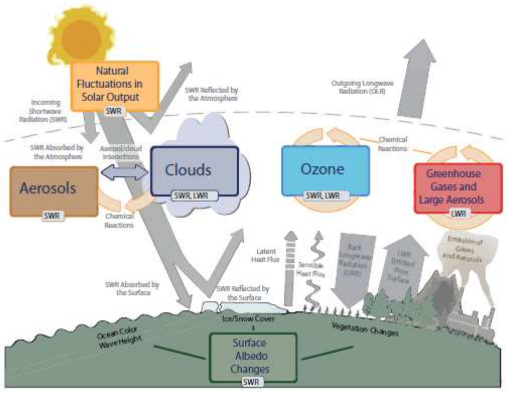
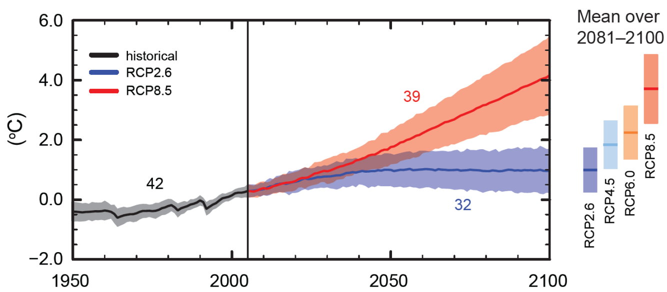
Energy, Environment and Sustainability

Lecture

Climate science: history and present status

Climate: issues and new challenges





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Vítor Leal | 2019.12.04

Who and **when** “discovered” human-induced climate change ?

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THE ARTIFICIAL PRODUCTION OF CARBON DIOXIDE 223

551.510.4 : 551.521.3 : 551.524.34

THE ARTIFICIAL PRODUCTION OF CARBON DIOXIDE AND ITS INFLUENCE ON TEMPERATURE

By G. S. CALLENDAR

(Steam technologist to the British Electrical and Allied Industries Research Association.)

(Communicated by Dr. G. M. B. Dobson, F.R.S.)

[Manuscript received May 19, 1937—read February 16, 1938.]

Summary

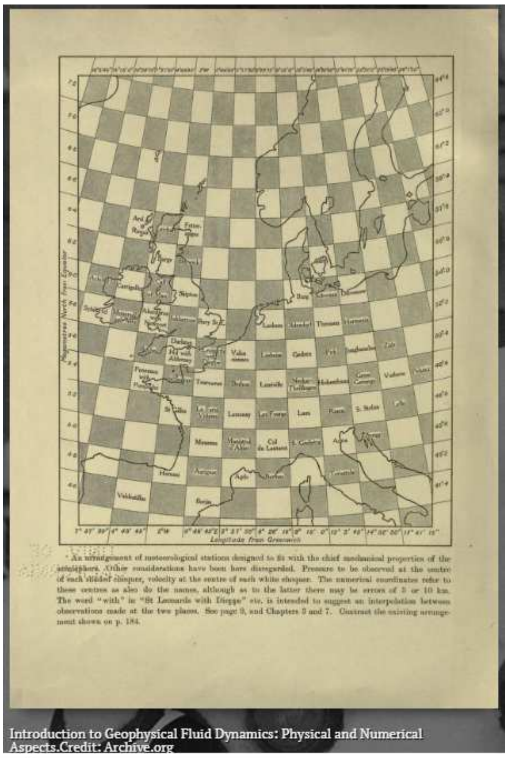
By fuel combustion man has added about 150,000 million tons of carbon dioxide to the air during the past half century. The author estimates from the best available data that approximately three quarters of this has remained in the atmosphere.

The radiation absorption coefficients of carbon dioxide and water vapour are used to show the effect of carbon dioxide on " sky radiation." From this the increase in mean temperature, due to the artificial production of carbon dioxide, is estimated to be at the rate of 0·003°C. per year at the present time.

The temperature observations at 200 meteorological stations are used to show that world temperatures have actually increased at an average rate of 0·005°C. per year during the past half century.

Callendar. 1938. The artificial production of carbon dioxide and its influence on temperature. Quarterly Journal of the Royal Meteorological Society.

When did "climate modelling" begin ?



Introduction to Geophysical Fluid Dynamics: Physical and Numerical Aspects.Credit: Archive.org

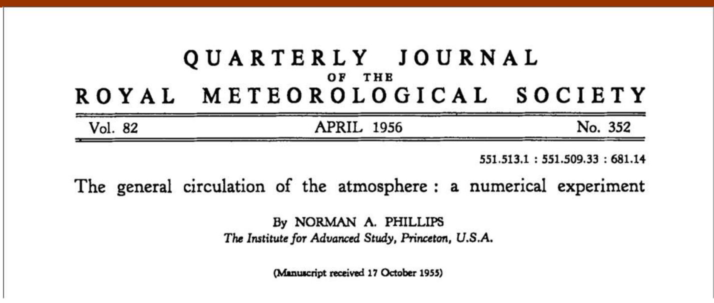
1922 - The story of **climate modelling using numerical methods** begins with Lewis Fry Richardson, an English mathematician and meteorologist, when he publishes a book, entitled "Weather Prediction by Numerical Process".

The book describes his idea for a new way to forecast the weather using differential equations and viewing the atmosphere as a network of gridded cells. But when he applies his own method, it takes him six weeks doing calculations by hand just to produce an eight-hour forecast. He imagines a stadium full of "computers" (64,000 human calculators) all working together to speed up the process. But without mechanical computers, his attempts fail.

Richardson builds upon the earlier ideas of the Norwegian meteorologist, Vilhelm Bjerknes, who had argued at the turn of the 20th century that atmospheric changes could be calculated from a set of seven “primitive equations”.

Before them both, in 1895, the Swedish physical chemist Svante Arrhenius had described an **energy budget model that considered the radiative effects of carbon dioxide** in a paper presented to the Royal Swedish Academic of Sciences.

Source: carbonbrief.org



QUARTERLY JOURNAL OF THE ROYAL METEOROLOGICAL SOCIETY

Vol. 82 APRIL 1956 No. 352

551.513.1 : 551.509.33 : 681.14

The general circulation of the atmosphere : a numerical experiment

By NORMAN A. PHILLIPS
The Institute for Advanced Study, Princeton, U.S.A.

(Manuscript received 17 October 1955)

1956 - FIRST GENERAL CIRCULATION MODEL

- Norman Phillips, a member of the team at Princeton working under John von Neumann, publishes a paper entitled, “The general circulation of the atmosphere: A numerical experiment”, in the Quarterly Journal of the Royal Meteorological Society.
- His numerical experiment, which realistically depicts seasonal patterns in the troposphere, is later hailed as the first “general circulation model” (GCM) of the atmosphere.
- As a theoretical meteorologist, he is less interested in weather forecasts, more in what drives the circulation of the atmosphere and whether this can be modelled. He does this using a computer with just 5K of memory and a further 10K on a separate disc.
- Phillips works with von Neumann, Charney and Smagorinsky over this period.

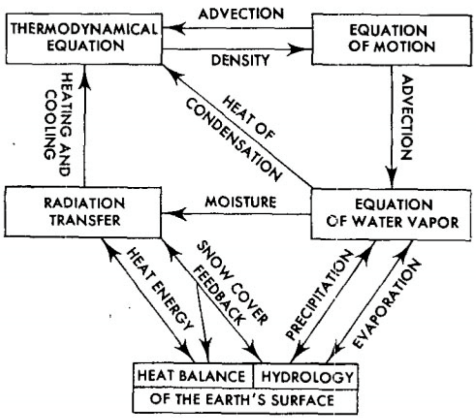
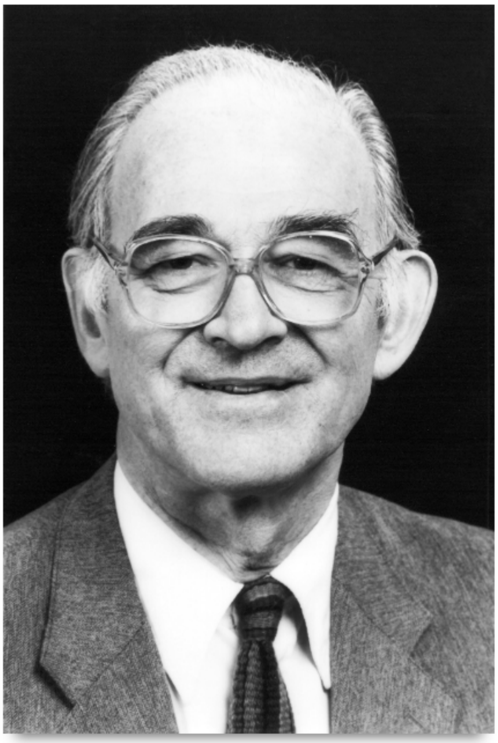


FIG. 2. Box diagram indicating the major components of the model. Arrows represent the links between components.

1975 - DOUBLING OF CO_2

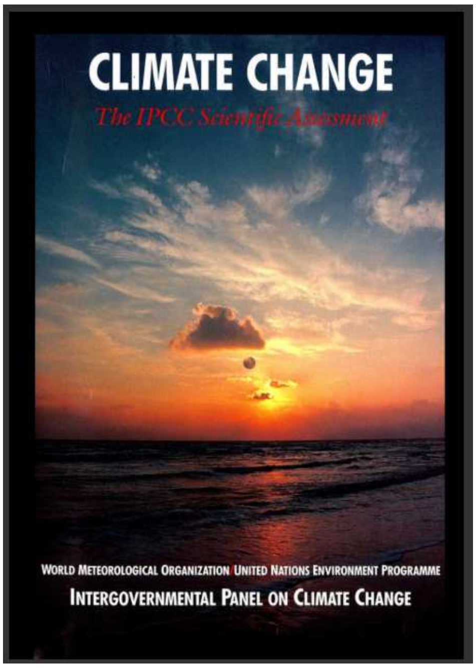
- Manabe and Wetherald publish another seminal paper in the Journal of the Atmospheric Sciences, entitled "The Effects of Doubling the CO2 Concentration on the climate of a General Circulation Model".
- They use a 3D GCM to investigate for the first time the effects of doubling atmospheric CO2 levels.
- The results reveal, among other things, disproportionate warming at the poles and a "significantly" increased intensity of the hydrologic cycle.
- It also shows a value for climate sensitivity of 2.9C – which is still, broadly, the mid-range consensus among climate scientists



Bert Bolin. Credit: KVA

1988
IPCC ESTABLISHED

- The United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) establish the Intergovernmental Panel on Climate Change (IPCC).
- It becomes the leading international body for publishing periodic assessments of climate change. Its aim is to "provide the world with a clear scientific view on the current state of knowledge in climate change and its potential environmental and socio-economic impacts".
- The first IPCC chair is Bert Bolin, a Swedish meteorologist, who had spent a year in 1950 working towards his doctorate at Princeton running early models on ENIAC, alongside the likes of Jule Charney and John von Neumann.



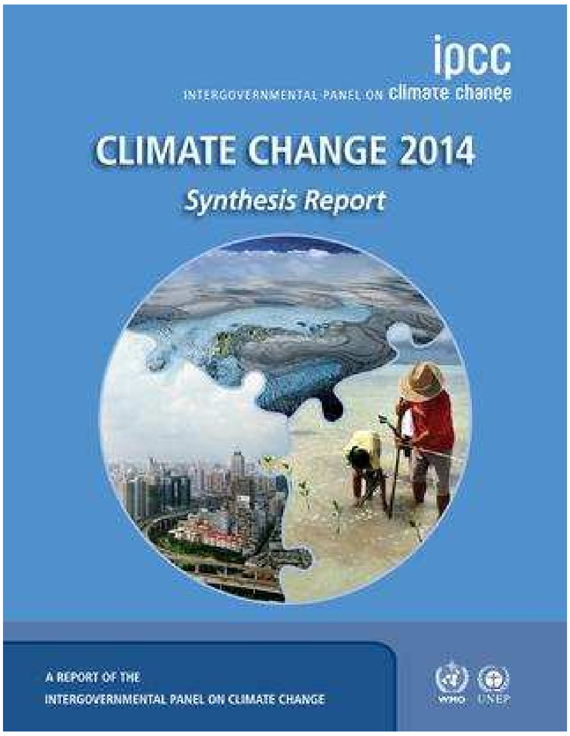
1990

FIRST IPCC REPORT

At a meeting in Sweden, the IPCC formally adopts and publishes its first assessment report. Its summary of the latest climate model projections states that "under the IPCC business-as-usual emissions of greenhouse gases, the average rate of increase of global mean temperature during the next century is estimated to be about 0.3C per decade".

(...)

But there's a note of caution: "Although the models so far are of relatively coarse resolution, the large scale structures of the ocean and the atmosphere can be simulated with some skill. However, the coupling of [these] models reveals a strong sensitivity to small-scale errors which leads to a drift away from the observed climate. As yet, these errors must be removed by adjustments to the exchange of heat between ocean and atmosphere."



SEPTEMBER 2013

IPCC'S FIFTH ASSESSMENT REPORT

At a meeting in Stockholm, Sweden, the IPCC publishes the first report of its fifth assessment cycle (AR5). The report includes an evaluation of the models. It concludes: "The long-term climate model simulations show a trend in global average surface temperature from 1951 to 2012 that agrees with the observed trend (very high confidence). There are, however, differences between simulated and observed trends over periods as short as 10 to 15 years (eg, 1998 to 2012)."

(…)

Reflecting new understanding of radiative forcings, AR5 also slightly adjusts the IPCC's range of equilibrium climate sensitivity to "1.5C to 4.5C (high confidence)". It adds: "The lower temperature limit of the assessed likely range is thus less than the 2C in the AR4, but the upper limit is the same."

Valerie Masson-Delmotte, co-chair of Working Group I, at the 46th Session of the Intergovernmental Panel on Climate Change, 6 September 2017. Photo by IISD/ENB | Mike Muzurakis

2021-2022
IPCC'S SIXTH ASSESSMENT REPORT

Climate scientists gathered in Montreal in October 2017 for the IPCC's annual meeting agree to the chapter outline for AR6, which is due to be published in parts over a few months in 2021-22. The working group one report will include various "evaluations" of how the models have developed and performed since AR5. It will incorporate modelling results from the sixth cycle of CMIP, as well as an extended set of RCP scenarios. Each RCP will be paired with one or more "Shared Socioeconomic Pathways", or SSPs, which describe potential narratives of how the future might unfold in terms of socioeconomic, demographic and technological trends.

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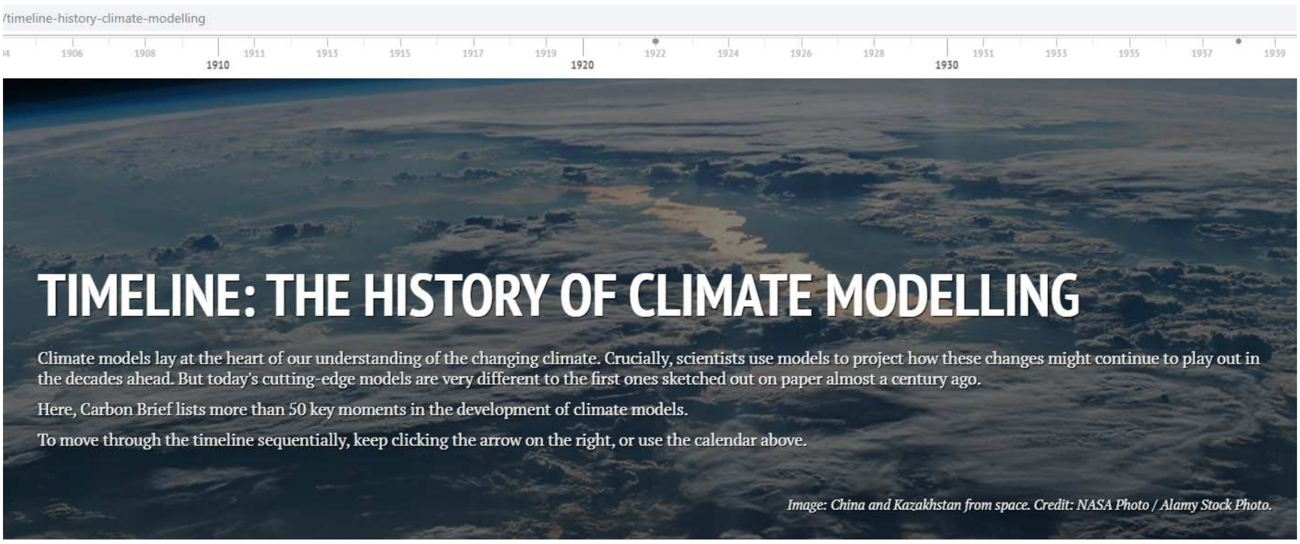
https://www.carbonbrief.org/timeline-history-climate-modelling



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Outline

- Understanding the Earth Climate System
- Climate Historical Observations
- Climate Models
- Climate Forecasts
- Likely Impacts (W & w/o Adaptation)
- Implications for Mitigation
- Paris Agreement and follow-up

The Earth Climate System

What is the Climate ?

Mid-term *Average* and *Variability* of key meteorological variables:

- Temperatures (Air, water…)
- Precipitation
- Wind

→ Difference between Weather and Climate ?

Essentially the time scale of analysis :

→ Weather refers to "hours or days"

→ *Climate typically a sequence of > 30 years.*

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Elements of the Climate System:

- Atmosphere
- Land surface
- Snow and Ice
- Oceans
- Other bodies of Water
- Living beings

All in strong, dynamic interaction.

The main factor "powering" the climate system is solar radiation

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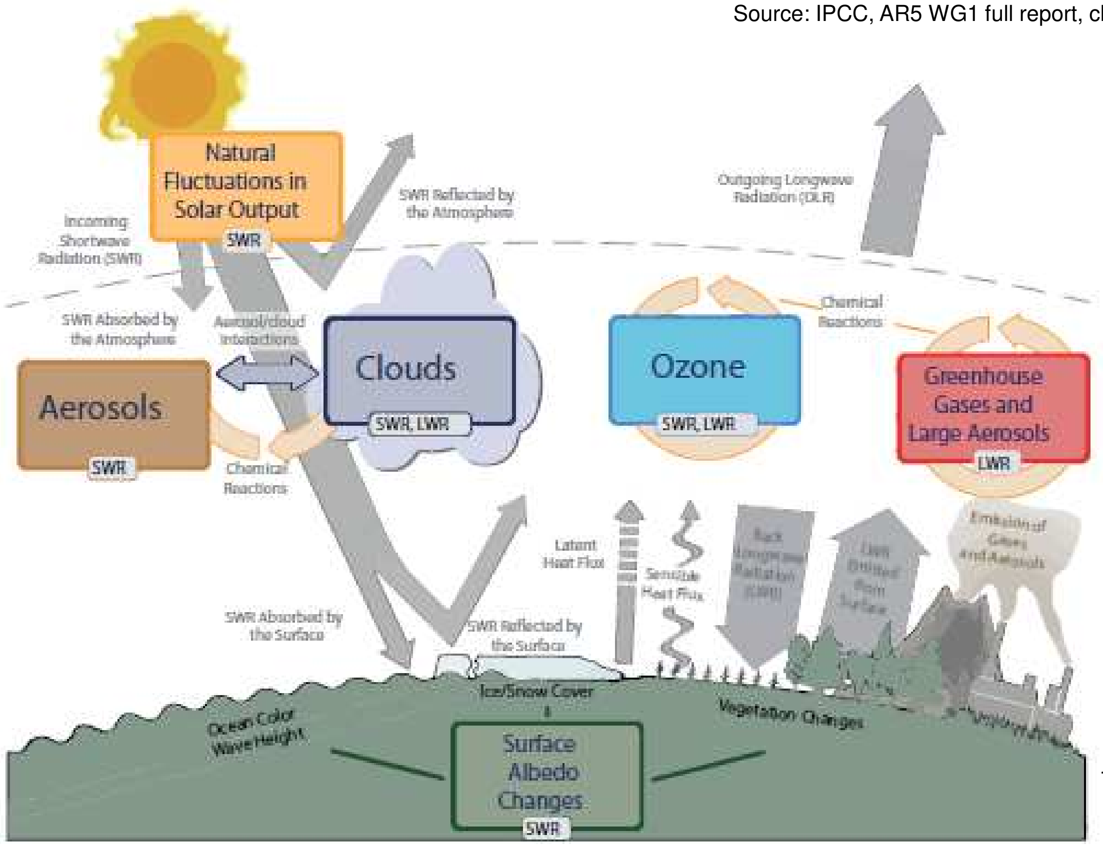
Source: IPCC, AR5 WG1 full report, chapter 1



- In fact, from the 1366 W/m^2 arriving from the Sun, "only" about 240 W/m^2 of SR are actually retained by the Earth and Atmosphere
- In principle, to remain at "constant" temperature, the Earth should emit the same through IR.

Q: At what temperature does a black body emit 240 W/m^2 ?

A: T=(q/σ)^(1/4)= 255K = - 18ºC

However, the observed Average T at Earth's surface is + 14ºC. How to explain this ?

The clouds and "green house gases" intercept a significant amount of the IR radiation emitted by the Earth, preventing it from leaving the planet and thus exerting a "blanket effect".

So, a certain amount of "greenhouse gases" has "always existed" / is necessary to allow life / is "Good".

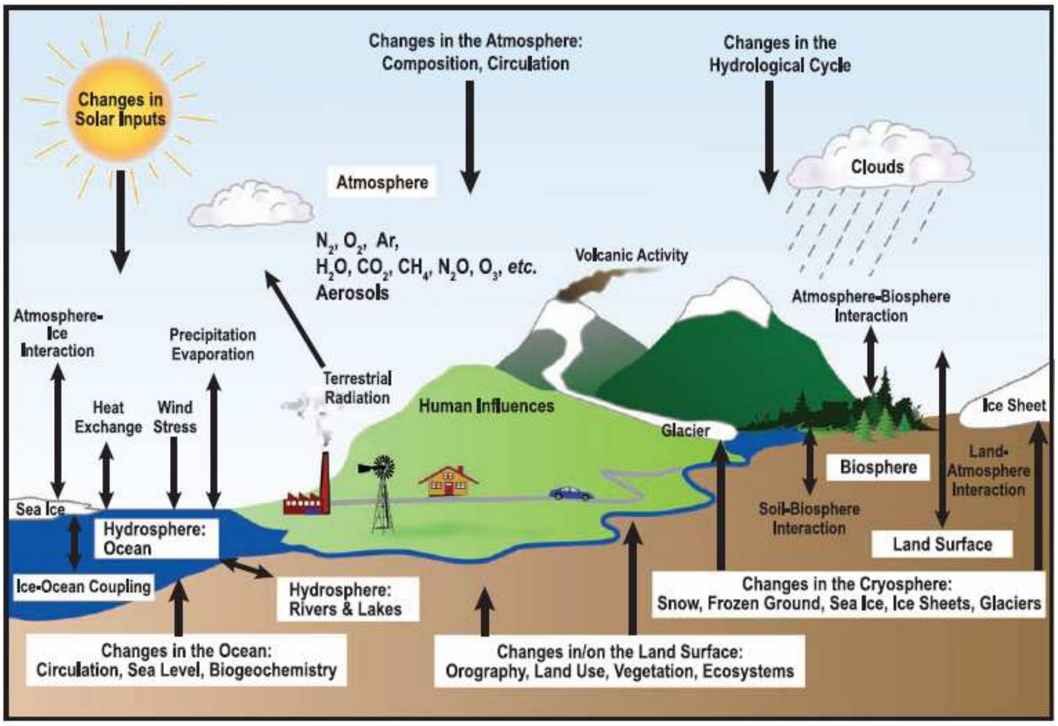
However, increasing them will lead to changes in the temperature at which total energy gains equal total energy losses (balance temperature)...

Forcings

Changes in Climate are due to changes in the driving factors. These changes are called "forcings". Examples:

- Ash due to Volcanic Eruptions
- Changes in (Outer) Solar Radiation
- Changes in the concentrations of some gases in the atmosphere.

Sources of *Forcings*

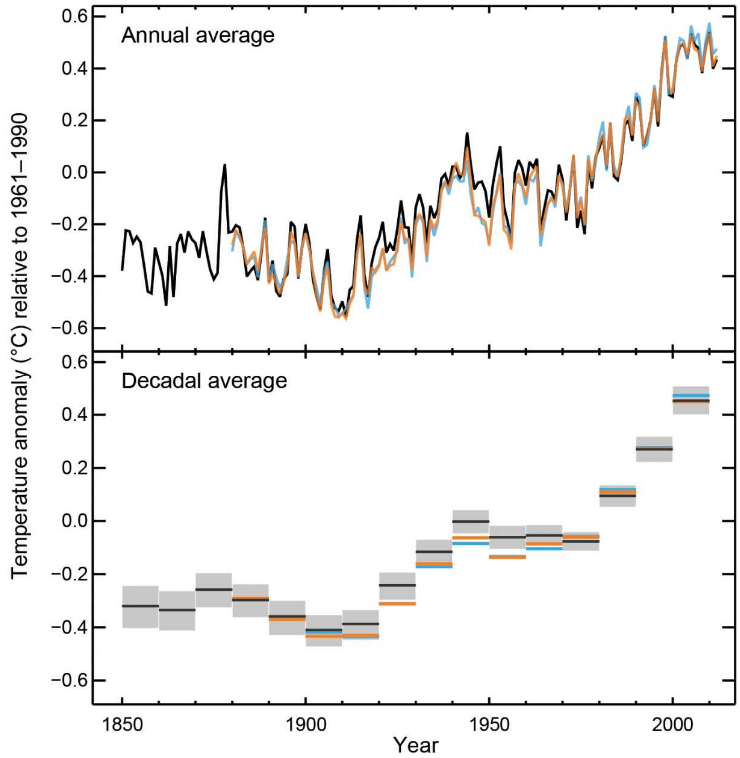


FAQ 1.2, Figure 1. *Schematic view of the components of the climate system, their processes and interactions.*

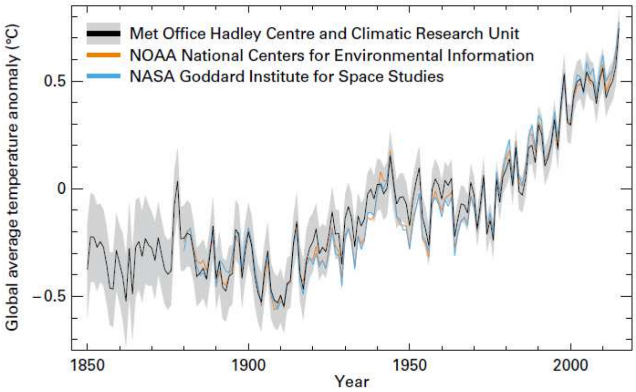
Source: IPCC, AR4 WG1 full report, chapter 1

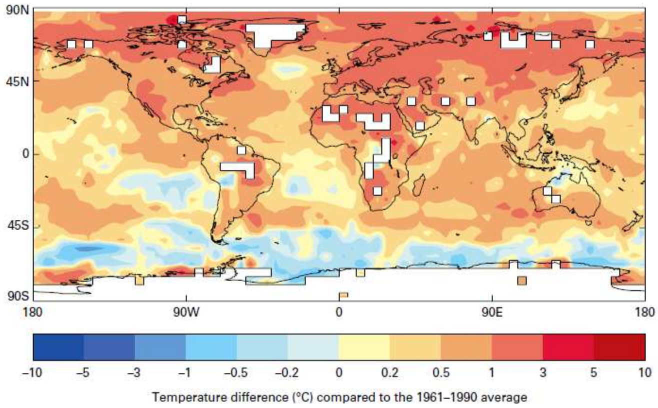
Climate

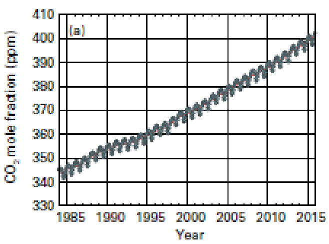
Historical Observations

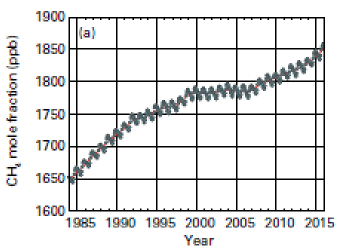


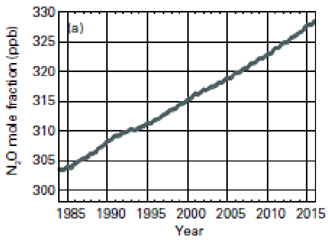
Source: IPCC 5th AR WGI











Source: WMO 2016

Sea level

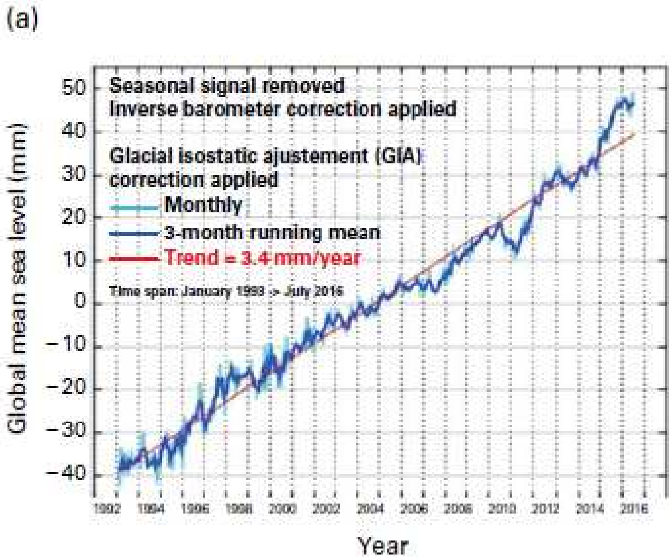


Figure SPM.1b

Observed change in surface temperature 1901-2012

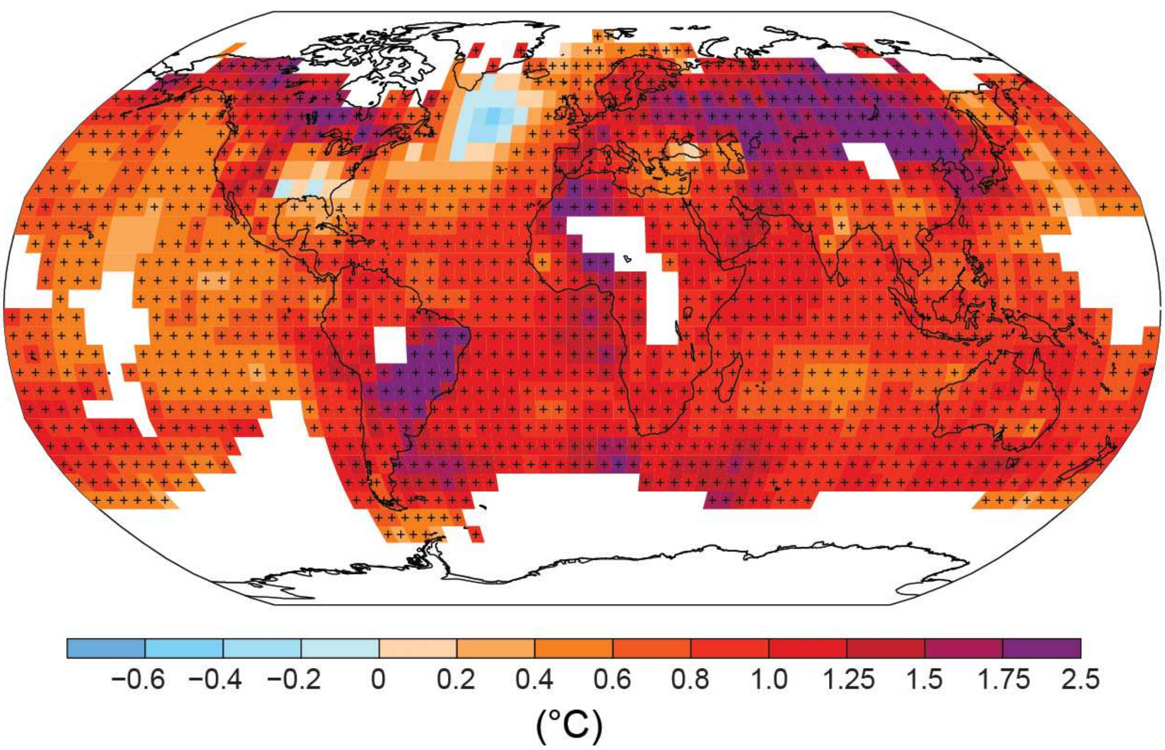


Figure SPM.2
Observed change in annual precipitation over land

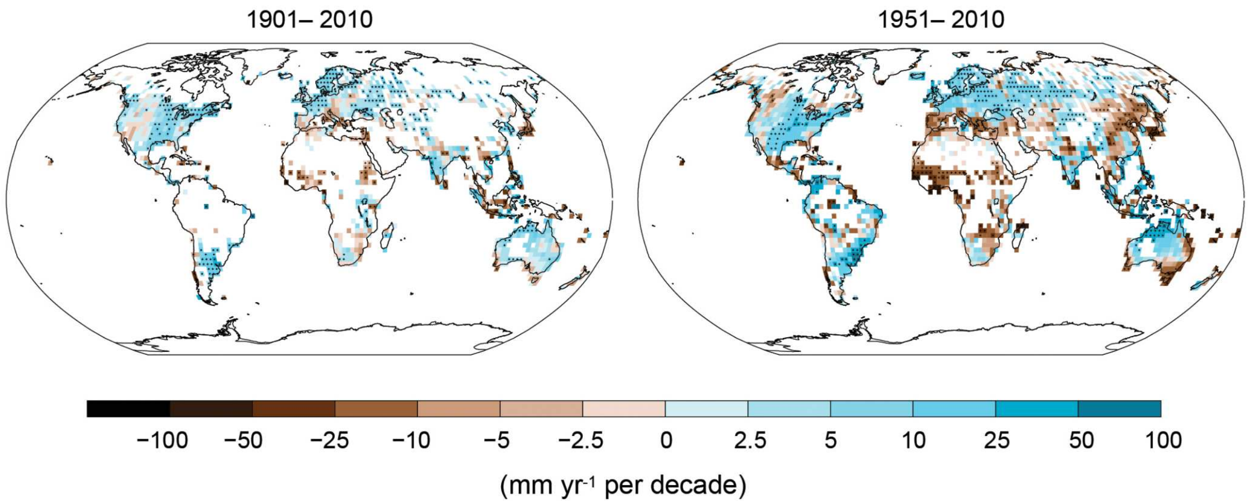


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Figure SPM.3
Multiple observed indicators of a changing global climate

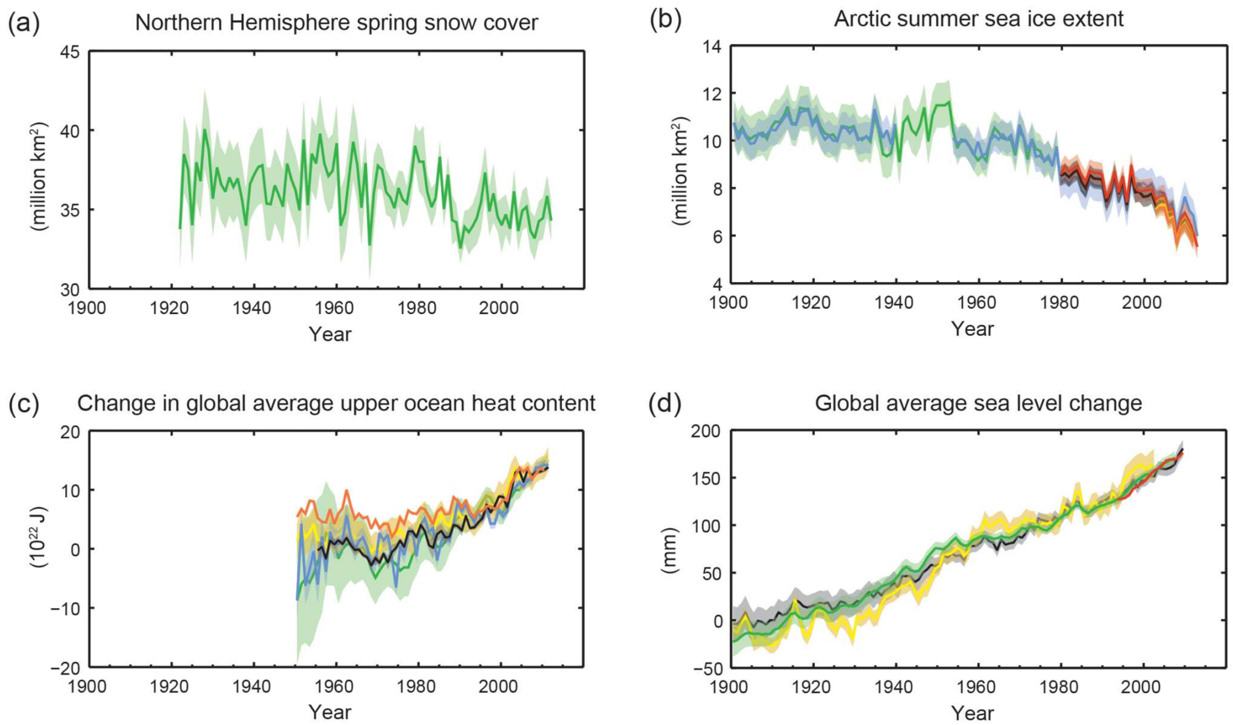

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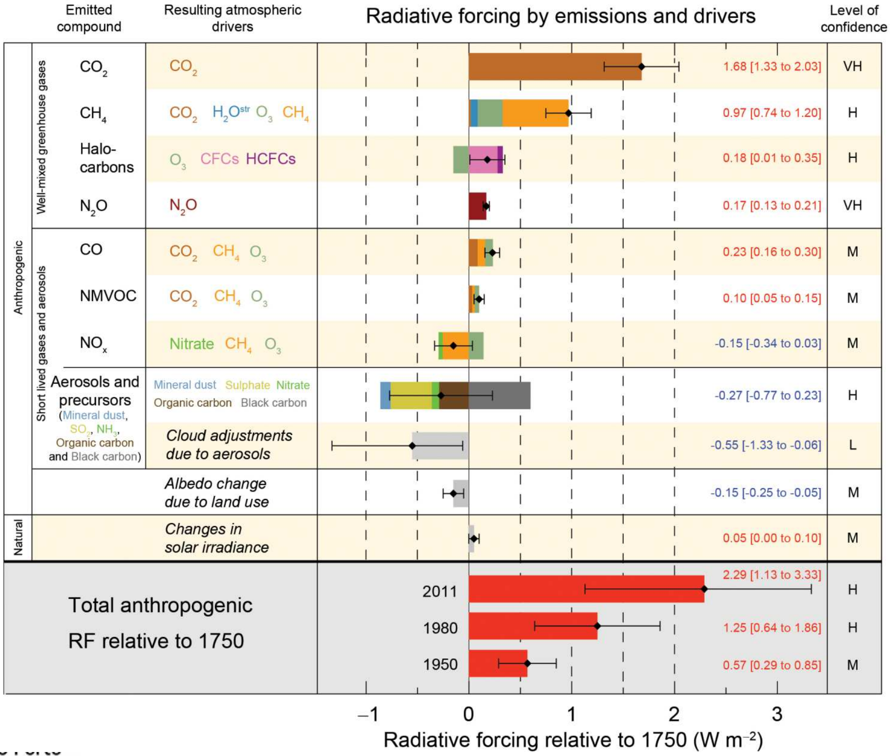
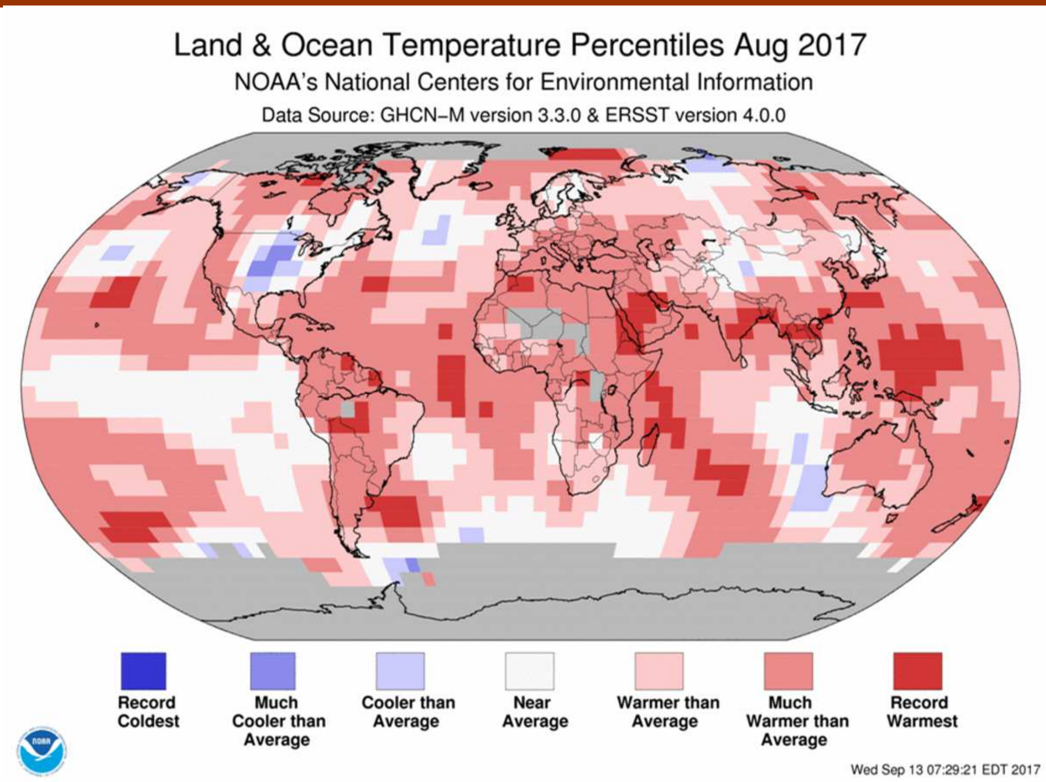
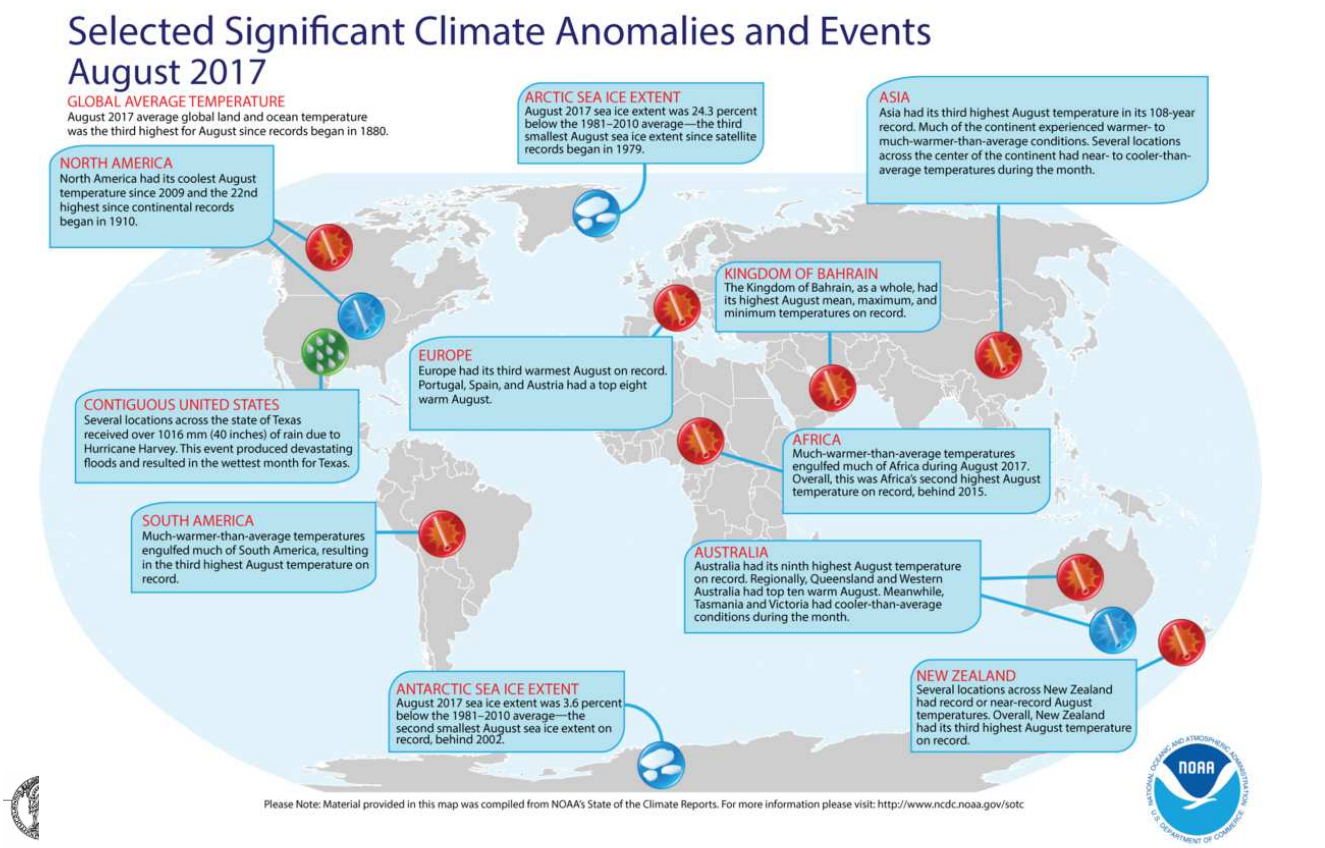
Figure SPM.5

Radiative forcing estimates in 2011 relative to 1750







National Centers for Environmental Information
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

www.ncei.noaa.gov/news/global-climate-201708

- The globally averaged temperature over land and ocean surfaces for August 2017 was the third highest for the month of August in the NOAA global temperature dataset record, which dates back to 1880.
- The June–August seasonal global temperature was also third highest on record, while the year-to-date global temperature was second warmest in the 138-year record.

06 Novembro 2017 às 23:23

COMENTAR

A seca atingiu a nascente do rio Douro, nos Picos de Urbión, Espanha. Não há sinal de água no local, a 2150 metros de altitude.

Segundo testemunhos ouvidos pelo jornal espanhol "El Mundo", os habitantes mais idosos daquela povoação não têm memória de uma seca tão severa num mês de novembro.

https://hipertextual.com/2017/10/sequia-espana-pantanos-embalses-barrios-luna-riano-aguilar

- Can we say that climate has changed ?
- Can we say that the changes are due to human action (anthropogenic origin) ?

Climate Models

How to "predict" future climate ?

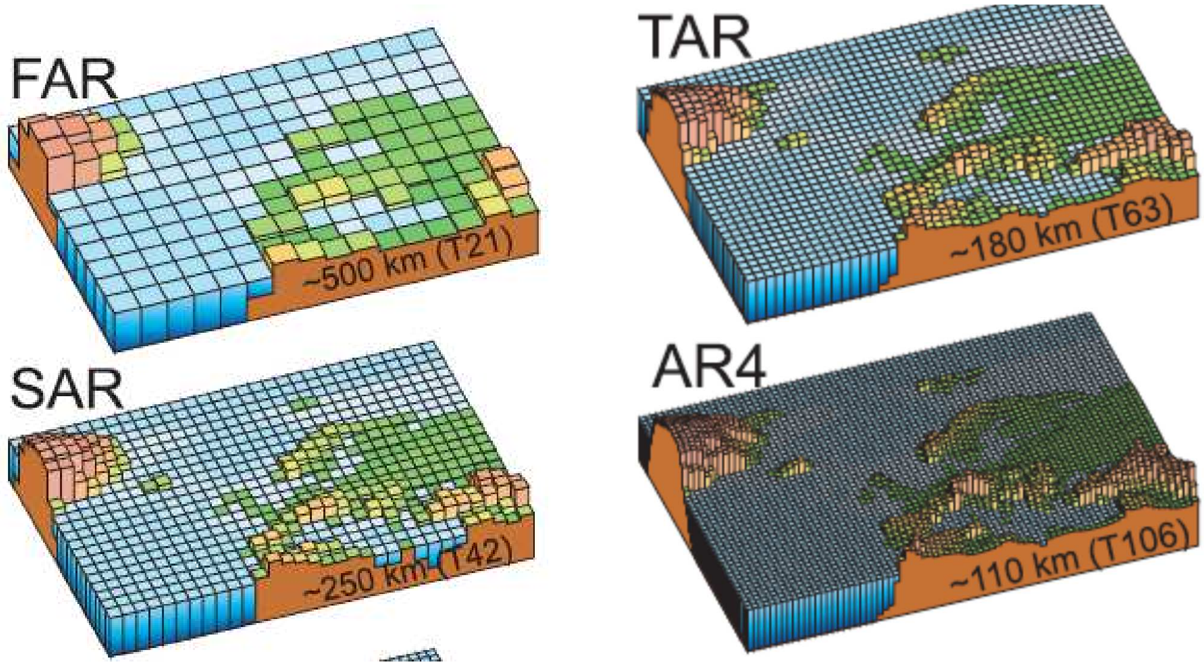
The typical answer in engineering would be "build a model".

Let's see briefly how climate models are built.
https://www.youtube.com/watch?feature=player_embedded&v=PN3Nr_43mvg#t=0

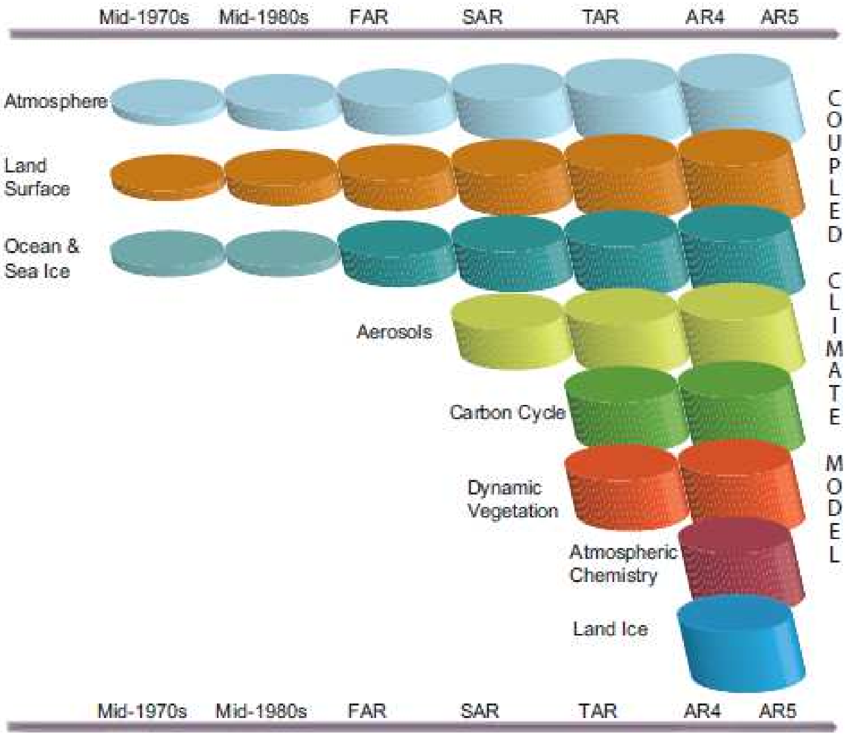
Yet, in Engineering a model only becomes worthy of trust after being validated.

The "ultimate" way of validating a model is performing an experiment.

However, like in Astronomy, we cannot "perform experiments"… Or can we ?



Source: IPCC, AR4 WG1 full report, chapter 1



Source: IPCC, AR5 WG1 full report, chapter 1

	Model name		AOGCM: Atmos	AOGCM: Land Surface	AOGCM: Ocean	AOGCM: Sea-Ice	FC	ESM: Aerosol	ESM: Atmos Chem	ESM: Land Carbon	ESM: Ocean BGC
CMIP5	ACCESS1.0, ACCESS1.3	Australia									
	BCC-CSM1.1, BCC-CSM1.1(m)	China									
	BNU-ESM	China									
	CanCM4	Canada									
	CanESM2										
	CCSM4	USA									
	CESM1 (BGC)										
	CESM1 (WACCM)		HT								
	CESM1 (FASTCHEM)										
	CESM1 (CAM5)										
	CESM1 (CAM5.1-FV2)	USA									
	CMCC-CM, CMCC-CMS	Italy	HT								
	CMCC-CESM		HT								
	CNRM-CM5	France									
	CSIRO-Mk3.6.0	Australia									
	EC-EARTH	Europe									
	FGOALS-g2	China									
	FGOALS-s2										
	FIO-ESM v1.0	China									
	GFDL-ESM2M, GFDL-ESM2G	USA									
	GFDL-CM2.1										
	GFDL-CM3		HT								
	GISS-E2-R, GISS-E2-H	USA	HT					p2,p3*	p2, p3*		
	GISS-E2-R-CC, GISS-E2-H-CC		HT					p2,p3*	p2, p3*		
	HadGEM2-ES	UK									
	HadGEM2-CC		HT								
	HadCM3										
	HadGEM2-AO	Korea									
	INM-CM4	Russia									
	IPSL-CM5A-LR / -CM5A-MR / -CM5B-LR	France	HT								
	MIROC4h, MIROC5	Japan	HT								
	MIROC-ESM		HT								
	MIROC-ESM-CHEM		HT								
	MPI-ESM-LR / -ESM-MR / -ESM-P	Germany	HT								
	MRI-ESM1	Japan	HT								
	MRI-CGCM3		HT								
	NCEP-CFSv2	USA									
	NorESM1-M	Norway									
	NorESM1-ME										
AMIP	GFDL-HIRAM C180 / -HIRAM C360	USA									
	MRI-AGCM3.2S / -AGCM3.2H	Japan									

- How do we know if the models are “right” ?

//

- How do we know the level of precision of the models ?

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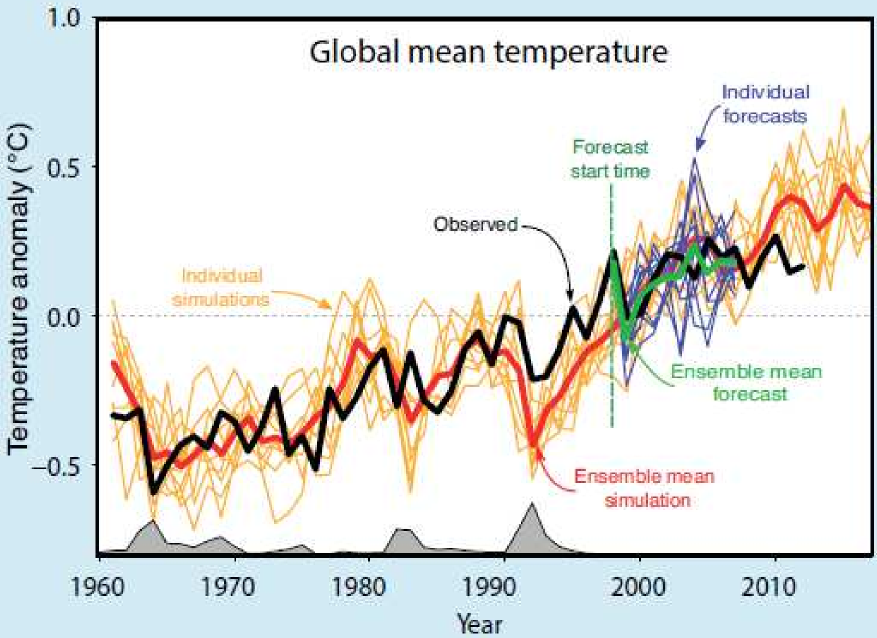
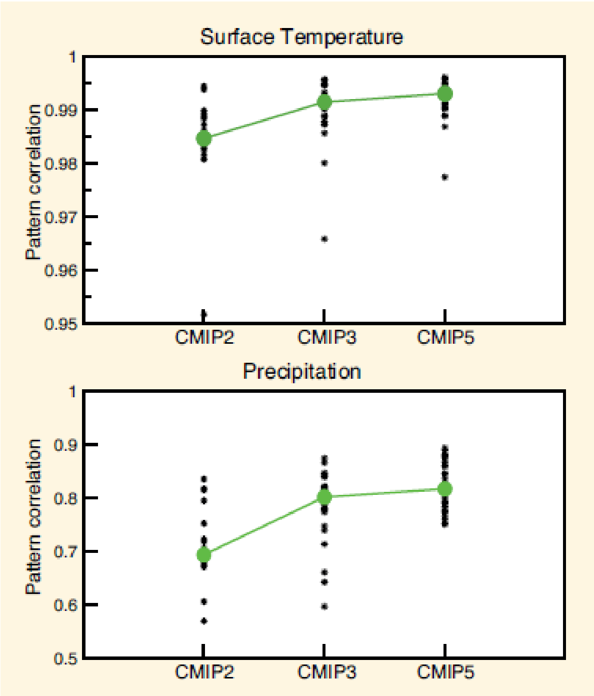


Box 11.1, Figure 1 | The evolution of observation-based global mean temperature *T* (the black line) as the difference from the 1986–2005 average together with an ensemble of externally forced simulations to 2005 and projections based on the RCP4.5 scenario thereafter (the yellow lines). The model-based estimate of the externally forced component T_f (the red line) is the average over the ensemble of simulations. To the extent that the red line correctly estimates the forced component, the difference between the black and red lines is the internally generated component T_i for global mean temperature. An ensemble of forecasts of global annual mean temperature, initialized in 1998, is plotted as thin purple lines and their average, the ensemble mean forecast, as the thick green line. The grey areas along the axis indicate the presence of external forcing associated with volcanoes.



FAQ 9.1, Figure 1 | Model capability in simulating annual mean temperature and precipitation patterns as illustrated by results of three recent phases of the Coupled Model Intercomparison Project (CMIP2, models from about year 2000; CMIP3, models from about 2005; and CMIP5, the current generation of models). The figure shows the correlation (a measure of pattern similarity) between observed and modelled temperature (upper panel) and precipitation (lower panel). Larger values indicate better correspondence between modelled and observed spatial patterns. The black symbols indicate correlation coefficient for individual models, and the large green symbols indicate the median value (i.e., half of the model results lie above and the other half below this value). Improvement in model performance is evident by the increase in correlation for successive model generations.

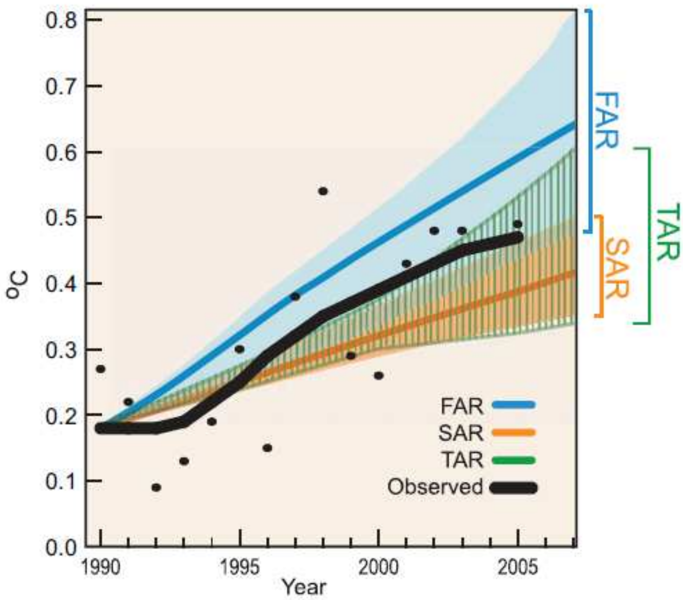
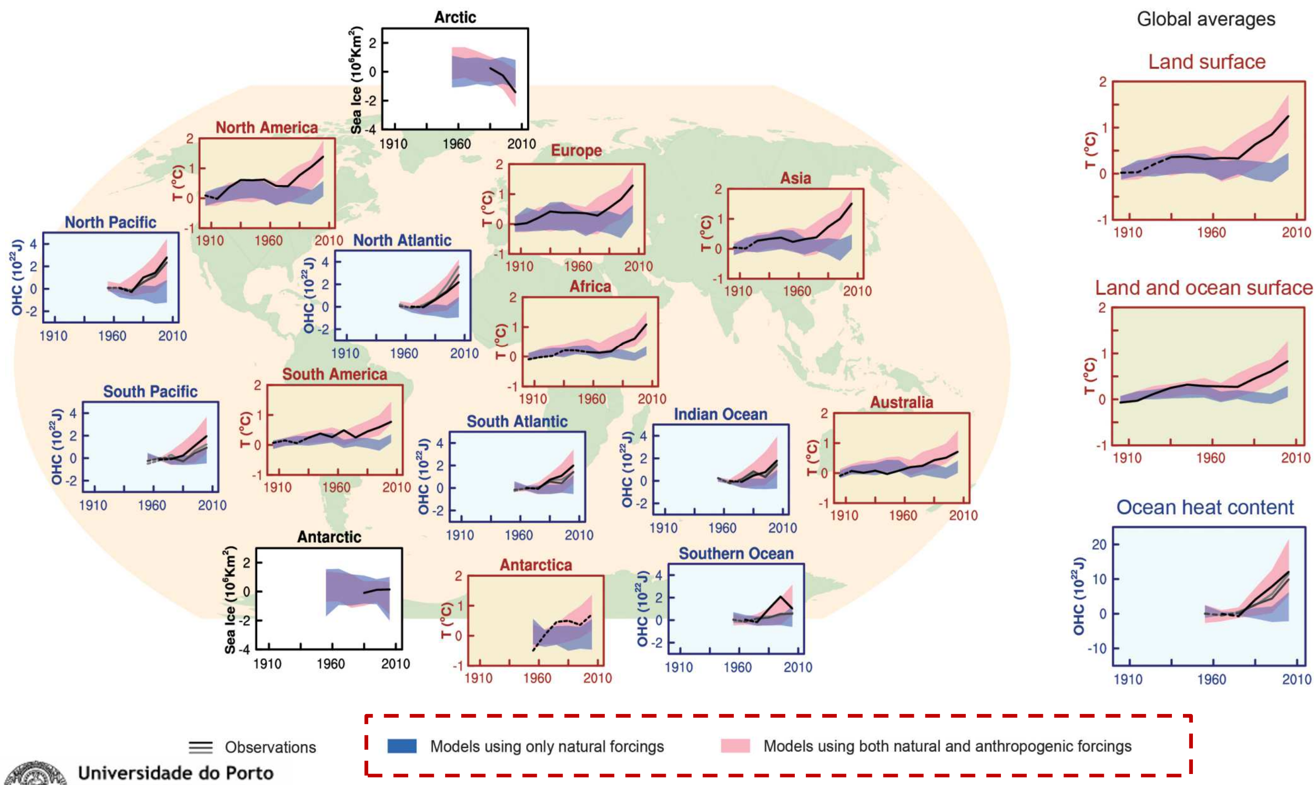


Figure SPM.6

Comparison of observed and simulated climate change



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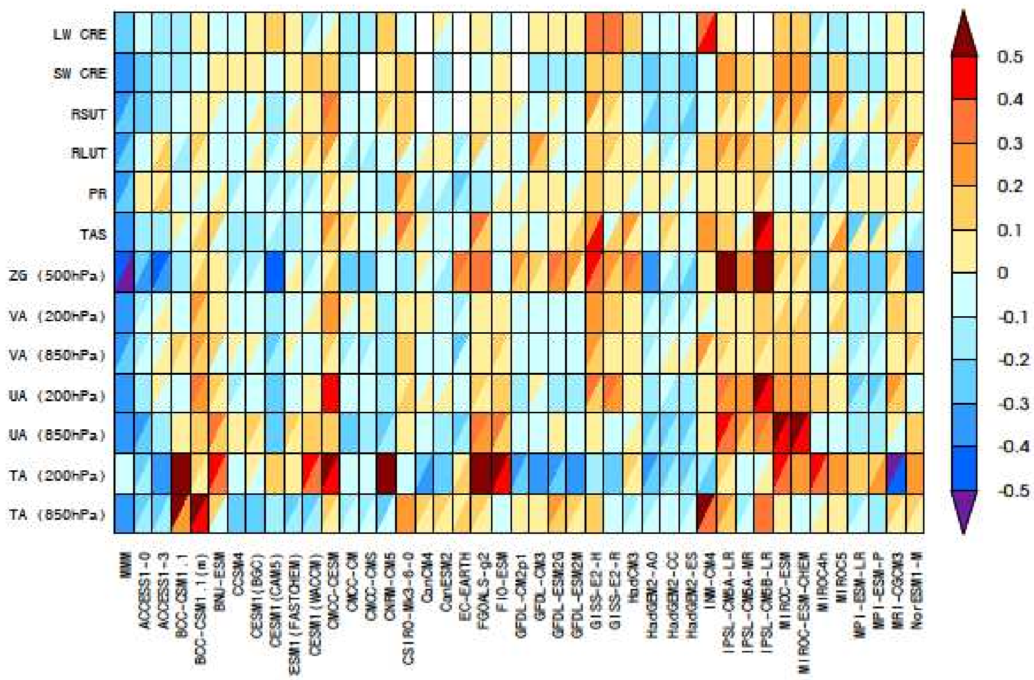
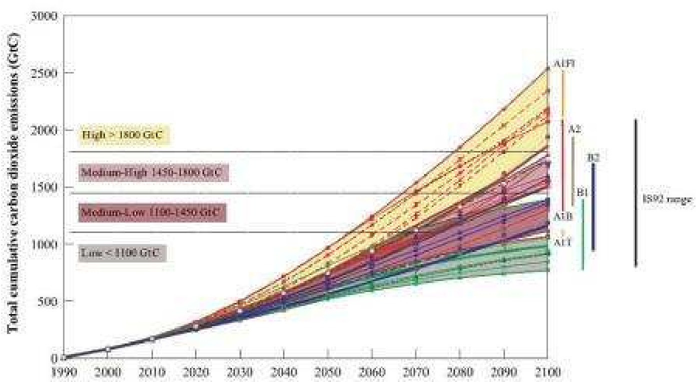


Figure 9.7 | Relative error measures of CMIP5 model performance, based on the global seasonal-cycle climatology (1980–2005) computed from the historical experiments. Rows and columns represent individual variables and models, respectively. The error measure is a space–time root-mean-square error (RMSE), which, treating each variable separately, is portrayed as a relative error by normalizing the result by the median error of all model results (Gleckler et al., 2008). For example, a value of 0.20 indicates that a model's RMSE is 20% larger than the median CMIP5 error for that variable, whereas a value of –0.20 means the error is 20% smaller than the median error. No colour (white) indicates that model results are currently unavailable. A diagonal split of a grid square shows the relative error with respect to both the default reference data set (upper left triangle) and the alternate (lower right triangle). The relative errors are calculated independently for the default and alternate data sets. All reference data used in the diagram are summarized in Table 9.3.

Current/Latest

Forecasts

IPCC 4th AR Emissions scenarios (2007)



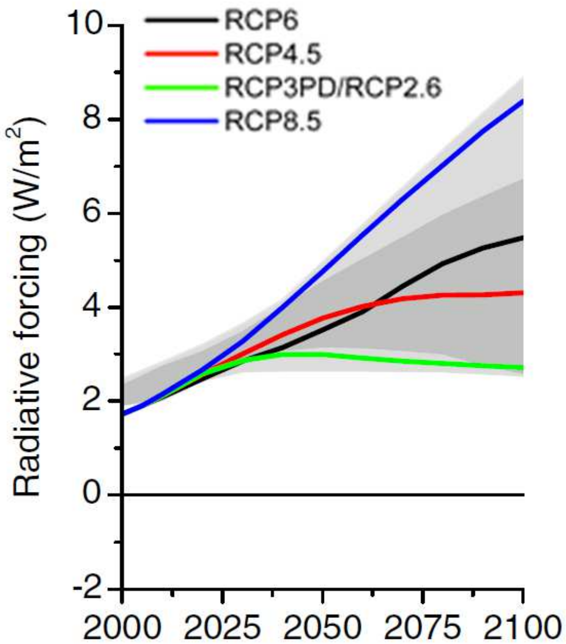
The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B).

The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines.

The B1 storyline and scenario family describes a convergent world with the same global population that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.

The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

IPCC 5th AR Emissions scenarios (2013)



Description	IA Model
RCP8.5	Rising radiative forcing pathway leading to 8.5 W/m2 in 2100.
RCP6	Stabilization without overshoot pathway to 6 W/m2 at stabilization after 2100
RCP4.5	Stabilization without overshoot pathway to 4.5 W/m2 at stabilization after 2100
RCP2.6	Peak in radiative forcing at ~ 3 W/m2 before 2100 and decline

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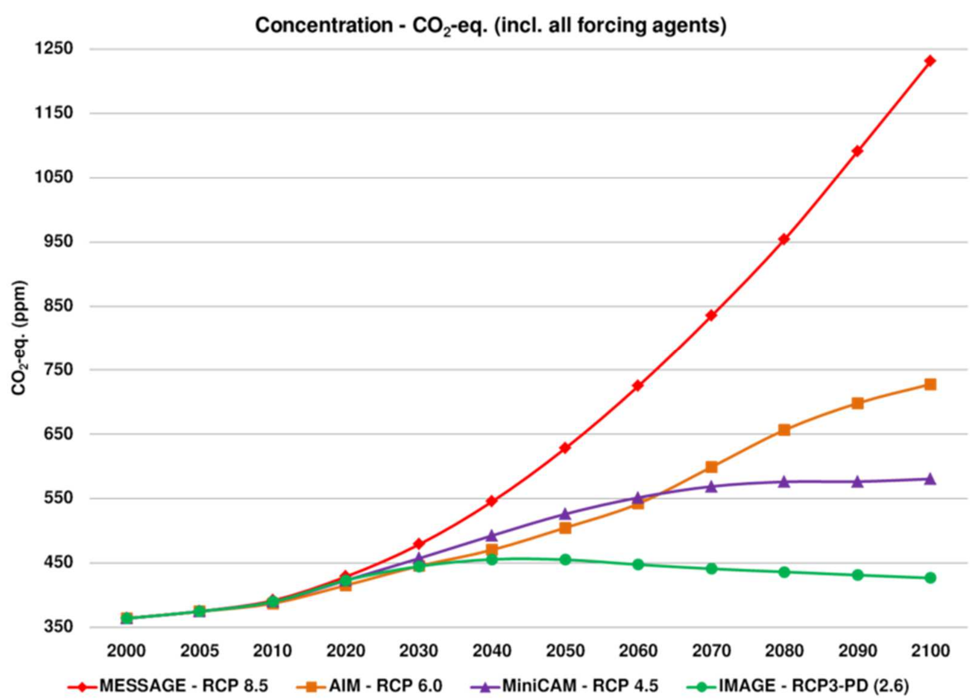
RCP- GHG concentration (rough) correlations



http://en.wikipedia.org/wiki/Representative_Concentration_Pathways#mediaviewer/File:All_forcing_agents_CO2_equivalent_concentration.png

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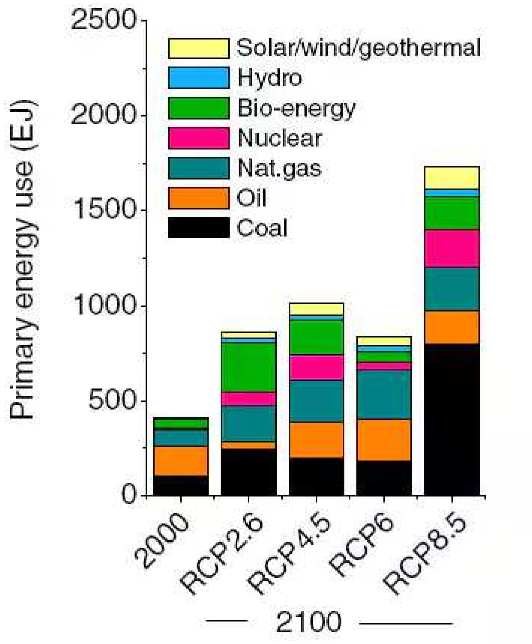
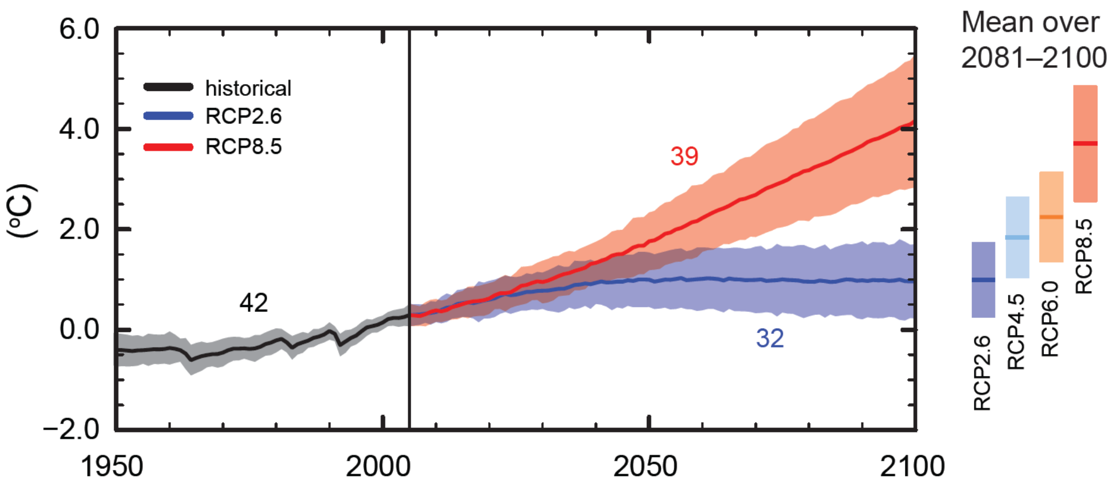


Source: (van Vuuren et.al. 2011) / fide: https://www.theguardian.com/environment/climate-consensus-97-per-cent/2013/aug/30/climate-change-rcp-handy-summary

Figure SPM.7a

Global average surface temperature change



	Near-term: 2031–2050		End-of-century: 2081–2100	
Scenario	Mean (°C)	*Likely* range (°C)	Mean (°C)	*Likely* range (°C)
RCP2.6	1.6	1.1 to 2.0	1.6	0.9 to 2.4
RCP4.5	1.7	1.3 to 2.2	2.5	1.7 to 3.3
RCP6.0	1.6	1.2 to 2.0	2.9	2.0 to 3.8
RCP8.5	2.0	1.5 to 2.4	4.3	3.2 to 5.4

Figure SPM.8a,b

Maps of CMIP5 multi-model mean results

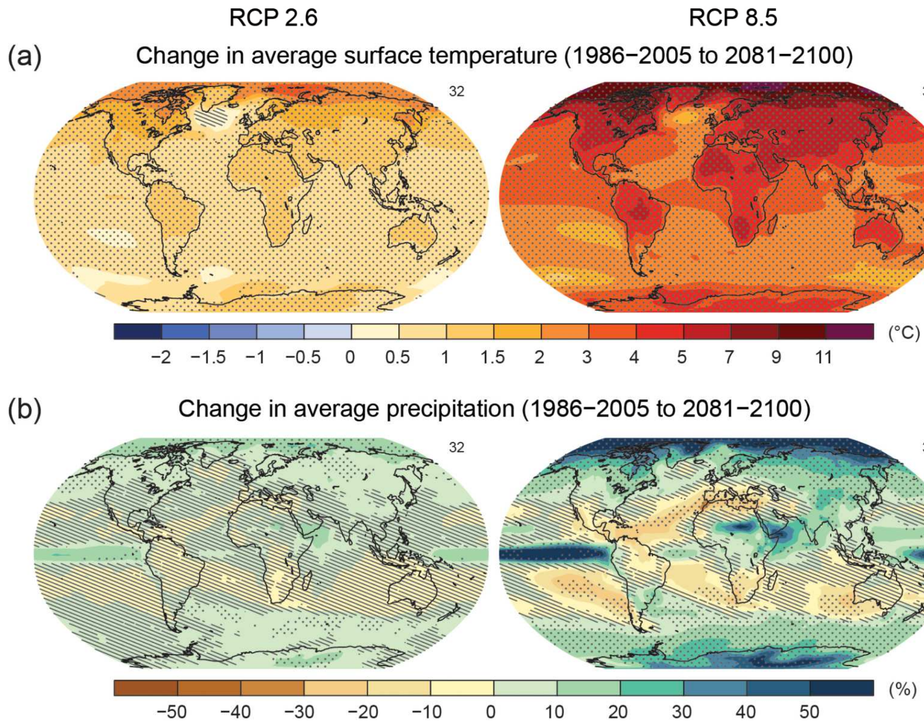


Figure SPM.7c

Global ocean surface pH

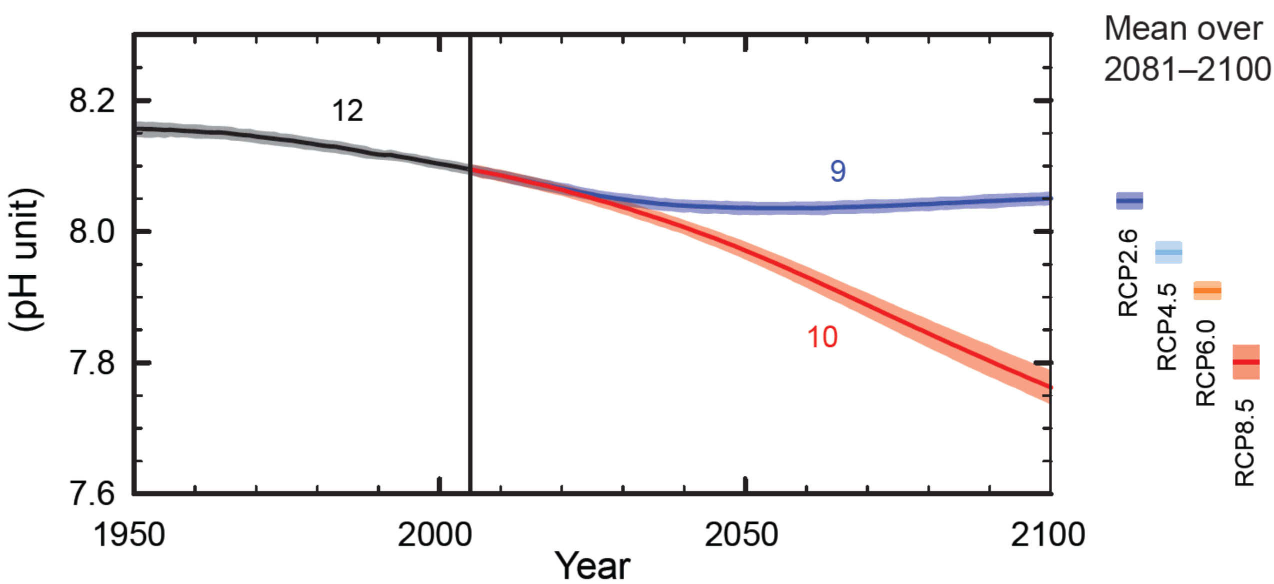
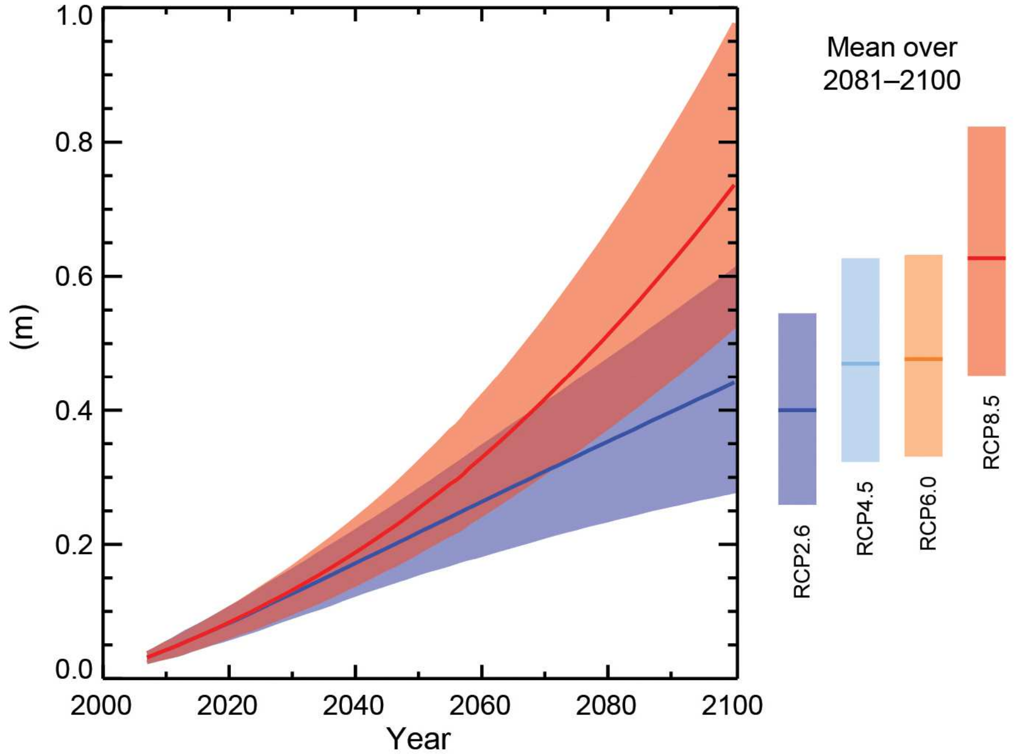
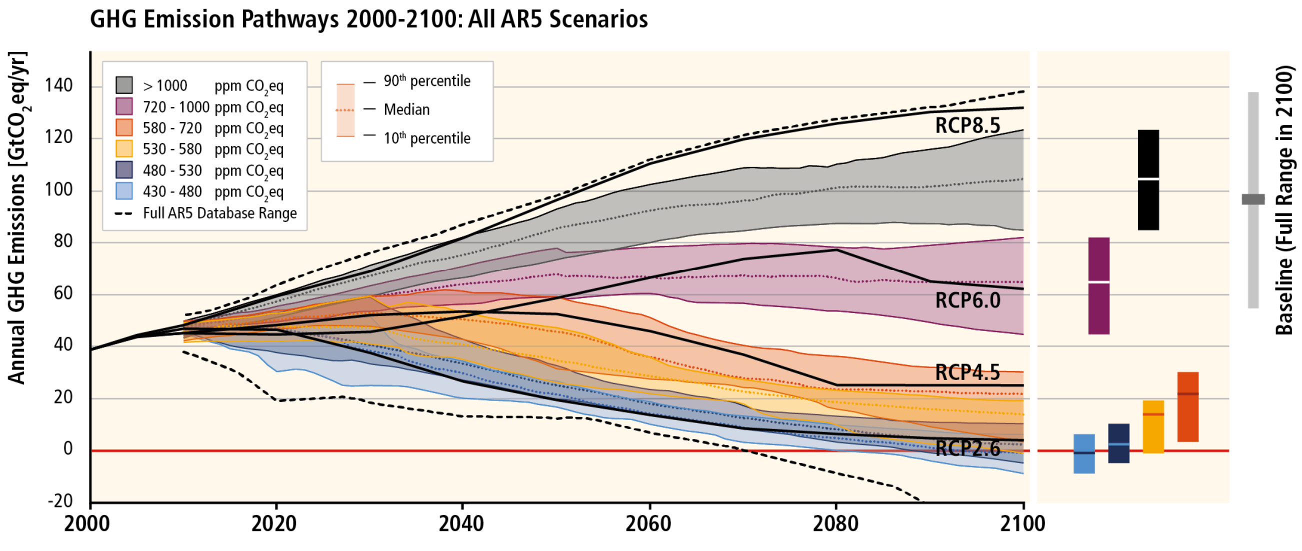


Figure SPM.9

Global mean sea level rise



Without more mitigation, global mean surface temperature might increase by 3.7° to 4.8°C over the 21st century.



Likely Impacts

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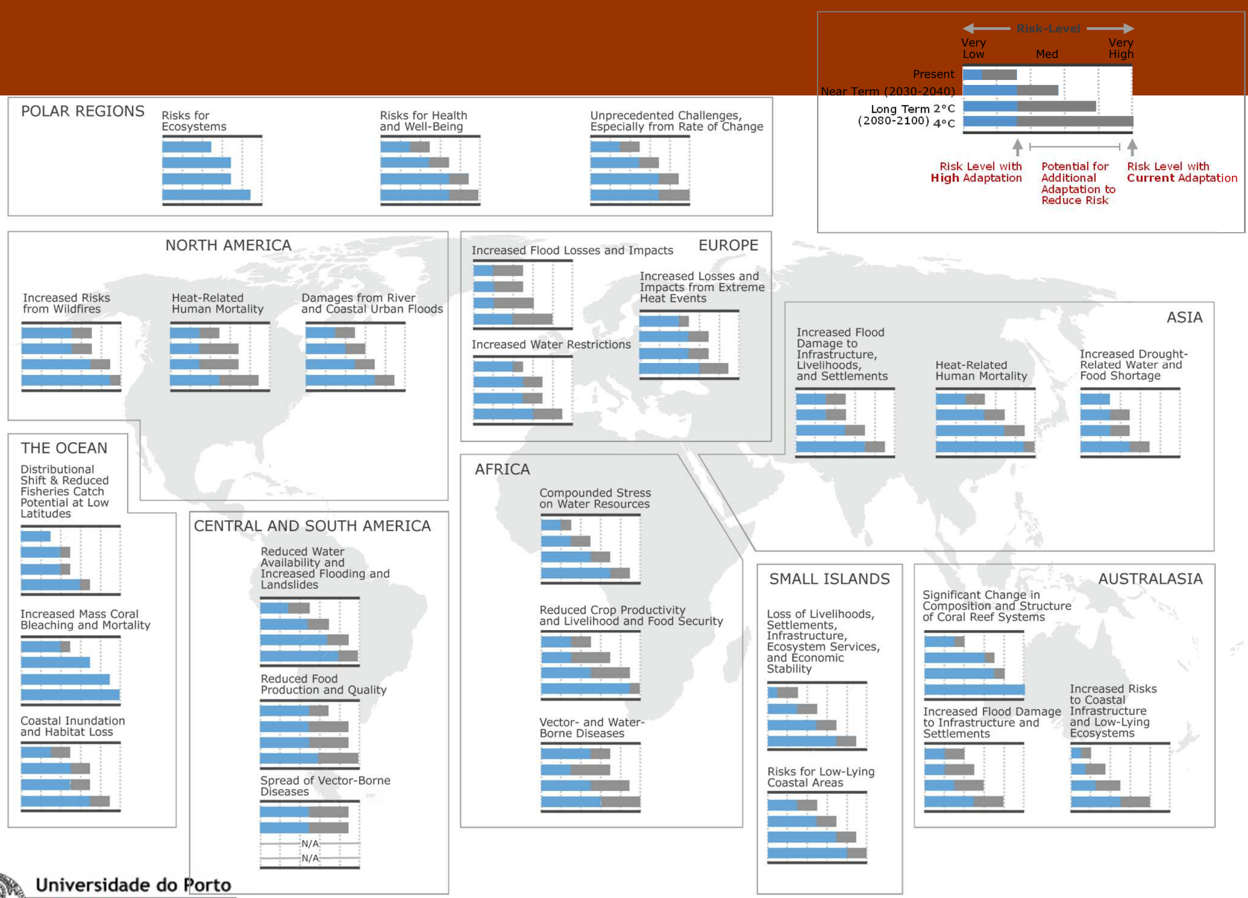

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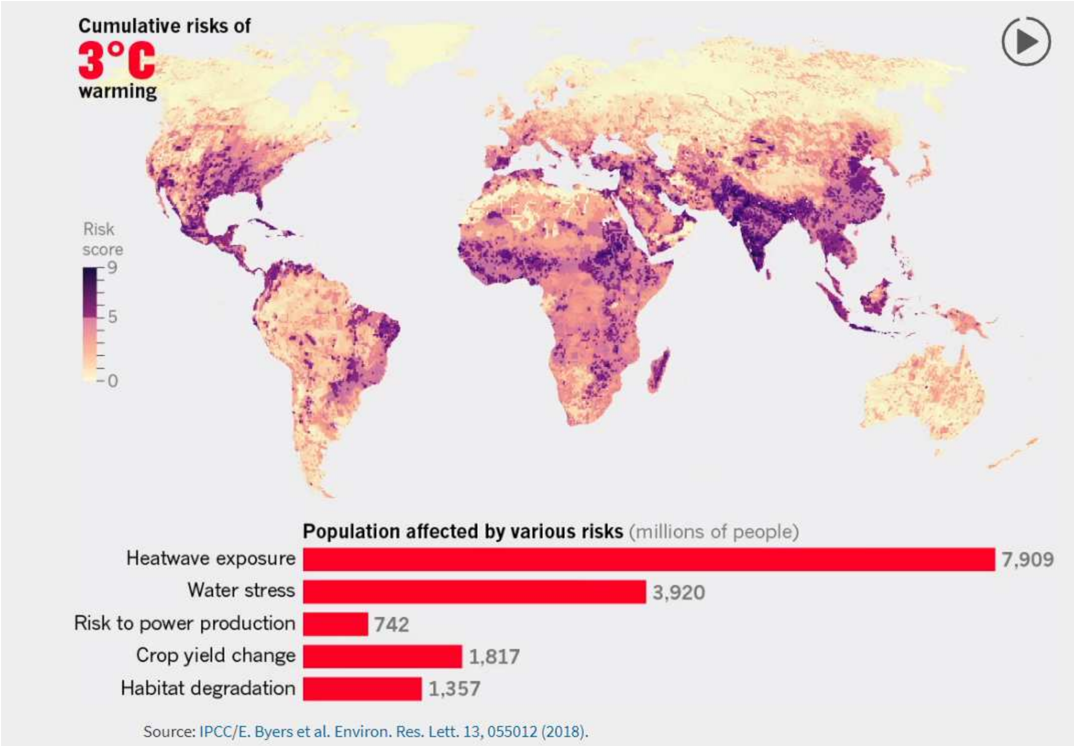
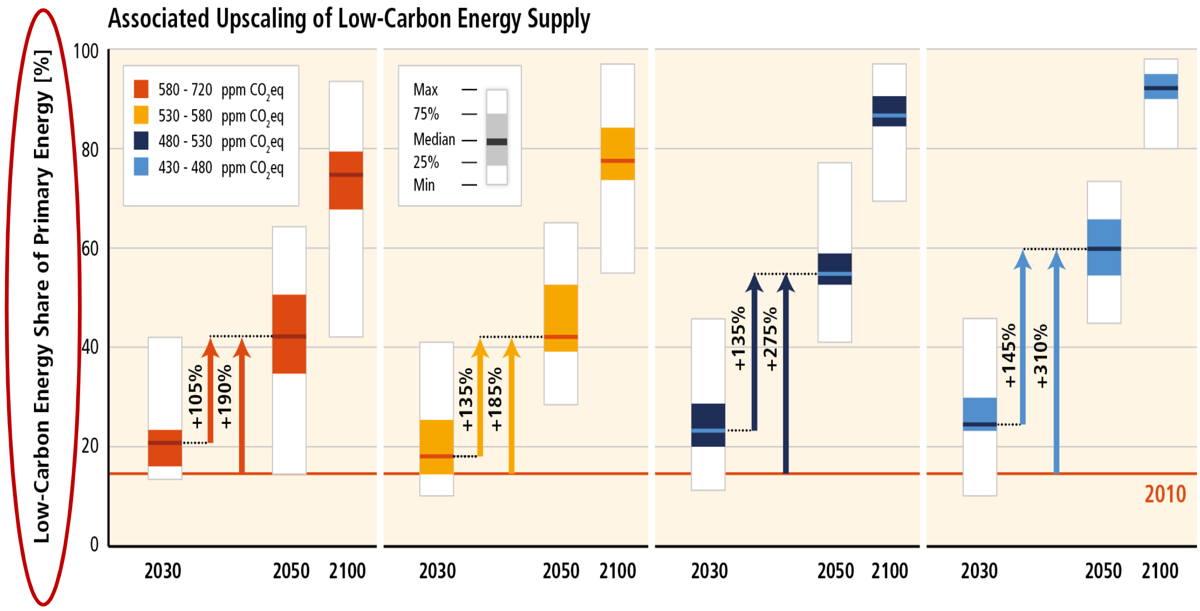


Implications for Mitigation

Mitigation requires major technological and institutional changes including the upscaling of low- and zero carbon energy



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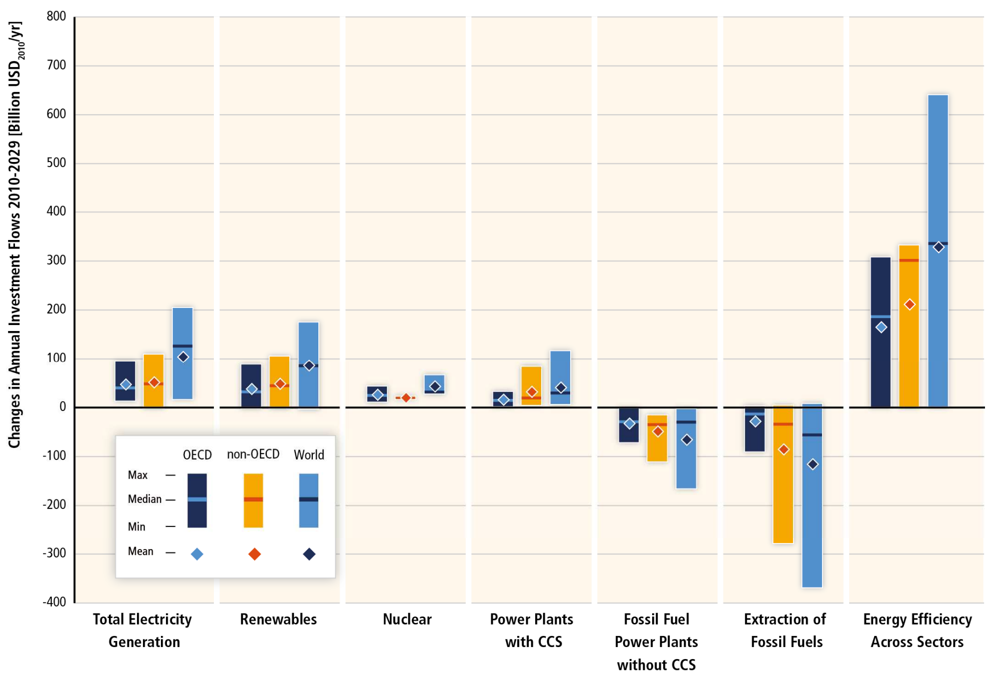
Substantial reductions in emissions would require large changes in investment patterns.



# of Studies:																					
	4	4	5	4	4	5	4	4	5	4	4	5	4	4	5	4	4	5	3	3	4

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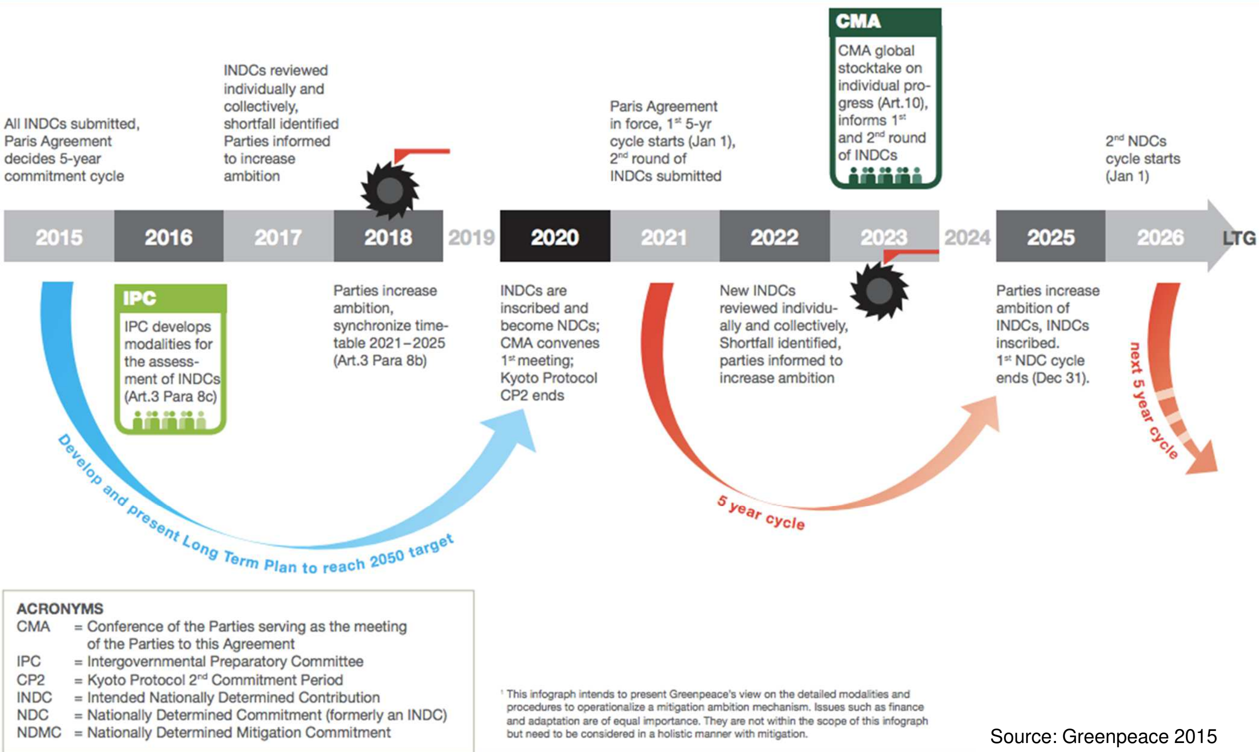
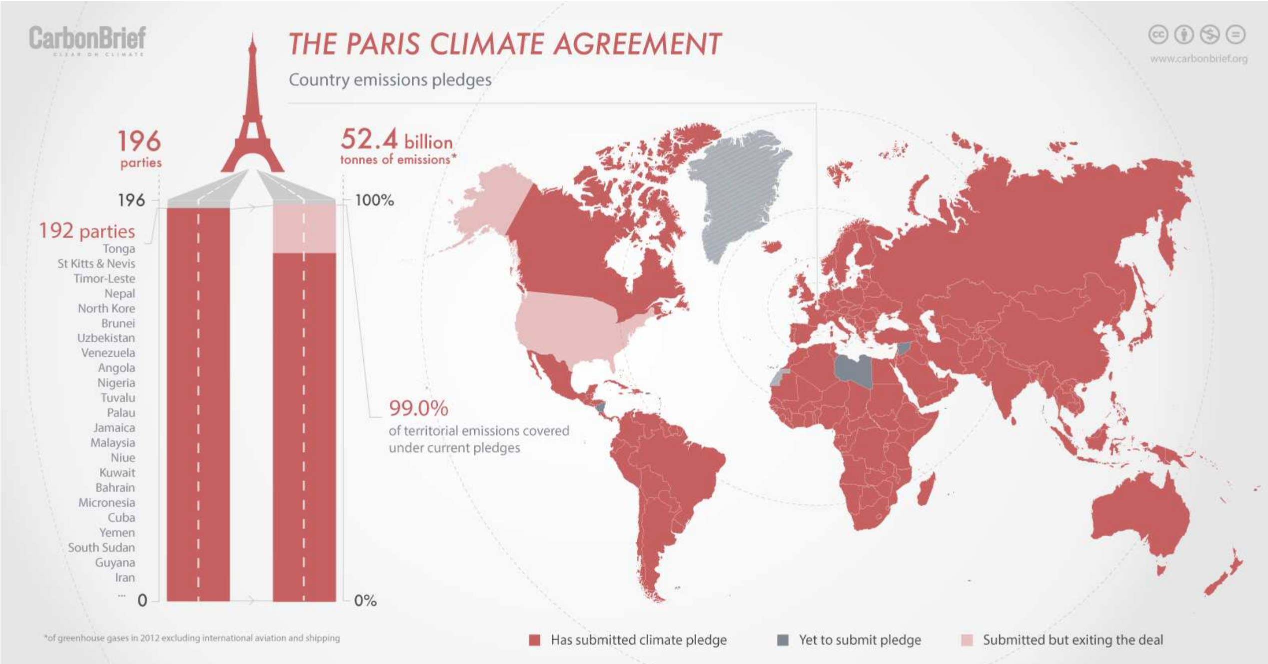
Paris Agreement

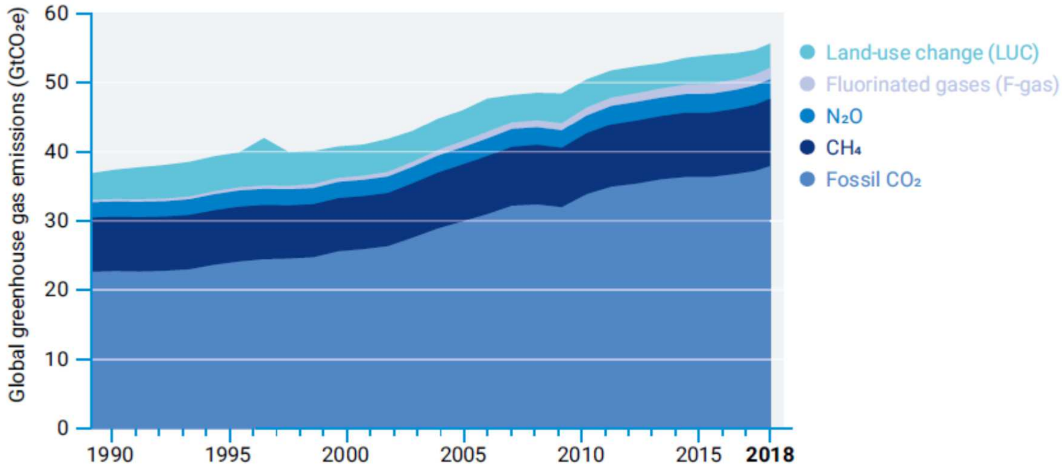


Source: Greenpeace 2015



Source: www.carbonbrief.org/paris-2015-tracking-country-climate-pledges

Figure 2.1. Global greenhouse gas emissions from all sources



Source: Olivier and Peters (2019), Houghton and Nassikas (2017) for land-use change emissions, and Friedlingstein *et al.* (2019) for updates from 2016 to 2018

Figure ES.2. Top greenhouse gas emitters, excluding land-use change emissions due to lack of reliable country-level data, on an absolute basis (left) and per capita basis (right)

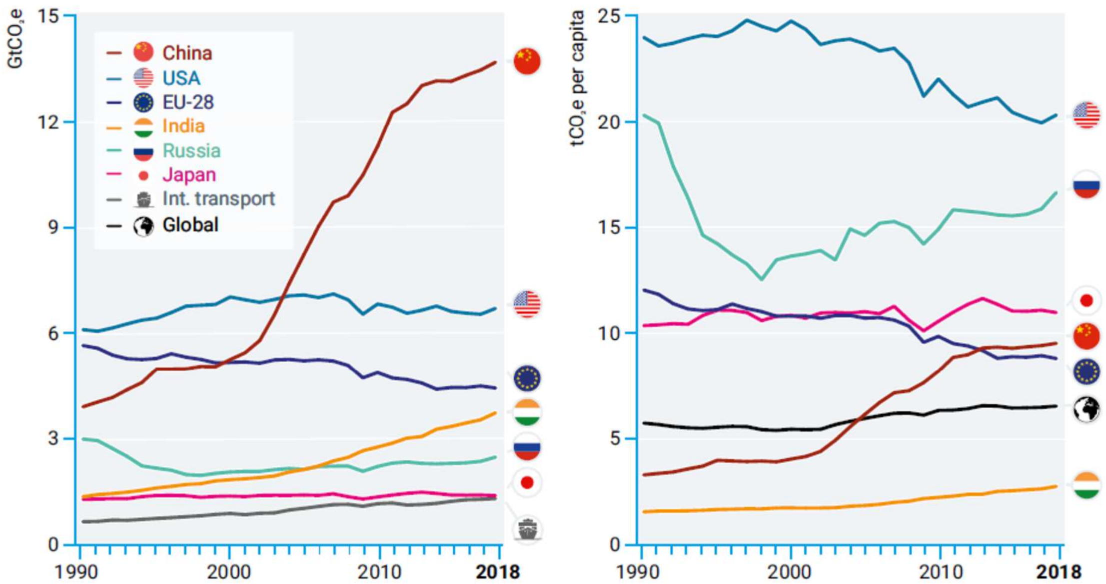
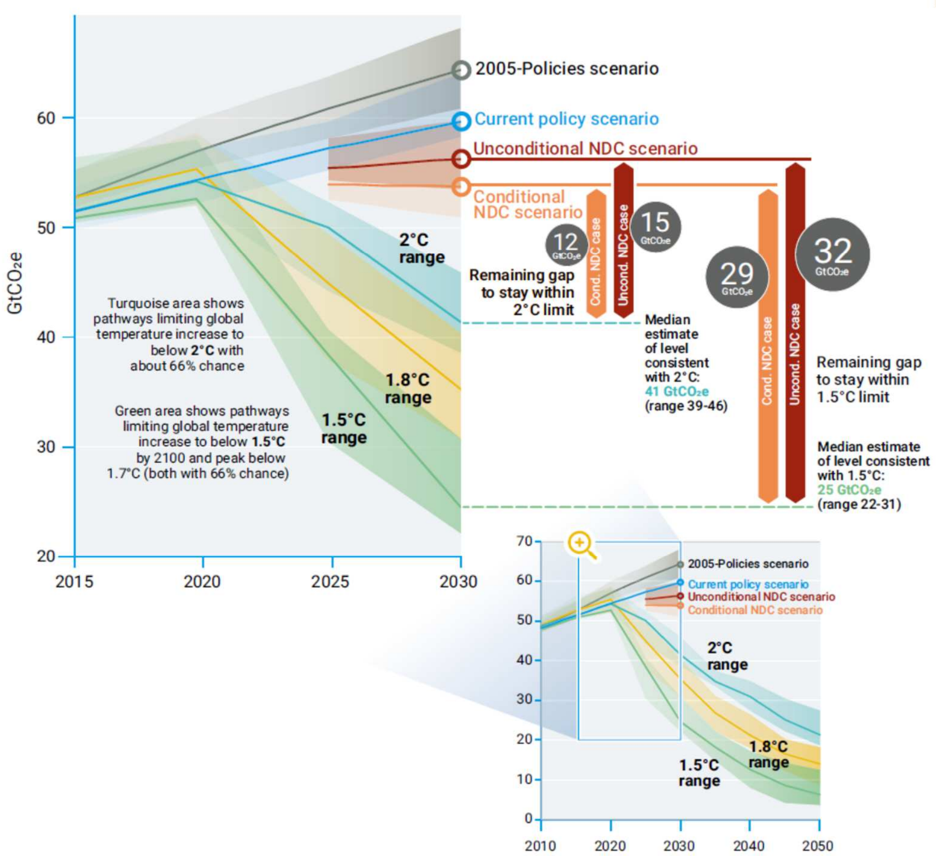
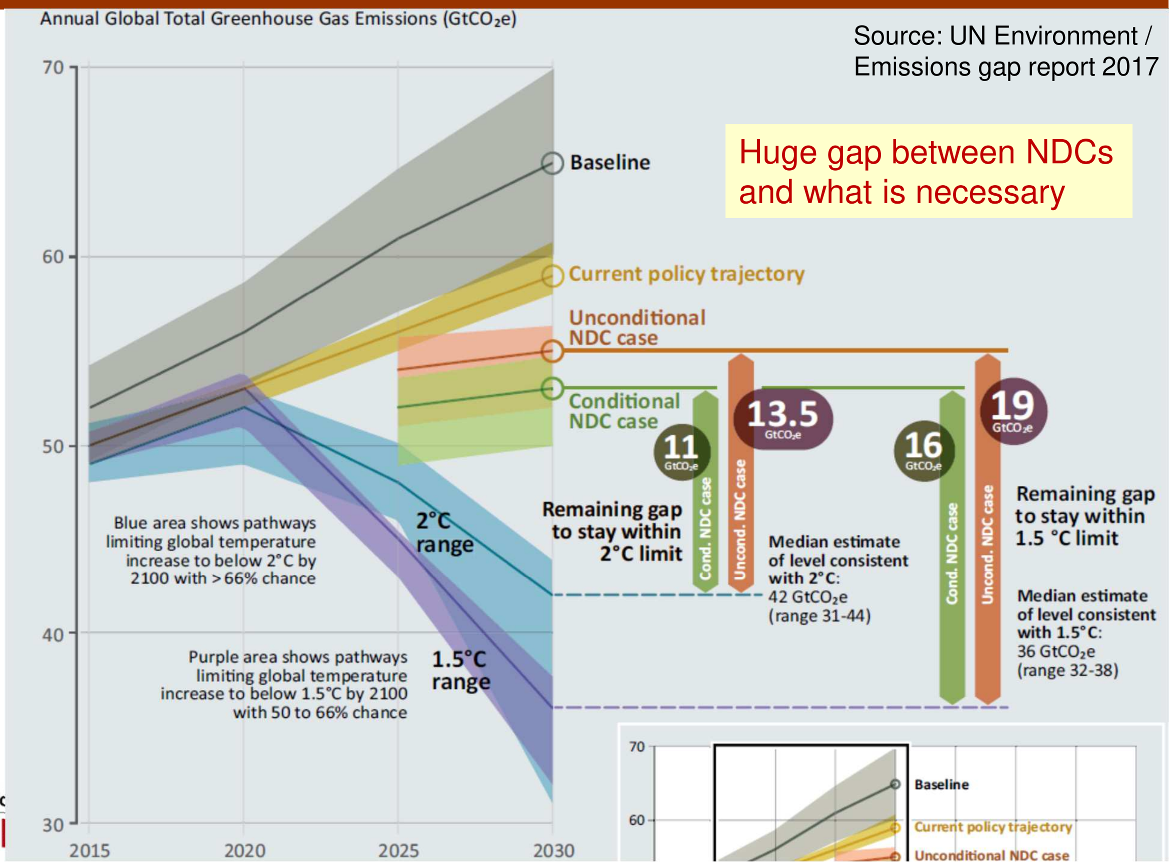


Figure ES.4. Global GHG emissions under different scenarios and the emissions gap by 2030





Source: UN Environment / Emissions gap report 2017

Huge gap between NDCs and what is necessary

Types of conditionalities:

- **Collective ambition**: Several Parties indicated that they would be willing to increase the level of their contribution in the case of an increase in the collective ambition of other countries' contribution;
- **Provision of international financial and technical support** for the implementation of mitigation actions: over 80% of conditional contributions are attached to the provision of financial support for all or part of the proposed actions;
- **Other / Miscalleneous / Vague:** many INDC submissions indicate explicitly that the Parties would be interested to use international flexibility mechanisms or market based approaches to fulfil their contributions; Etc [e.g: ""if circumstances allow"].

Source: Day et al, 2016: Conditionality of Intended Nationally Determined Contributions (INDCs)

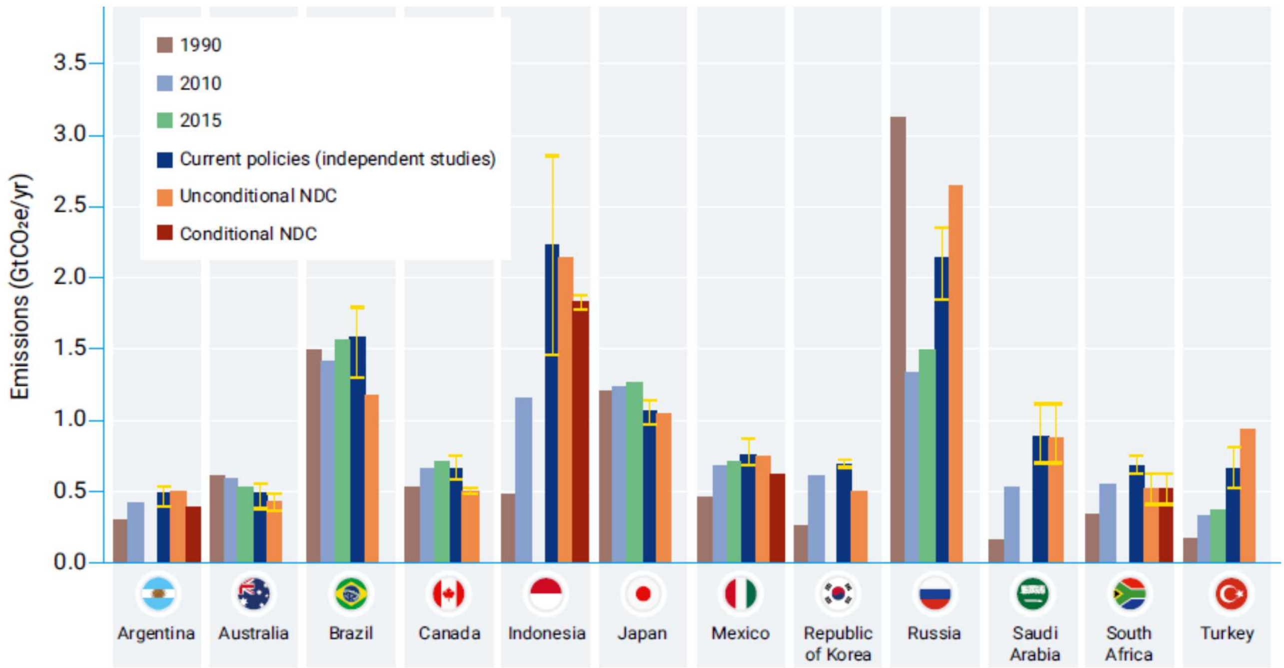


Table ES.2. Selected current opportunities to enhance ambition in seven G20 members in line with ambitious climate actions and targets

Argentina

- Refrain from extracting new, alternative fossil-fuel resources
- Reallocate fossil-fuel subsidies to support distributed renewable electricity-generation
- Shift towards widespread use of public transport in large metropolitan areas
- Redirect subsidies granted to companies for the extraction of alternative fossil fuels to building-sector measures

Brazil

- Commit to the full decarbonization of the energy supply by 2050
- Develop a national strategy for ambitious electric vehicle (EV) uptake aimed at complementing biofuels and at 100-per cent CO_2-free new vehicles
- Promote the 'urban agenda' by increasing the use of public transport and other low-carbon alternatives

China

- Ban all new coal-fired power plants
- Continue governmental support for renewables, taking into account cost reductions, and accelerate development towards a 100 per cent carbon-free electricity system
- Further support the shift towards public modes of transport
- Support the uptake of electric mobility, aiming for 100 per cent CO_2-free new vehicles
- Promote near-zero emission building development and integrate it into Government planning

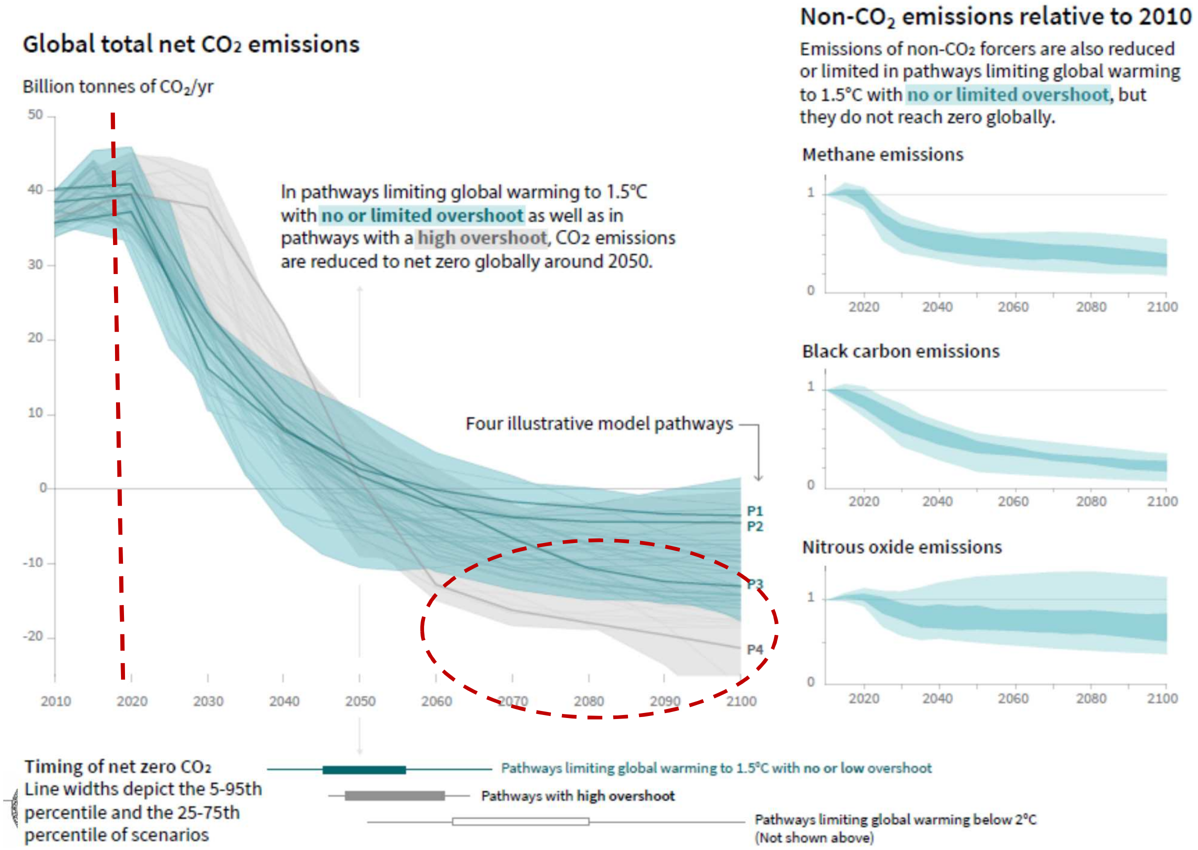
European Union

- Adopt an EU regulation to refrain from investment in fossil-fuel infrastructure, including new natural gas pipelines
- Define a clear endpoint for the EU emissions trading system (ETS) in the form of a cap that must lead to zero emissions
- Adjust the framework and policies to enable 100 per cent carbon-free electricity supply by between 2040 and 2050
- Step up efforts to phase out coal-fired plants
- Define a strategy for zero-emission industrial processes
- Reform the EU ETS to more effectively reduce emissions in industrial applications
- Ban the sale of internal combustion engine cars and buses and/or set targets to move towards 100 per cent of new car and bus sales being zero-carbon vehicles in the coming decades
- Shift towards increased use of public transport in line with the most ambitious Member States
- Increase the renovation rate for intensive retrofits of existing buildings

India

- Plan the transition from coal-fired power plants
- Develop an economy-wide green industrialization strategy towards zero-emission technologies
- Expand mass public transit systems
- Develop domestic electric vehicle targets working towards 100 per cent new sales of zero-emission cars

Beyhond 2030: SR1.5 Pathways



https://www.ipcc.ch/srocc/

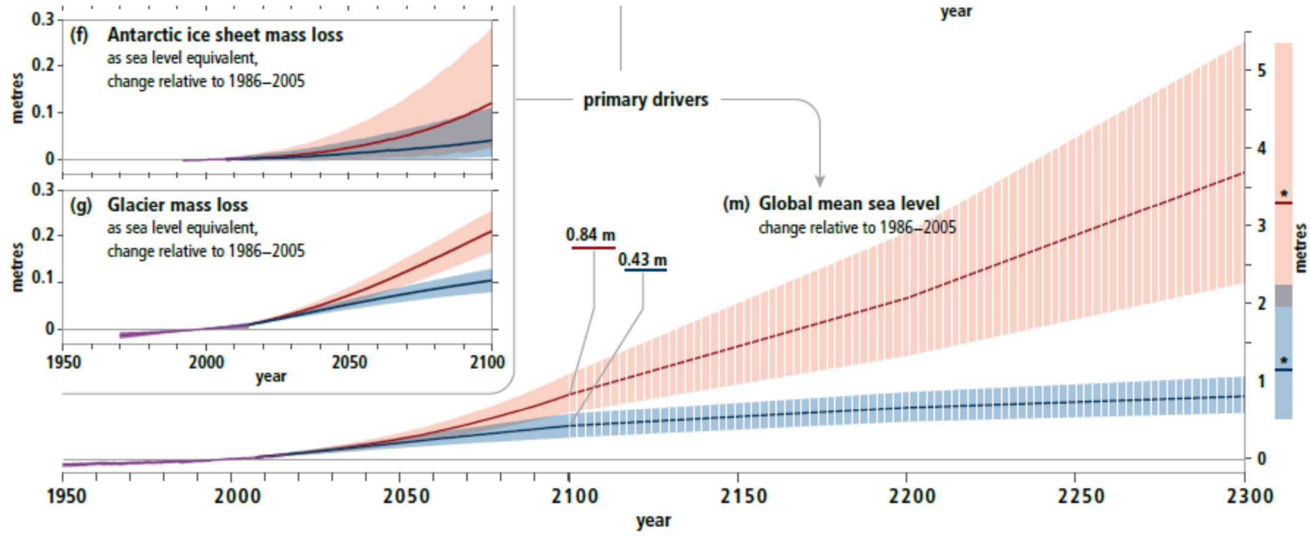
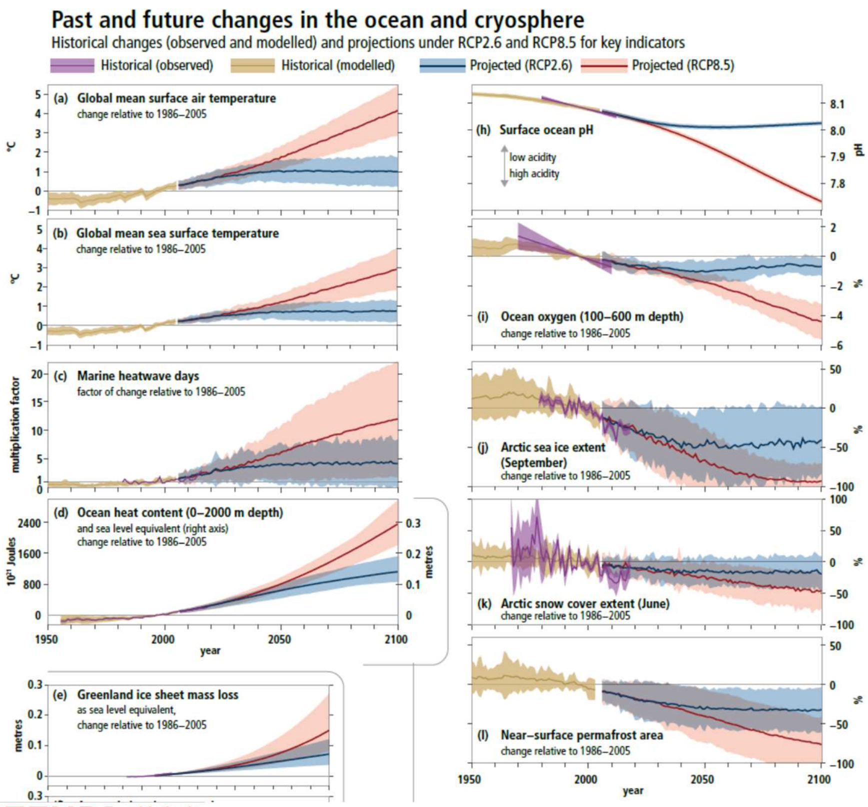


Figure SPM.1 | Observed and modelled historical changes in the ocean and cryosphere since 1950[11], and projected future changes under low (RCP2.6) and high (RCP8.5) greenhouse gas emissions scenarios. {Box SPM.1}



A.2.3 Globally, marine heat-related events have increased; marine heatwaves[18], defined when the daily sea surface temperature exceeds the local 99th percentile over the period 1982 to 2016, have doubled in frequency and have become longer-lasting, more intense and more extensive (*very likely*). It is *very likely* that between 84–90% of marine heatwaves that occurred between 2006 and 2015 are attributable to the anthropogenic temperature increase. {Table 6.2, 6.4, Figures SPM.1, SPM.2}

A.2.6 Datasets spanning 1970–2010 show that the open ocean has lost oxygen by a *very likely* range of 0.5–3.3% over the upper 1000 m, alongside a *likely* expansion of the volume of oxygen minimum zones by 3–8% (*medium confidence*). Oxygen loss is primarily due to increasing ocean stratification, changing ventilation and biogeochemistry (*high confidence*). {5.2.2, Figures SPM.1, SPM.2}

A.3.2 Sea level rise has accelerated (*extremely likely*) due to the combined increased ice loss from the Greenland and Antarctic ice sheets (*very high confidence*). Mass loss from the Antarctic ice sheet over the period 2007–2016 tripled relative to 1997–2006. For Greenland, mass loss doubled over the same period (*likely, medium confidence*). {3.3.1, Figures SPM.1, SPM.2, SPM A.1.1}

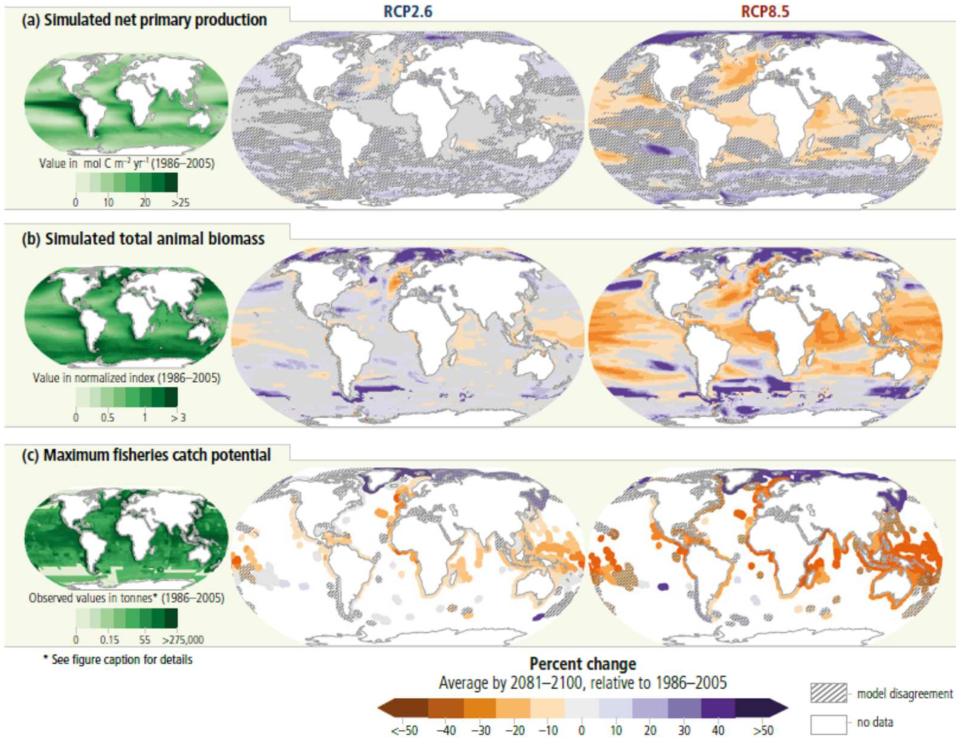
A.3.5 Extreme wave heights, which contribute to extreme sea level events, coastal erosion and flooding, have increased in the Southern and North Atlantic Oceans by around 1.0 cm yr^{-1} and 0.8 cm yr^{-1} over the period 1985–2018 (*medium confidence*). Sea ice loss in the Arctic has also increased wave heights over the period 1992–2014 (*medium confidence*). {4.2.2, 6.2, 6.3, 6.8, Box 6.1}

A.5 Since about 1950 many marine species across various groups have undergone shifts in geographical range and seasonal activities in response to ocean warming, sea ice change and biogeochemical changes, such as oxygen loss, to their habitats (*high confidence*). This has resulted in shifts in species composition, abundance and biomass production of ecosystems, from the equator to the poles. Altered interactions between species have caused cascading impacts on ecosystem structure and functioning (*medium confidence*). In some marine ecosystems species are impacted by both the effects of fishing and climate changes (*medium confidence*). {3.2.3, 3.2.4, Box 3.4, 5.2.3, 5.3, 5.4.1, Figure SPM.2}

A.6 Coastal ecosystems are affected by ocean warming, including intensified marine heatwaves, acidification, loss of oxygen, salinity intrusion and sea level rise, in combination with adverse effects from human activities on ocean and land (*high confidence*). Impacts are already observed on habitat area and biodiversity, as well as ecosystem functioning and services (*high confidence*). {4.3.2, 4.3.3, 5.3, 5.4.1, 6.4.2, Figure SPM.2}

A.6.2 Increased sea water intrusion in estuaries due to sea level rise has driven upstream redistribution of marine species (*medium confidence*) and caused a reduction of suitable habitats for estuarine communities (*medium confidence*). Increased nutrient and organic matter loads in estuaries since the 1970s from intensive human development and riverine loads have exacerbated the stimulating effects of ocean warming on bacterial respiration, leading to expansion of low oxygen areas (*high confidence*). {5.3.1}

Projected changes, impacts and risks for ocean ecosystems as a result of climate change



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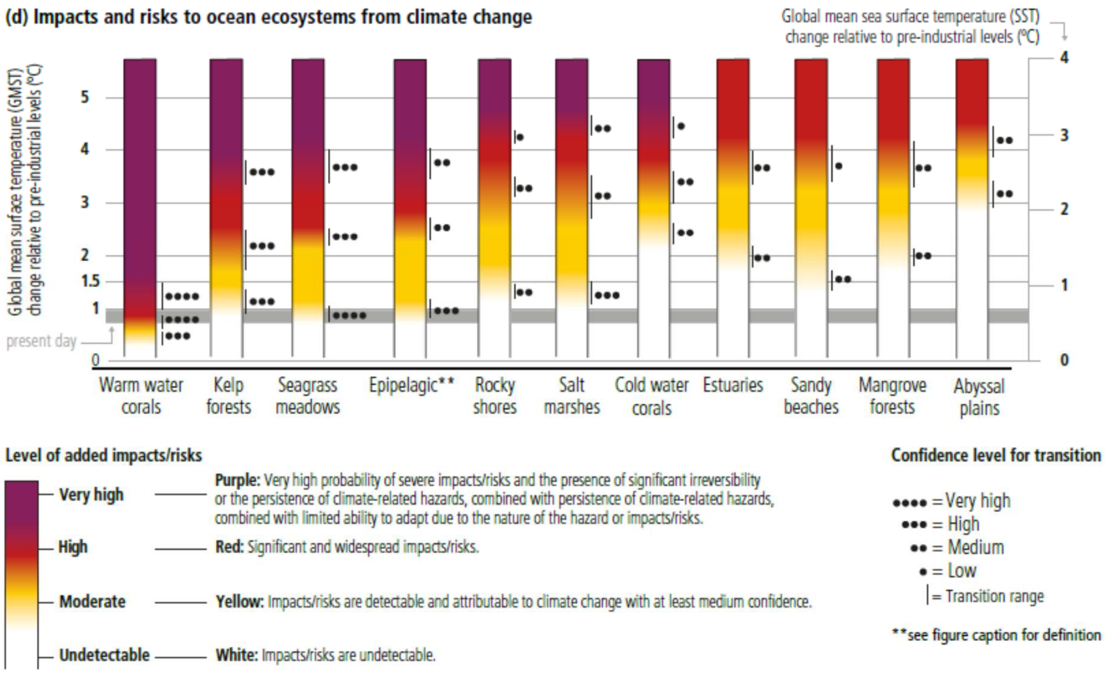

Figure SPM.3 | Projected changes, impacts and risks for ocean regions and ecosystems.

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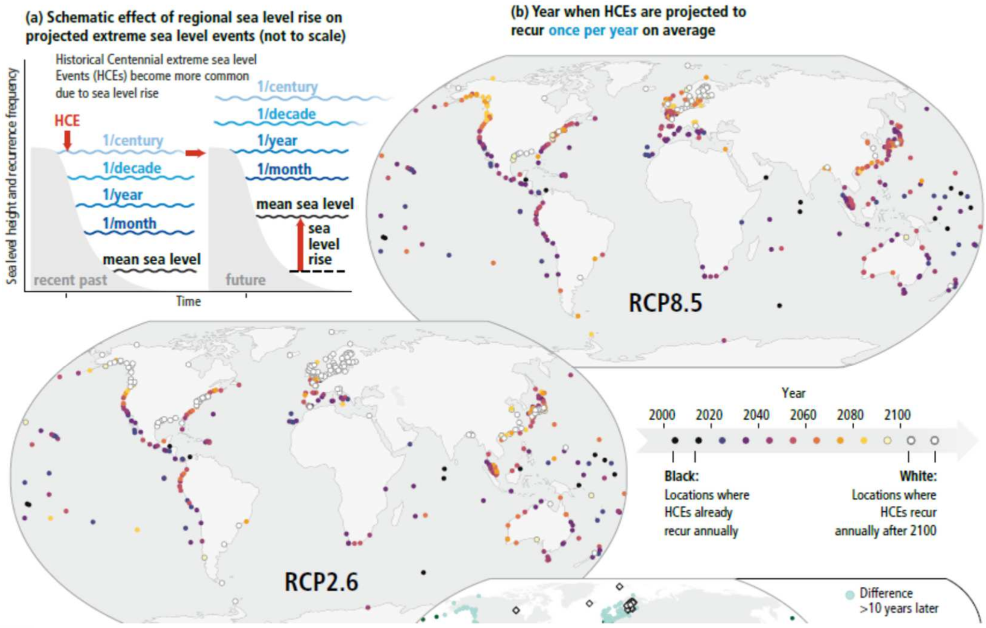
Projected Risks for People and Ecosystem Services

Future cryosphere changes on land are projected to affect water resources and their uses, such as:

- Hydropower (high confidence) and
- Irrigated agriculture in and
- Downstream of high mountain areas (medium confidence), as well as
- Livelihoods in the Arctic (medium confidence).
- Changes in floods, avalanches, landslides, and ground destabilization are projected to increase risk for infrastructure, cultural, tourism, and recreational assets (medium confidence).

Extreme sea level events

Due to projected global mean sea level (GMSL) rise, local sea levels that historically occurred once per century (historical centennial events, HCEs) are projected to become at least annual events at most locations during the 21st century. The height of a HCE varies widely, and depending on the level of exposure can already cause severe impacts. Impacts can continue to increase with rising frequency of HCEs.

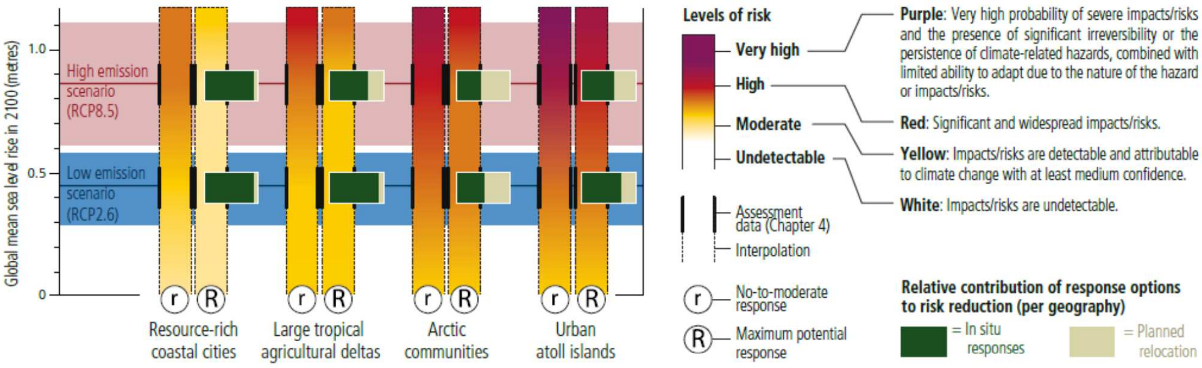


Sea level rise risk and responses

The term response is used here instead of adaptation because some responses, such as retreat, may or may not be considered to be adaptation.

(a) Risk in 2100 under different sea level rise and response scenarios

Risk for illustrative geographies based on mean sea level changes *(medium confidence)*

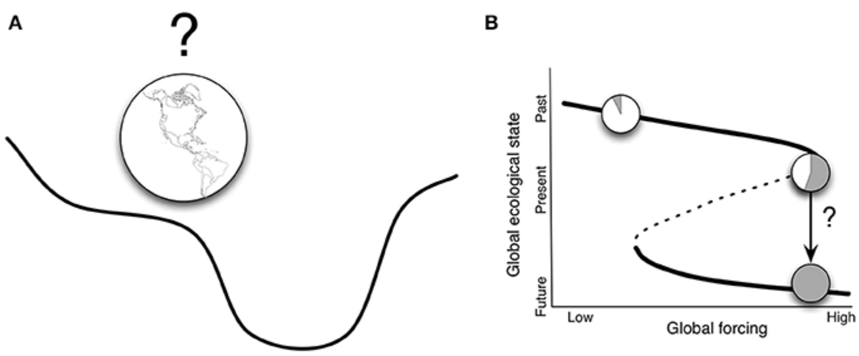


In this assessment, the term response refers to in situ responses to sea level rise (hard engineered coastal defenses, restoration of degraded ecosystems, subsidence limitation) and planned relocation. Planned relocation in this assessment refers to proactive managed retreat or resettlement only at a local scale, and according to the specificities of a particular context (e.g., in urban atoll islands: within the island, in a neighbouring island or in artificially raised islands). Forced displacement and international migration are not considered in this assessment.

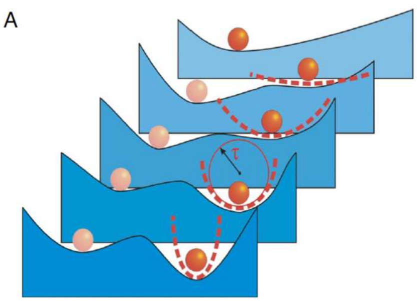
The illustrative geographies are based on a limited number of case studies well covered by the peer reviewed literature. The realisation of risk will depend on context specifities.

Sea level rise scenarios: RCP4.5 and RCP6.0 are not considered in this risk assessment because the literature underpinning this assessment is only available for RCP2.6 and RCP8.5.

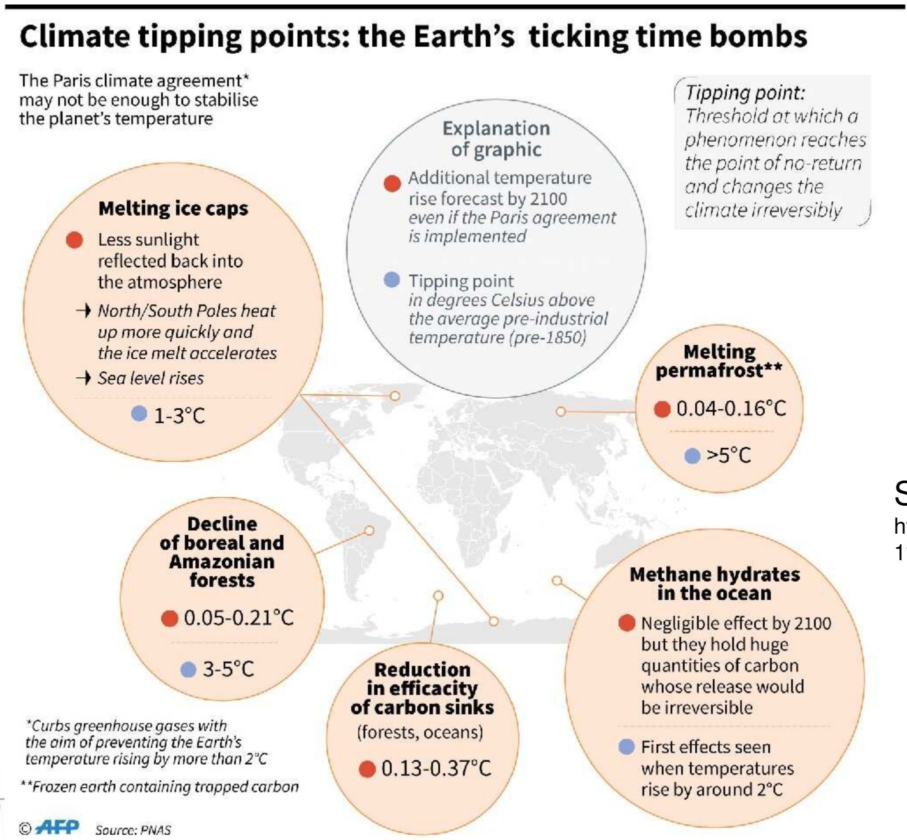
Concerns about tipping points



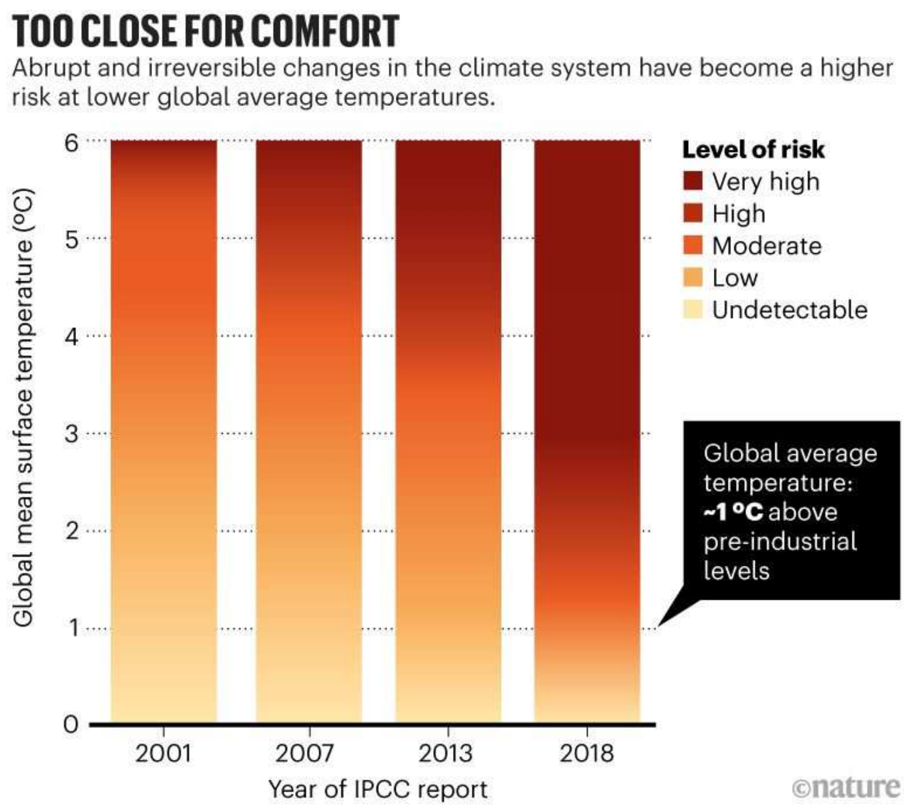
Source: Barnosky et al., 2012, *fide* Bentley et al, 2014



Source: Lenton et all (2008)



Source:
https://phys.org/news/2019-11-climate-comfort.html



Suggested readings:

- IPCC 5th AR: https://www.ipcc.ch/assessment-report/ar5/
- https://www.carbonbrief.org/timeline-history-climate-modelling
- http://www.realclimate.org/
- Emissions gap report 2019: https://www.unenvironment.org/resources/emissions-gap-report-2019
- Timothy M. Lenton, Hermann Held, Elmar Kriegler, Jim W. Hall, Wolfgang Lucht, Stefan Rahmstorf, and Hans Joachim Schellnhuber: Tipping elements in the Earth's climate system. https://doi.org/10.1073/pnas.0705414105
- Bentley et al. 2012. Social tipping points and Earth systems dynamics, Front. Environ. Sci., 19 August 2014 | https://doi.org/10.3389/fenvs.2014.00035
- Climate tipping points — too risky to bet against: https://www.nature.com/articles/d41586-019-03595-0
- A set of troubling charts shows how little progress nations have made toward limiting greenhouse-gas emissions: https://www.nature.com/immersive/d41586-019-02711-4/index.html

THANK YOU