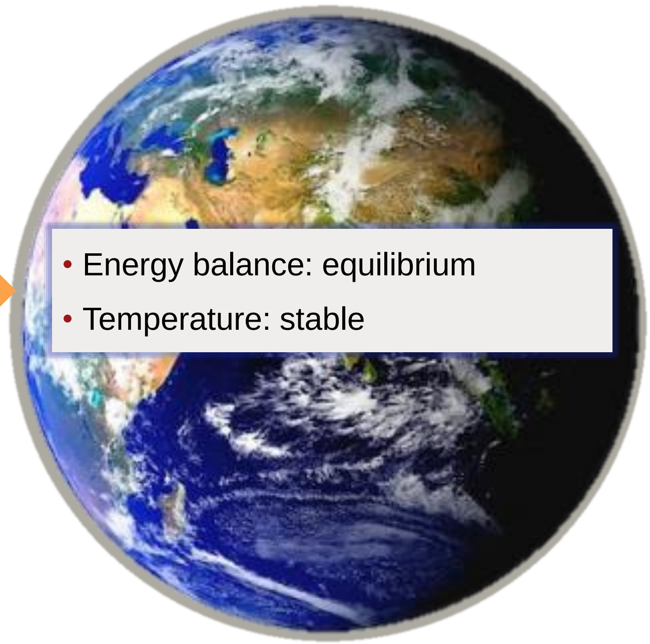
Earth's energy budget viewed from the top of the atmosphere

Incoming solar radiation[1]



Emitted heat radiation[3]
= Incoming radiation

1 **Initial equilibrium state**[2]
- ✓ Incoming and outgoing fluxes balanced
- ✓ Global average surface temperature stable

Greenhouse gases

1. Omitting solar radiation reflected before entering into the atmosphere; 2. In reality, the Earth's energy balance is never in perfect equilibrium because of internal variations: oceans and atmosphere are actively moving energy around the globe, temporarily storing more or less energy and changing global mean temperatures; 3. Emitted radiation is of similar intensity to incoming radiation (in W/m²), but differs in other respects (lower wavelengths, mostly invisible infrareds).
2. Source: A.T. Kearney Energy Transition Institute analysis

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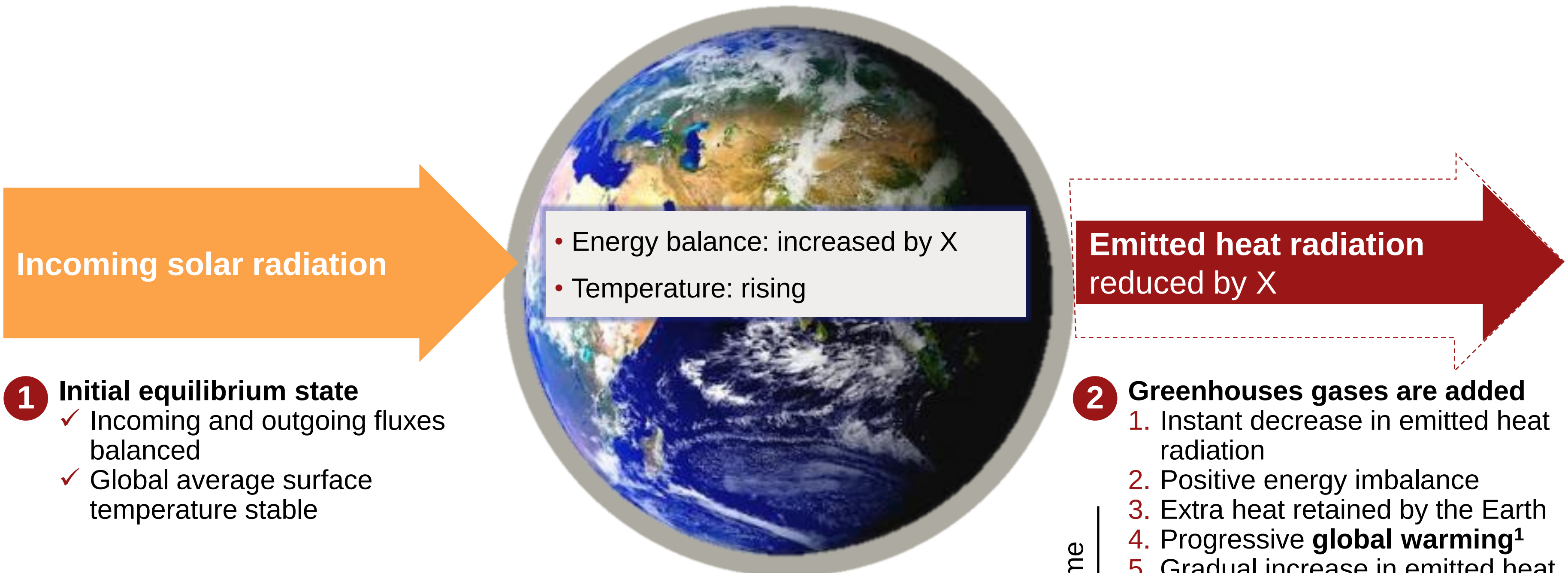
What is the greenhouse effect? (2/3)

Earth’s energy budget viewed from the top of the atmosphere



1 Initial equilibrium state

- ✓ Incoming and outgoing fluxes balanced
- ✓ Global average surface temperature stable

2 Greenhouses gases are added

time

1. Instant decrease in emitted heat radiation
2. Positive energy imbalance
3. Extra heat retained by the Earth
4. Progressive **global warming**[1]
5. Gradual increase in emitted heat radiation

Greenhouse gases

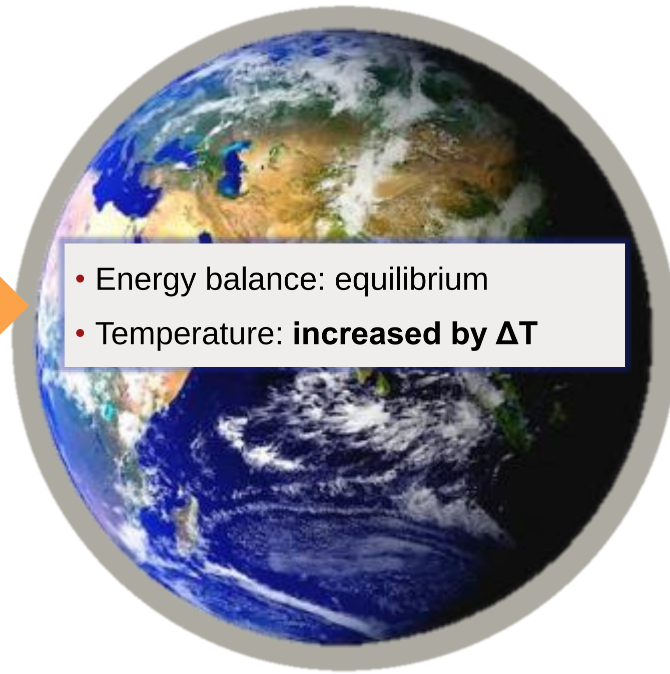
1. Global warming refers to the increase in global average surface temperature, measured over a period of at least 30 years. The atmosphere may warm differently at different altitudes, but it is at the surface that changes have the most direct impacts on people and ecosystems.

Source: A.T. Kearney Energy Transition Institute analysis

What is the greenhouse effect? (3/3)

Earth's energy budget viewed from the top of the atmosphere

Incoming solar radiation
(~340 W/m²)



Emitted heat radiation
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1 Initial equilibrium state
- ✓ Incoming and outgoing fluxes balanced
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2 Greenhouses gases are added

time

1. Instant decrease in emitted heat radiation
2. Positive energy imbalance
3. Extra heat retained by the Earth
4. Progressive global warming
5. Gradual increase in emitted heat radiation

3 New equilibrium reached
- ✓ Stabilization takes several centuries (climate lag)
- ✓ Energy balance back to equilibrium
- ✓ New average temperature (increased by ΔT)
- ✓ Induced **climate change**[1]

Greenhouse gases

1. Climate change refers to a significant change in the statistical distribution of weather patterns over a sustained period, of at least 20-30 years.
Source: A.T. Kearney Energy Transition Institute analysis

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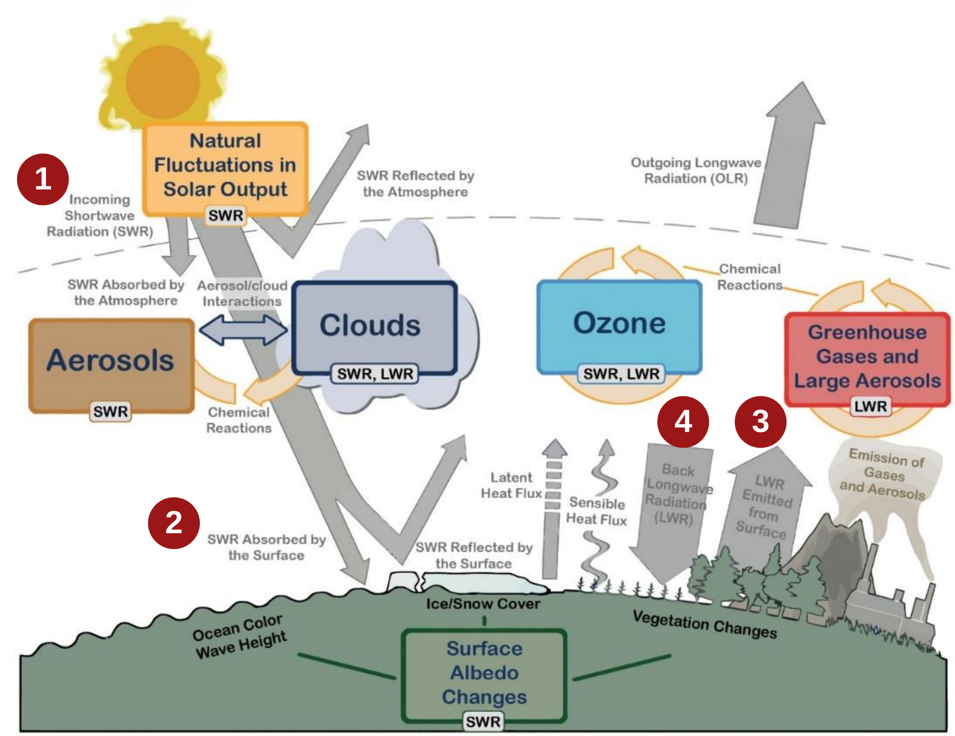
The Earth's energy balance is influenced by the intensity of solar radiation and the properties of its atmosphere, surface and oceans

Earth's energy balance at equilibrium

Energy flux, (W/m2)



How to read this graph

1. Incoming solar radiation (shortwave radiation, SWR) is partially reflected by the atmosphere and the surface.
2. The remaining radiation is absorbed and heats the surface (continents, oceans and troposphere - the lower part of the atmosphere).
3. The warm Earth emits infrared radiation upward (longwave radiation, LWR). The intensity of this LWR depends on how atmospheric & oceanic circulation move this absorbed heat about.
4. 90% of the upwardly directed LWR is absorbed by GHGs and radiated back downwards, limiting the ability of the surface to cool. Without GHGs or any albedo1, Earth would be about 15°C cooler.

1. Albedo: the fraction of solar radiation reflected by a surface or object, often expressed as percentage
Source: Picture adapted from IPCC (2013), "AR5-WGI"

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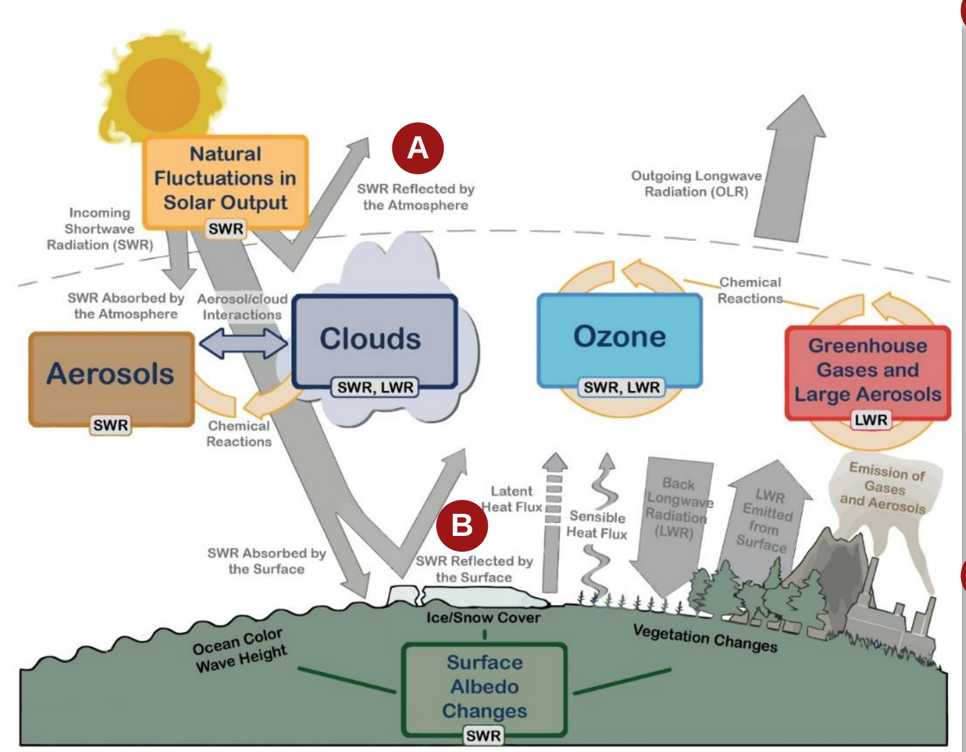
On the one hand, clouds, aerosols and the surface partially reflect incoming solar radiation and contribute to cooling the Earth

Earth's energy balance at equilibrium

Energy flux, (W/m2)



A Atmospheric albedo

About 30% of solar radiation is reflected back into space before it can heat the Earth's surface.

- **The amount of cloud** cover and its reflectivity are influenced primarily by humidity and atmospheric circulation, which can be affected by human-induced climate change.
- **Aerosols** reflect sunlight and generally have a cooling effect. They also greatly influence cloud albedo. Aerosols are small particles in suspension in the air resulting from fossil-fuel combustion, and natural volcano eruptions, dust and sea salt.
- **Black carbon** (smoke, industrial ash, soot) is a dark aerosol with a warming effect.

B Surface albedo

- **Forest, fields and deserts areas** are either darker or clearer than average, influencing surface albedo
- **Snow/ice** reflects light. The surface it covers is indirectly influenced by human activity through climate change

Source: Picture adapted from IPCC (2013), "AR5-WGI"

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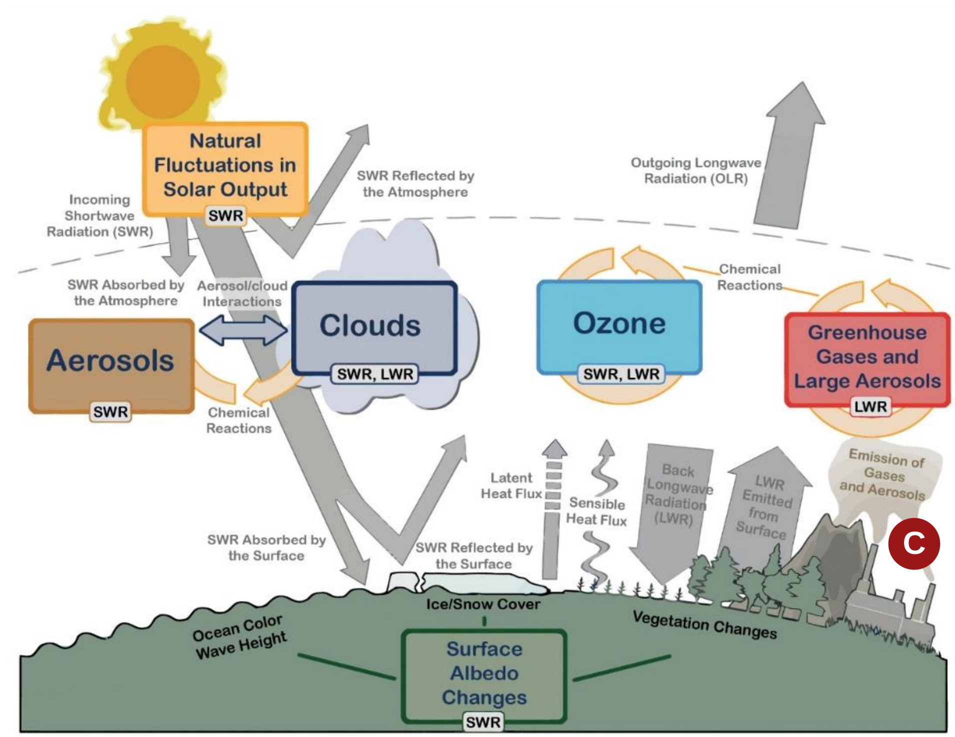
On the other hand, greenhouse gases (GHGs) partially retain emitted infrared radiation in the lower atmosphere and contribute to warming the surface

Earth's energy balance at equilibrium - Energy flux, (W/m2)



C **Greenhouse gases**

Directly emitted by human activities

- **Carbon dioxide (CO_2)**: results from the natural atmospheric carbon cycle (photosynthesis, respiration, ocean absorption…), hydrocarbon combustion, deforestation…
- **Methane (CH_4)**: naturally present in the atmosphere, its concentration is also influenced by human activity (agriculture, waste, fossil-fuel exploration, natural-gas transport and use…).
- **Nitrous oxide (N_2O)**: mostly from the use of fertilizers.
- **Fluorinated gas (F-gas)**: mostly from the use of refrigeration, etc…
- **Enablers**: CO and NOx emitted from incomplete combustion are not GHGs but indirectly raise GHG atmospheric concentration

Not directly emitted by human activities

- **Tropospheric Ozone (O_3)**: results from natural and human-emitted unburned hydrocarbons
- **Water vapor[1] (H_2O)**: the dominant GHG, naturally present in the lower atmosphere in very large quantities. Its concentration increases exponentially with temperature

Source: Picture adapted from IPCC (2013), "AR5-WGI"

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Global warming potential and CO_2-equivalence are used to compare the potential warming influence of emissions of the same mass of different greenhouse gases

Global warming potential (GWP)

- Global warming potential (GWP) compares the warming effect of a given mass of GHGs to the same mass of CO_2 over a specified time
- Because GHGs do not have the same lifetime in the atmosphere, the GWP depends on the time-horizon chosen

Gas name	Chemical formula	Half-life[1] (years)	Global warming potential (GWP) for given time horizon	
			20-yr	100-yr
Carbon dioxide	CO_2	100-1,000 years[2]	**1** (by definition)	**1** (by definition)
Methane	CH_4	12.4	~80	~30
Nitrous oxide	N_2O	121	~270	~300
Tetrafluoro-methane	CF_4	50,000	~5,000	~7,000

Co₂-equivalence (co₂e)

- The instantaneous warming effect of a given concentration of a GHG is measured by its radiative forcing3 (in W/m²)
- CO2e is a quantity that describes, for a given GHG, the amount of CO2 that would have the same GWP over a given period. For instance, comparing CO_2 and CH_4 emissions in CO2e-100yr shows the relative **cumulated warming effect** of each gas over 100 years.
- Almost all policymakers and most scientific studies use a 100-year horizon, which has become the tacit convention. However, as indicated by the IPCC, "there is no scientific argument for selecting 100 years compared with other choices. The choice of time horizon is a value judgement because it depends on the relative weight assigned to the effects at different times".
- A GWP of 100 years should be used to emphasize the effects of long-lived GHGs such as CO2 on long-term processes such as temperature or sea-level rises;
- A shorter-duration GWP (e.g. 20 years) should be used to emphasize the effects of short-lived GHGs such as CH4 on short-term processes, when the process's rate of change is of greater interest than its eventual magnitude, or if imminent and potentially non-linear climate impacts were to be regarded as more pressing climate concerns.

1. Half-life defines the period of time it takes for the amount of a substance undergoing decay to decrease by half. 2 CO2 lifetime in the atmosphere is a complex issue, which depends on the dynamics of carbon cycles and is not known with precision. 3 The net change in Earth energy balance induced by the GHG concentration in the atmosphere. Refer to slide 12.
2. Source: IPCC (2013), "AR5-WGIII, Table 8.7"

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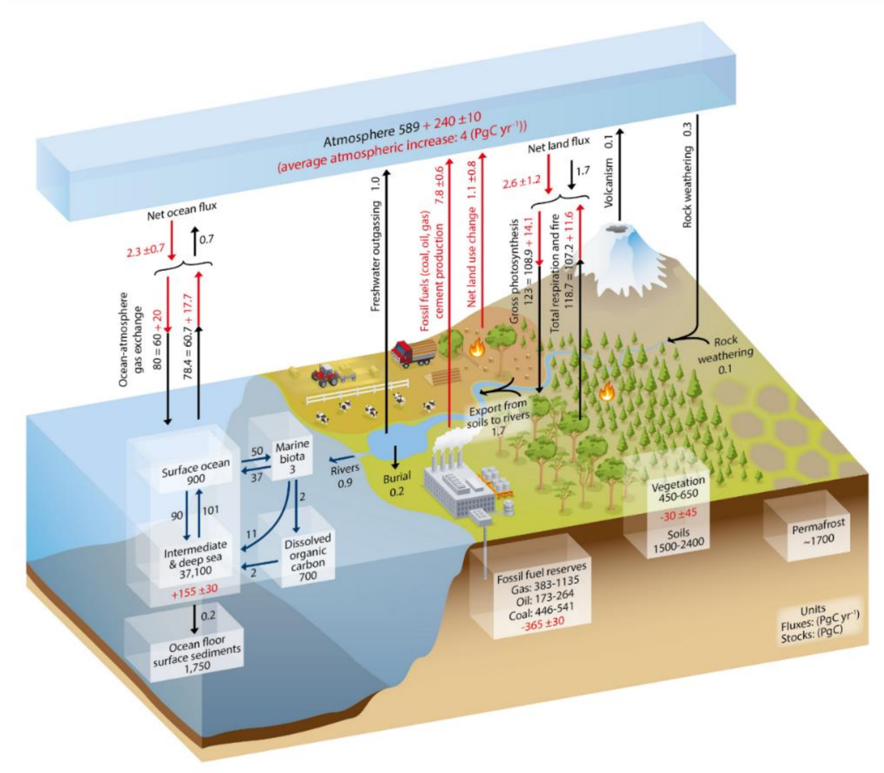
Earth's carbon is stored in various reservoirs (atmosphere, oceans, fossil fuels...), interconnected through the biogeochemical carbon cycle

Global Biogeochemical carbon cycle



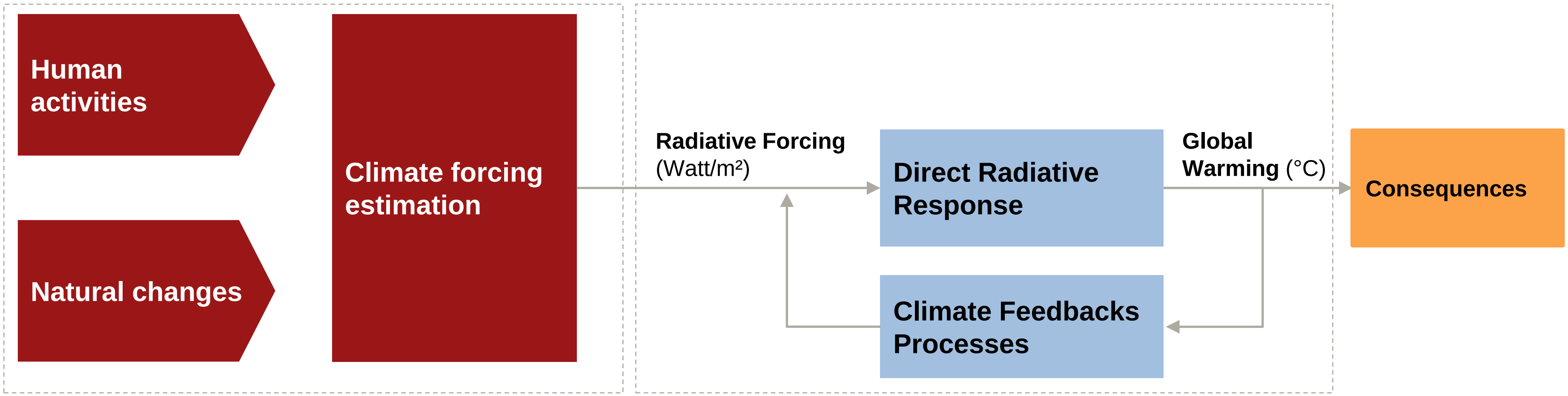
- The global carbon cycle can be represented as a series of carbon reservoirs in the Earth system, connected to one another by carbon fluxes. Two distinct domains exist:
  - The "fast domain", which consists of carbon in the atmosphere, oceans and land vegetation, with fast exchanges (~200 PgC/year with the atmosphere) and rapid reservoir turnover (from decade to millennia);
  - The "slow domain", which consists of huge carbon reserves in rocks and sediments, only naturally exchanging carbon with the fast domain through volcanic events and other erosion or sedimentation phenomena, at much slower speeds (~0.2 PgC/year, turnover ~10,000 years).
- Prior to the industrial revolution, the fast domain was close to a steady state: In the atmospheric reservoir, where carbon atoms are arranged mainly in the form of CO2 and CH4 greenhouse gases, carbon fluxes were balanced and GHG concentrations approximately constant (see section 2).
- Since the beginning of the industrial era, fossil-fuel extraction has resulted in the transfer of a significant amount of carbon from the slow domain to the fast domain (7.8 PgC/year today), altering carbon budgets and fluxes in the fast domain

1. Black arrows: Annual carbon fluxes (PgC/year) prior to the industrial era; Red arrows: Additional anthropogenic carbon fluxes averaged over the 2000-2009 period; Black numbers in boxes: Carbon reservoirs mass (PgC) prior to the industrial era; Red numbers: Additional anthropogenic change in carbon stock over the 1750-2011 period.
   One PgC (petagramme of carbon) equals one billion tonne of carbon (GtC). 1 g of carbon is contained within 3.67 g of CO2.

Source: IPCC (2013), "AR5-WGI, section 6.1"

Changes in climate are triggered by climate forcings

Conceptual diagram of Climate models & key scientific vocabulary



1 Climate forcings

- Climate forcings are the initial drivers of climate change.
- Expressed as a change in **radiative forcing**[1] (W/m²): the net change in Earth energy balance in immediate response to this perturbation.
- Positive radiative forcings have a warming effect (e.g., an increase in CO_2 concentration).
- Negative radiative forcings have a cooling effect (e.g., volcanic eruptions).

2 Climate response

- This function defines how much warming will result from a given radiative forcing, after a given time. The climate response is determined by:
  - **Climate sensitivity**[2]**:** the total amount of warming per unit of forcing, once the system has returned to equilibrium (in °C per W/m²). This is a measure of how responsive the temperature of the Earth is to radiative forcing.
  - **Climate lag:** the time taken (in years) for the temperature to reach this equilibrium.
  - **Climate feedbacks:** internal processes that amplify or moderate the direct radiative response to climate forcings. Positive feedbacks amplify this response, while negative feedbacks moderate it.

1. Throughout this report, radiative forcing will refer to the concept of effective radiative forcing (ERF), an adjusted value better taking into account fast-acting feedbacks, which are directly linked to the emitted compound, rather than a result of an increase in Earth's temperature. This distinction is mostly relevant for forcing caused by Aerosol-Cloud interactions. 2 The technical scientific terminology is equilibrium climate sensitivity (ECS), often referred to only as "sensitivity".

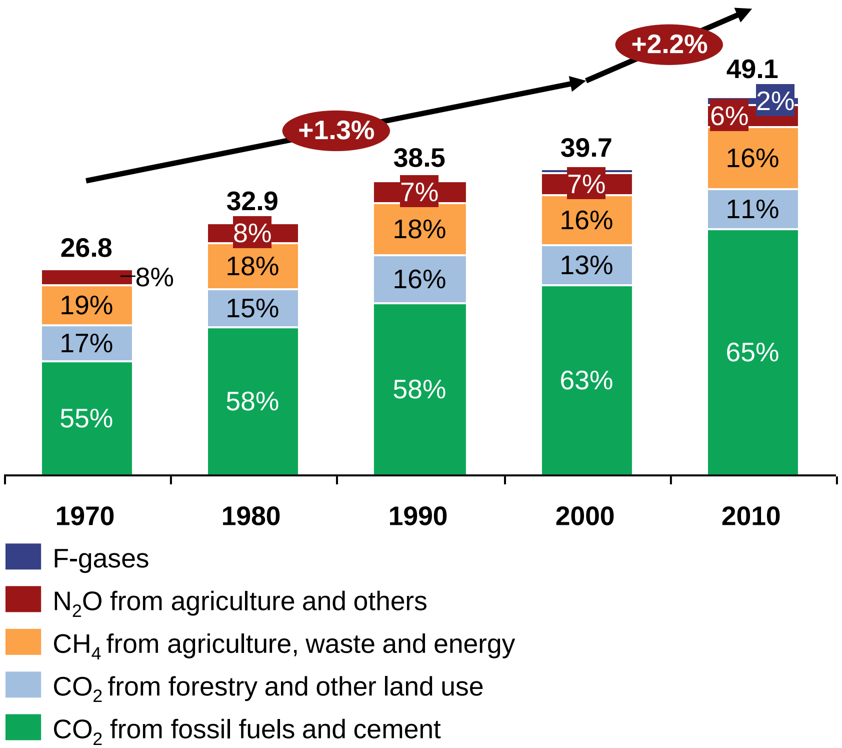
Source: A.T. Kearney Energy Transition Institute analysis

2. Past and recent climate changes

Increases in anthropogenic GHG emissions and atmospheric concentrations since the Industrial Revolution are well established

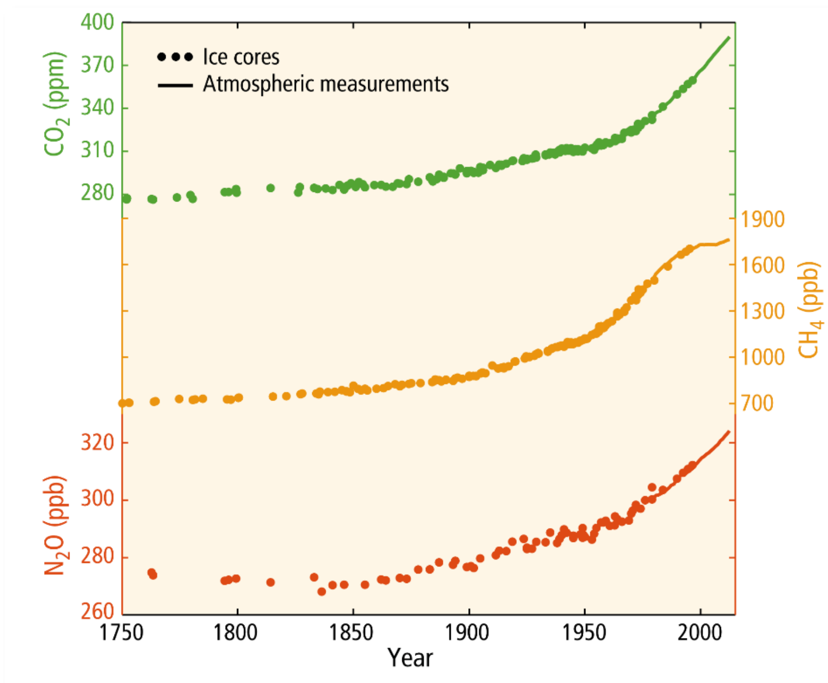
Human GHG Emissions by Activity[1]

Gigatonne of CO_2-e per year, and % of total emissions



Atmospheric concentration of GHGs

Parts per billion (ppb), parts per million (ppm)



1. CO_2 equivalent over 100 years. The observed acceleration in CO_2 emissions in the 2000-2010 decade is mostly due to an acceleration in coal-based electricity production.

Source: IPCC (2013), "AR5-WGIII"; IPCC (2014) "AR5-SYR"

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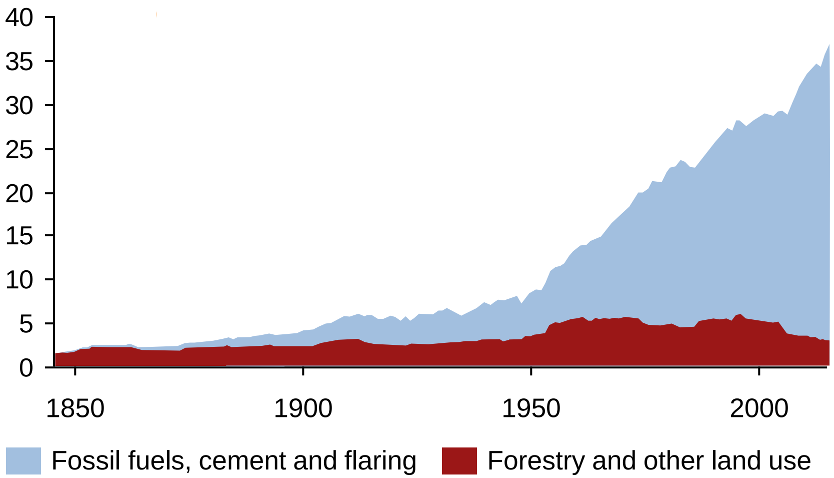
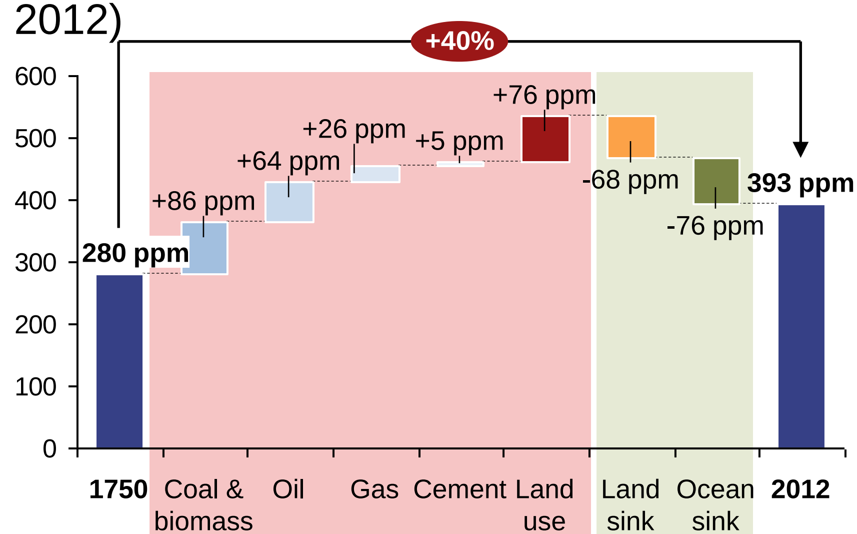
Anthropogenic CO2, in particular, has been building up in the atmosphere, despite being partially stored by ocean and land sinks

Global Anthropogenic CO_2 emissions by primary source (1850-2011)



- CO_2 emissions have increased exponentially since the beginning of the Industrial Revolution: about half of the 2040 ± 310 $GtCO_2$ emitted between 1750 and 2011 have occurred in the past 40 years.
- Fossil-fuel combustion is the main activity responsible for anthropogenic CO_2 emissions.

Changes in Global CO_2 Atmospheric concentration by source and sink (1750-2012)



- About 60% of anthropogenic CO_2 emissions since 1750 have been removed from the atmosphere and stored on land (in plants and soil), or dissolved into the ocean (contributing to acidification). Refer to slide 11 for more details about natural carbon-cycle reservoirs.
- The remaining CO_2 has led to a 40% increase in atmospheric concentration since the Industrial Revolution.

Biogeochemical models and direct observations of ocean acidity have been used to estimate ocean sink. Land sink has been calculated as the residual differences between sources and sinks.
Source: (Left) IPCC (2014), “Climate Change 2014: Synthesis Report”. (Right) Shrinkthatfootprint “Global carbon emissions and sinks since 1750” based on IPCC (2007) “AR5-WGI” and CDIAC “Global Carbon Budget”

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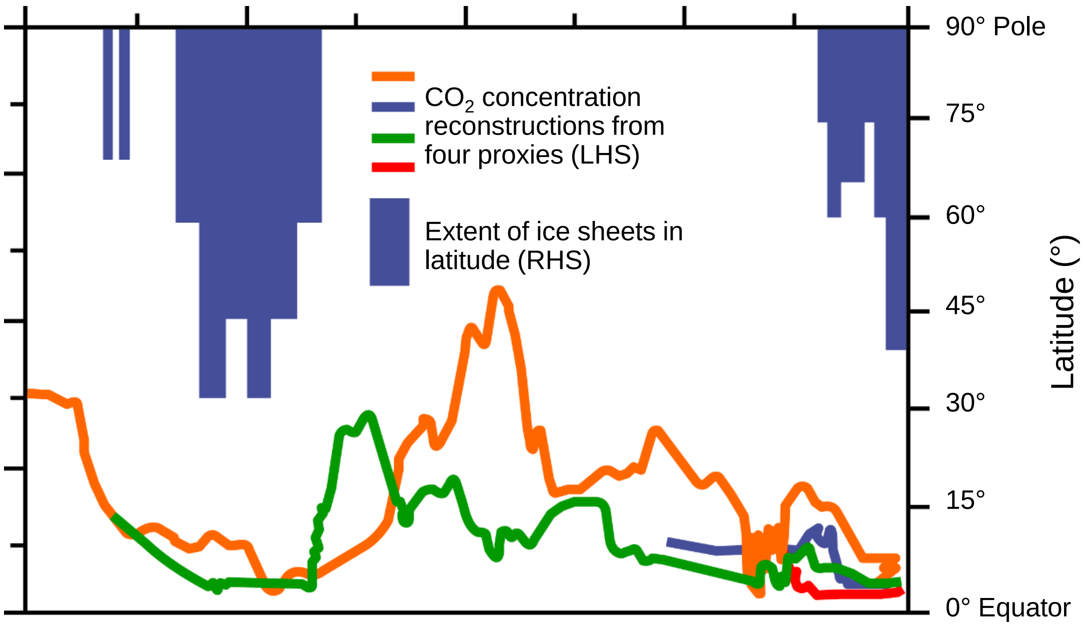
While the Earth has remained predominantly ice-free over the course of its history, we are currently in a major glaciation period, which started 40 million years ago

Atmospheric CO_2 concentrations (LHS) and continental glaciation (RHS) **Over the last 400 million years** (Horizontal scale)

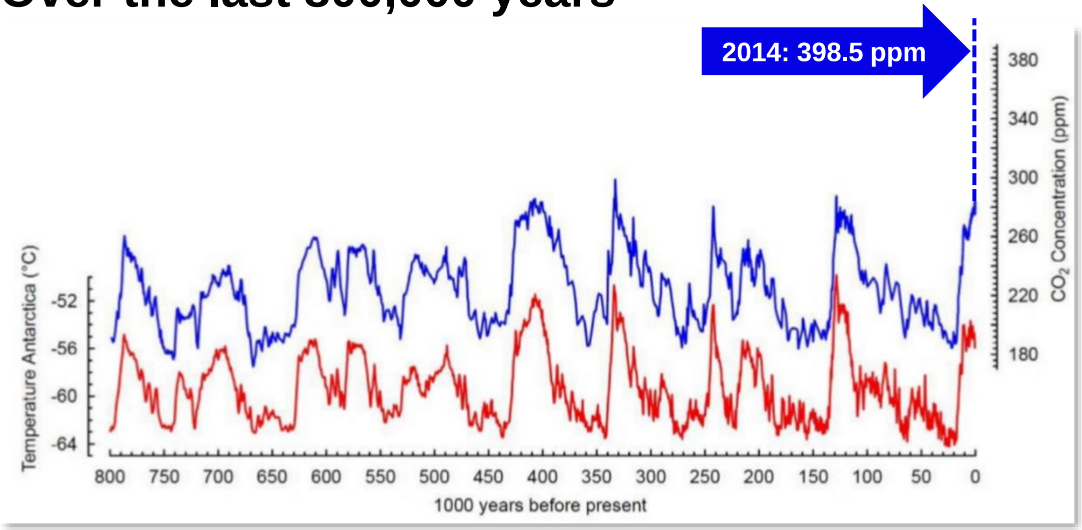


- This graph plots various CO_2 concentration reconstructions (colored lines) and the extent of ice sheets in latitude (blue bars) over the last 400 million years.
- Over the course of its history, the Earth has predominantly remained ice-free, indicating a much warmer climate, while **the magnitude of CO_2 concentration has generally greatly exceeded current values** (up to 4,000ppm).
- Two major glaciation periods have occurred in the last 400 million years, with ice covering the globe down to 40° latitude. Each time, **the magnitude of CO_2 concentration has been generally lower than during ice-free periods.**
- We are currently in a major glaciation period, which started 35-40 million years ago.

LHS: Left hand scale; RHS: Right hand scale.
Source: IPCC (2007), "AR4-WGI, section 6.1"

We entered an interglacial warm period 8,000 years ago, a naturally cyclical event that seems to have had correlated impacts on temperature and CO_2 concentrations over the past million years

Reconstruction of Atmospheric CO_2 concentrations and Antarctic Temperatures Over the last 800,000 years[1]



CO_2 concentration (right scale) — Antarctic temperature (left scale)

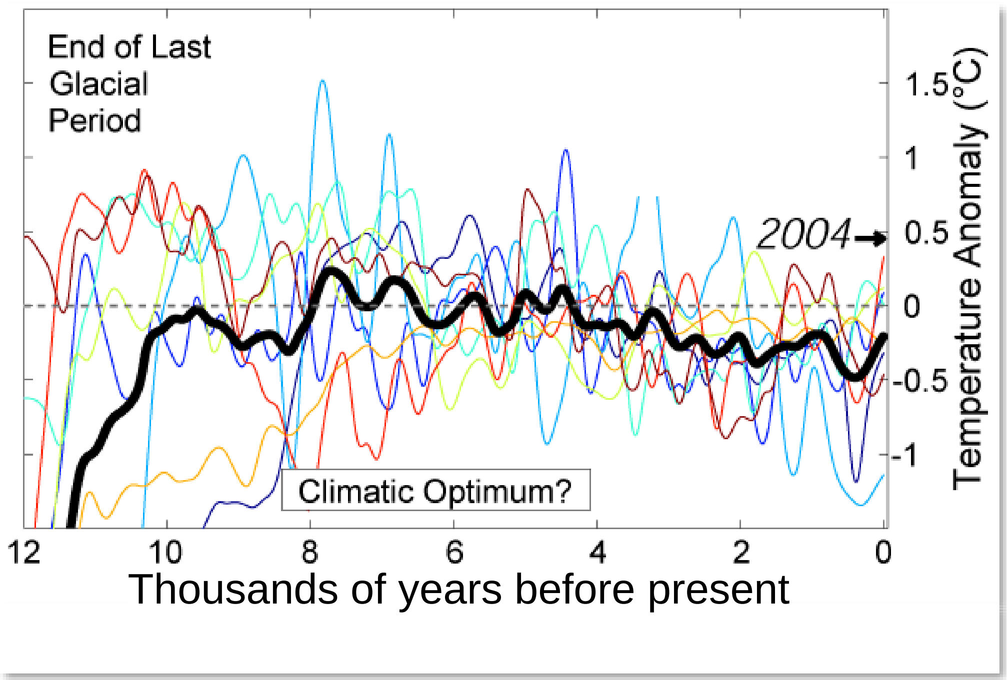
- Within the current major glaciation period, the past million years saw regular interglacial warm periods, initiated by natural variations in the Earth's orbit around the Sun (~100,000 year Milankovitch cycles[2]).
- During these cycles, Antarctic temperatures and variations in global CO_2 concentrations appear closely correlated.
- CO_2-concentration rises do not precede temperature rises:
  - Temperature rises are initiated by Milankovitch cycles.
  - Warmed oceans naturally release more dissolved CO_2 into the atmosphere, causing CO_2 concentrations to increase.
  - Induced greenhouse effect amplifies the initial warming as part of a positive feedback loop.
  - Overall, about 90% of the temperature rise is estimated to occur after the CO_2 increase[3].
- We are currently in an interglacial warm period that started ~8,000 years ago.
- CO_2 concentrations have increased rapidly since the Industrial Revolution and are now higher than at any time over the past million years.

1. The solid lines are reconstructions based on data from air bubbles contained in the Vostok ice cores – the oldest direct reconstruction of the Earth's climate. The dashed blue line indicates recent atmospheric measurements. 2. The Milankovitch theory describes the collective effects on the Earth's climate of cyclical changes in Earth's orbit around the Sun. For each cycle, it took an average 5,000 years for temperatures to rise by 4-7°C and for the global average CO2 concentrations to rise by ~80 ppm.

Source: Graph: adapted from IPCC (2007), "AR4-WGI"; 3. Shakun et al. (2012), "Global warming preceded by increasing carbon dioxide concentrations during the last deglaciation"

On a 8,000-year time horizon, the long-term cooling trend observed in the Northern Hemisphere has been reversed by the 20th century warming

Holocene Temperature Variations based on eight local temperature Reconstructions - Temperature anomaly (°C) relative to mid-20th century average



- There is no scientific consensus on how to reconstruct global temperature variations during the Holocene.
- Eight local temperature reconstructions (colored lines) vary within a ~3°C range in the last 8,000 years.
- The black line, which represents the average of these eight local-temperature reconstructions, should be interpreted only as a rough, quasi-global approximation of the temperature history of the Holocene.
- The slight cooling trend observed is likely a result of a changing precession of the Earth's orbit.
- The 2004 global average temperature data point has been added for comparison purposes.
- There is high confidence that warming since the 20th century has reversed long-term cooling trend of the past 5,000 years in mid-to-high latitudes of the Northern Hemisphere.[1]

Source: Graph: Adapted from Rohde (2010); 1 IPCC-WG1 (2013), "AR5-WGI"

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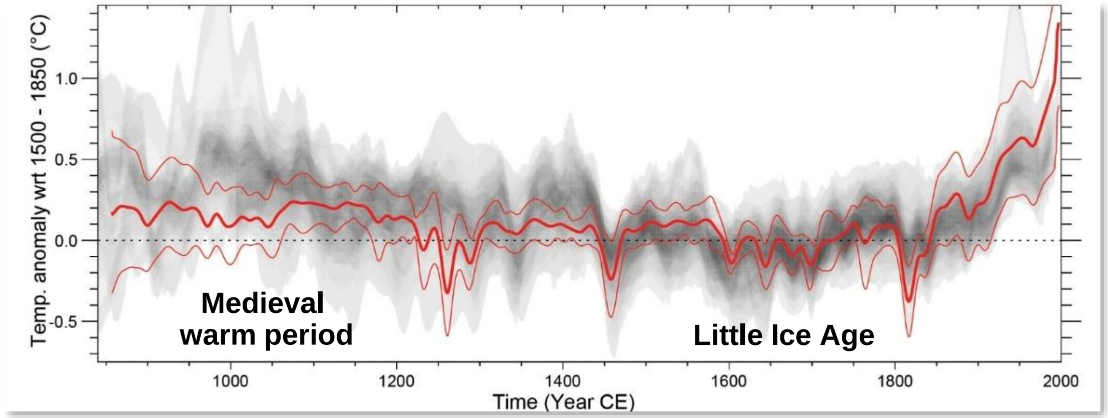
Temperatures are very likely warmer now than at any time in the past millennium, at least in the northern hemisphere

Northern hemisphere temperature reconstructions (Grey) and Simulated (Red)
Temperature anomaly (°C) relative to 1500-1850 average



- A dozen reconstructions of northern hemisphere temperature variations have been compared and overlapped (in grey).
- These reconstructions converge in darker zones, indicating where past temperatures are most likely to have really been.
- The red lines show the results of the latest climate-model simulations (mean in bold, and 90% confidence interval).
- The IPCC's Fifth Assessment Report (2013) concluded that, with a high degree of confidence, "the period 1983-2012 was very likely1 the warmest 30-year period of the last 800 years, and likely the warmest of the last 1,400 years".

1. Throughout this report, in keeping with IPCC terminology, "likely" means greater than a likelihood of 66%, "very likely" greater than 90%, "extremely likely" greater than 95%, and "virtually certain" greater than 99%.

Source: IPCC (2013), "AR5-WGI"

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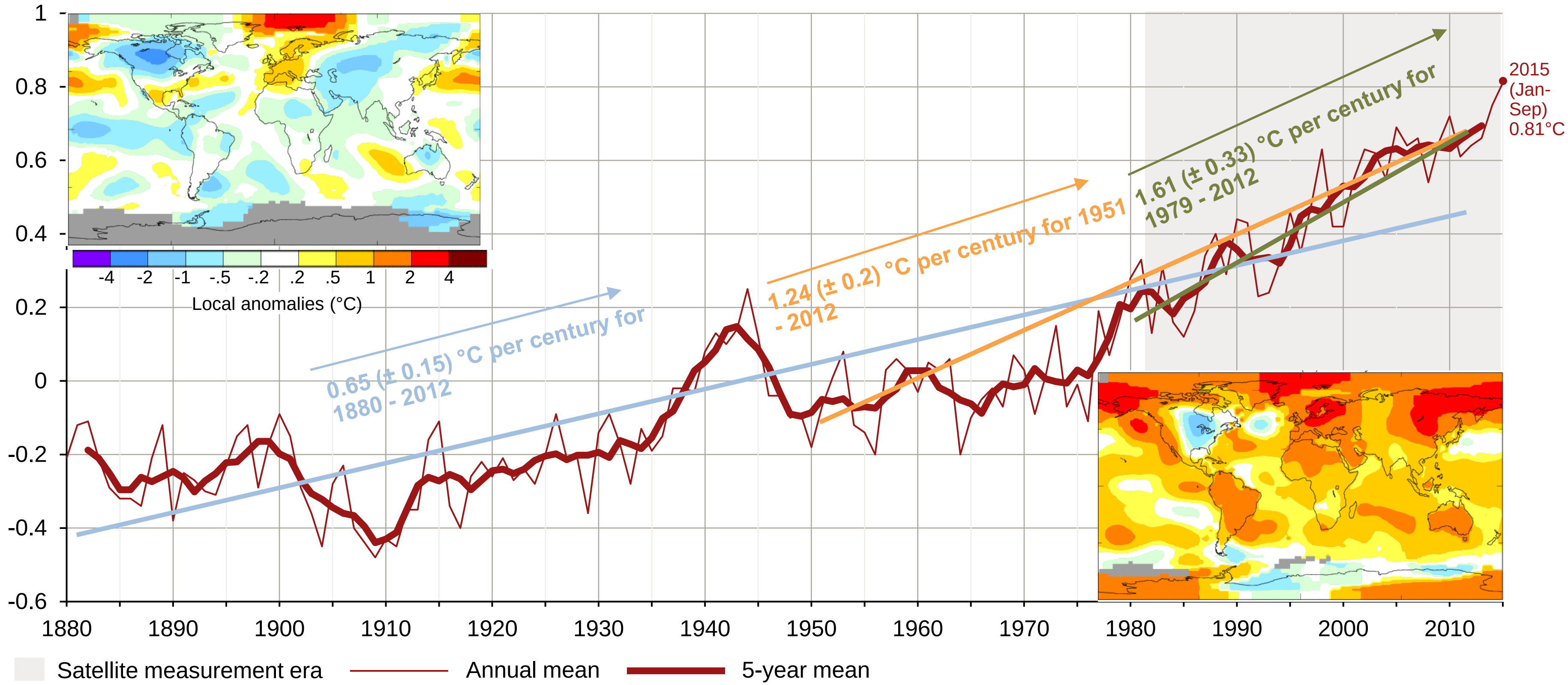
Since 1880, temperature records show an accelerating increase in the global average surface temperature

Measured changes in global mean surface temperature (GMST), land and sea combined - Anomalies relative to 1951-80 average (°C)

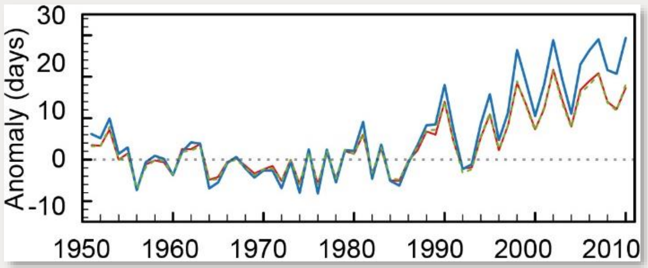


2015 data only covers Jan-Sep period. GMST is based monthly average series from local records (stations, balloons, ships, buoy etc…) potentially adjusted for errors, in addition to satellite data after 1980. Observed temperature increase is more pronounced during daylight (as opposed to night), in winter (vs. summers), and at the poles.
Source: NASA (2015) "GISS Surface Temperature Analysis (GISTEMP), Land-Ocean Temperature Index (LOTI)", accessed on October 16, 2015; based on NOAA GHCN v3 (meteorological stations), ERSST (ocean areas), and SCAR (Antarctic stations). Hansen et al. (2010) "Global surface temperature change".

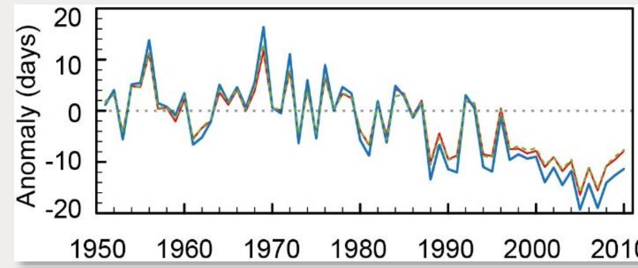
As a consequence, records indicate an increase in the frequency of extreme temperature events from 1970 onwards

Annual Frequency of Extreme Temperature Events[1] - 1950-2010

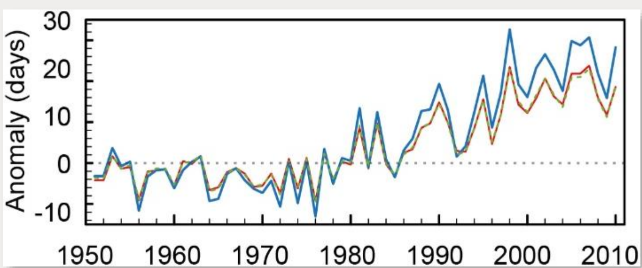
Warm days



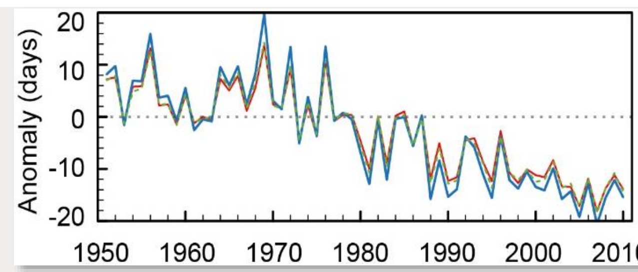
Cold days



Warm nights



Cold nights



- Widespread changes in extreme temperatures have been observed over the last 50 years: cold days, cold nights, and frost have become less frequent, while hot days, hot nights, and heat waves have become more frequent.
- However, there is less confidence that there have been discernible increases in other extreme weather events:
  - Increases in heavy precipitation have probably also occurred over the past 50 years, but vary by region.
  - There is a low degree of confidence that there has been an increase in drought or dryness globally.
  - There have been no discernible changes in the frequency of tropical cyclones, except in a small number of regions.

1. Near-global time series of annual anomalies with respect to 1961-1990 for three global indices data sets (three colored lines)

Source: IPCC (2013), "AR5-WGI, section 2.6.1"

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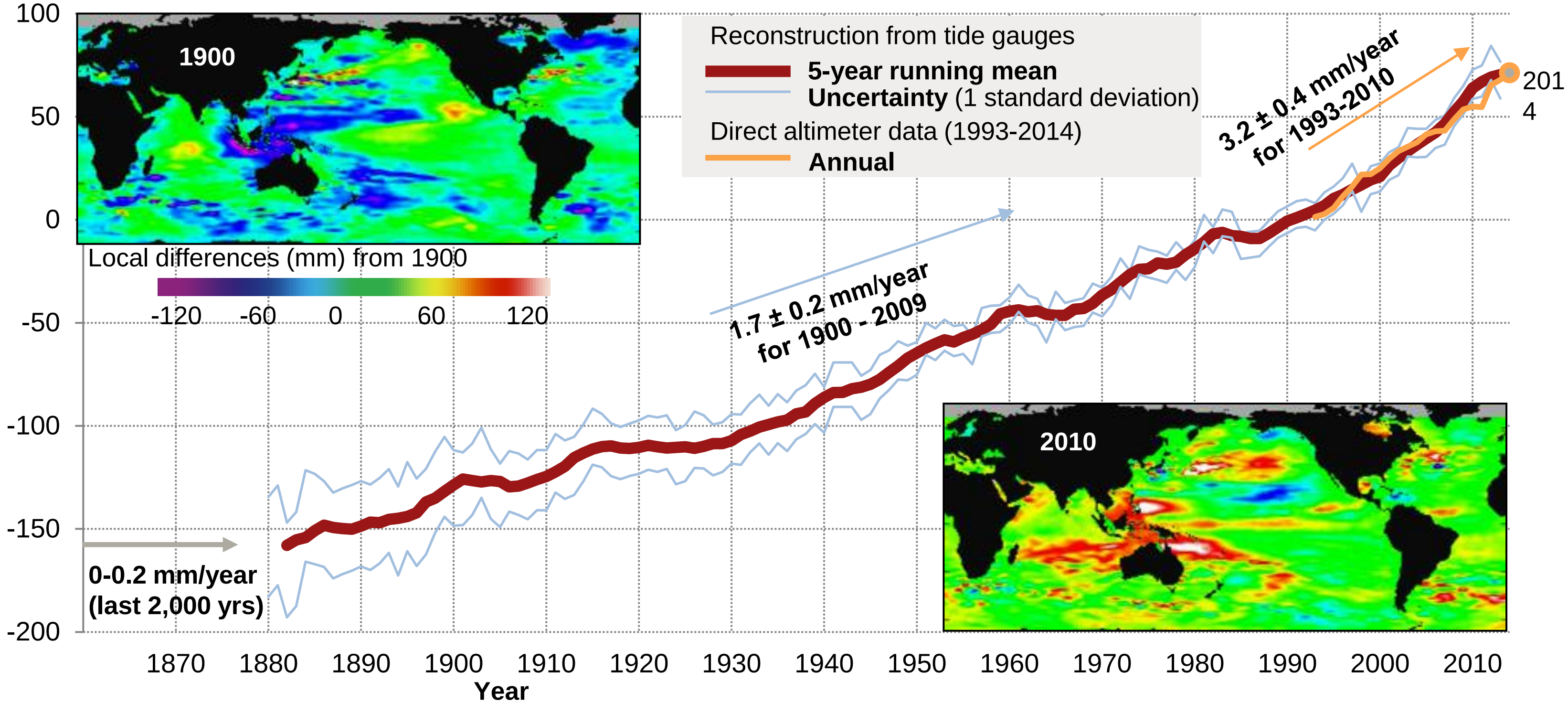
In parallel, global sea levels have been rising at an accelerating rate since 1880

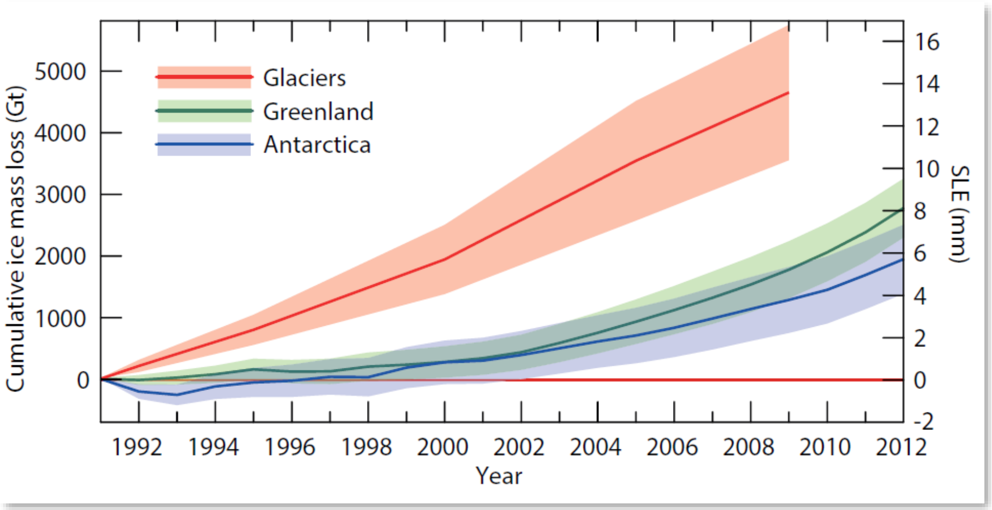
Measured changes in global mean sea level (GMSL)
Difference (mm) from 1990



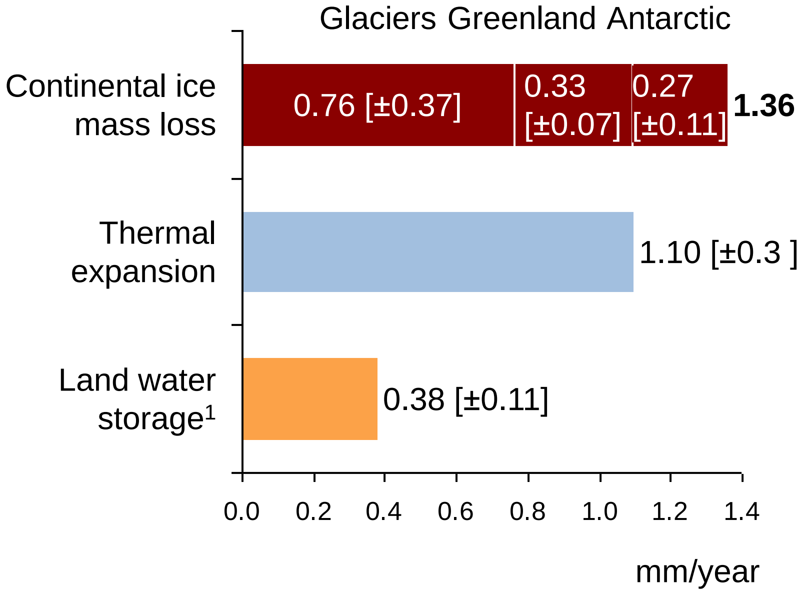
Note: GMSL is based on non-tidal sea-level measurements from local records (costal and island tide gauge) and, since January 1999, reliable satellite altimeter data. Results are adjusted for vertical land motion (recorded since late 1990s and extrapolated for past periods), and potential measurement errors or inhomogeneity.
Source: Church et al. (2011), "Sea-Level Rise from the Late 19th to the Early 21st Century". Dataset and satellite images are provided by CSIRO CMAR (accessed in 2015). Last 2,000 years rate: IPCC (2013), "AR5-WGI"

Half of this sea level rise is now due to continental ice melting into the ocean

Cumulated continental Ice mass loss (1991-2012)
Ice mass (Gt); and Sea Level Equivalent SLE (mm)



Observed contribution to global mean sea level rise for the 1993-2010 period
mm/year, [90% uncertainty range]



- Continental ice[2] (glaciers and polar ice sheets) are currently melting and losing mass.
- Over the past decade, this has contributed to roughly half the sea-level rise, the other half being mostly caused by the thermal expansion of the oceans, which have been warming up.
- Ice from glaciers has been the main contributor to sea-level rise so far, but the real threat comes from polar ice sheets, which have the largest remaining continental ice mass.

1. Includes accounting for changes (mostly reductions) in water stored in rivers, lakes, wetlands, groundwater aquifers, snow-pack, and reservoirs.
2. Sea ice melting has no effect on sea level.
Source: IPCC (2013), "WG1-AR5"

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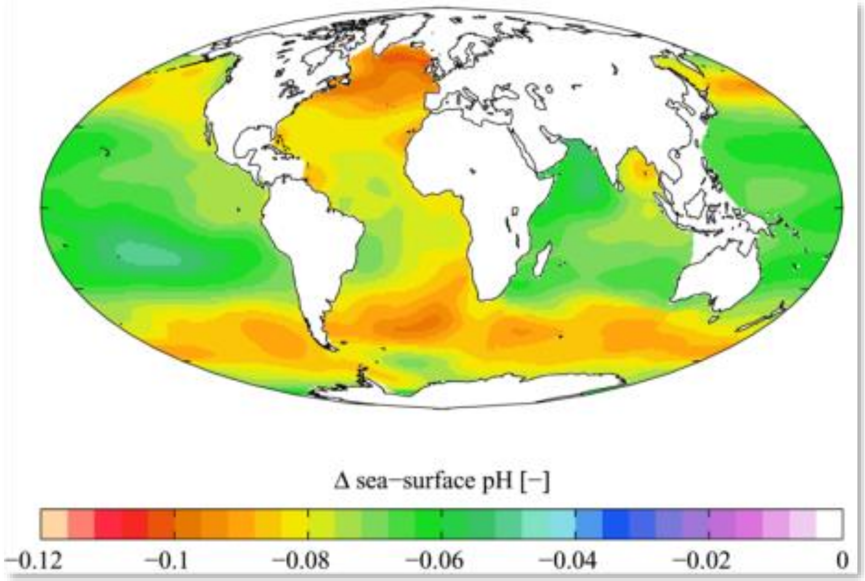
Another observed effect on the oceans has been a decrease in pH (tendency to acidification) as a result of increasing atmospheric concentration of CO_2

Change in annual mean sea surface ACIDITY between the pre-industrial period (1700s) and the present day (1990s)



- One-third of anthropogenic carbon dioxide emissions have been absorbed by the oceans, partially mitigating the greenhouse effect (refer to slide 15).
- The result is a degree of ocean acidification that stresses entire marine ecosystems, particularly reefs.
  - "*The pH[1] of ocean surface water has decreased by 0.1 since the beginning of the industrial era (high confidence), corresponding to a 26% increase in hydrogen ion concentration*" (IPCC, 2013)[2].
- The US National Oceanic and Atmospheric Administration (NOAA) now considers ocean acidification to be climate change's "*equally evil twin*"[3].

1. pH is a logarithmical measure of ocean acidity. A decrease in pH is associated with an increase in acidification.
Source: Graph: IPCC (2007), "AR4-WGI". 2 IPCC(2013), "AR5-WGI Summary for Policymaker". 3 Washington Post (9 July 2012), "US Official: Higher Ocean Acidity Is Climate Change's 'Evil Twin,' Major Threat to Coral Reefs".

3. Attribution of observed changes: climate forcings

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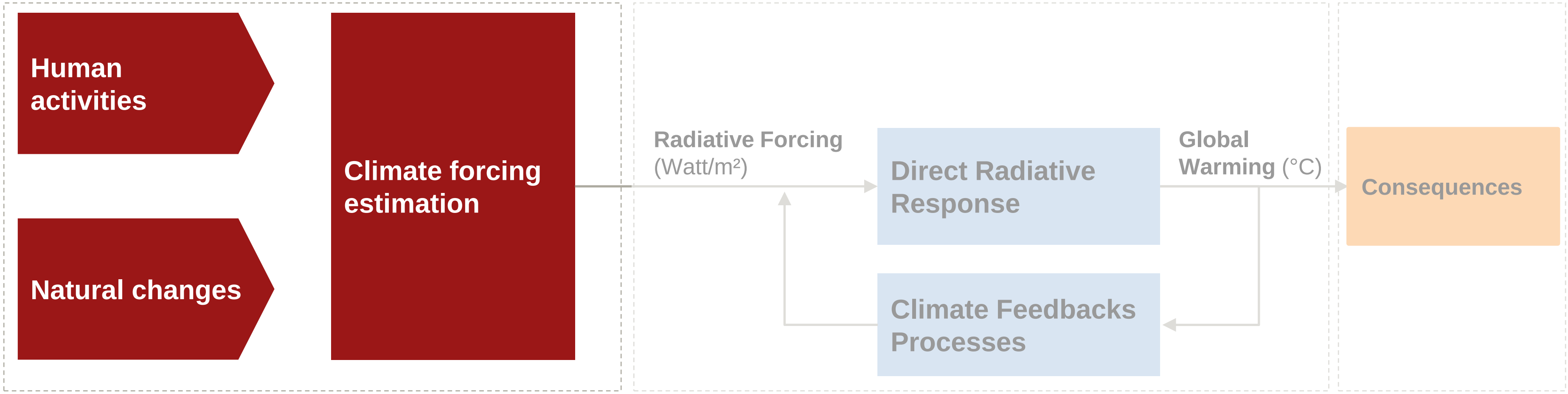
An analysis of the history of individual climate forcings since the Industrial Revolution enables scientists to attribute observed warming to specific causes

Conceptual Diagram of Climate models



1 Climate forcings
- Has forcing caused the Earth to accumulate energy?
- What forcing(s) has been responsible for this imbalance?

2 Climate sensitivity analysis
- How much and how fast will the Earth warm in response to a given radiative forcing?

3 Consequences
- What is the projected global warming in the 21st century?
- What will be the effects on climate, and the impacts on ecosystems and societies?

Source: A.T. Kearney Energy Transition Institute analysis

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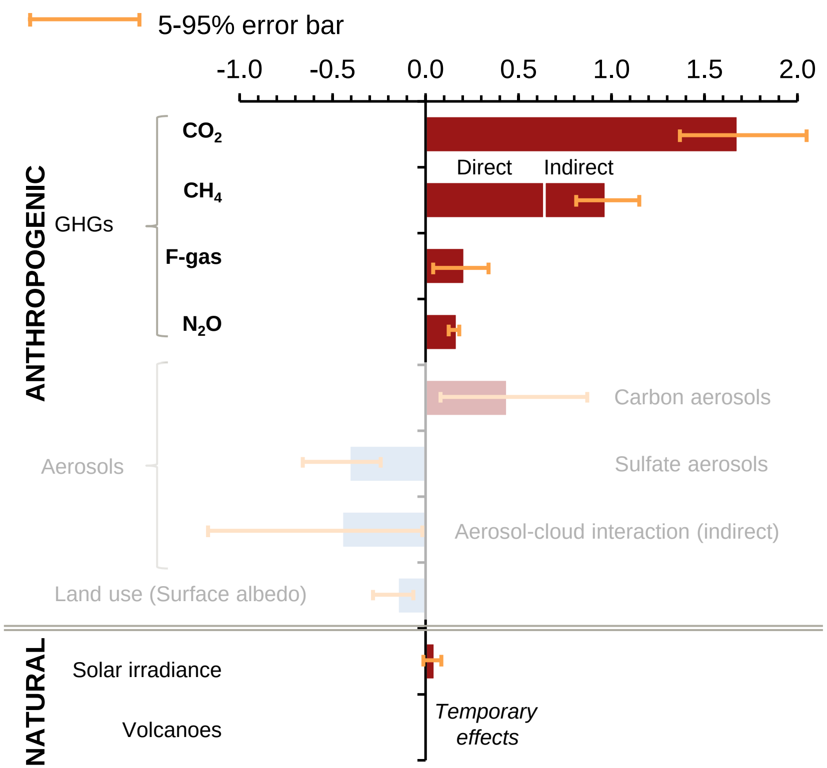
The main contributors are greenhouse gases, whose warming effects are well known, being a direct function of their atmospheric concentration

Major Climate forcing agents in the industrial area[1]

W/m² of radiative forcing in 2011, relative to 1750



Climate Forcings are the elements responsible for the observed change in the Earth's energy budget. This graph shows the strength of their warming effect (if positive) or cooling effect (if negative) today, when compared with the Earth's equilibrium state prior to the Industrial Revolution. They comprise both natural phenomena and anthropogenic emissions, which include the following GHGs:

- **CO_2** emissions since 1750 have built up in the atmosphere, even though ~60% has been removed by land and ocean sinks. The remaining concentration is now contributing to half of Bthe current human-caused warming. The warming effect is well understood and largely irreversible (several centuries).
- **CH_4** is the second-largest anthropogenic forcing currently influencing the climate. In addition to its well-known direct greenhouse effect, it is a precursor to ozone, water vapor and CO_2, thereby indirectly warming the Earth further, albeit in more uncertain amounts
- **F-gases** (halocarbons) have extremely high global-warming potential by mass and derive from industrial and domestic use (e.g., refrigeration). Most are to be phased out under the Montreal Protocol and will progressively disappear from the atmosphere within 100 years
- **N_2O** is a long-lived, powerful GHG and its concentration is steadily increasing, mostly due to intensive agriculture

1. The current radiative forcing of an atmospheric agent relative to 1750 expresses the change in the Earth's energy balance that would instantly follow the release of a quantity of that agent equal to that emitted since 1750, minus the amount removed via natural decay, oceans and land sinks over the same period.

Source: IPCC (2013), "AR5-WGI"

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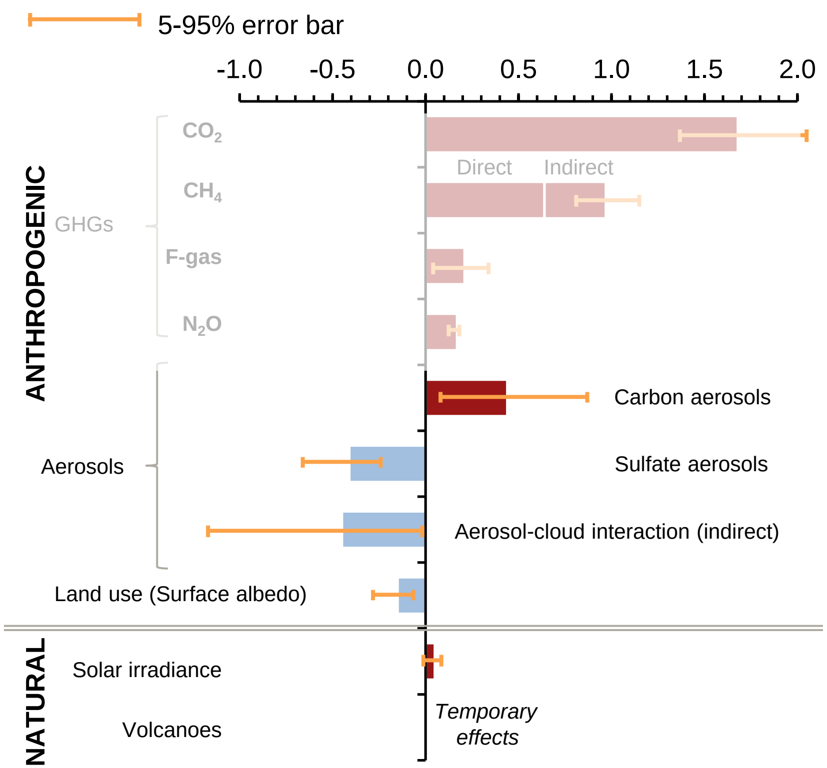
Aerosols emitted by human activities have both warming and cooling effects, and are the most uncertain climate forcings

Major Climate forcing agents in the industrial area[1]

W/m² of radiative forcing in 2011, relative to 1750



- **Carbon aerosols** consist of small carbon particles (such as soot), resulting from incomplete combustion of fossil fuels and biomass. They warm the atmosphere by absorbing solar radiation, and warm the surface by covering snow, which reduces its albedo. Because they have an atmospheric lifetime of only a few days, reducing their emissions now would rapidly reduce both near-term warming and local air pollution.
- **Sulfate aerosols** are emitted mostly by fossil-fuel power plants and volcanic eruptions. Their direct cooling effect is relatively well understood, acting as a veil in high altitude and shading sunlight. Uncertainty lies in the many different aerosol compositions distributed inhomogeneously around the planet.
- **Aerosol-cloud interactions** comprise the greatest uncertainty in climate modelling: aerosols affect the properties and formation of clouds, which can alter atmospheric motions and radiation transport. The net effect, although very likely to be cooling, depends on details such as the type and altitude of clouds affected.
- **Land-use** forcing refers to changes that modify surface albedo. Deforestation typically tends to increase sunlight reflection, and open areas tend to become covered by snow.

1. The current radiative forcing of an atmospheric agent relative to 1750 expresses the change in the Earth's energy balance that would instantly follow the release of a quantity of that agent equal to that emitted since 1750, minus the amount removed via natural decay, oceans and land sinks over the same period.

Source: IPCC (2013), "AR5-WGI"

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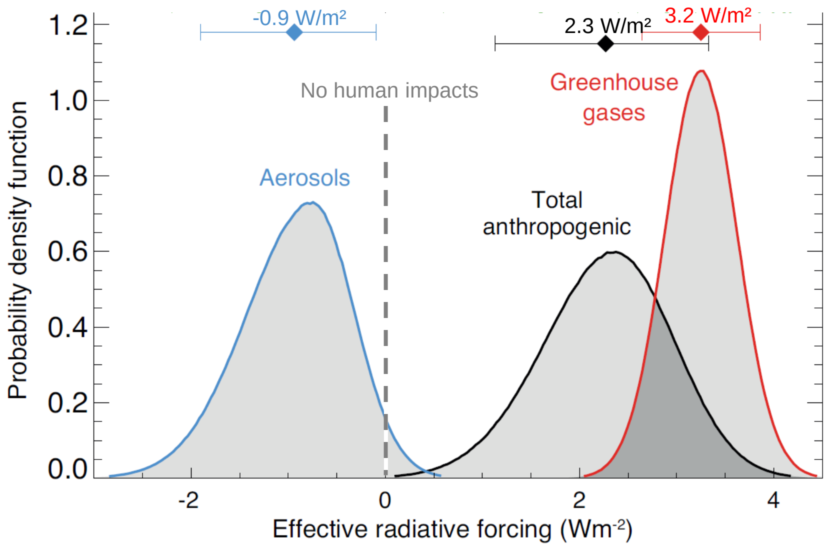
The net effect of human activities is forcing the Earth to accumulate energy, although at an uncertain pace

Range of uncertainty for Anthropogenic forcing agents in the industrial area[1]



- Probability density curves display the range of results of anthropogenic forcing calculated by current climate models: the most likely value is to be read in the abscissa corresponding to the top of the bell, and its width reflects uncertainty.
- As indicated by the black curve, the net effects of human activities are not known precisely but they are certain to cause warming: the likeliest value is about 2.3 W/m² today, compared with the equilibrium prior to the Industrial Revolution.
- The degree of uncertainty in relation to total human forcing is relatively large, mostly because of the impact of aerosols: the 90% confidence interval is 1.1-3.3 W/m² (horizontal bar).
- Current atmospheric GHG concentrations are well known, and calculated to be contributing to 3.25 W/m² of additional radiative forcings compared with the pre-industrial era (red curve).
- By comparison, the cooling effect of aerosols is much more uncertain because effects are both localized and indirect (blue curve).

1. Forcing figures are for 2011, relative to 1750.
Source: IPCC (2013), "AR5-WGI"

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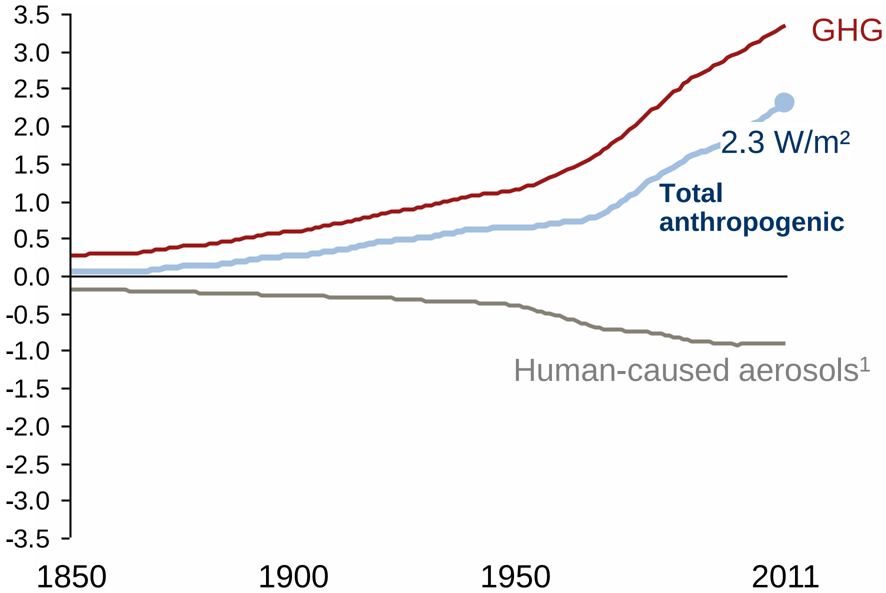
Anthropogenic forcing has been increasing since the Industrial Revolution, and at a faster rate since the 1970s

Anthropogenic climate forcing since 1850

W/m² of radiative forcing in a given year, relative to pre-industrial levels (best estimates)



- The graph illustrates the importance of human-caused (anthropogenic) forcing over the past 150 years.
- The increasing trend is due to the build-up of long-lived GHGs in the atmosphere.
- On the contrary, the cooling effect of aerosols has stabilized, because short-lived emissions from aerosols have stabilized.
- In the near future, the net anthropogenic warming effect will continue to increase, even if GHGs emissions stabilize.
- The cumulative effect of radiative forcing applied throughout the years has an impact on the Earth's energy budget and average temperature.

1. Includes both carbon & sulfate aerosols
Source: IPCC (2013), "AR5-WGI"

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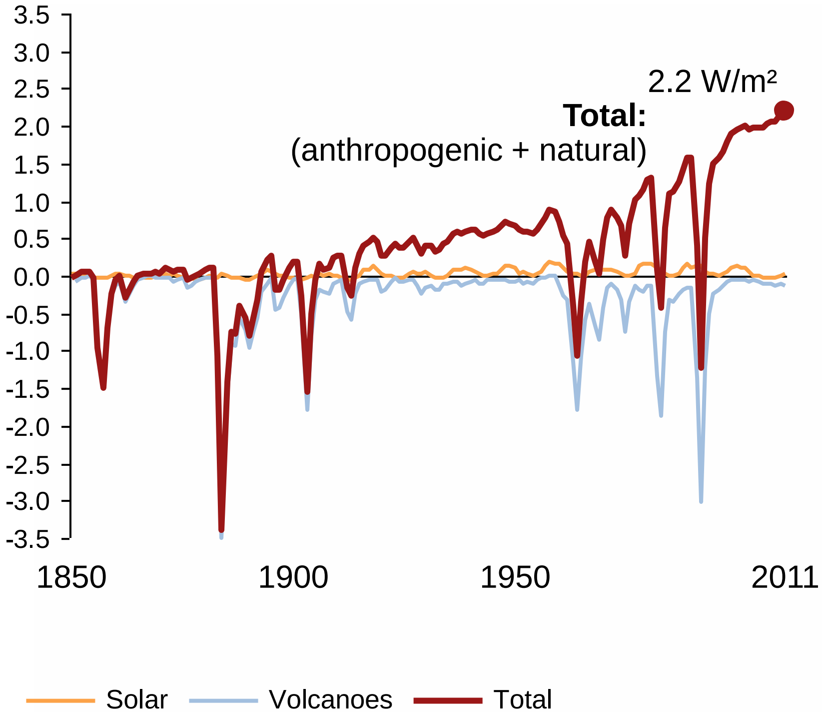
Natural forcings, by contrast, have had much less severe cumulated impacts on the Earth's energy budget

Natural & total climate forcing since 1850

W/m² of radiative forcing in a given year, relative to pre-industrial levels (best estimates)



- **Solar forcing** undergoes 11-year cycles of roughly 0.2 W/m² amplitude. In addition, decadal averaged solar forcing has increased by 0.05 ± 0.01 W/m² since a minimum reached in the 18th century[1]
- **Large volcanic eruptions** inject aerosols 10-30 km into the stratosphere, where they persist for 1-2 years and have had strong but episodic cooling effects by reflecting sunlight.
- **Overall**, natural forcings have not been sustained at significant levels compared with anthropogenic forcings. Therefore, the Earth's energy uptake resulting from the cumulated effect of total forcing since the Industrial Revolution has mostly resulted from human activities.
- No other natural forcings have been proved or assessed so far but may nonetheless exist: e.g. potential impact of solar magnetic field on cloud formation.[2]

1. Refer to IPCC (2007), "AR4-WGI, chapter 2.7" for detailed explanation on the 'Maunder Minimum' of solar irradiance.
2. Kirkby et al. (2011), "Role of sulphuric acid, ammonia and galactic cosmic rays in atmospheric aerosol nucleation".

Source: Graph: IPCC (2013), "AR5-WGI"

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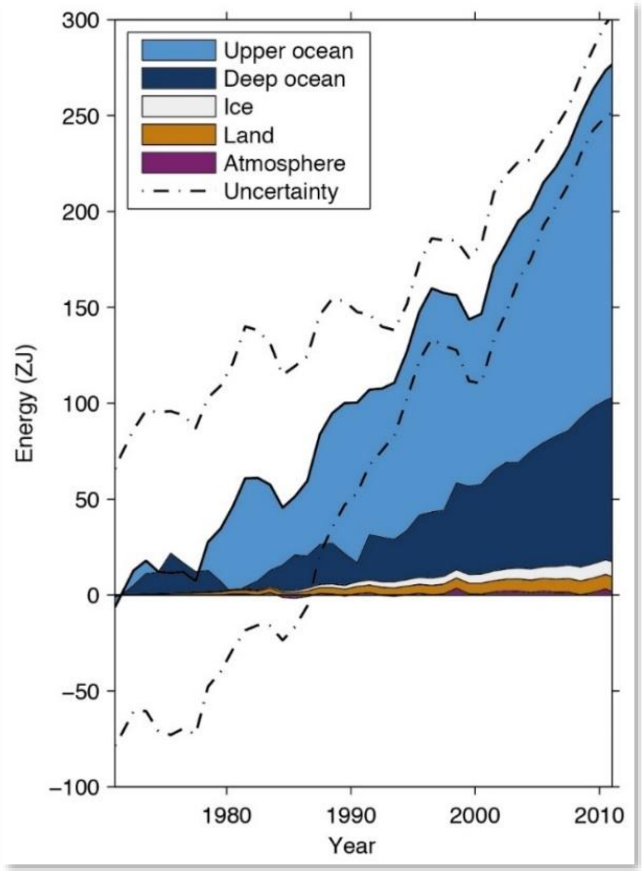
Sustained positive forcing has resulted in the Earth accumulating energy, which has so far mostly ended up heating the oceans

Cumulative earth energy content since 1971

Zetajoules (10^{21} Joules), relative to 1971



- New observation tools (improved satellite sensors and drifting profiling floats) have recently enabled improved understanding of the Earth's energy budget.
- It is now virtually certain[1] that the Earth gained substantial energy from 1971 to 2010: **globally, the planet is warming.**
- The rate of increase in energy content from 1971 to 2010 is equivalent to applying a radiative forcing of 0.42 W/m² continuously during this period.
- Oceans serve as the main reservoir for heat added to the Earth (93% of energy accumulated since 1971), because they have a low albedo and so reflect little solar radiation and because they can convect heat down away from the surface.
- Yet, because of their very large thermal inertia, oceans warm much more slowly, so that global mean surface temperatures take several decades to adjust, leading to climate lag (see next slide).

1. The 90% confidence interval is indicated on the graph by the dashed lines.
Source: IPCC (2013), "AR5-WGI, section 3"

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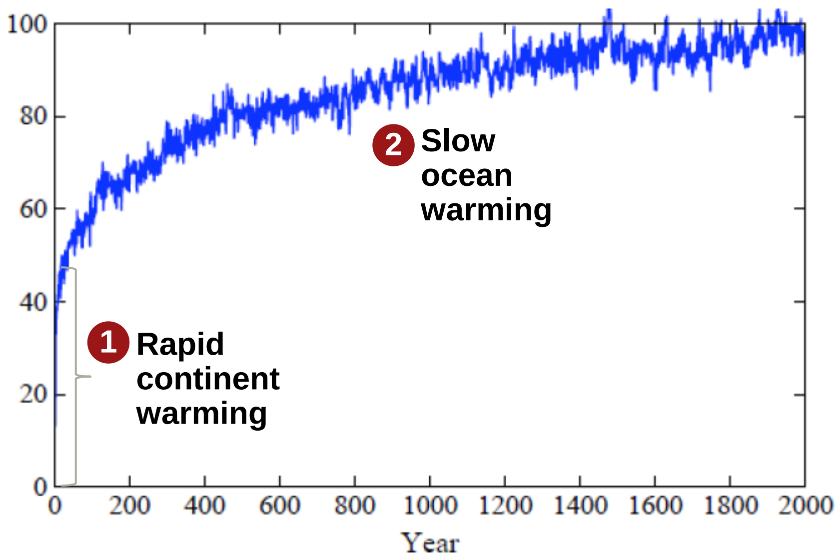
The oceans' massive thermal inertia slows down surface warming by several centuries

Evolution of surface warming (land and ocean combined) after instantaneous doubling of CO_2 concentration in the atmosphere

In % of final surface warming at equilibrium



A sudden doubling in the concentration of CO_2 would create a positive climate forcing, provoking an energy imbalance that would be progressively reduced as the Earth warms toward equilibrium. The time taken for the temperature to reach this equilibrium is called **climate lag**, and is greatly influenced by the oceans' thermal inertia:

1. **Rapid continent warming**: 10 years after the climate forcing, surface warming reaches about 40-50% of its final value. Lower atmosphere has warmed rapidly but oceans are still cooler because of their thermal inertia.
   – Heat exchanges between atmosphere and shallow ocean layers can temporarily cool the surface in the short run (<10 yrs), which is not incompatible with global warming on the long run (ex: El Niño-Southern Oscillation).
2. **Slow ocean warming**: It takes much longer for the Earth's surface temperature to adjust and harmonize: ~60% of the final warming is reached after 100 years, and the equilibrium takes two millennia.
   – Over the long run (>10 yrs), surface and oceans have enough time to exchange heat, and both warm together at the same pace.
   – The total lag is driven by oceanic thermal inertia, which depends on ocean dynamics, in particular on how well cold/deep layers of the ocean are mixing with hotter/shallower layers (non-linear phenomena that are difficult to model).

Note: The forcing is an instant doubling of CO_2, which corresponds approximately to a radiative forcing of 3.7 W/m². The climate model has fixed ice sheets, vegetation distribution and other GHGs. This is a very generalized case and not really what happens in reality.
Source: Hansen et al. (2011), "Earth's energy imbalance and implications"

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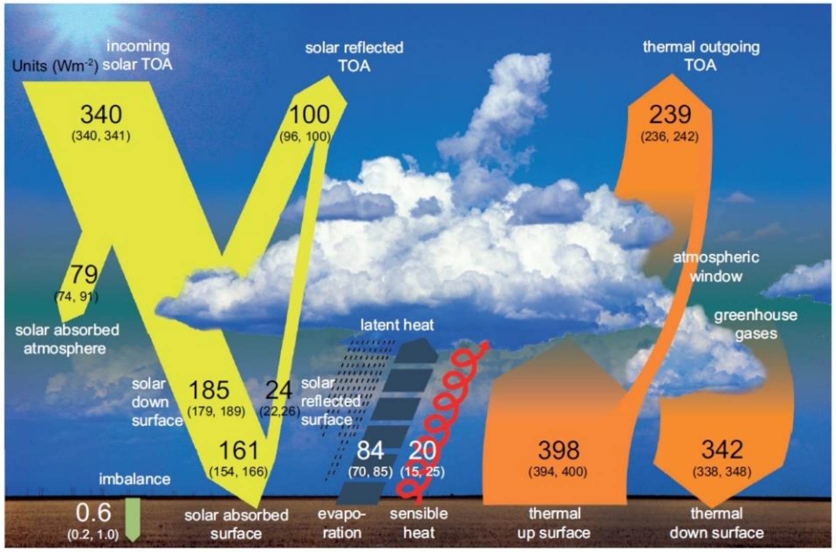
This lag in surface warming explain why our planet remains in energy imbalance, currently measured at +0.6W/m²

Global Mean Energy Budget under Present-day conditions

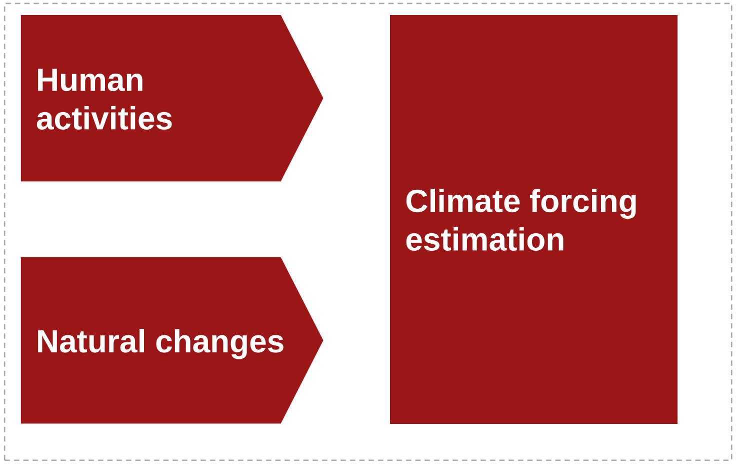
W/m², (90% uncertainty interval)



- As shown in slide 31, current forcing relative to pre-industrial equilibrium is about 2.2W/m².
- Yet, since 1750, the Earth has had time to warm up and the temperature has had time to adjust partially to this forcing.
- As a result, **Earth's outgoing IR radiation has rebounded slightly from its 2.2W/m² depression**, partially closing the energy imbalance (as explained in slide 4).
- **The current energy imbalance has been measured at about 0.6 W/m²** [0.2 to 1W/m²].
- This energy imbalance persists today due to the combined effect of climate lag and ever-increasing forcing from GHG emissions (dynamic effect).
- Uncertainty is lower in relation to the overall imbalance at the top of the atmosphere, as opposed to the intermediate energy flows between the surface, clouds, lower atmosphere etc…

Note: TOA: Top of the atmosphere
Source: IPCC (2013), "AR5-WGI"

Conclusion: The observed Earth's energy uptake and consequent warming since the industrial revolution mostly results from human activities



1 Climate forcings

- Has forcing caused the Earth to accumulate energy?
- What forcing(s) has been responsible for this imbalance?

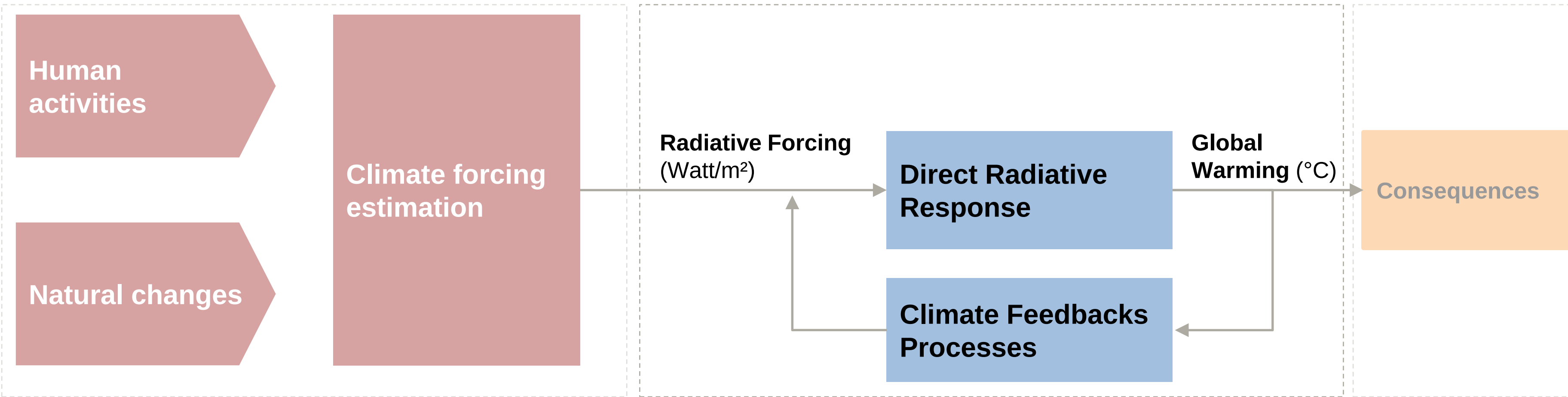
- Analyses of the history of human and natural climate forcings since the Industrial Revolution enable scientists to determine, with reasonable certainty, the causes of observed climate change.
- **Human activities**, in particular the cumulated effect of GHG and aerosol emissions, **are having a much more significant impact on the Earth's energy balance today than any natural forcing.**
- **The Earth has been forced to accumulate energy since 1750**, with a current net forcing relative to the 1750 equilibrium of about 2.2W/m².
- Uncertainty in this forcing value is relatively high because of the cooling effects of aerosols, which are subject to a much greater degree of uncertainty than the warming effects of GHGs.
- The warming effect of human activities has increased steadily since the beginning of the Industrial Revolution, because the temporary cooling effect of short-lived aerosols has been overwhelmed by the long-lived GHGs that are building up in the atmosphere.
- **Energy accumulated by the Earth since 1750 has mostly ended up heating the oceans**. Yet because oceans have very large thermal inertia and take longer to warm up, an extensive climate lag exists between the initial forcing and the final surface warming.
- **This lag in surface warming explains why our planet remains in energy imbalance today** – currently measured at +0.6 W/m² – given that GHG climate forcing continues to increase (dynamic effect).
- The difference between the current measured imbalance (0.6W/m²) and the current estimated forcing relative to the 1750 equilibrium (2.2W/m²) is explained by the observed global warming since the Industrial Revolution.

Source: A.T. Kearney Energy Transition Institute analysis

4. Climate models: sensitivity

Analyzing the sensitivity of our climate to radiative forcing is a prerequisite for estimating future global warming

Conceptual diagram of Climate sensitivity models



1 Climate forcings
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2 Climate sensitivity analysis
- How much and how fast will the Earth warm in response to a given radiative forcing?

3 Consequences
- What is the projected global warming in the 21st century?
- What will be the effects on climate, and the impacts on ecosystems and societies?

Source: A.T. Kearney Energy Transition Institute analysis

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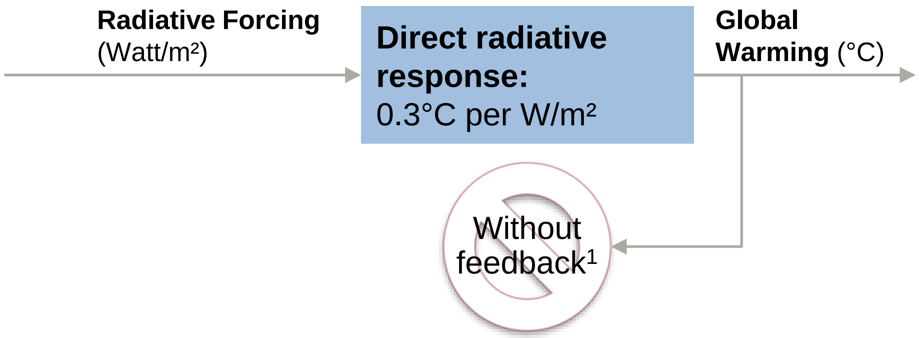
The effects of forcing without feedbacks (direct radiative response) are limited and well known

“No-feedback” climate sensitivity analysis



- The direct radiative response corresponds to the theoretical increase in the Earth’s average surface temperature for a given radiative forcing, in the following idealized situation:
  - No oceans or lag effect, no atmosphere, greenhouse effect, or any other radiative feedbacks[1], no seasons and a fixed-surface reflectivity equal to the Earth’s average at present.
- In the idealized calculation above, an increase in incoming solar radiation of 1 W/m² would increase the surface temperature by about 0.3ºC[3]. A doubling of the concentration of CO_2 (which correspond to a fixed forcing of 3.71 W/m²)[2] would raise the temperature by 1.2°C.[4]
- This purely radiative response is a totally unrealistic estimation of climate sensitivity, which would lead to an average surface temperature of -18ºC.[5]
- **For a realistic estimation of climate sensitivity, feedbacks must be considered.**

1. Except Planck blackbody feedback, which results in the stabilization of temperature increases, given that any heated body in space naturally increases its outgoing thermal radiation until it reaches thermal equilibrium.
2. CO_2 climate forcing is approximately logarithmic; that is, each doubling of the concentration of CO_2 causes about the same increase in radiative forcing.

Source: 3 Bony et al (2006). 4 Hansen et al. (1984); Bony et al. (2006). 5 Dr. MacCracken (Interview, July 2014)

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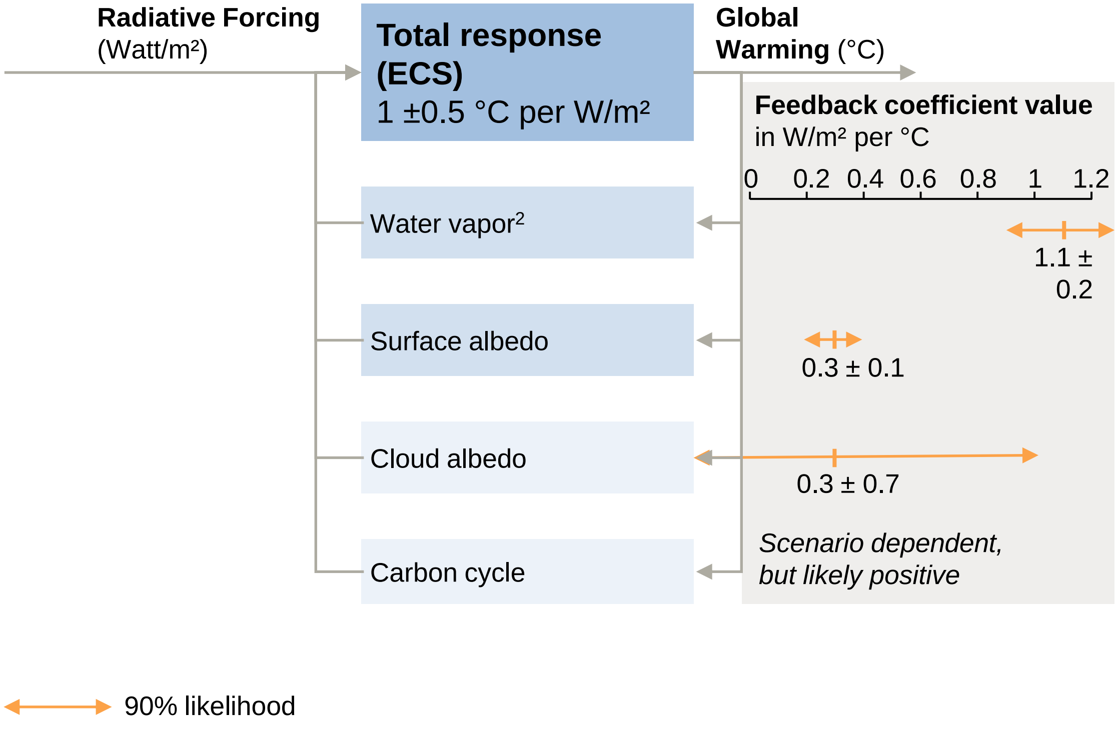
The best-understood feedbacks are water vapor and surface albedo, which together more than double climate sensitivity

Climate feedbacks included in Climate Models[1]

Amplify (if positive) or dampen (if negative) the primary warming response



This figure illustrates the four most important feedbacks, based on the IPCC's latest assessment of climate models:

- **Water vapor[2]** is the dominant and best-understood feedback: global warming increases atmospheric water vapor content – a powerful GHG – which would alone roughly double primary warming.
- **Surface albedo** Surface albedo changes in a number of ways as the temperature changes. For example, when the surface warms, melted snow and ice no longer reflect solar radiation, which means more solar radiation is absorbed to heat the Earth.

1. Other potential abrupt feedbacks with relatively unknown tipping points are not included here (refer to slide 46). The purple arrows span a 90% likelihood interval. 2 Water vapor feedback in this report includes the negative "Lapse Rate feedback", which moderates water vapor feedback because warming induced by heated vapor will not be spread homogeneously throughout the atmospheric column, but will be weaker near the surface than at higher altitudes in the atmosphere, where it has less influence on global mean surface temperature.

Source: Summary of the results from the climate models participating in the Coupled Model Intercomparison Project Phase 5, in IPCC (2013), "AR5-WGI, Chapter 9.7"

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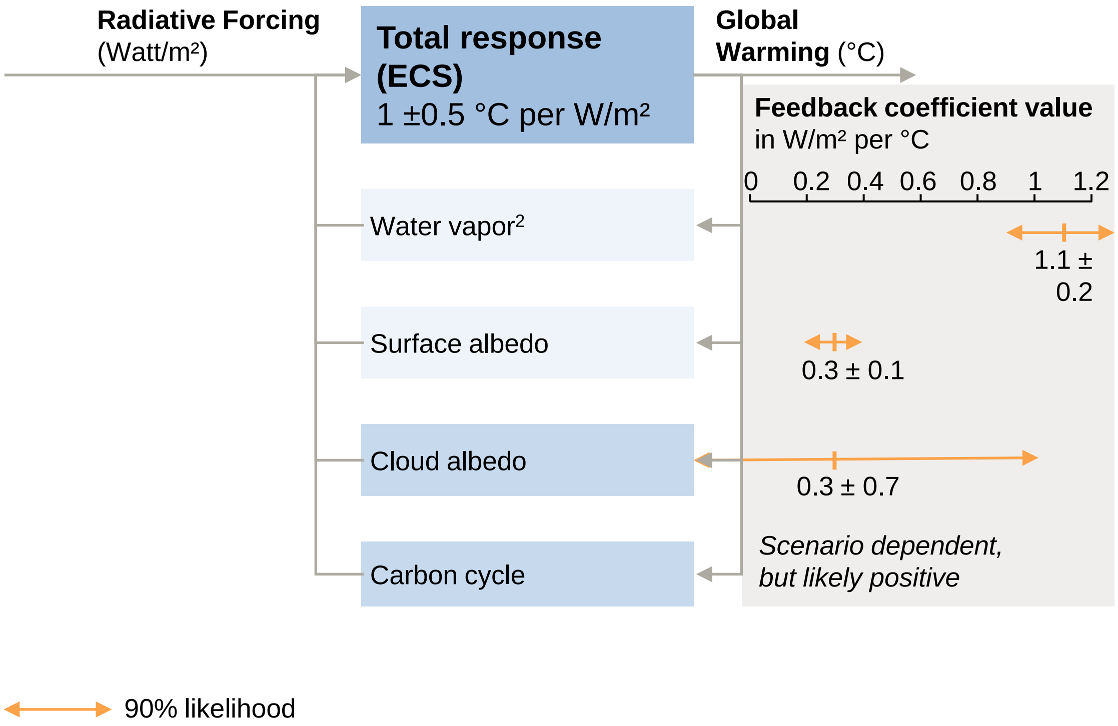
Cloud feedbacks represent the main cause of uncertainty about climate sensitivity

Climate feedbacks included in Climate Models

Amplify (if positive) or dampen (if negative) the primary warming response



3. **Cloud feedbacks** are the most uncertain and debated climate model parameters. Global warming can change the amount and type of clouds, and their optical thickness, a measure of their reflexivity. Dense, low-lying clouds reflect sunlight and thus exert a cooling influence on the Earth, while thin, high-altitude clouds have the opposite effect. Overall, the net effect of cloud feedback on climate sensitivity is probably positive, but remains uncertain: observations alone cannot currently indicate robust upper and lower bounds for its value (see slide 43).
4. **The carbon** cycle exerts an indirect feedback on the CO_2 concentration rather than directly amplifying radiative forcing. The ability of the Earth's land and oceans to continue absorbing CO_2 may decline as the world warms, since warmer soils increase respiration and warmer oceans dissolve CO_2 less rapidly. However, this feedback may be balanced by the increased plant growth stimulated by increased CO_2 concentration. Yet the glacial cycling during the last 800,000 years provides the best evidence that such feedback is positive overall.

- Taking into account all feedbacks, the total response, called **Equilibrium Climate Sensitivity**" (ECS) is estimated to be **1 ±0.5 °C per W/m².**

Source: Summary of the results from the climate models participating in the Coupled Model Intercomparison Project Phase 5, in IPCC (2013), "AR5-WGI, Chapter 9.7"

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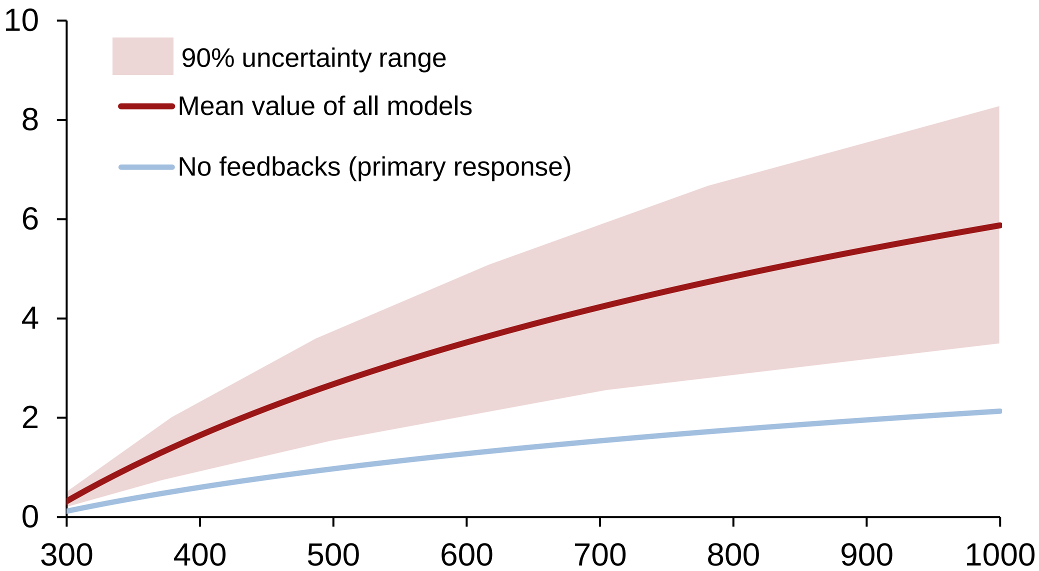
With all feedbacks taken into account, climate sensitivity is estimated to be two to four times higher than the direct radiative response

Long-term global warming relative to GHG concentration

(summary of 30 models)[2]

Global warming at equilibrium, in degrees above pre-industrial temperatures (°C)



Radiative forcing at stabilization level, in GHG concentration equivalent (ppm of CO_2-e)

- A common way to summarize sensitivity is to show expected global warming as a function of future GHG concentrations, since each increase in GHG concentration leads to a readily calculated increase in radiative forcing.
- The trend is logarithmic: each doubling in GHG concentration (when measured in CO_2-equivalent) is expected to lead to a fixed amount of global warming in the long run, usually referred to as Equilibrium Climate Sensitivity (ECS).
- In the unrealistic case of there being no feedbacks, any increase in the concentration of GHG would be less of a reason for concern in terms of global warming[1], with 1°C warming per doubling of GHG concentration.
- **Taking climate feedbacks into account, climate sensitivity is 2 to 4 times higher.** The current international set of climate models[2] estimates ECS at **3.2°C (±1.3°C, 90% likelihood)** of long-term warming for each doubling of GHG concentrations.

1. The rise in CO_2 concentration would still be contributing to ocean acidification and still lead to some changes in climate.

Source: 2 Based on 30 climate models of the Coupled Model Intercomparison Project Phase 5, as summarized in IPCC (2013), "AR5-WGI"

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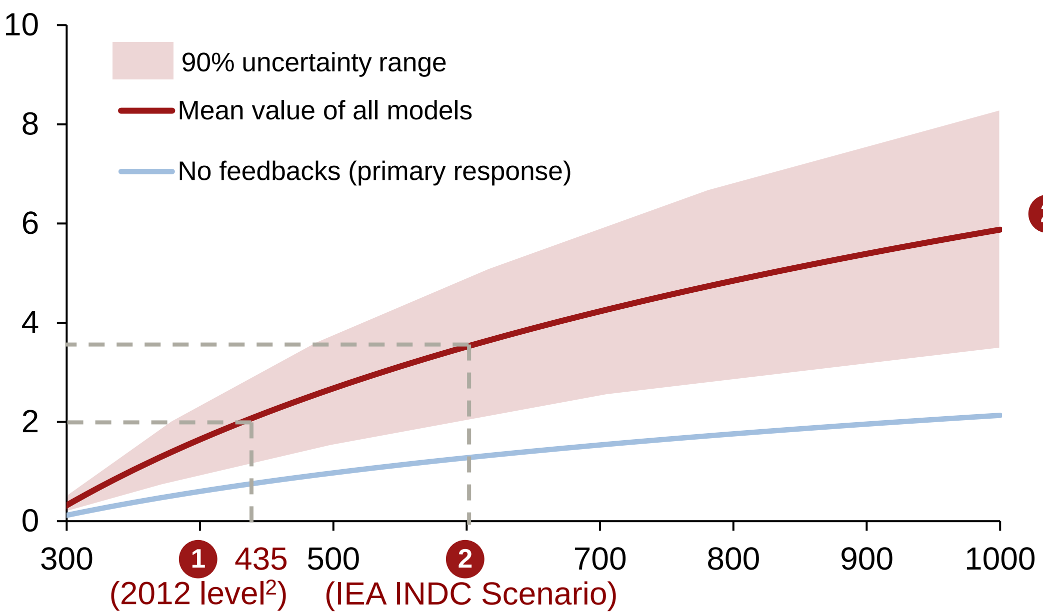
According to the IEA, the latest national emissions-reduction pledges would result in global warming exceeding the UNFCCC's 2°C target

Long-term global warming relative to GHG concentration
(summary of 30 models)[1]

Global warming at equilibrium, in degrees above pre-industrial temperatures (°C)



Radiative forcing at stabilization level, in GHG concentration equivalent (ppm of CO_2-e)

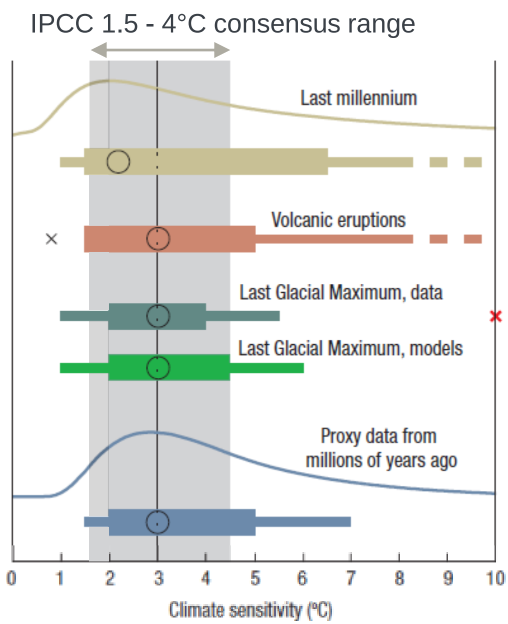
1. According to these models, if anthropogenic forcing were maintained at its current level, equilibrium global warming would most likely reach around 2ºC after several centuries.
   – The result should be interpreted as indicative only, as it also depends on the type and trajectory of GHG emissions. Refer to section 5 for detailed warming projections.
2. Under the IEA's 2015 INDC Scenario[3] – which takes into account, as of 14 May 2015, the Intended Nationally Determined Contribution that countries are required to submit for the COP21 climate conference – emissions "would be consistent with an average temperature increase of around 2.6°C by 2100 and 3.5°C after 2200."[4]
   – The dashed line on the graph corresponding to the IEA's INDC Scenario should be interpreted as indicative only.

1. UNFCCC: United Nations Framework Convention on Climate Change.
Source: 1 30 climate models of the Coupled Model Intercomparison Project Phase 5, as summarized in IPCC (2013), "AR5-WGI". 2 This value includes cooling aerosols. EEA (2015), "Atmospheric Greenhouse Gas Concentrations". 3 IEA (2015), "World Energy Outlook Special Report, Energy and Climate Change" 4 Updated INDC Scenario with pledges submitted as of mid-October forecasts quite similar temperature increase: around 2.7°C by 2100. IEA (2015), "World Energy Outlook 2015 Special Briefing for COP21".

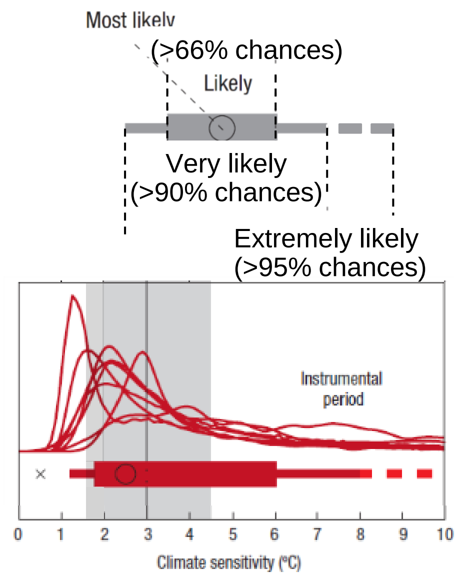
Taking into account additional evidence from past climate events, the latest IPCC assessment of equilibrium sensitivity is likely between 1.5 and 4.5ºC

Sensitivity range derived from analogs from the past[1]

Paleoclimate reconstructions



Instrumental periods
(~past 150 years)



- As well as the bottom-up (physical principles) approach to climate modeling presented in the previous slides, analyses of past climate events provide additional lines of evidence concerning the sensitivity of the Earth's climate system to radiative forcing (top-down approach).
- Looking at both, the latest UN consensus for ECS, as reflected IPCC (2013) summary for policymakers, is **likely between 1.5°C and 4.5°C, very likely above 1°C, and extremely likely below 6°C**. No single best estimate for ECS has been highlighted.[2]
- While Earth's climatic history seems to clearly indicate a lower bound to climate sensitivity, it does not provide such clear evidence for an upper bound, which calls for precaution.
- Using records of past climate changes to narrow the range of sensitivity estimates is difficult because of uncertainties in past records:
  - For paleoclimate or volcanic eruptions:
    - ✓ Accurate CO_2 concentration reconstructions
    - × Uncertain temperature reconstructions
  - For the instrumental period:
    - ✓ Accurate temperature measurements
    - × Uncertain forcing (**aerosols**)
    - × Uncertain **lag**

1. The colored lines show distribution probabilities of various empirical estimates of sensitivity based on analogs from the past. The horizontal bars summarize uncertainty ranges, and the vertical grey area indicate the IPCC's consensus sensitivity range, of 5-4.5°C. 2 Because different climate forcers operate in different ways and the climatic state can affect the climate sensitivity, there is no single best value that can be applied and it is best to consider the value as being within the range indicated (see slide 45).

Source: Graph adapted form Knutti et al. (2008), "The equilibrium sensitivity of the Earth's temperature to radiation changes". Sensitivity range from IPCC (2013), "AR5-WGI, Summary for Policymaker"

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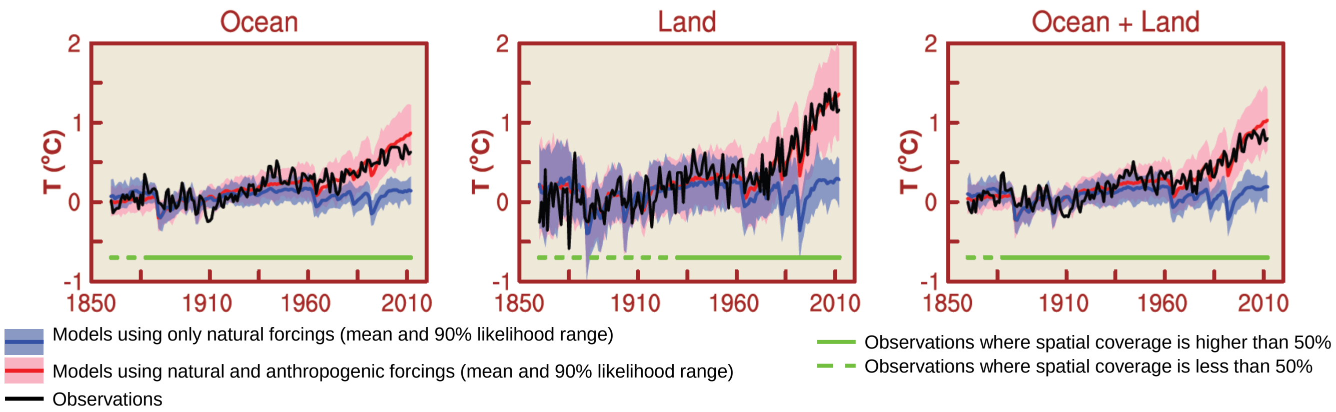
In general, the level of confidence in climate-model projections is reinforced by their ability to reproduce the temperature variations of the last century

Comparison of observed temperature changes with results simulated by climate models



- Estimated climate forcings from the past century are applied to climate models, and simulated warming is compared with observations.
- Models accurately reproduce the observed global warming of the past century, when looking at decal trends:
  - Accelerated surface warming in the second half of the 20th century;
  - Slower surface warming over the oceans than over land;
  - Regional differences (not shown in this graph).
- Without taking into account anthropogenic forcing, calculated warming differs significantly from past observed warming.
- There is further detail in slide 61 on the slowdown in oceanic temperature increases apparent during the past 15 years.

Note: The shaded bands show the 90% likelihood range of the simulated response to forcing, as per international set of climate models.
Ranges are due to intermodal differences as well as natural variability.
Source: IPCC (2013), “AR5-WGI”

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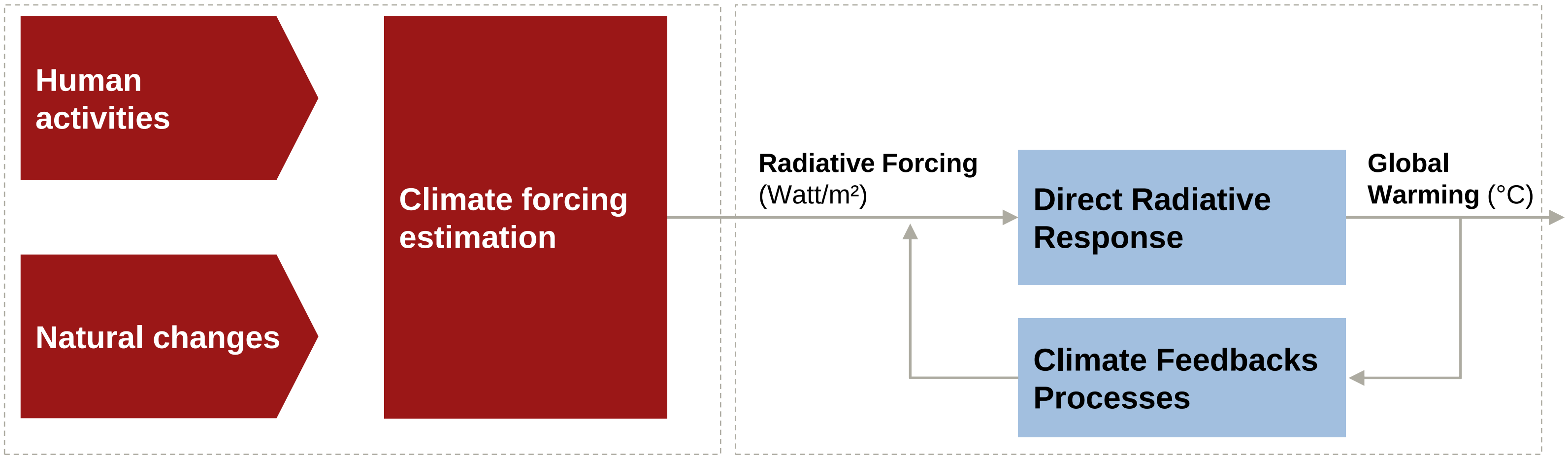
Yet, there are known limitations to the concepts of forcing, feedback and sensitivity that are important to keep in mind

Conceptual diagram of Climate models



Climate forcing analysis | Climate sensitivity analysis

- **Feedback coefficients are conceptual** – They derive from physical principles. These coefficients cannot be individually validated against observations, since climate models only calculate their integrated effect before comparing their results with observed temperatures.
- **Equilibrium Climate Sensitivity (ECS) is not a physical constant:**
  - **Sensitivity may not have remained constant** throughout Earth's geological history, being a function of the state of the climate (e.g., global average temperature or biogeochemical conditions).
  - **Sensitivity may depend on the type of forcing:** Various types of climate forcings have qualitative differences that may not be entirely reflected by their radiative forcing value in W/m² or global warming potential in ppm CO_2-eq (e.g., black-carbon forcing has local effects, CO_2 has seasonal effects, water vapor has latitudinal effects, and cloud-aerosols have fast-acting effects…).
  - **Sensitivity may depend on the magnitude of the forcing**: Care should be taken in extrapolating models beyond a doubling or halving of CO_2 concentrations. For instance, some potentially abrupt feedbacks with relatively uncertain tipping points are not taken into account in current models (next slide).
- As a result, no single best estimate for ECS has been highlighted in the latest IPCC assessment, which instead mentions ranges of uncertainty.

Source: A.T. Kearney Energy Transition Institute analysis

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For instance, a number of potentially abrupt and significant positive feedbacks are yet to be included in climate models or in projections of future warming

Potentially large, abrupt or irreversible positive feedbacks with mostly uncertain tipping points

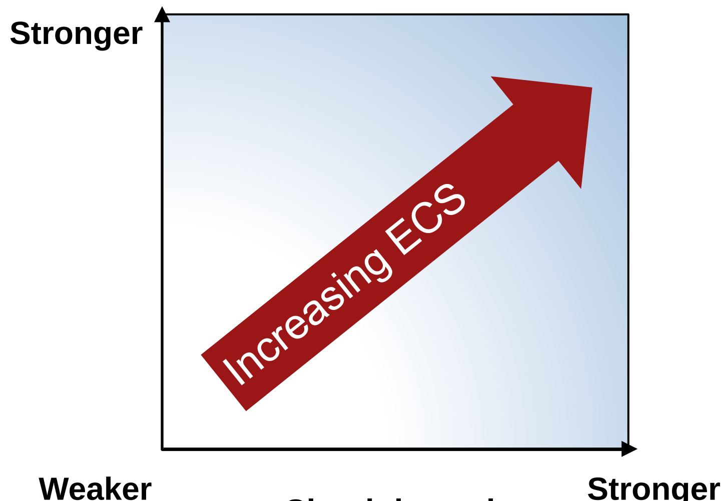
1. **Methane release from the melting of permafrost or oceanic methane hydrates**
   - The destabilization of frozen soil (permafrost) in Arctic latitudes has only recently begun and its ultimate path is uncertain, but it is considered a potential threat. Release of all permafrost carbon as methane would have the same potential to induce global warming as an increase in the atmospheric concentration of CO_2 of 58-116 ppm, but most of its influence would occur in the first 20 years.
   - Over a longer time-scale, methane hydrates released as a result of the ocean warming the seabed could increase radiative forcing, adding an additional positive feedback, but on a multi-millennial time scale: a catastrophic release of methane in the 21st century is considered very unlikely in any plausible emissions scenario.
2. **Shutdown of the thermohaline circulation of the global ocean**
   - Thermohaline circulation plays a meaningful role in carrying ocean heat to high latitudes, taking dissolved CO_2 to the deep ocean, bringing up nutrients that sustain marine life, etc…When sea surface temperature patterns have been disrupted in the past, abrupt changes in atmospheric circulation have occurred, dramatically altering the climate in the affected regions (e.g. altering monsoon patterns).
   - A shutdown could be triggered by a massive release of fresh water from the melting of the Greenland ice sheet. Models suggest that the Atlantic meridional overturning (AMOC) should weaken in the 21st century, but the probability of an abrupt change in circulation patterns is estimated to be below 10% in the 21st century (even in the high-emissions scenario).
3. **Polar continental ice-sheet collapse**
   - Greenland ice-sheet collapse could happen as a result of sustained temperatures in excess of 2-4°C for one millennium, and would add 6.6 meters to the sea level.
   - The Antarctic ice sheet is a more complex system of large glacial flows, and has recently shown signs of instability, suggesting that the West Antarctic ice sheet could be more vulnerable than previously expected, and would significantly retreat if the CO_2 concentration stays above 350-450 ppm for several millennia.

Note: Other potentially abrupt feedbacks include tropical or boreal forest dieback.
Source: IPCC (2013), “AR5-WGI”

Conclusion: Sensitivity calculated by climate models is supported by analogous climate changes in the past, but uncertainty relating to cloud feedback persists

Key underlying uncertainty parameters for Equilibrium climate sensitivity – (ECS)

Ocean dynamics
(increasing climate lag)



Cloud dynamics
(strengthening the positive feedback from cloud-albedo, or the cooling effect of cloud-aerosol interactions)

- Equilibrium Climate Sensitivity (ECS) can be independently estimated using physical principles (climate models) or analogs from the past. Together, they suggests a **long-term warming per doubling of GHG concentrations in the likely range of 1.5 to 4.5 °C** (66% confidence interval), with no central estimate.
- Climate models do not explicitly differentiate direct radiative response from feedback processes, but the latter tend to amplify the former by a factor of roughly two to four.
- How clouds respond to climate change (**cloud dynamics**) is the main reason for the model-generated range of estimates for climate sensitivity.
- The second-largest uncertainty parameter is **ocean dynamics**, driving the lag in climate response to radiative forcing.
- **It is difficult to narrow down the range of the ECS estimates** using records of past climate changes, because past records are uncertain:
  - Past climate forcing is uncertain: The higher the forcing actually was, the lower the sensitivity to this forcing must have actually been.
  - Climate lag is uncertain: The higher the lag, the higher the ECS.
- **Knowing ECS alone does not determine the temporal evolution** of warming during the 21st century (see next section).
- A number of potentially large, abrupt and irreversible positive feedbacks are yet to be included in climate models, but could significantly exacerbate the impact of human activities on the Earth's climate.

Source: A.T. Kearney Energy Transition Institute analysis

5. Projected global warming and related consequences

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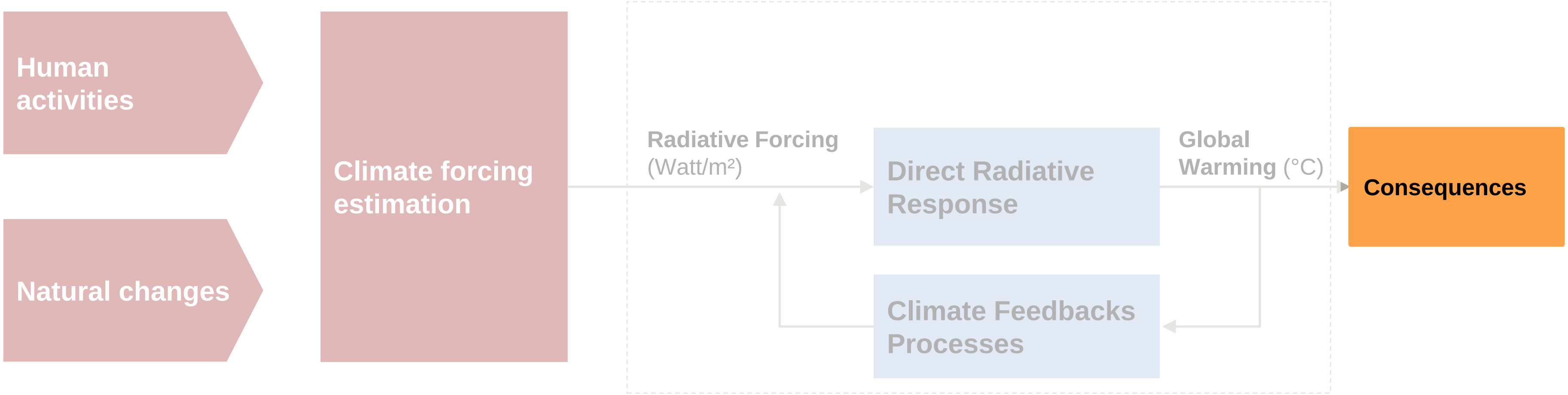
To estimate future global warming and its related consequences, it is first necessary to project future forcings resulting from human activities

Conceptual Diagram of climate models



3 Consequences

- What is the projected global warming in the 21st century?
- What will be the effects on climate, and the impacts on ecosystems & societies?

Source: A.T. Kearney Energy Transition Institute analysis

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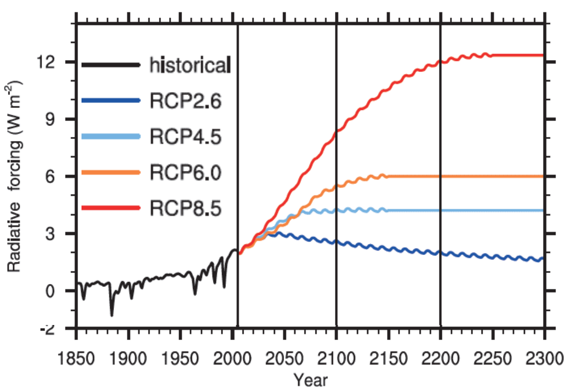
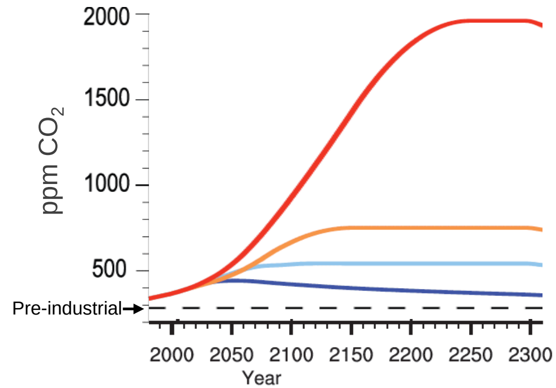
Four possible scenarios for future climate forcings are considered by the IPCC, from which four compatible GHG emissions and concentrations pathways are derived

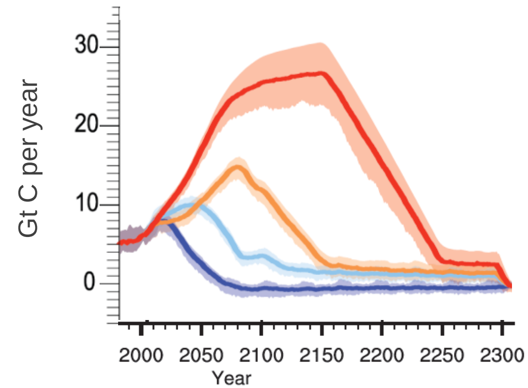
Representative Concentration Pathways (RCP) scenarios



Compatible CO_2 concentration[1]



Compatible CO_2 emissions[2]



- Four scenarios (RCP) for radiative forcing have been built to span the extent of realistic socioeconomic storylines[3], providing a representative spread of possible outcomes, from best to worse. The RCP number (e.g. 2.6) indicates the maximal radiative forcing (W/m^2) reached by each scenario.
- In all RCPs, radiative forcing is nearly entirely due to human activities[4]. CO_2 represents 80-90% of the cumulated forcing.
- Compatible CO_2 concentrations and emissions have been estimated for each RCP:
  - **RCP2.6:** GHG concentration peaks below 480 ppmCO_2-eq by 2040, thanks to emissions decrease by 2020 and active use of biomass and CCS[5].
  - **RCP4.5 & 6.0** stabilize GHG concentration at 650 and 850 ppmCO_2-eq respectively, with emissions peaking in 2040 & 2080. As of mid-October 2015, the IEA's *INDC scenario* falls between these two RCPs.
  - **RCP8.5** is a worst-case scenario, with the highest forecast energy demand and the slowest forecast rate of technology development.

1. CO_2 only, not including other gases. The dashed line represents the pre-industrial level of concentration.
2. The light color represents a 90% uncertainty range.
3. That is, future demographic and economic development, regionalization, energy production and use, technology, agriculture, forestry, and land use.
4. The only natural forcings are the small oscillations due to 11-year solar cycles (no volcanic eruptions).
5. Carbon Capture and Storage.

Source: IPCC (2013), "AR5-WGI". IEA (2015), "World Energy Outlook 2015 Special Briefing for COP21".

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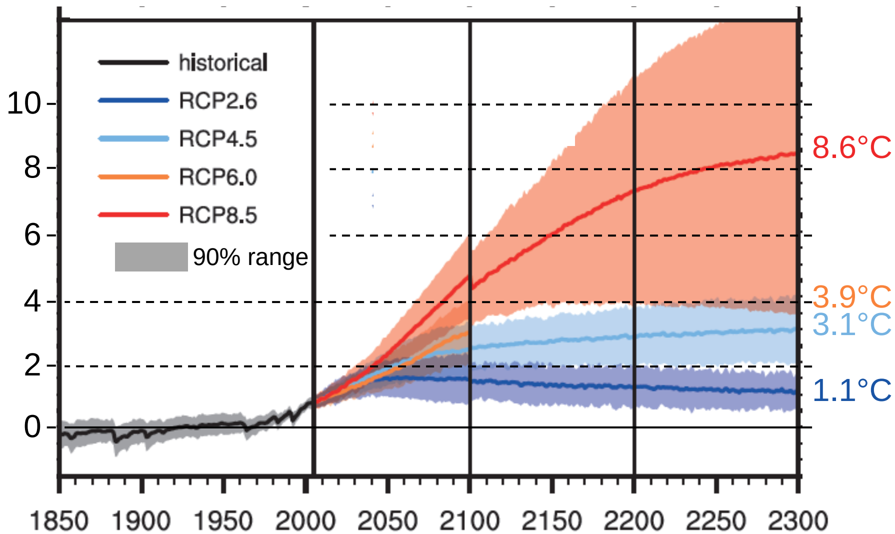
Mean model estimates for global warming exceed the UNFCCC target of 2°C relative to pre-industrial temperature in all but the most optimistic scenario

Forecasted global surface warming (land and sea combined)[1]

(°C relative to pre-industrial average 1861-1880)



°C to pre-industrial[2]	2016-2035	2081-2100	2300
RCP2.6	(0.9 - 1.3)	1.6 (0.3 – 2.3)	1.1 (0.6 – 1.6)
RCP4.5		2.4 (1.7 – 3.2)	3.1 (2.1 – 4.1)
RCP6.0		2.8 (2 - 3.7)	3.9 (2.5 – 5.1)
RCP8.5		4.3 (3.2 – 5.4)	8.6 (3.6 – 13)

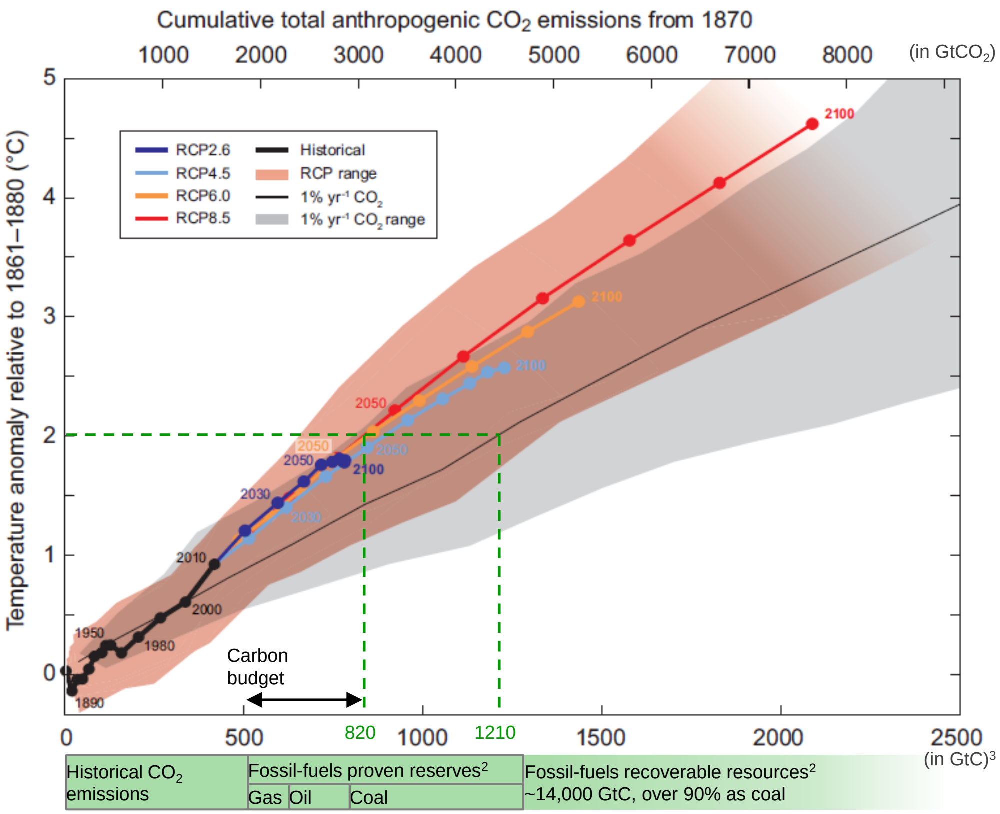
- The four RCPs are put into various climate models to project global mean surface warming.
- In all except the most conservative scenario (RCP2.6), the central estimate from the international set of climate models exceeds the UNFCCC[3] target of 2°C relative to the pre-industrial average.
- For the three other RCPs, global warming continues to increase until 2300, even after stabilization of the forcing, because of the time it takes for the oceans to warm fully (ocean inertia).
- Furthermore, warming is projected to remain approximately constant for many more centuries following a complete cessation of CO_2 emissions (not shown here).
- Because projections centuries into the future are necessarily based on models rather than observations, and extend some model parameterizations beyond the range where they can be tested, the IPCC treats the *very likely* range (90%) of climate models shown in the graph as *likely* only (66%).

1. Depending on the particular scenario, the indicated results are drawn from between 12 and 42 models. Discontinuities in 2100 have no physical meaning and are due to changes in the number of models that made the simulation. RCP6.0 is not shown after 2100 for visibility purpose.
2. The likely range is indicated in parenthesis. Original data table expresses values relative to 1986-2005 average. 0.61°C has been added to express warming values in °C relative to pre-industrial average, as per IPCC estimate. 3 United Nations Framework Convention on Climate Change.

Source: Multi-model ensemble average summarized by IPCC (2013), "AR5-WGI"

Limiting global warming below 2°C by 2100 would require limiting future cumulative CO_2 emissions, but to an uncertain extent

Global Warming by 2100 as a function of cumulative CO_2 emissions from 1870



- Cumulative emissions of CO_2 largely determine global mean surface warming by the late 21st century and beyond, because the atmospheric lifetime of CO_2 mostly exceeds a century.
- If the only forcing considered is CO_2, having a 50% chance of limiting transient global warming by 2100 to below 2ºC would require cumulative emissions from 1870 to be less than 1210 GtC. This is represented by the thin black line, simulating a 1%/yr increase in cumulated CO_2 emitted.
- RCP scenarios – represented by the thick colored lines – account for other anthropogenic forcings as well, such as methane or aerosols.[1] With these additional forcings considered, only 820 GtC are allowed to meet the 2°C limit with a probability over 50%.
- Because about 515 GtC was emitted between 1870 and 2011 (green rectangles), the remaining CO_2 budget to meet the 2°C target with 50% probability is 305 GtC (or 275 GtC to give a 66% chance).
- By comparison, proven fossil-fuel reserves as of 2012 amount to 780GtC (63% as coal, 22% as oil and 15% as natural gas, including unconventional oil and gas).

1. In all RCP scenarios, methane and other GHG emissions are roughly proportional to CO2 emissions, while man-made aerosols gradually decrease to about half of the current estimated value, reflecting expected progress in reducing pollution from the combustion of fossil fuels.
2. Figures as of 2012. Reserves are those volumes that are expected to be produced economically using today's technology; often associated with a project that is already well-defined or ongoing. Resources are those volumes that have yet to be fully characterised, or that present technical difficulties or are costly to extract.
3. 1 gC equals 3.67 gCO2.

Source: IPCC (2013), "AR5-WGI, TFE.8". Reserves and resources: IEA (2012) "World Energy Outlook".

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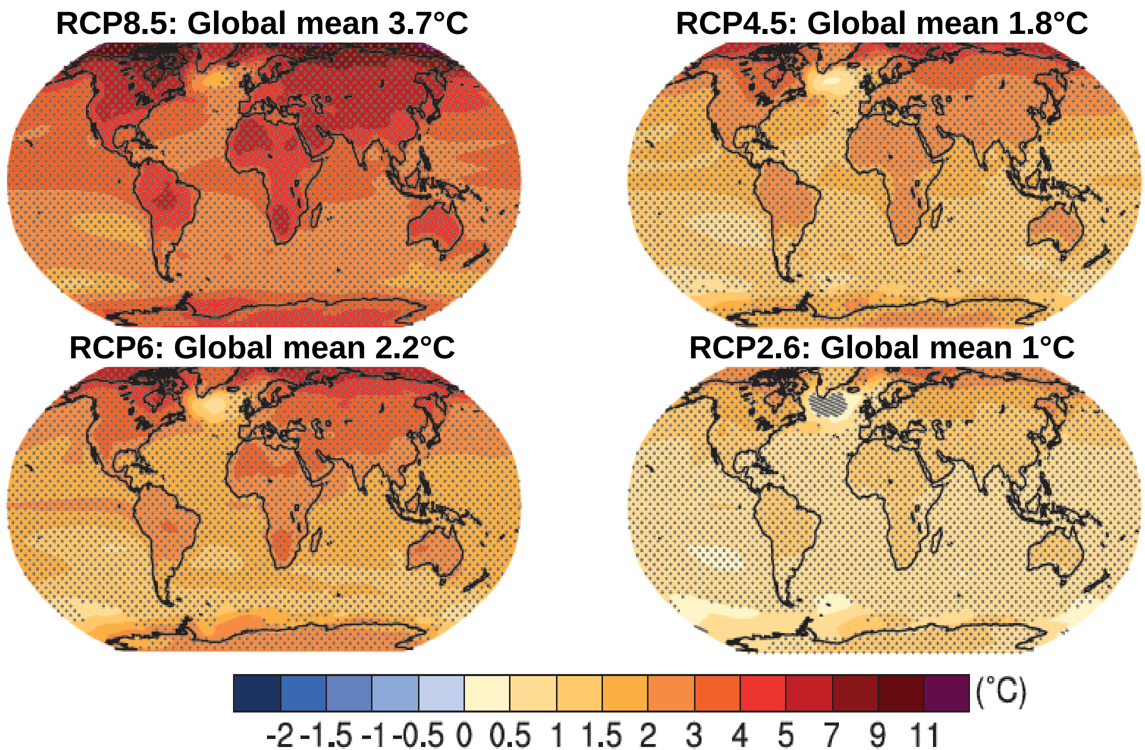
Local temperature changes are likely to be significantly larger than the increase in the global average temperature

Regional distribution of projected temperature change in 2100

°C in 2080-2099 average, relative to recent 1986-2005 average



(Add ~0.6°C to convert to warming relative to pre-industrial levels)

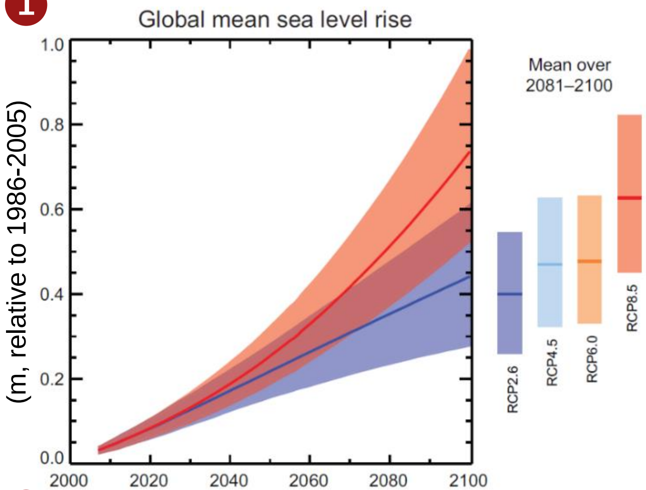
- Global warming will not be homogeneous, leading to leading to greater warming in some regions than others.
- In general, continents are expected to warm faster than oceans (40 to 70% more warming by 2100, likely range).
- Northern regions are projected to warm the most due to ice albedo feedback and a lower fraction of additional energy going into evaporating water.
- For instance, in RCP4.5, Eastern Canada's average annual temperature will most likely increase by up to 4°C compared with the past decade, versus 1.8°C for the global mean.

Note: Multi-model ensemble average (25 to 42 CMIP5 models). Hatching indicates regions where the multi-model mean signal is less than one standard deviation of internal variability. Stippling indicates regions where the multi-model mean signal is greater than two standard deviations of internal variability and where 90% of the models agree on the sign of change.
Source: IPCC (2013), "AR5-WGI, Technical Summary TS.15"

Sea-level rises will accelerate, Arctic Sea ice will shrink substantially, and oceanic waters will become more acidic in all RCP scenarios

Projected effects on the oceans of the four RCP scenarios to 2100
(non-exhaustive list)

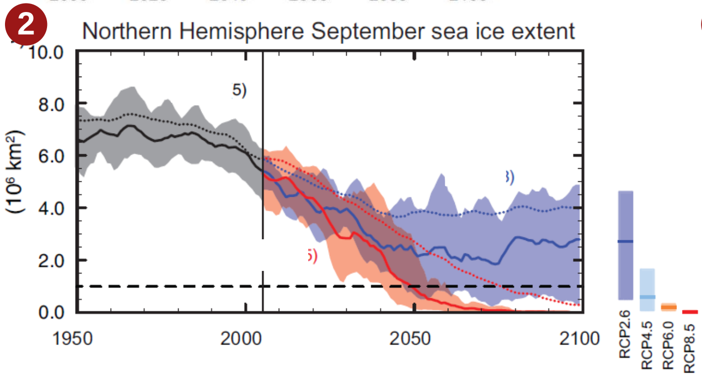
1



Sea level rise in cm relative to 1986-2005 mean (likely range)

Scenario	2046-2065	2081-2100
RCP2.6	24 (17-32)	40 (26-55)
RCP4.5	26 (19-33)	47 (32-63)
RCP6.0	25 (18-32)	48 (33-63)
RCP8.5	30 (22-38)	63 (45-82)

2



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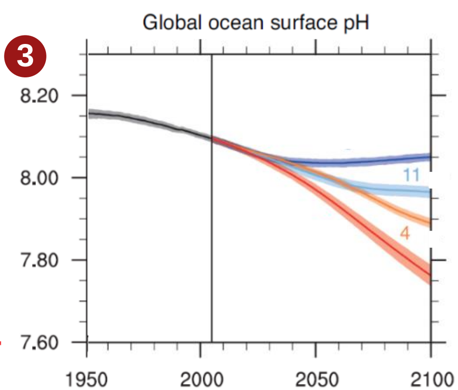

How to read these graphs?

In each graph, the solid line represents the multi-model mean, and the shaded area the 90% probability range based on model simulations:

1. Global mean sea level (GMSL) will certainly continue to rise in the 21st century and beyond. According to the IPCC, "Only the collapse of the marine-based sectors of the Antarctic ice sheet, if initiated, could cause GMSL to rise substantially above the likely range during the 21st century." As in the case of temperatures, sea-level rises will not be uniform around the world, although with smaller relative variations1.
2. It is very likely that Arctic Sea ice cover will continue to shrink and become thinner as temperature rises. It is likely to become ice-free before 2100 in RCP8.5, but a projection for when this might happen cannot be made with confidence in the other scenarios.
3. In all scenarios, continued uptake of carbon by the ocean, although slowed down by ocean warming, will increase ocean acidification.

1. Reasons for this include varying changes in ocean temperature, gravitational effects as ice sheets melt, the local rise and fall of coastlines, and the oblate shape of the Earth's surface due to its rotation.

Source: Multi-model ensemble average (CMIP5 models) summarized by IPCC (2013), "AR5-WGI"

As the climate warms, more energy will be available to power atmospheric circulation and the water cycle, increasing the volatility of weather patterns globally

Projected long-term (2100) changes in weather patterns - (Non-Exhaustive list)

>99% likelihood
"Virtually certain"

- Hot temperature extremes, daily & seasonal (increased frequency)
- Cold temperature extremes, daily & seasonal (decreased frequency)
- Extreme-high sea-level events (increased frequency and/or intensity)
- Mean precipitation, globally and in high latitudes (increase)

>90% likelihood
"Very likely"

- Heat waves and warm spells (increased frequency and/or duration)
- Heavy precipitation in mid-latitudes and wetter, tropical land masses (increased frequency and/or intensity)

>66% likelihood
"Likely"

- More intense storms and fewer weak storms, globally
- Heavy precipitation over land (increased frequency and/or intensity)
- Droughts in regions that are dry at present (increased in intensity and/or duration, for high forcing RCP only)
- Monsoon areas and precipitation (increase)

50%-66% likelihood
"More likely than not"

- Tropical cyclones in North Atlantic and North Pacific (increase in average intensity)

?
Low confidence
"Models can't predict"

- Tropical cyclones (frequency)
- Attribution of any single event solely to anthropogenic climate change

Source: IPCC (2013), "AR5-WGI, TFE.9"

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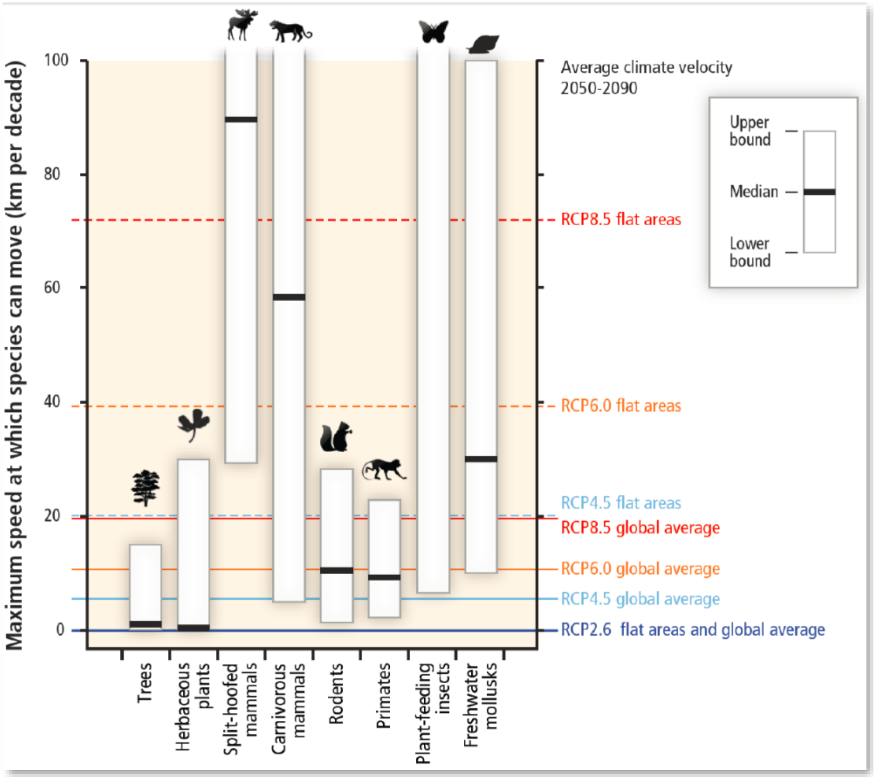
Impacts on ecosystems include an increased risk of species extinction in all RCP scenarios, increasing with both magnitude and rate of climate change

Maximum speeds at which species can move across landscapes in the absence of human intervention, compared with speed at which temperatures are projected to move



- The rate at which temperatures change, rather than the total amount of warming, is the most dangerous threat to biodiversity.
- As shown in the graph, many species are projected to be unable to keep up with climate change in scenario RCP4.5 or higher: The maximum speed at which they can move across land is lower than the average climate velocity in their environment. This is especially true in flat areas, where small temperature changes correspond to larger geographical shifts.
- In such scenarios, and in the absence of human intervention, tree mortality and associated forest dieback will occur in many regions (e.g. boreal-tundra Arctic system and the Amazon forest). Small mammals and primates also face risks in flat areas.
- Marine species (not shown in the graph) can shift their ranges more easily, yet invasions and warming may cause high local extinction rates in the tropics and semi-enclosed seas.
- For RCP4.5 and above, ocean acidification will pose substantial risks to polar ecosystems, coral reefs and mollusks during the 21st century.

Source: IPCC (2014), "AR5-WGII, Summary for Policymakers"

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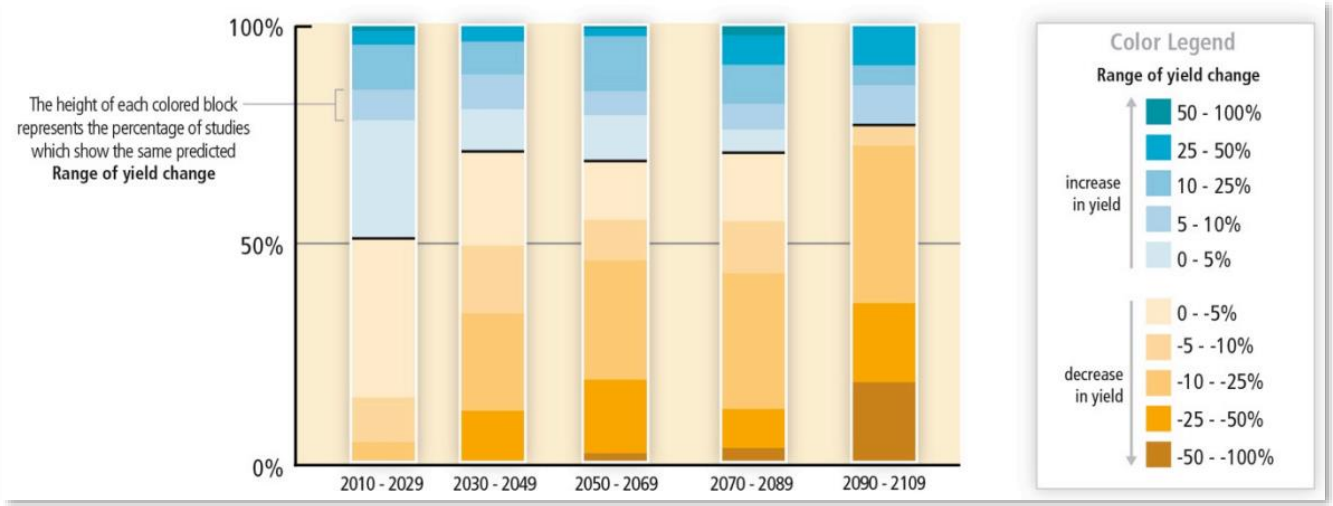
Impacts on agriculture may include a decline in major crop yields in tropical and temperate regions, if no adaptation measures are implemented

Projected changes in crop yield, with or without adaptation measures

In % of peer-reviewed studies published



Quotes from IPCC (2014), *AR5-WGII*, Summary for Policymakers

- "For the major crops (wheat, rice, and maize) in tropical and temperate regions, climate change without adaptation is projected to negatively impact production for local temperature increases of 2°C or more above late-20th-century levels, although individual locations may benefit"
- "Without adaptation, local temperature increases of 1°C or more above pre-industrial levels are projected to negatively impact yields for the major crops (wheat, rice, and maize) in tropical and temperate regions, although individual locations may benefit (medium confidence). With or without adaptation, climate change will reduce median yields by 0 to 2% per decade"
- "Positive and negative yield impacts projected for local temperature increases of about 2°C above pre-industrial levels maintain possibilities for effective adaptation in crop production (*high confidence*)."

Source: IPCC (2014), "AR5-WGII, Summary for Policymakers"

Consequences for society will include impacts on human health, security, water and food, livelihoods and poverty

Quotes from IPCC (2014), AR5-WGIII, Summary for policymakers

Human health

- “Until mid-century, projected climate change will impact human health mainly by exacerbating health problems that already exist *(very high confidence)”*

Human security

- “Climate change over the 21st century is projected to increase displacement of people (medium evidence, high agreement).”

Economy, livelihoods and poverty

- Throughout the 21st century, climate-change impacts are projected to slow down economic growth, make poverty reduction more difficult, further erode food security, and prolong existing and create new poverty traps, the latter particularly in urban areas and emerging hotspots of hunger (medium confidence).
- “For most economic sectors, the impacts of drivers such as changes in population, age structure, income, technology, relative prices, lifestyle, regulation, and governance are projected to be large relative to the impacts of climate change *(medium evidence, high agreement).”*

Food and water security

- “For the major crops (wheat, rice, and maize) in tropical and temperate regions, climate change without adaptation is projected to negatively impact production for local temperature increases of 2°C or more above late-20th-century levels, although individual locations may benefit (medium confidence).”
- “Positive and negative yield impacts projected for local temperature increases of about 2°C above preindustrial levels maintain possibilities for effective adaptation in crop production *(high confidence).”*
- “Freshwater-related risks of climate change increase significantly with increasing greenhouse gas concentrations (robust evidence, high agreement). The fraction of global population experiencing water scarcity and the fraction affected by major river floods increase with the level of warming in the 21st century”

Source: IPCC (2014), “AR5-WGII, Summary for Policymakers”

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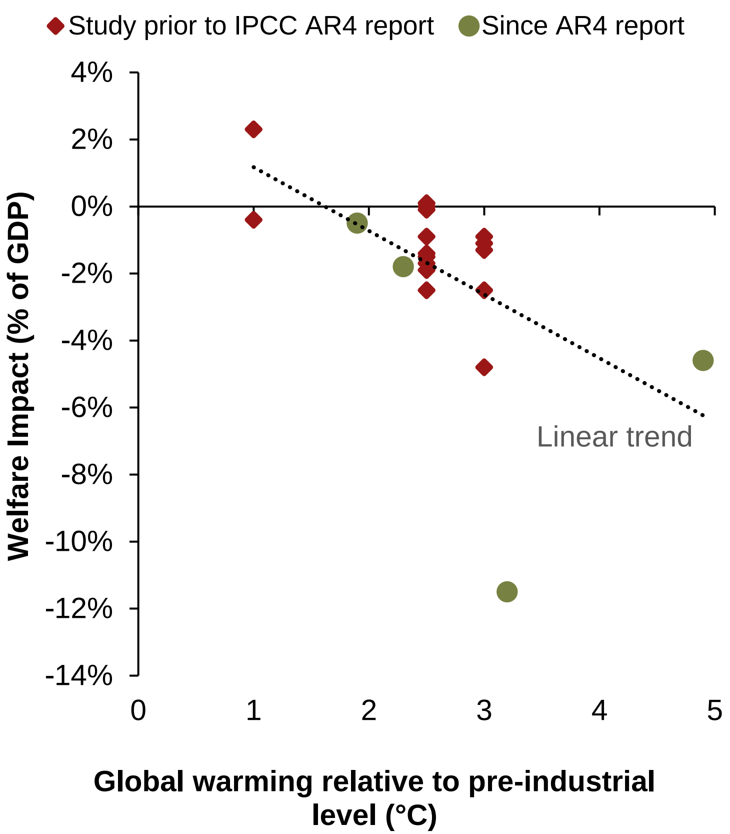
Economic impacts on society and economies are difficult to estimate because of uncertainties in climate change, and society's potential to adapt and innovate

Economic impact of climate change, as function of assumed global warming

(Collection of 19 peer-reviewed studies completed over the past 20 years)



Economic impact (see graph)

- Various studies have attempted to assess the global aggregated impact of global warming on human welfare. Agreement is generally low because they vary in their coverage of economic sectors and in other assumptions. Yet, in general:
  - Climate-change is projected to slow down economic growth in the 21st century.
  - Aggregate economic losses accelerate with increasing temperature.
  - Developing countries experience relatively larger percentage losses.
- These estimates are considered to represent lower bounds, because indirect impacts are generally not included, such as cultural heritage, ecosystem services…
- In general, the smaller the geographic scale studied, the larger the cost of impacts

Social cost of carbon (in $/t$CO_2$ emitted)

- This useful indicator for policy-making represents the marginal net present value of economic damage of emitting a tonne of CO_2 at any point in time.
- Uncertainty is even greater than for economic impacts, and strongly dependent on the discount rate used. According to 84 existing studies:
  - With a 0% discount rate, estimates average 160 ± 180 $/t$CO_2$.
  - With a 1% discount rate, estimates average 56 ± 77 $/t$CO_2$.
  - With a 3% discount rate, estimates average 11 ±10 $/t$CO_2$.
  - Delaying action could increase it by 2-4% per year.

1. ± refers here to the standard deviation of the distribution.
Source: IPCC (2014), "AR5-WGII, Chapter 10.9"

Appendix

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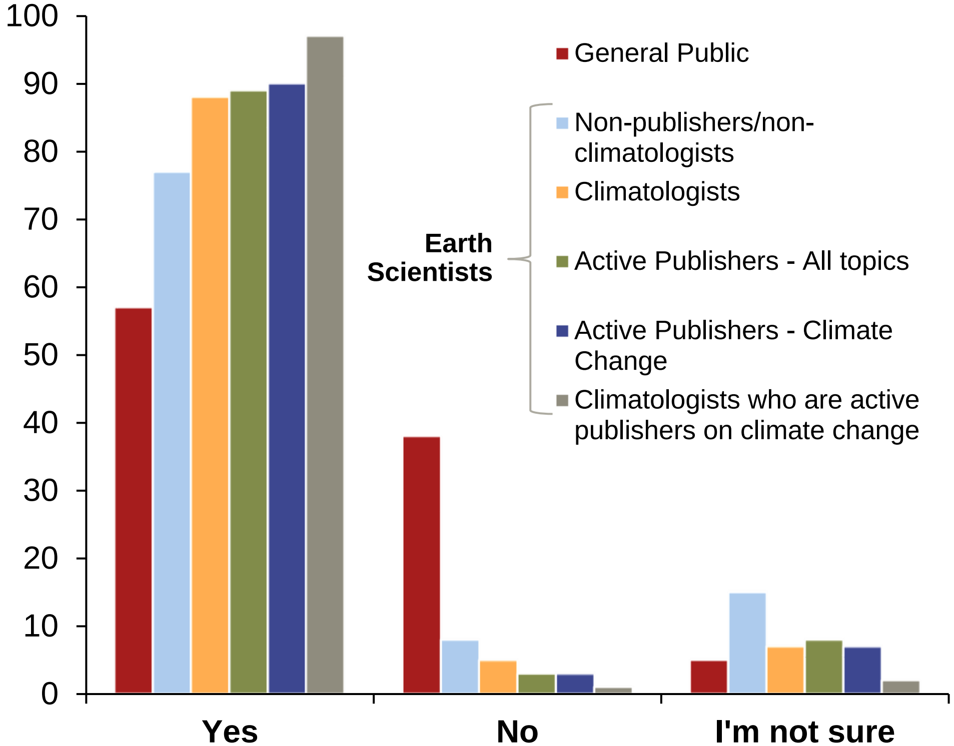
Is there a scientific consensus about climate change?

Response Distribution To Question: “Do you think human activity is a significant contributing factor in changing mean global temperatures?”

(in % of respondents)



- This survey shows a scientific consensus that human activity is causing global warming, which differs significantly from public opinion.
- Nevertheless, science is not based on poll results: scientific agreements are best expressed when quantified with mean estimates and probabilistic ranges of uncertainty.
- In climate science, the IPCC is the UN body that plays this role, summarizing all peer-reviewed papers without intentional omissions, and imposing a very expansive and transparent review process on its own results.
- IPCC assessment reports have been unanimously accepted by the 190+ participating nations over five assessment cycles since 1990, and the summaries for policymakers (SPMs) have been unanimously approved on a word-by-word basis by these nations. In addition, the process and findings have been endorsed by virtually all of the leading national academies of science around the world.

Note: Respondents: 3,146 Earth Scientists working in the Unites States. General Public data comes from a 2008 Gallup opinion poll.
Source: Doran et al. (2009), “Examining the Scientific Consensus on Climate Change”

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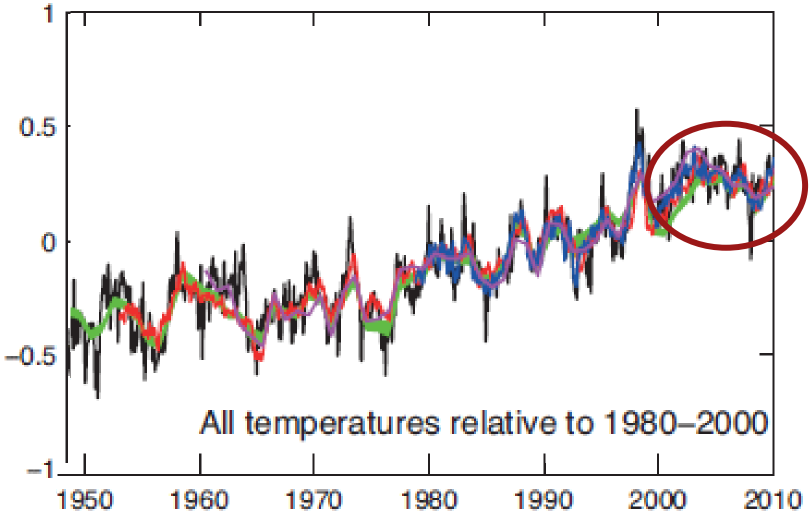
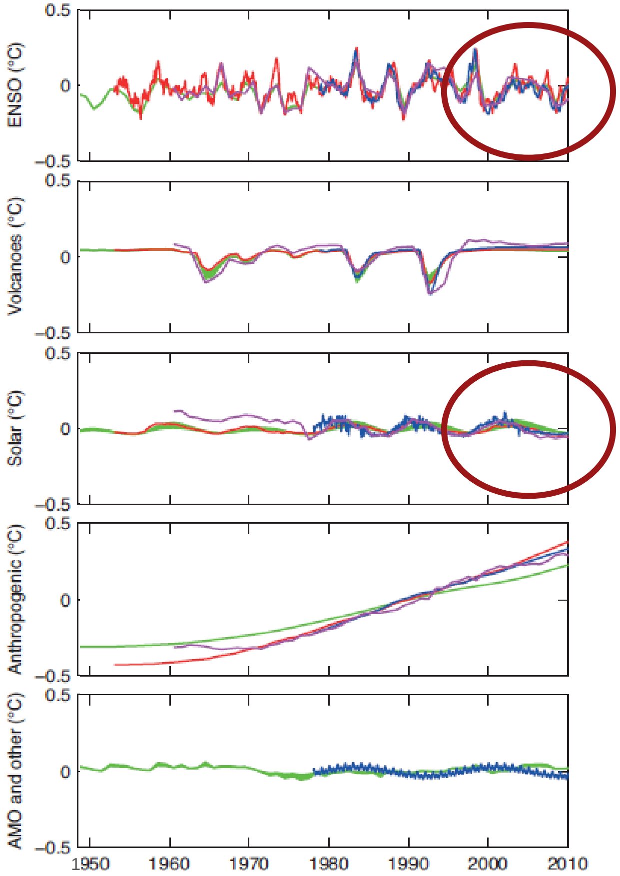
Why have global temperature seemingly stabilized over the past 15 year?

Observed Global Surface Temperature Anomaly

°C relative to 1980-2000 average



Estimated contribution to global temperature (from climate models)



FACT: Linear trend over 1998-2012 is one-third to one-half of that over 1951-2012

ELEMENTS OF ANSWER:

- A 15-year period does not challenge multi-decadal (20-30-year) trends, which are widely recognized as the minimum period over which climate change should be measured, so that instances of internal variability, such as ENSO or AMO oscillations, may be ruled out.
- The IPCC attributes this hiatus roughly in equal measure to a cooling contribution from internal oceanic variability (ENSO) and a reduced trend in external solar forcing.
- 2015 is on track to stand out as exceptionally hot, with ENSO being a major contributor.

Note: ENSO: El Niño-Southern Oscillation. AMO: Atlantic Multi-decadal oscillation. (Graph) Real observation data in black. Climate-models results in colored lines.
Source: Imbers et al. (2013), “Testing the robustness of the anthropogenic climate change detection statements using different empirical models“

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What can be done about climate change, and at what cost?

Definition of mitigation

- 'Climate mitigation' is defined by the IPCC as "a human intervention to reduce the source or enhance the sink of GHGs".
  - Reducing sources means limiting carbon-based fuel burning, process CO2 emissions (e.g. from cement), methane leaks, etc…
  - Enhancing sinks can be achieved by forestry/biomass management, and carbon capture and storage technology.
- Some geoengineering options (see next slide), which only tackle the effect (global warming) and not the cause (GHGs) of climate change, are not strictly speaking mitigation measures and are not included in these cost estimates.

Cost estimates for GHG Mitigation measures (not including ASSOCIATED CLIMATE BENEFITS)

IPCC (2014) - AR5-WGIII: scenarios for 430-480ppmCO_2-eq by 2100

- Net present costs of mitigation (5% discount rate) summed over the 2015-2100 period, compared with what would happen without mitigation (in these projections, it is assumed that the economy will grow by a factor of between four and 10 over the century):
  - GDP losses: 2.9% (2 to 5.7%, 50% range);
  - Consumption losses: 2.7% (2.2 to 4.5%);
  - GHG abatement costs 1.3% of GDP (0.8 to 1.6%).
- Carbon price (marginal abatement cost), in USD2010/tCO2:
  - $40-70 in 2020, $70-120 in 2030, $120-300 in 2050, $900-2000 in 2100;
  - Weighted average price over 2015-2100 period with 5% discount rate: $37 (20-54).

IEA (2014) – ETP: 2DS scenario for 450ppmCO_2-eq

- Requires an additional USD 44 trillion investment by 2050 compared with business as usual, but saves USD 115 trillion in fuel.
- Delivers net present benefits of USD 5 trillion at 10% discount rate.
- Carbon price (USD_{2013}/tCO_2): $30-50 in 2020, $80-100 in 2030, $140-170 in 2050.

Source: IPCC (2014), "AR5-WGIII Section 6.3.6"; IEA (2014), "Energy Technology Perspective"

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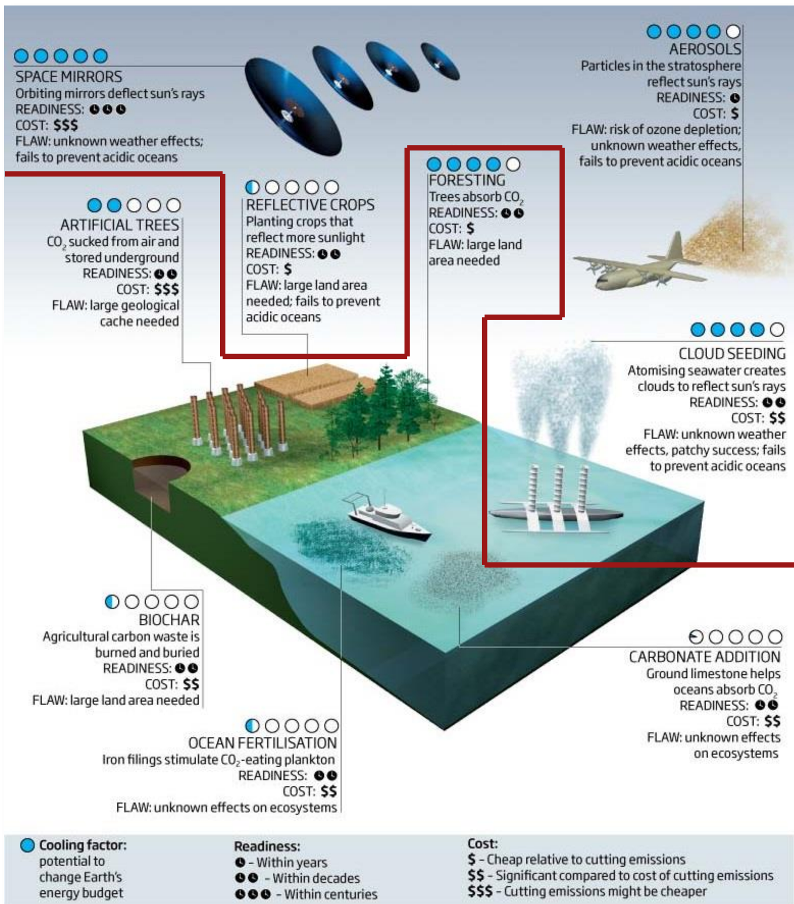
Could geoengineering complement GHG mitigation in reducing global-warming impacts?

Geoengineering options



- Geoengineering refers to the large-scale engineering and manipulation of the planetary environment to moderate or counteract global climate change in response to the emission of GHGs to the environment
- Two fundamental approaches to geoengineering have been proposed, but neither appears to be ready for implementation:

  1. **Solar radiation management**
     (Reflect more sunlight back into space to cool the Earth)
  2. **CO_2 management**
     (Enhance the removal of atmospheric CO_2 to reduce greenhouse effect)

- Initiating geoengineering as early as possible while actively pursuing GHG reductions might help maintain the climate close to its present state.

Source: Brahic Catherine (2009), "Geoengineering weighed up". High definition graph available at http://www.newscientist.com/data/images/archive/2697/2697360jpg

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Is solar radiation management a plausible geoengineering option for the long term?

PROS

- Some of the approaches to limiting incoming solar radiation could be relatively inexpensive to implement, but must be sustained over time to produce meaningful effects:
  - Stratospheric aerosol injections would imitate the cooling effects of volcanic eruptions, but on a continuous basis;
  - Brightening marine stratus clouds with tiny seawater particles would reflect more sunlight back into space, but could change the amount of rain;
  - Increasing surface reflectivity is possible, but would restrict use of land areas for other high-priority needs.
- Other approaches to limiting global warming resemble science fiction:
  - Putting a solar screen in space would involve tremendous expense and very clever navigation and engineering.
- Applying suggested approaches mainly to moderate impact hotspots such as the Arctic might be possible.

CONS

- Only treats the symptoms, not the cause:
  - Excuse not to reduce GHGs?
- Only treats some aspects of the problem:
  - Only mitigates the rise of global mean temperatures;
  - Not a cure for ocean acidification.
- Cannot be a substitute for GHG emissions reductions:
  - Very high rate of warming in the case of failure of implemented geoengineering solution.
  - Once started, it would need to be maintained until the concentration of GHGs returned to pre-industrial levels (potentially centuries).
- Potential unintended consequences:
  - Reducing direct solar beams needed for some renewable energy technologies such as Solar CSP;
  - Diminishing monsoons?
- Who would pay for any unintended consequences?
- Ethical/political questions: How to decide what the temperature should be? Who would decide?
  - If it is surprisingly inexpensive, could a country or rich individual do it unilaterally?

Source: Robock (2008), “20 reasons why geoengineering may be a bad idea”

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Dr. Michael MacCracken's point of view (1/2)

Chief Scientist for Climate Change Programs, Climate Institute, Washington DC.

Overall position on global warming

"Study of the Earth system over the past two centuries has identified periods both much warmer and much colder than present, providing a diverse record to explore and from which to gain understanding. Particularly over the last 50 years, significant progress has been made in identifying the natural factors that likely contributed to these past changes and assembling representations of their influences into a quantitatively consistent model framework. Human activities, particularly combustion of fossil fuels, are now significantly increasing the concentrations of greenhouse gases. When natural factors (e.g., shifts in continental distribution, major sequences of volcanic eruptions, etc.) have led to a higher atmospheric CO_2 concentration over the course of Earth's history, the world has become warmer, consistent also with what is observed and understood about temperatures on Venus and Mars and with theoretical analyses. While uncertainties remain, the changes in atmospheric composition projected for the 21st century have in the past caused warming of several degrees Celsius and been periods with much smaller ice sheets and much higher sea level. If there is a model bias, it is that current models, which do not yet include some of the slower-acting processes, underestimate rather than overestimate climate sensitivity. Global warming just cannot be summarily dismissed."

About sensitivity derived from analogs from the past

[From the paleoclimate record] *"Analyses of past climates make clear that climate changes for a reason. While analyses are complicated […] the wide range of past conditions allows for intercomparison and cross-checking. The analyses generally indicate that past changes in climate cannot be explained if the climate sensitivity (i.e., by definition, the equilibrium response to the forcing that would result from a doubling of the CO_2 concentration) is less than about 2ºC. In addition, were the equilibrium climate sensitivity more than about 5ºC, it would be very difficult to explain the relative stability of the climate during the Holocene."*

[From the instrumental period] *"For most of the last 150 years, changes in both climate and in the natural and anthropogenic factors that have the potential to influence the climate are reasonably well-documented or reconstructed from proxies that can be calibrated against observations. In seeking to derive the climate sensitivity from this information, the effects of all possible factors must be quantitatively accounted for simultaneously, plus the delaying effect of the time it will take to warm the ocean. Detailed detection-attribution studies look for the characteristic temporal-spatial fingerprint of each type of forcing in not only global average temperature, but also in its vertical and latitudinal distribution, in patterns of ocean heating, in water vapor concentration, and more. Results indicate a consistency only when the influences of natural and anthropogenic factors are contributing, and only when the climate sensitivity is consistent with the values from paleoclimatic and modeling studies."*

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Dr. Michael MacCracken’s point of view (2/2)

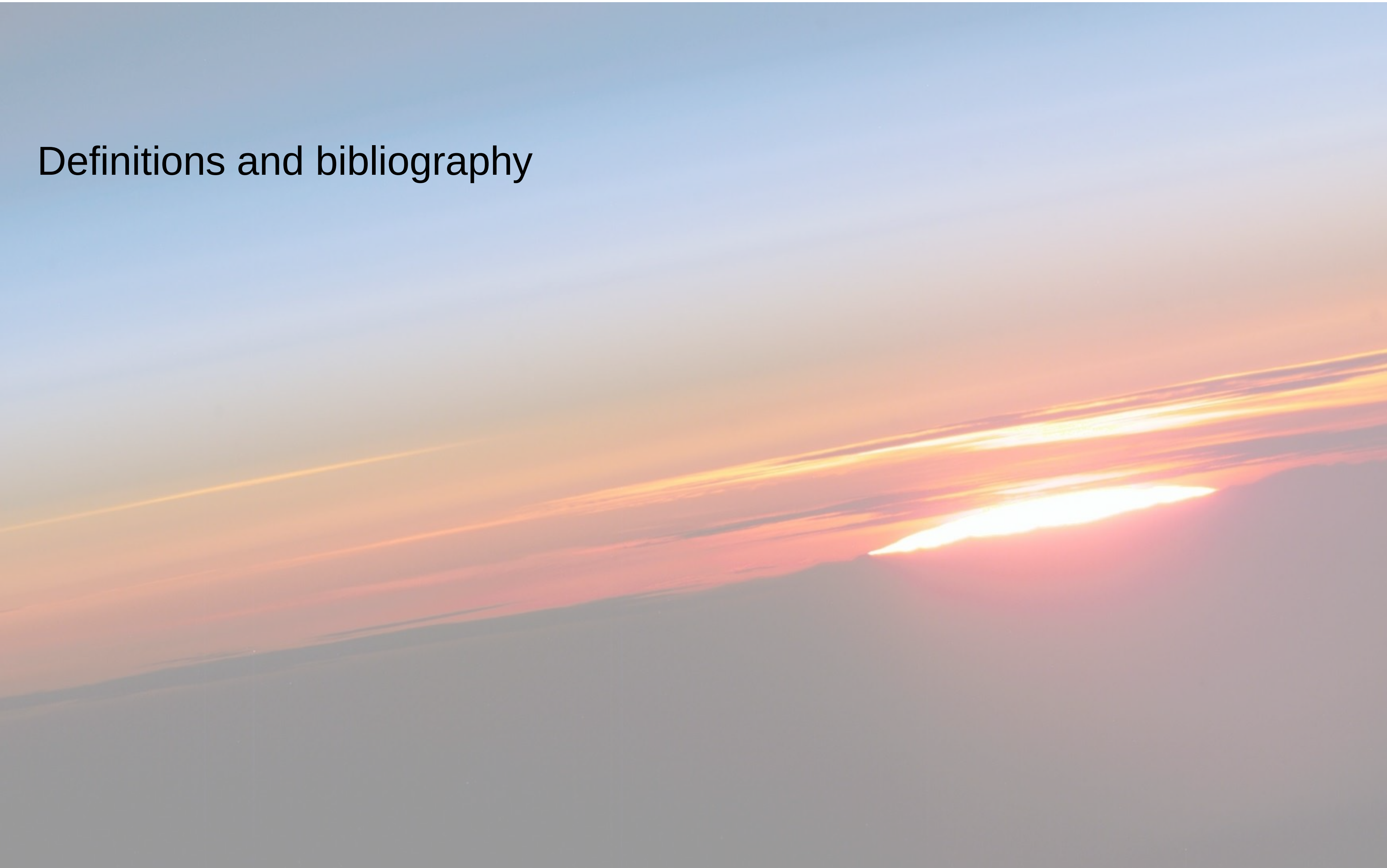
Chief Scientist for Climate Change Programs, Climate Institute, Washington DC.

About climate forcing analysis

“ [it is] correct that models are not yet simulating all aspects of unforced internal variability (ENSO, PDO, AMO, etc.) as well as will be needed to make seasonal to interannual predictions, but these phenomena mainly lead to regional fluctuations in the climate over a few years rather than a long-term response in global average temperature. Detection-attribution studies indicate that the temporal and spatial patterns of these variations do not explain the temporal and spatial patterns of the observed multidecadal changes in temperature as well as the changes in natural and anthropogenic external forcings. [The fact that the Earth’s surface temperature is never in equilibrium with solar input] is exactly why the thermal inertia of the ocean must be accounted for. Were one to evaluate model performance against [the] assertion that Milankovitch variations alone quantitatively explain the ice ages, one would have to conclude that the climate models have too low a climate sensitivity”

About climate feedbacks

“The models used for climate change studies include the same physics representations that are in weather forecast models. Decades of experience with those models makes clear that it is essential to include the feedback processes […]. That the atmospheric water vapor concentration responds as the temperature changes is evident in the seasonal cycle and latitudinal variation of the water vapor concentration; satellite data confirm that model simulations and observations of water vapor feedback are in good accord, indicative of a strong positive feedback. The snow- and ice-albedo feedbacks are also obviously positive in that the warmer it gets, the more the snow and ice melt, the lower the surface reflectivity, and the greater the solar absorption and warming. Whether cloud feedbacks are amplifying or moderating is indeed not clear—generally, the low-lying and highly reflective clouds are present where the surface is so cool that convection is not excited, whereas deep, but narrow, convective clouds are present when it is warmer, and so the average areal albedo goes down with warming, creating a positive feedback. But warming also changes the amount of water vapor in clouds, droplet sizes, the amount of cirrus clouds, and more, so uncertainties remain. It is this uncertainty that is the main reason that the IPCC has not narrowed its 1.5 - 4.5ºC range for the climate sensitivity. It is the consistency and agreement of paleoclimate, instrumental, and theoretical approaches (the last as represented in climate models based on the fundamental laws of physics and tested against observations on seasonal to multi-centennial time scales) in estimating climate sensitivity that underpins the conclusions of the IPCC that human activities are very likely responsible for most of the climate change over the last half century, and will be responsible for much greater change in the future.



Definitions and bibliography

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Definitions

Aerosols: small particles in suspension in the air (lofted ash, black carbon, sulfate, small water droplets…).

Albedo: The fraction of solar radiation reflected by a surface or object, often expressed as a percentage.

Atmosphere: The gaseous envelope surrounding the Earth. It consists of the *troposphere* (lower atmosphere) and the *stratosphere* (higher atmosphere). The boundary between these two layers is called the *tropopause*.

Anthropogenic: manmade

CO_2e: CO_2-equivalent: CO_2e is a quantity that describes, for a given GHG, the amount of CO_2 that would have the same GWP over a given period, usually 100 years (see GWP).

Climate feedback: a response to a change in the Earth's temperature that in turn increases or decreases radiative forcing (W/m² per °C).

Climate change: a significant change in the statistical distribution of weather patterns, sea level or ocean acidification over a sustained period of at least 20-30 years.

Climate forcing: any change in a factor influencing the Earth's energy balance, expressed as a change in radiative forcing (W/m²).

Climate sensitivity: the amount of global warming resulting from a given climate forcing (°C per W/m²).

Earth energy imbalance: difference between incoming solar radiation and the sum of outgoing radiations (reflected visible and infrared).

Equilibrium Climate Sensitivity (ECS), often shortened to 'sensitivity', is a measure of how responsive the temperature of the Earth is to a change in the radiative forcing. ECS is the total warming resulting from a given climate forcing (often using a doubling of the CO_2 concentration as a reference case).

GHG: greenhouse gas, a molecule that has three or more atoms and can absorb and radiate infrared radiation, causing greenhouse effect.

Greenhouse effect: The infrared radiative effect of all greenhouse gases in the atmosphere. It consists a warming of the troposphere and a cooling of the stratosphere: were the atmosphere a single isothermal and perfectly mixed layer, there would be no warming effects due to added greenhouse gases.

Global warming: In this report, global warming refers to the increase of global average surface temperature (land and sea combined), measured over a period of at least 30 years. Various altitudes of the atmosphere may not warm uniformly, but it is at the surface that changes have the most direct impacts on ecosystems. Surface warming is nearly equivalent to troposphere warming, since this layer is dynamically mixed by winds.

GWP: Global Warming Potential: The relative warming effect of a given mass of GHGs compared with the same mass of CO_2 over a specified time (usually 100 years).

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Definitions

IEA: International Energy Agency

IPCC: Intergovernmental Panel on Climate Change

Lag in climate response: time it takes for the Earth to restore energy balance after its equilibrium has been altered by a climate forcing.

Likelihood: “likely” refers to a likelihood greater than 67%, “very likely” greater than 90%, “extremely likely” greater than 95%, and “virtually certain” greater than 99%.

Primary (or direct) radiative response: The theoretical increase in the Earth’s average surface temperature for a given radiative forcing, in the following idealized situation: Earth considered as a grey body with a fixed surface reflectivity equal to present Earth’s average, no oceans, no seasons or lag effect, no atmosphere, greenhouse effect, or any other radiative feedbacks.

ppm/ppb: parts per million/billion.

Radiative forcing (W/m^2): The net radiative influence at the tropopause resulting from an instantaneous change in the concentration of a given GHG or other substance, sometimes allowing for a return to equilibrium of stratospheric temperatures. Positive value meaning a gain in energy, and vice versa. For instance, the current radiative forcing of an atmospheric agent relative to 1750 expresses the change in the Earth’s energy balance that would instantly follow the release of a quantity of that agent equal to that emitted since 1750, minus the amount removed via natural decay, oceans and land sinks over the same period. When this value is adjusted to take into account fast-acting feedbacks (which are directly linked to the emitted compound rather than a result of an increase in Earth’s temperature), it is generally referred to as Effective Radiative Forcing (ERF). This distinction, mostly relevant for local climate forcing such as aerosols, is not covered in this report, which uses only ERF values.

Stratosphere: Portion of the atmosphere above the troposphere.

TOA: Top of the atmosphere.

Troposphere: The lowest portion of the Earth’s atmosphere (<17 km on average), at which all weather phenomena occur. Since this layer is dynamically mixed by winds, an average surface warming is nearly equivalent to an average troposphere warming.

Tropopause: The boundary in the Earth atmosphere between the troposphere and the stratosphere.

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