Key Points from the IPCC WGI Fifth Assessment Report. Climate Change 2013: The Physical Science Basis

Produced by the Cambridge Centre *for* Climate Science for climate-related scientists within the University of Cambridge and British Antarctic Survey. This document highlights some of the important scientific points from the IPCC Summary for Policymakers (SPM, approved 27-Sept-2013) and the AR5 WGI Final Draft (released online 30-Sept-2013). Please note that this document is not in any way officially linked to the IPCC.

Edited by: Amanda Maycock, Scott Hosking and Tom Bracegirdle

Contributors: Alex Archibald, Tom Bracegirdle, Linda Capper, Hans Graf, Peter Hitchcock, Scott Hosking, John King, Amanda Maycock, Nicola Warwick, Eric Wolff

Last updated: 18 October 2013

Cambridge Centre
***for* Climate Science (CC*f*CS)**
http://www.climatescience.cam.ac.uk

UNIVERSITY OF CAMBRIDGE

British Antarctic Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

A few take-home messages from the IPCC WGI AR5

It is *extremely likely* (95-100% probability) that human influence has been the dominant cause of the observed warming since the mid-20th century. (up from 90-100% probability since AR4)
Climate models have improved since the AR4. Models reproduce observed continental-scale surface temperature patterns and trends over many decades, including the more rapid warming since the mid-20th century and the cooling immediately following large volcanic eruptions (*very high confidence*).
The atmospheric concentrations of carbon dioxide (CO_2), methane, and nitrous oxide have increased to levels unprecedented in at least the last 800,000 years.
see also: Headline Statements from the Summary for Policymakers

Other useful links

Official IPCC Reports: • Climate Change 2013: The Physical Science Basis [*WGI AR5 Final Draft*] • Summary for Policy Makers (SPM)
What is the Intergovernmental Panel on Climate Change (IPCC)?
How does the IPCC review process work?
IPCC WGI AR5 fact sheet
Briefing Notes on Recent Slowdown in Global Temperature Rise
The Beginner's Guide to Representative Concentration Pathways (RCPs)
CPSL IPCC AR5 Implications for Business document

Contents

A few take-home messages from the IPCC WGI AR5
Other useful links
Glossary and description of key scientific concepts
Treatment of Uncertainties in the Working Group I Assessment

Chapter 1: Introduction
Chapter 2: Observations: Atmosphere and surface
Chapter 3: Observations: Oceans
Chapter 4: Observations: Cryosphere
Chapter 5: Information from Paleoclimate Archives
Chapter 6: Carbon and Other Biogeochemical Cycles
Chapter 7: Clouds and aerosols
Chapter 8: Anthropogenic and Natural Radiative Forcing
Chapter 9: Evaluation of Climate Models
Chapter 10: Detection and Attribution of Climate Change: from Global to Regional
Chapter 11: Near-term Climate Change: Projections and Predictability
Chapter 12: Long-term Climate Change: Projections, Commitments and Irreversibility
Chapter 13: Sea Level Change
Chapter 14: Climate Phenomena and their Relevance for Future Regional Climate Change

Further Scientific Information

Glossary and description of key scientific concepts

AR4	Fourth Assessment Report of the IPCC
AR5	Fifth Assessment Report of the IPCC
CMIP5	Coupled Model Intercomparison Project Phase 5
ECS	Equilibrium Climate Sensitivity is the equilibrium steady-state change in global mean near-surface air temperature resulting from an instantaneous doubling in atmospheric carbon dioxide concentrations compared to preindustrial times. This therefore accounts for both the short term transient response and longer term feedbacks (e.g. changes in the oceans / cryosphere / carbon cycle).
ERF	The AR5 uses a new Effective Radiative Forcing (ERF) definition – this is the change in the net (down minus up) irradiance (longwave + shortwave) at the top of the atmosphere after all 'fast' feedbacks in the climate system (e.g. changes in cloud properties) are allowed to take place in response to an initial climate perturbation, with the exception of changes in the ocean and sea ice which are held fixed.
IPCC	Intergovernmental Panel on Climate Change
ppb/ppm	parts per billion / parts per million (by mass unless otherwise stated)
Radiative forcing	The change in global mean net (down minus up) irradiance (longwave + shortwave) at the tropopause due to a perturbation in a radiatively active species once stratospheric temperatures have been allowed to re-adjust to radiative equilibrium.
RCP	The Representative Concentration Pathway scenarios are labelled according to their approximate global mean radiative forcing by 2100 relative to preindustrial times. They are used to drive climate models to produce projections of possible future climates in response to a given set of external forcings. ● RCP2.6 is an emissions reduction scenario where greenhouse gas emissions (and indirectly emissions of air pollutants) are reduced substantially over time ● RCP4.5 is a stabilization scenario where total radiative forcing is stabilized before 2100. ● RCP6.0 is a stabilization scenario where total radiative forcing is stabilized after 2100. ● RCP8.5 is a 'business as usual' scenario with continued strong increases in greenhouse gases. For the first time these future scenarios also include emission-based rather than concentration-based specifications - see here for more information [PDF]
TCR	Transient Climate Response is a measure of the near-surface temperature change while the climate system has not reached equilibrium. It is the warming at the time of CO_2 doubling (70 years) in a transient 1%/year increasing CO_2 experiment.

TCRE	Transient Climate Response to cumulative carbon Emissions is the ratio of global mean near-surface warming to cumulative emissions after a doubling of CO_2 in a 1% yr^{-1} CO_2 increase experiment.
WGI	The IPCC Working Group I (WGI) assesses the physical scientific aspects of the climate system and climate change.
WMGHG	well-mixed greenhouse gas

Treatment of Uncertainties in the Working Group I Assessment

The level of confidence in a scientific statement is assessed based on the available evidence (robust, medium and limited) and the degree of agreement across different sources (high, medium and low). The combined assessment of these two factors is synthesised into five levels of confidence (*very high, high, medium, low and very low*). The scale of confidence used in the IPCC WGI report is illustrated in the figure below.

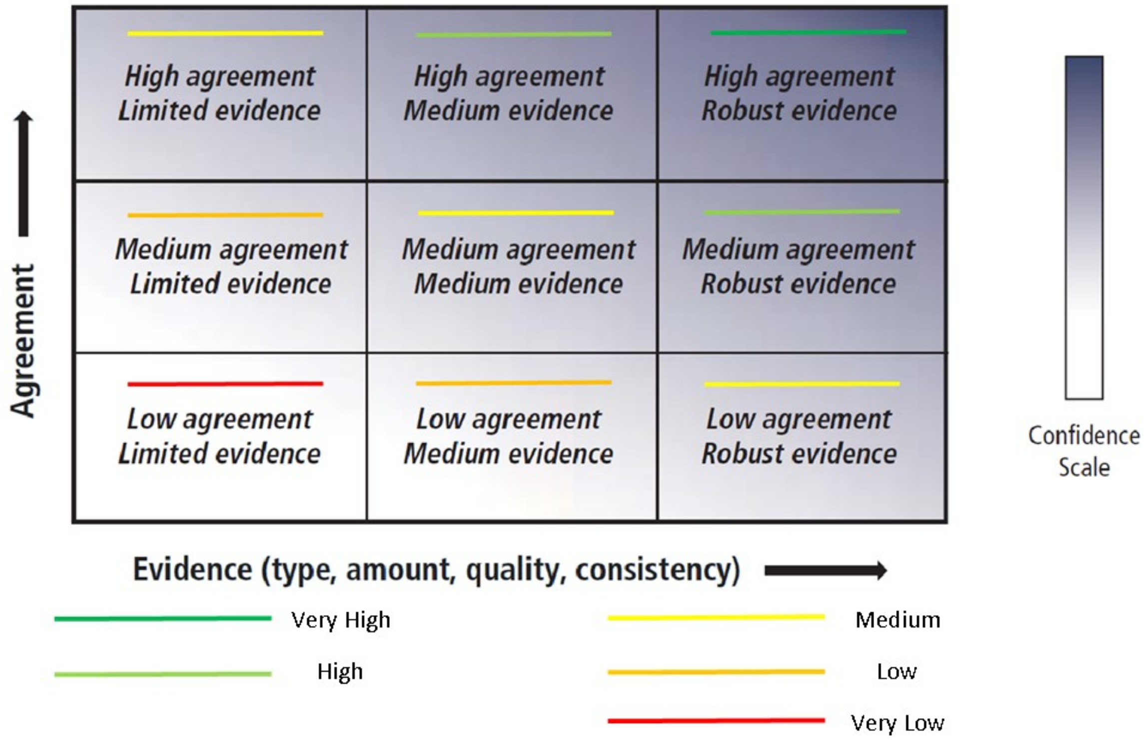

Figure: Confidence levels are a combination of level of agreement and evidence. There are five levels shown with colours. (IPCC 2013)

In addition to an assessment of how confidently a given statement can be made based on the evidence available, a level of statistical likelihood may also be assigned to a statement. These definitions are listed in Table TS.1; they appear in *italicized* text throughout the AR5 report and this document.

Table TS.1. Official IPCC terminology used to define likelihood

Term*	**Likelihood of the Outcome**
Virtually certain	99-100% probability
Extremely likely	95-100% probability
Very likely	90-100% probability
Likely	66-100% probability
More likely than not	50-100% probability
About as likely as not	33 to 66% probability
Unlikely	0-33% probability
Very unlikely	0-10% probability
Extremely unlikely	0-5% probability
Exceptionally unlikely	0-1% probability

Chapter 1: Introduction

Prepared by Scott Hosking

The IPCC consists of three working groups (WGI/II/III) which each focus on a different aspect of climate change. The reports by WGI present the physical science basis and evidence for climate change. WGII focuses on the possibilities for socio-economic and natural systems to adapt to climate change. WGIII deals with options for mitigation of climate change through reductions in greenhouse gas emissions and carbon capture technologies.

The Fifth Report of the IPCC WGI (AR5) described here follows on from the Fourth Assessment Report (AR4) released in 2007. The previous three WGI reports came in 2001, 1995 and 1990. Chapter 1 provides a broad overview of the AR5 report with many of the key highlights being expanded upon in subsequent chapters.

Key Highlights

- Unequivocal evidence from in situ observations and ice core records show that atmospheric concentrations of the most influential anthropogenic greenhouse gases (carbon dioxide (CO_2), methane and nitrous oxide) have increased over the last few centuries.
- There is clear evidence for climate change from many sources, including:
    - Global mean surface air temperature increases over land and ocean during the last 100 years
    - A continuing upward trend in ocean heat content
    - A small positive energy imbalance in the Earth's radiative budget calculated using measurements
    - Significant reductions in mass balance from most ice masses
    - Acidification of ocean by CO_2 uptake
    - Analysis of past climate variability puts recent rapid climate change into perspective
    - Sea level rise predominantly driven by the thermal expansion of the oceans and melting of ice masses
- Recent observed changes in globally averaged CO_2, temperature and sea level rise are generally well within the range of projections shown in earlier IPCC WGI reports.
- Since their introduction in the late 1970s, satellite measurements of the Earth's atmosphere and surface have significantly increased the number and coverage of observations.
- Modern high-performance computers have enabled the development of more sophisticated climate models which describe the multitude of physical and chemical interactions that take place within the Earth system. The models used in AR5 generally show better agreement with observed continental-scale surface temperature patterns and trends than those in AR4.

Chapter 2: Observations: Atmosphere and surface

Prepared by Alex Archibald, Amanda Maycock

This chapter focuses on the observational evidence for recent global change based on surface and atmospheric data. The analysis mainly discusses evidence for changes and/or trends in measured quantities over time. One important issue for trend analysis is the length of the available data records. By far the longest observational record is the land surface air temperature record. However, many observational records are much shorter than this, or are limited in their geographic extent, which makes it harder to draw robust conclusions. One very important set of atmospheric observations, which have become more widely used since the AR4, are the satellite records.

Key highlights

- Climate scientists around the world agree, unequivocally, that the world has warmed since the 19th century. Evidence for this statement comes from a range of indicators including changes in: surface, atmospheric, and oceanic temperatures; glaciers, snow cover and sea ice; sea level; and atmospheric water vapour content.
- Combined land and ocean surface datasets show an increase in global mean surface temperature of ~0.89°C (0.69°C–1.08°C) over the period 1901–2012. It is also *virtually certain* that the stratosphere has cooled in the global mean since the mid-20th century.
- The atmospheric burdens of well-mixed greenhouse gases (WMGHGs), which are controlled under the Kyoto protocol, have increased since AR4 at a rate that is comparable to that in previous decades. The atmospheric concentration of carbon dioxide in 2011 was 40% higher (390.5 ppm) than in the pre-industrial era.
- After undergoing rapid loss during the 1980s and 1990s, the short-lived greenhouse gas ozone (O_3) has shown signs of stabilizing in the stratosphere over the last decade. In the troposphere, it is *likely* that surface O_3 trends over Europe and North America have levelled off or decreased since 2000, but have strongly increased over South East Asia since the 1990s.
- A number of indicators show that it is *very likely* that tropospheric water vapour content has increased since the 1970s at a rate that is generally consistent with the Clausius-Clapeyron relation (~7% °C^{-1}).
- Since 1950s the number of heavy rain events has *likely* increased in more regions than it has decreased.
- Observations indicate it is *likely* that levels of surface solar radiation over land decreased between the 1950s and 1980s ("global dimming"), but have subsequently increased ("brightening").
- Satellite data suggest that there has been little net change in stratospheric water vapour during the period 1992-2011, although there has been substantial year-to-year variability. The confidence in these trends is *low* given the large year-to-year variations and short data records.
- Evidence from a range of observations indicates that it is *likely* that the tropical belt has widened over the period 1979-2005.
- A range of observations suggest that there is *very likely* to have been strong negative trends in total aerosol loading over Europe and eastern USA during the 1990s and 2000s, with positive trends observed over eastern and southern Asia.

What's new?

- Since AR4, significant progress has been made in identifying and accounting for data issues in the land surface air temperature (LSAT) record. In particular, revised datasets and new analyses have been produced. These innovations have further strengthened the overall understanding of the global LSAT records.
- In contrast to the AR4 conclusion that there is *likely* to have been an increase in intense tropical cyclone activity since 1970, reassessment of the data in AR5 indicates that it is hard to draw robust conclusions about long-term tropical cyclone trends in many regions. However, it is *virtually certain* that there has been an increase in the frequency and intensity of the strongest tropical cyclones in the North Atlantic since the 1970s.
- New results indicate that the conclusion in AR4 stating that there has been a positive trend in global droughts since the 1970s is no longer supported and that the overall confidence in global drought trends is *low*.
- There is *medium confidence* in reported decreases in observed global Diurnal Temperature Range (DTR), noted as a key uncertainty in the AR4. It is *virtually certain* that both daily maximum and minimum temperatures have increased since 1950.
- Much greater use of meteorological reanalysis products is made in AR5. These have proven to be valuable for studying a wide range of atmospheric phenomena given their global coverage and high temporal resolution; however, there remain issues with their suitability for use to detect long-term trends due to changes in atmospheric observing systems over time.
- Since AR4, new satellite measurements have helped to improve our understanding of the global mean annual mean energy budget.

Chapter 3: Observations: Oceans

Prepared by Scott Hosking, Amanda Maycock

This chapter summarises the findings from physical and biogeochemical observations of the global oceans. These provide strong evidence of both sea level rise and ocean acidification over the past forty years.

Key Highlights

- It is *virtually certain* that the heat content of the upper ocean (0-700 m) increased over the period 1971-2010.
- The largest increase in deep ocean temperature (below 700 m depth) has been observed around the sources of deep bottom water (North Atlantic and especially in the Southern Ocean)
- Around 93% of the extra energy stored by the Earth between 1971-2010 has been taken up by the oceans.
- Since the 1950s, it is *very likely* that regional trends have enhanced geographical contrasts in sea surface salinity. Surface waters in mid-latitudes have become more saline ('salty') due to increased rate of evaporation, while at tropical and polar latitudes waters are freshening due to increased rainfall. These patterns indicate an intensification of the global water cycle.
- It is *likely* that observed changes in the properties of water masses reflect the combined effect of long-term trends in surface forcing (e.g., changes in temperature and evaporation-precipitation) and interannual-to-multidecadal variability related to climate modes.
- It is *very likely* that the mean rate of global mean sea level was between 1.5-1.9 mm yr^{-1} between 1901-2010, and between 2.8-3.6 mm yr^{-1} between 1993-2010. It is *very unlikely* that these rates are significantly biased by the movement of land masses.
- Since the 1970s, it is *likely* that the magnitude of extreme high sea level events has increased.
- There is *very likely* that the global ocean storage of anthropogenic carbon increased between 1994-2010.
- It is *very likely* that increased uptake of anthropogenic CO_2 has steadily acidified ocean surface waters.
- High agreement among analyses provides *medium confidence* that oxygen concentrations have decreased over much of the open ocean thermocline since the 1960s. It is also *likely* that the tropical oxygen minimum zones have expanded in recent decades.

What's new?

- Since AR4, the international Argo project has deployed a global network of ~3600 underwater robots which are now measuring the sub-surface ocean for temperature and salinity. This activity has contributed to a substantial increase in the number and coverage of observations of the global oceans. Further information about the Argo project can be found here.
- Errors in the instrumental record which produced spurious decadal variations in temperature and upper ocean heat content reported in AR4 have since been mitigated.

- There have been considerable decreases in the level of uncertainty in salinity and freshwater content trends since AR4; this has increased confidence in the inferred changes of evaporation and precipitation over the ocean.
- Since AR4, the longer data record from the Gravity Recovery and Climate Experiment (GRACE) satellite mission has enabled the mass component of sea level change to be assessed for the first time; it is estimated to have been increasing at a rate of between 1-2 mm yr^{-1} since 2002.

Chapter 4: Observations: Cryosphere

Prepared by Scott Hosking

This chapter summarises the observed changes in sea ice and land ice (glaciers, ice shelves, ice sheets, snow cover and permafrost), found mainly in the two polar regions, over the last few decades.

Key Highlights

- There is *high confidence* that over the period 1979-2012 there has been a significant reduction in perennial and multi-year Arctic sea ice coverage, thickness and volume.
- It is *very likely* that there has been a small yet significant increase in total annual Antarctic sea ice extent of 1.2-1.8% per decade between 1979-2012.
- Globally, almost all glaciers continue to shrink and lose mass. There is *high confidence* that they will continue to shrink in the future.
- There is (*very) high confidence* that the (Greenland) Antarctic ice sheet has lost mass over the past two decades and it is (*very) likely* that the rate has accelerated since the early 1990s.
- There is *high confidence* that ice shelves around the Antarctic Peninsula will continue their long-term trend of retreat and partial collapse.
- Over the past 90 years, there is *very high confidence* that there has been a significant reduction in Northern Hemisphere snow cover extent during spring.
- There is *high confidence* that permafrost temperatures have risen over large areas since the early 1980s. The southern boundary of permafrost in the Northern hemisphere has migrated northwards by up to 80 km, while the boundary of the area covered with permafrost year-round has moved north by up to 50 km (1975-2005).

What's new?

- Since the AR4, improvements to observational instruments, and longer records has led to substantially improved understanding of the processes that govern cryospheric change.
- The global coverage of regional-scale estimates of glacier change has increased providing a more comprehensive global picture of the worlds ice and its evolution.

Chapter 5: Information from Paleoclimate Archives

Prepared by Eric Wolff

This chapter concentrates on learning about processes in the Earth system using data from time periods before the instrumental period. It uses data from palaeoclimate archives such as marine sediments, tree rings and ice cores, as well as modelling studies.

Key highlights:

- The present concentration of CO_2 (around 400 ppm) exceeds any value measured in ice cores covering the last 800,000 years.
- Other climate periods during the last 50 million years suggest that warmer temperatures and higher CO_2 are closely linked.
- Sea level has been higher than today during periods (some interglacials, mid-Pliocene) when temperatures (and particularly polar temperatures) were warmer than today, suggesting that either the Greenland or West Antarctic Ice sheet (or both) are vulnerable to persistent temperatures as high as those expected in the next century.
- The last three decades were *very likely* the warmest thirty year period of the last 800 years, and *likely* longer. However, we should temper this by pointing out that a paper released since AR5 shows that global temperature was warmer in the early Holocene (about 6000-10000 years ago) than it is currently.
- There is *high confidence* that changes in atmospheric CO_2 concentration play an important role in glacial-interglacial cycles. New updates on the phasing between climate changes and CO_2 changes coming out of the last glacial period suggest that the rise in CO_2 is (within uncertainty) synchronous with the rise in Antarctic temperature, and leads Northern hemisphere temperature rise.

What's new?

- Many of the changes have come about from new data (either more precise, better resolved, or extending further in time) that strengthen the confidence of statements that appeared in AR4. The ability to run more complex models over palaeoclimate time periods (including transient model runs) has also added confidence to some conclusions.
- The extension of the ice core record of greenhouse gases back to 800,000 years and new data that fill some of the gaps in the recent record have allowed the statement about the unusual nature of the recent CO_2 levels to be strengthened.

Chapter 6: Carbon and Other Biogeochemical Cycles

Prepared by Nicola Warwick, Scott Hosking

This chapter focuses on the biogeochemical cycles of the three most influential anthropogenic greenhouse gases: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), which together account for ~80% of the total radiative forcing from well-mixed greenhouse gases. There is *very high confidence* that the increases in atmospheric concentrations of these gases is caused by human activity, and modulated by natural processes.

Key Highlights

- Over the period 1750 to 2011, the atmospheric abundance of CO_2 increased by 40% (from 278 to 390.5 ppm), CH_4 by 150% (722 to 1803 ppb), and N_2O by 20% (from 271 to 324.2 ppb).
- There is *very high confidence* that the dominant cause of the increased atmospheric concentrations of CO_2 since 1750 is from the burning of fossil fuels and land use changes.
- CO_2 emissions from fossil fuel burning and cement production increased faster during the 2000-2011 period than during the 1990-1999 period.
- Global atmospheric CH_4 concentrations have continued to increase since 2007 following stabilization in the early 2000s. The causes for the resumed increase in concentrations are still being debated, with implicated sources including natural wetlands and fossil fuel production. There is *high confidence* that fluctuations in CH_4 emissions from natural wetlands are the main driver of interannual variability.
- In 2010, human-caused creation of reactive nitrogen was at least two times larger than the rate of natural terrestrial creation. This was dominated by the production of ammonia for fertilizer and industry, with important contributions also from legume cultivations and the burning of fossil fuels.
- Anthropogenic CO_2 emissions from early land use change is *unlikely* to be sufficient to explain the increase in CO_2 prior to 1750.
- In the last 800,000 years before 1750, atmospheric CO_2 concentrations varied from 180 ppm during glacial (cold) periods to 300 ppm during interglacial (warm) periods. In 2013, the CO_2 concentration reached 400 ppm.
- There is a *very high confidence* that carbon uptake of anthropogenic CO_2 by the oceans will continue under all four RCP scenarios out to 2100, with higher uptake under the higher greenhouse gas forcing scenarios.
- There is *high confidence* that reductions in the extent of permafrost driven by near-surface warming will cause thawing of some currently frozen carbon. However, there is *low confidence* on the magnitude of the resulting carbon release.
- Food and animal feed production and the reliance on nitrogen fertilizers will *likely* increase the emissions of N_2O from soils in the future.
- There is *high confidence* that it would take a few hundred thousand years for the human-emitted CO_2 in the atmosphere to be removed by natural processes alone.

What's new?

- New advancements in data availability and data-model synthesis have improved constraints on individual flux terms in the anthropogenic CO_2 budget in comparison to AR4. Evidence from decade-long experiments demonstrates that ecosystems are capable of higher rates of carbon accumulation under elevated atmospheric CO_2 levels. However, some ecosystems showed limited or no CO_2 fertilization effect, with nutrient limitation the likely primary cause. Land carbon models including the nitrogen cycle predict a reduced land carbon sink for a given trajectory of CO_2 concentrations relative to models that neglect the nitrogen cycle.
- Uncertainties in present day CH_4 emissions from the major CH_4 sources have decreased since AR4, although they still remain significant. Recent estimates of natural geological sources, which were not accounted for in previous budgets, has resulted in an upwards re-evaluation of the combined contribution of leaks in the fossil fuel industry and natural geological leaks from around 20 to 30% of total CH_4 emissions (*medium confidence*).

Chapter 7: Clouds and aerosols

Prepared by Hans Graf, Amanda Maycock

This chapter outlines the current understanding of clouds and aerosols (tiny particles in the atmosphere) in the climate system, their impacts on past climate variability and change, and their role in climate model projections of future climate.

Key highlights

- The net effect of clouds on the Earth's radiation budget has been better established and is estimated to be around -20 W m^{-2}, with a substantial compensation between warming (+30 W m^{-2}) and cooling (-50 W m^{-2}) effects.
- Evidence from theory and models indicates that the net impact of changes in water vapour and lapse rate under global warming is *extremely likely* to enhance the effects of LLGHGs on global mean surface air temperature (i.e. a self-reinforcing climate feedback).
- There are many potential changes in clouds in response to climate change which can both reinforce or offset the effects of increases in greenhouse gases on global mean near-surface temperature. It is now understood that many of the changes in cloudiness simulated by climate models do not appear to depend strongly on subgrid-scale model processes, which are more uncertain, but are rather driven changes in by large-scale circulation. For example, there is now *high confidence* that increases in the altitude of high cloud acts to enhance the effects of LLGHGs on near-surface global temperature. However, there is still *low confidence* in the contribution of changes in low cloud (e.g. large-scale stratocumulus decks) to the climate response to WMGHGs.
- Changes in clouds (distribution, altitude, optical properties) still represent the largest contributor to the spread in climate sensitivity across climate models.
- Aerosol effects on clouds and their radiative properties (so-called aerosol indirect effects) have been better constrained since AR4, but still carry large uncertainties.
- Individual studies have found that the impact of near surface warming on aerosol-cloud interactions could either enhance or partly offset the effects of LLGHGs on temperature; the net effect appears to depend on the aerosol properties and cloud system characteristics; confidence in the overall effects of aerosol-cloud interactions on the climate system remains *low*.
- The effect of cosmic rays on the concentration of cloud condensation nuclei is too weak to have any detectable climatic influence (*medium evidence, high agreement*). No robust association between changes in cosmic rays and cloudiness has been identified.
- Geoengineering options involving clouds and aerosols may offset some of the global temperature change due to increases in atmospheric greenhouse gases, but there is *high confidence* that the compensation of changes in other aspects of climate, such as precipitation, would be imprecise.

What's new?

- Generally clouds of different sizes and their interactions remain a challenge, both in terms of theoretical understanding and modelling. Although there has been considerable progress since

AR4 in understanding individual processes from new observations and higher resolution models, there are still large uncertainties regarding the impact of clouds on the climate system.

- Many climate models now incorporate some aerosol-cloud processes (aerosol indirect effects) which were not included at the time of AR4.
- There have been significant advances in the observation of clouds since AR4. Satellites have provided new information on vertical profiles of clouds, their properties, and interactions with atmospheric aerosols.

Chapter 8: Anthropogenic and Natural Radiative Forcing

Prepared by Amanda Maycock

This chapter quantifies the impact of changes in atmospheric composition, land use and natural forcings (solar and volcanoes) on the Earth's energy budget. The key diagnostics used for this purpose are radiative forcing (RF[1]) and effective radiative forcing (ERF[2]), which are used to quantify the strength of different mechanisms in causing climate change. The main constituents discussed in this chapter are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3), and aerosols.

Key highlights

- It is certain that the anthropogenic effective ERF is positive (see Fig. SPM.5 below).
- The most rapid rate of increase in total anthropogenic ERF has been since the 1970s. However, there is *high confidence* that the growth rate in ERF due to well-mixed greenhouse gases (WMGHGs) has been smaller in the last decade than in the 1970s and 1980s because of a slow-down in the rate of increase of non-CO_2 greenhouse gases.
- Emissions of CO_2 from volcanic eruptions are at least 100 times smaller than anthropogenic emissions, and are inconsequential for climate on timescales of a millennium or less.
- The total RF due to ozone is estimated to be 0.35 ± 0.20 W m^{-2}. This is the net result of opposing effects due to increases in tropospheric ozone (positive RF) and stratospheric ozone depletion (negative RF).
- The uncertainty in aerosol RF is the dominant contributor to the uncertainty in the total RF over the industrial era. However, there is *high confidence* that aerosols have offset a substantial fraction of the RF due to WMGHGs.
- The maximum forcing from aerosol-radiation interactions (also known as the aerosol direct effect - see glossary) has shifted from eastern North America and Europe to south and east Asia, primarily as a result of pollution control in the former and economic growth in the latter.
- *Robust evidence* suggests that anthropogenic land use change has increased the land surface albedo over the industrial era. However, other non-radiative mechanisms are more uncertain, and there is therefore *low agreement* on the sign of the net impact of land use changes on global near-surface temperature.
- The is *very high confidence* that the net contribution of natural forcings to the total RF over the industrial era is only a small fraction of that due to human activities. However, the contribution of natural forcings has *likely* offset a substantial fraction (10 - 95%) of the anthropogenic forcing over the last 15 years.
- CO_2 concentrations account for the majority of the difference in RF at the end of the 21st century between the RCP scenarios.

[1] A positive Radiative Forcing (more incoming energy) warms the surface-troposphere system, while a negative forcing (more outgoing energy) cools it.

[2] The difference between ERF and RF is that the former includes additional 'fast adjustments' which take place in the troposphere that are independent of the global near-surface temperature change e.g changes in cloud properties. These are important for e.g. the effects of aerosols on the Earth's energy budget.

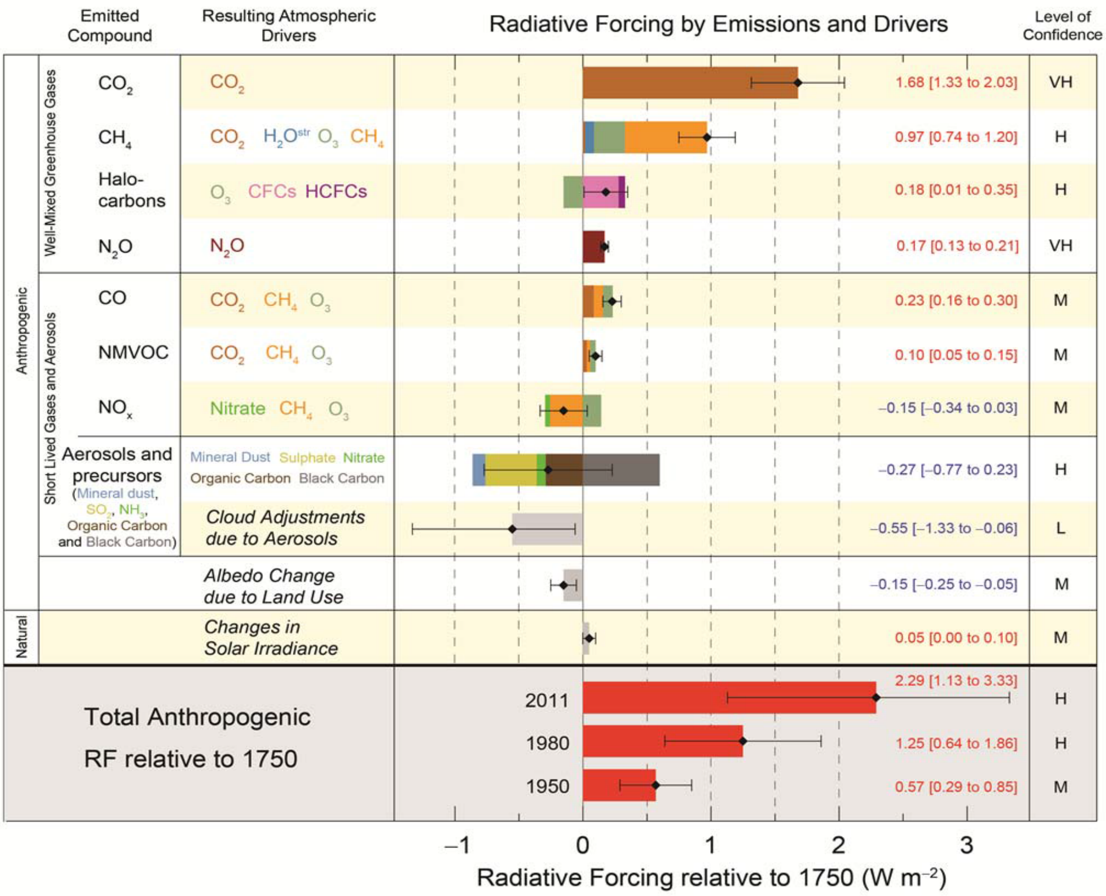

Figure SPM.5 (Sept. 2013)

What's new?

- The estimated total anthropogenic ERF for 2011 is 44% higher than the estimate for 2005 in AR4; this is due to the continued growth in the greenhouse gas ERF, but also a decrease in the estimated negative ERF due to aerosols.
- Since 2011, N_2O has become the third largest WMGHGs contributor to the total RF (6% increase since AR4), after CO_2 (~10% increase since AR4) and CH_4 (2% increase since AR4). In the AR4, the third largest contributor was chlorofluorocarbon-12 (CFC-12).
- Since AR4, the contribution of hydrofluorocarbons (HFCs) to the total RF has almost doubled, but it is still only a small component of the total anthropogenic RF.
- The estimated RF due to aerosol effects (aerosol-radiation plus aerosol-cloud interactions) is ~30% smaller than in AR4; this is due to improved knowledge of aerosols rather than changes in aerosol abundances.
- Relative to AR4, the confidence level of radiative forcing mechanisms has been elevated for seven drivers due to improved evidence and agreement. These are:
    - aerosol-radiation-interactions (now *high confidence* due to more robust estimates from independent methods).
    - stratospheric water vapour (now *mediumconfidence* due to more studies).
    - surface albedo due to land use change (now *high confidence* due to new high quality satellite data).
    - contrails (now *medium confidence* due to more studies).
    - contrail induced cirrus (now *low confidence*).
    - solar irradiance (now *medium confidence* due to better agreement of weak RF. effect).
    - volcanic aerosol (now *high confidence* due to improved understanding).

Chapter 9: Evaluation of Climate Models

Prepared by Tom Bracegirdle

The scope of this chapter is to assess the capability of climate models used for the research cited in chapters 10-14 of the AR5 report. It includes discussion both of climate model performance and observational datasets.

Key highlights:

- As with AR4, there is still a *very high confidence* that general features of the observed global-scale surface temperature changes are reproduced by climate models and that their responses to climate forcings are realistic. On a more regional scale the results are less clear.
- The global warming slowdown (or hiatus) between 1998-2012 gives smaller trends than the majority of climate model simulations of the same period. The differences between simulated and observed trends is estimated with *medium confidence* to be substantially due to internal climate variability superimposed onto the background warming signal. It is possible that there are also contributions from missing processes and/or an overestimation of the response to WMGHG increases. A comprehensive and useful summary can be found here [PDF].
- There has been a widespread introduction of earth system models (ESMs) since the AR4. ESMs include additional biogeochemical cycles (e.g., carbon cycle, sulphur cycle). About two thirds of CMIP5 ESMs produce carbon sinks within the range of observations in the latter part of the 20th century.
- There has been significant progress since AR4 in the simulation of the following: (i) large-scale patterns of precipitation, (ii) El Nino – Southern Oscillation (ENSO), (iii) extreme events, (iv) stratospheric ozone, (v) Arctic sea ice.
- Since AR4, the typical regional climate model grid spacing has decreased from around 50 km to around 25 km. Regional climate models show improved performance in regional climate simulations, particularly in relation to complex orography (e.g. coastal regions) and relatively small intense storms (e.g., cyclones smaller than 1000 km in diameter).
- A number of CMIP5 models now include improved representation of atmospheric aerosols (tiny particles suspended in the air).

What's new?

- In summary, climate model skill at reproducing many aspects of historical climate have improved compared to AR4. More processes have been included and in particular ESMs have been introduced widely in CMIP5. It is important to note that model skill can only be evaluated with respect to historical observations. Good skill at simulating past observations is important for building confidence in projections of future change. However, a key limitation is that the projections themselves cannot be verified.

Chapter 10: Detection and Attribution of Climate Change: from Global to Regional

Prepared by Tom Bracegirdle

This chapter looks at the significance of observed climate changes and what might be causing them. In particular the relative importance of anthropogenic and natural factors is assessed.

Key highlights:

- Since AR4 there is now stronger evidence that humans have contributed significantly to observed global warming and related changes in the water cycle, cryosphere and atmospheric circulation.
- The century time-scale response (transient climate response (TCR) - see glossary) is estimated to be *likely* in the range 1.0 to 2.5°C. The equilibrium climate sensitivity (ECS) - see glossary) is *likely* in the range 1.5 to 4.5°C. The lower part of the range is slightly below that given in AR4 (2.0 to 4.5°C).
- The greenhouse gas contribution to global surface temperature change between 1951 and 2010 is *likely* in the range 0.5-1.3 °C. The actual observed warming was approximately 0.6-0.7 °C, with an estimated aerosol-induced contribution of between 0.1 °C and -0.6 °C.
- It is *very likely* that humans have substantially contributed to the observed increase in global ocean heat content of the upper 700 m of the ocean since the 1970s. In AR4 there was large uncertainty in this conclusion which has since been reduced due to improved observational estimates.
- Over the last six years there has been increasing evidence of rapid and significant changes in the Arctic, with the 2007 minimum in summer sea ice followed by a series of years of low sea ice extents and a new record in summer 2012. It is considered *very likely* that Arctic sea ice retreat since 1979 has been caused at least in part by anthropogenic forcings. The increased surface melt of Greenland since the year 1990, and reductions in snow cover since 1970, are also *likely* to have a significant anthropogenic contribution (increased confidence than AR4).
- Since AR4 evidence has strengthened for an anthropogenic contribution to observed changes in temperature extremes since the mid 20th century, which is now estimated to be *very likely* in AR5 compared with *likely* in AR4.
- There has also been a strengthening of the evidence for a human contribution to the global-scale intensification of heavy precipitation events since ~1950. There is now *medium confidence* in this conclusion.

What's new?

- It is now *extremely likely* that humans have contributed at least 50% to observed global near-surface warming since the mid 20th century compared with *very likely* in AR4. The reduction in the lower part of the ECS range in AR5 (1.5-4.5°C) compared to AR4 (2.0 - 4.5°C) is also notable. The reasons for this are (i) the use of observational datasets that extend further back in time (pre 1900 to 1851) and using the most recent decade and (ii) a wider range of studies are now available.

Chapter 11: Near-term Climate Change: Projections and Predictability

Prepared by Scott Hosking, Amanda Maycock

This chapter summarises projected changes in climate up to the middle of the 21st century, with the greatest emphasis on the period 2016-2035. In addition to the influence of natural variability, near-term climate will also depend strongly upon aerosol emissions, volcanic eruptions and land use changes, and these are all considered to be uncertain. Similarly to Chapter 12, this chapter makes extensive use of model data from the Coupled Model Intercomparison Project 5 (CMIP5) archive.

Key highlights

- The global mean near-surface air temperature in the period 2016-2035 is *more likely than not* to be at least 1.0 ºC warmer than the average during 1850-1900.
- The spread in projections of near-surface temperature between climate models is generally larger than the spread between the different RCP scenarios.
- A future volcanic eruption similar to the 1991 Mount Pinatubo eruption would cause a rapid reduction in global mean surface air temperature of several tenths of a degree (ºC) for one to two years after the eruption, but would have little effect in the longer term.
- Possible future changes in solar irradiance could influence on the rate of at which global near-surface temperature increases, but there is *high confidence* that this effect will be considerably smaller than the effect of increasing atmospheric greenhouse gases.
- It is *very likely* that anthropogenic warming over land areas will be larger than over the oceans, and that the warming over the Arctic in winter will be greater than in the global mean.
- Over the next few decades, near-surface specific humidity will *very likely* rise as a result of increasing evaporation rates.
- In the near-term, stratospheric ozone recovery and increases in greenhouse gases are *likely* to have opposing effects on the width of the Hadley Circulation and the latitude of the storm track in the Southern hemisphere during austral spring/summer. It is therefore *unlikely* that the rate of poleward expansion of the Southern hemisphere Hadley cell will be as rapid as it has been in recent decades.
- It is *very likely* that the global mean upper ocean temperature will increase over the next few decades.
- Arctic sea ice extent, and the coverage of snow and permafrost, are all *very likely* to continue to decrease. It is possible that the Arctic will be virtually ice free in late summer by 2050.
- The frequency of warm days and warm nights will *very likely* increase at the global scale, while cold days and cold nights will decrease.
- The frequency of heavy precipitation events will *likely* increase at the global scale over the next few decades, driven by greater capacity of water vapour within the atmosphere and changes to the atmospheric circulation. However, the trends are expected to be highly non-uniform given the effects of natural variability and possible regional influences such as aerosol loading.
- Projected changes in regional air quality are sensitive to the scenario for greenhouse gases and local emissions, with rising temperatures leading to an enhancement in global O_3 destruction (*high confidence*) but rising methane levels leading to an increase in O_3 production (*high confidence*).

What's new?

- There is increased understanding of where the signals of anthropogenically driven near-surface temperature change are expected to emerge against background natural variability in the near-term; the tropics and subtropics show detectable signals before the mid-latitudes in both seasonal and annual mean temperature changes.
- There has been considerable progress in understanding the factors that govern the patterns of change in precipitation and the general pattern of wet-get-wetter and dry-get-drier has been confirmed. However, the basic thermodynamic response is modified by changes in the atmospheric circulation, which are generally less well understood and less consistent across models.

Chapter 12: Long-term Climate Change: Projections, Commitments and Irreversibility

Prepared by Peter Hitchcock

This chapter summarises the projections of long-term (end of 21st century and beyond) climate change based on several plausible future pathways for anthropogenic forcings including greenhouse gas concentrations and aerosols. The chapter makes extensive use of model data from the Coupled Model Intercomparison Project 5 (CMIP5) archive.

Key highlights

Climate sensitivity

- The Equilibrium Climate Sensitivity (ECS) is considered *likely* to be in the range 1.5-4.5 °C. It is *extremely unlikely* to be below 1.0 °C and *very unlikely* to be above 6 °C.
- The Transient Climate Response (TCR) is considered *likely* to be between 1.0-2.5 °C.
- The Transient Climate Response to cumulative carbon Emissions (TCRE) is estimated to be *likely* in the range 0.8-2.5 °C per 1000 GtC (10^{12} metric tons of carbon). This implies that to restrict near-surface global warming to 2 °C would permit no more than ~1000 GtC to be emitted by 2100, of which around half has been emitted by 2011.

Near-surface temperature change

- The projected global mean near-surface temperature change by 2100 is 0.3-1.7 °C for RCP2.6, 1.1-2.6 °C for RCP4.5, 1.4-3.1 °C for RCP6.0 and 2.6-4.8 °C for RCP8.5.
- It is considered *likely* that the warming in the period 2081-2100 will exceed 2 °C compared to preindustrial for the RCP6.0 and RCP8.5 scenarios.
- There is *very high confidence* that globally averaged temperature change over land will be larger than over the ocean by a factor that is *likely* in the range 1.4–1.7.
- The total RF reaches 12 W m^{-2} by 2300 in the RCP8.5 scenario, for which the global near-surface temperature is projected to increase by 3.0–12.6 °C compared to pre-industrial times.

Circulation Changes

- It is considered *likely* that the mid-latitude tropospheric jets will shift polewards by 1-2° latitude under the RCP8.5 forcing scenario.
- The Hadley and Walker circulations are *likely* to slow down, the Hadley circulation is *likely* to widen, and the Brewer-Dobson circulation is *likely* to strengthen.

Water Cycle

- Global mean relative humidity is projected to remain roughly constant.
- Global precipitation is considered *likely* to increase by 1-3% per °C of global near-surface warming.
- It is *virtually certain* that changes in precipitation will not be uniform, with *high confidence* that the contrast between dry and wet regions and between wet and dry seasons will increase over most of the globe in the annual mean.
- The frequency of precipitation is *very likely* to change; more intense individual storms and fewer weak storms are *likely*. Extreme precipitation events will *very likely* become more intense and more frequent over midlatitude land masses and in wet tropical regions.

Cryosphere

- It is *very likely* that the Arctic sea ice cover will continue to shrink and thin as global mean surface temperature rises. A virtually ice-free Arctic Ocean in September is *likely* by the middle of the century under the RCP8.5 scenario.
- Overall models project a decline in Antarctic sea ice, but with large uncertainties due to the difficulties CMIP5 models have in capturing the observed annual cycle, interannual variability and overall increase of Antarctic sea ice area over recent decades.
- The retreat of the Arctic permafrost is *virtually certain* with rising global temperatures; the projected decreases range from 37% in RCP2.6 to 81% in RCP8.5 by 2100.
- It is considered *exceptionally unlikely* that the Greenland and West Antarctic ice sheets will undergo catastrophic collapse during the 21st century.

What's new?

- The projected decline in Arctic sea ice in CMIP5 models is more rapid than in AR4.
- The more consistent treatment of stratospheric ozone recovery in the CMIP5 models has led to an increase in our understanding of the role of ozone in Southern hemisphere climate change in austral spring/summer.
- Estimates of the amount of carbon stored in permafrost have been revised upwards since AR4. However, studies of the impact of possible future climate change on the permafrost carbon balance have not yielded consistent results with the exception that permafrost is expected to become a net emitter of carbon over the 21st century.
- In general, the projections of global, large-scale and regional long-term climate change in the CMIP5 models are remarkably consistent with those in AR4. Confidence in projected temperature changes remains higher than for quantities related to the hydrological cycle and atmospheric circulation.

Chapter 13: Sea Level Change

Prepared by Scott Hosking

This chapter quantifies the factors that drive global mean sea level change including thermal expansion/contraction, and the transfer of water between ocean and land. Sea level change depends upon the state of the global climate system (e.g., global mean surface air temperature) as well as changes at the local and regional scale (e.g., changes in atmospheric circulation and climate modes).

Key Highlights

- Paleo records indicate that global mean sea level was in excess of 5 m higher than the current level (*very high confidence*) during periods when global temperatures were up to 2 ºC higher than pre-industrial levels (*medium confidence*).
- For the period 1901 to 2010, it is *very likely* that global mean sea level rose by between 1.5-1.9 mm yr^{-1}, and by 2.8-3.6 mm yr^{-1} between 1993 and 2010.
- Oceanic thermal expansion and glacier melting (excluding Antarctic glaciers) can explain 75% of the observed global mean sea level rise since 1971 (*high confidence*).
- It is *very likely* that the rate of global mean sea level rise during the 21st century will exceed the rate observed during 1971-2010. See plot below for the range of global mean sea level projections that relate to RCP2.6 and RCP8.5.
- It is *virtually certain* that global mean sea level will continue to rise beyond 2100, and for many centuries into the future.
- It is *very likely* that future sea level change will vary regionally.
- It is *very likely* that there will be a significant increase in the frequency of sea level extremes by 2050 and 2100, mainly resulting from an increase in global mean sea level (*high confidence*). As illustrated in the figure below, sea level rise is projected to continue under the range of RCP scenarios, even RCP2.6 where CO_2 emissions are substantially reduced.

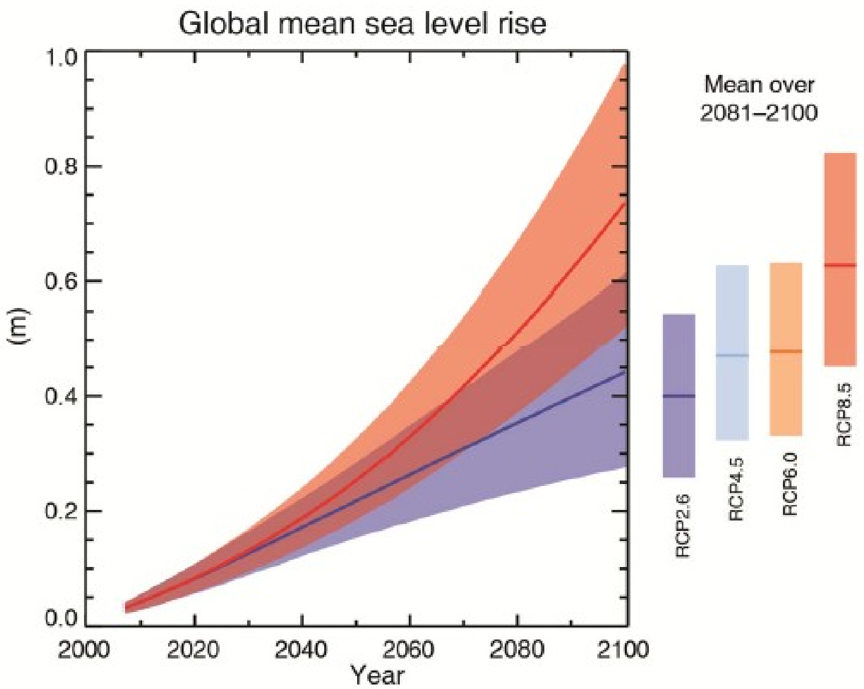

Figure SPM.9 (Sept. 2013)

What's new?

- Improvements in ice sheet modelling have enabled a more reliable assessment of the contribution of ice sheet dynamics and outflow to sea level rise.
- An improved global overview of glaciers has shown that almost all are shrinking, with the exception of those in New Zealand where the uncertainty in the trend spans the zero line.
- Due to improvements in mass balance budgets, there is now closure of the global mean sea level budget over the observational record to within the levels of uncertainty.

Chapter 14: Climate Phenomena and their Relevance for Future Regional Climate Change

Prepared by Scott Hosking

This chapter focuses on regional climate change and its drivers including: (i) local physical processes and, (ii) complex interactions with large-scale phenomena (e.g., monsoons, ENSO, large-scale modes of variability). This chapter mainly relies upon results from global coupled-climate models (CMIP5).

Key Highlights

- The global monsoon is *likely* to strengthen over the 21st century with increase in its area and intensity, while the monsoon circulation weakens. Many of the monsoon seasons are also expected to lengthen.
- The tropical Indian Ocean is *likely* to exhibit zonally asymmetric patterns of change in the future, with reduced (increased) warming and precipitation in the east (west), directly influencing East Africa (Southeast Asia) precipitation.
- El Niño-Southern Oscillation will *very likely* remain as the dominant mode of interannual climate variability in the future. El Niño and La Niña-induced teleconnection patterns over the extra-tropical Northern Hemisphere are *likely* to move eastwards in the future.
- The global water cycle will change, with increases in the contrast between wet and dry regions, and wet and dry seasons, with some regional exceptions (see Fig. SPM.8 below).
- Global mean tropical cyclone maximum wind speed and precipitation rates will *likely* increase.
- It is *likely* that there will be a small poleward shift in the future Southern Hemisphere storm track.
- The winter-time North Atlantic Oscillation index is *likely* to become slightly more positive on average.
- The austral summer/autumn positive trend in the Southern Annular Mode is *likely* to weaken considerably as the stratospheric ozone layer recovers up to the mid-21st century.
- The Atlantic Multi-Decadal Oscillation is *unlikely* to change its behavior in the future, although natural fluctuations are *likely* to influence regional climate variability (at least as strongly as the anthropogenic induced changes).

What's new?

- For the climate models used for AR5, there is evidence of improved skill in reproducing the climatological features and variability of the global monsoons, blocking events and the El Niño-Southern Oscillation

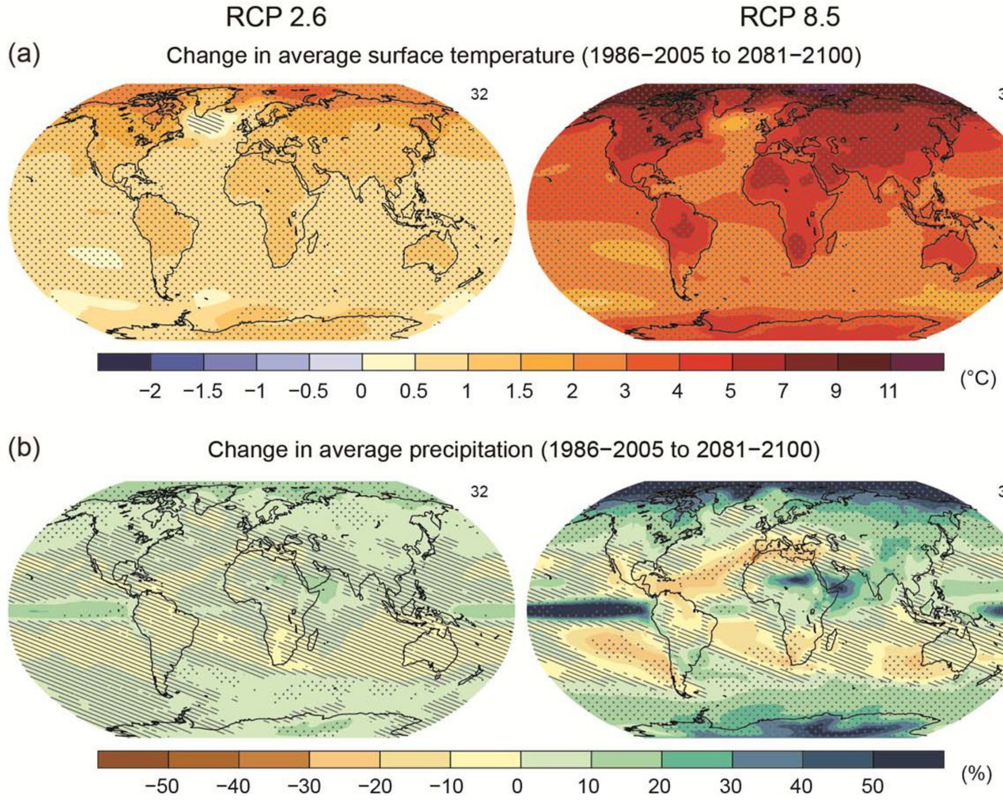

Figure SPM.8, cropped (Sept. 2013)

Further Scientific Information

The recent global near-surface temperature change 'hiatus'

Met Office reports published August 2013

- Report 1: Observing changes in the climate system
- Report 2: Recent pause in global warming
- Report 3: Implications for projections

Science Media Centre briefing published July 2013

Recent cold winters across Europe

Met Office report published April 2013, Why was the start to spring 2013 so cold?

Jiping Liu, Judith A. Curry, Huijun Wang, Mirong Song, and Radley M. Horton (2012), Impact of declining Arctic sea ice on winter snowfall, *PNAS*, 27, doi: 10.1073/pnas.1114910109

Recent summer heat waves across Europe and US

Otto, F. E. L., N. Massey, G. J. van Oldenborgh, R. G. Jones, and M. R. Allen (2012), Reconciling two approaches to attribution of the 2010 Russian heat wave, *Geophys. Res. Lett.*, 39, L04702, doi:10.1029/2011GL050422.