Commentary on Recent Climate Research

Ten Key Points: Global Warming and Greenhouse Gases

1. Concentration of CO_2 now exceeds 400ppm – a 43% increase over pre-industrial levels.
2. Non-CO2 GHGs in 2015, tracked by NOAA's Annual Greenhouse Gas Inventory, increase warming by a factor of 1.37 to a CO_2 equivalent of 485 ppm.
3. The Earth's global average surface temperature has warmed over 1°C since the 1880s; 2016 is likely to be the hottest year in the 136-year record.
4. Since 1975 the rate of global temperature increase has been 0.18°C per decade.
5. Industrial era ocean heat content has doubled since the late 1990s.
6. There is an improved understanding of how natural cycles such as the Interdecadal Pacific Oscillation and other processes can amplify or dampen anthropogenic warming on interannual to decadal timescales.
7. A recent climate sensitivity study of the response to a doubling of CO_2 of past climates finds that the temperature response is more sensitive during warm interglacial periods, such as the present.
8. Natural gas-related methane emissions from the fossil fuel industry are 20 to 60 percent greater than EPA and European Commission estimates.
9. Modeled projections of sea level rise from past assessments are on the low side of observations.
10. To achieve the less than 2°C Paris Agreement goal, there is a likely need for technologies that can achieve negative emissions ***unless*** substantial reductions occur before 2050.

Overview

Since the 1980s a vast amount of research from both the modeling and observation communities have focused on how the Earth system will respond to human activity, and in turn, how humanity and ecosystems will be affected. The climate change component of humankind's footprint has been codified in numerous scientific assessments including the flagship reports of the Intergovernmental Panel on Climate Change (IPCC), which are developed about every 6 years under the auspices of the United Nations Environmental Programme and World Meteorological Organization. Each of the IPCC assessments has built upon the growing knowledge base that increasingly refines the detection of climate change in greater detail and with deeper understanding of the underlying processes. The confidence that detected changes are attributable to human causes has steadily grown with each assessment. With the improving ability to observe and model the Earth, the confidence in the bottom-line statements about climate change have become more exacting.

Models and observations will likely continue to improve as more processes in the highly complex Earth system become better represented; however, the evidence of human influence is clear and mounting – not only in the temperature record, but in many aspects of the Earth system such as sea level rise, loss of sea ice, change in precipitation patterns, ocean acidification, and altered ecosystems. From a cumulative carbon budget standpoint, to avoid 2°C change, the window is closing. Longer delays in decreasing annual emissions, require a steeper rate of carbon reductions and potentially carbon removal. Meanwhile, societal and ecosystem impacts—principally from sea-level rise, heat stress, altered precipitation, and ocean acidification—are already present: their detrimental impacts will continue to accelerate, absent swift and sustained global response.

Introduction

This commentary is intended to provide a sampling of new research focusing on global mean surface temperature while also considering how greenhouse gas (GHG) emissions, concentrations and non-CO_2 GHGs have changed since the last IPCC assessment in 2013. In addition, we compare key model projections with observations and discuss updates to our understanding of the carbon cycle and carbon budget to stay within the 2°C goal.

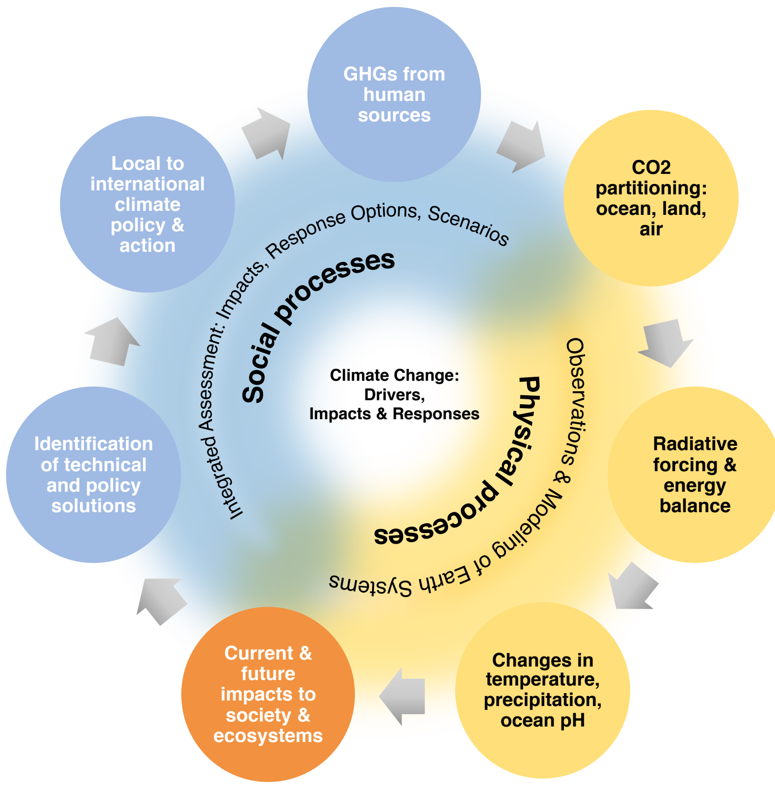

Figure 1. Climate Change: Drivers, Impacts and Responses

The IPCC series of major assessment reports result from a cycle of activity involving hundreds of scientists around the world. Figure 1 depicts some of the key elements in this process as well as the types of expertise and activities involved—the research components necessary for producing the IPCC reports and how they provide a scientific basis for policy consideration. The assessments go beyond change in temperature to explore biogeochemical cycles, ecosystem response, atmospheric chemistry, ocean dynamics and chemistry along with socioeconomic factors such as population, energy systems, economic growth, and land-use/land cover. The assessment process is codified in three Working Group Reports on (1) climate science, (2) impacts/adaptation/vulnerability, and (3) mitigation. Many disciplines in the physical, natural, and social sciences are involved in preparing the reports. These efforts continue to gain a deeper understanding of how and why the Earth is changing, the impacts on society and ecosystems, and possible response strategies. The IPCC Working Group Reports are not prescriptive, but rather serve as a basis for policy considerations as input to the UN Conference of the Parties—such as COP21 held December 2015 in Paris. The Paris Agreement went into effect November 2016 with the goal of staying below a 2°C increase from pre-industrial temperatures and an aspiration to be closer to a 1.5° C target.

Global Mean Surface Temperature Observations

Based on observations used to produce the global mean surface temperature since the 1800s through September 2016, the Earth has experienced an increase over 1°C. Figure 2, based on NASA and NOAA data and analysis shows a change in temperature from an 1880-1920 base period (NASAGISTEMP 2016, NOAA NCEI 2016). More than half of the warming since 1880 has occurred in the last forty years: since 1975 the trend has been approximately 0.18°C per decade (Hansen et al. 2016). The slowdown in the rate of warming (sometimes referred to as a warming 'hiatus') after 2000 up until 2013 precipitated more research into the interplay of anthropogenic drivers of global warming and natural cycles such as internal variability in the climate system. As a result of these recent studies there is a better understanding of the role of ocean heat uptake, observational biases, radiative forcing from aerosols (i.e. their cooling and warming effects), and the effect of ocean cycles such as the Interdecadal Pacific Oscillation on surface temperature.

More than half of warming since 1880 has occurred in the last forty years: since 1975 the trend has been approximately 0.18°C per decade.

The steep rise starting in the 1970s follows a long pause in warming which began after WWII. Even though fossil fuel combustion increased during this period, there is evidence to indicate that the warming pause and slight cooling was caused by a combination of natural and anthropogenic factors that included cooling from carbonaceous and sulfate aerosols from fossil fuel combustion along with a possible cool-phase influence from the ocean. The volcanic eruption of Agung in 1963 also contributed to offsetting the warming producing a cooling effect from dust and aerosols lofted into the stratosphere. These cooling effects thus neutralized the warming from an increase in anthropogenic GHGs, and led to a net cooling of 0.1 °C during this period (Nagashima et al. 2006, Meehl et al. 2004, Andronova and Schlesinger 2000, Tett et al. 1999). With the deleterious effects of sulfate aerosols forming sulfuric acid in the atmosphere and producing acid rain, western countries made concerted efforts to clean up sulfur dioxide emissions from power plants in the late 1960s and into the 1970s. This reduced acid rain and the cooling from visible air pollution from sulfate aerosols. However, unabated fossil fuel burning continued and CO_2 concentrations steadily increased. This, along with a natural climate fluctuation that warmed the tropical Pacific after the mid-1970s, produced a more rapid increase after the 1970s compared to the previous 30 years.

2016 is a major departure from previous years and on pace to be the warmest year ever in the 136 year record. A recent publication by Hansen et al. (2016) asserts that the change in temperature from a 1880 to 1920 base period will be a change of 1.25°C by year's end. While climate model projections of global temperatures were somewhat above observations between 2000-2012, the recent several years of record breaking

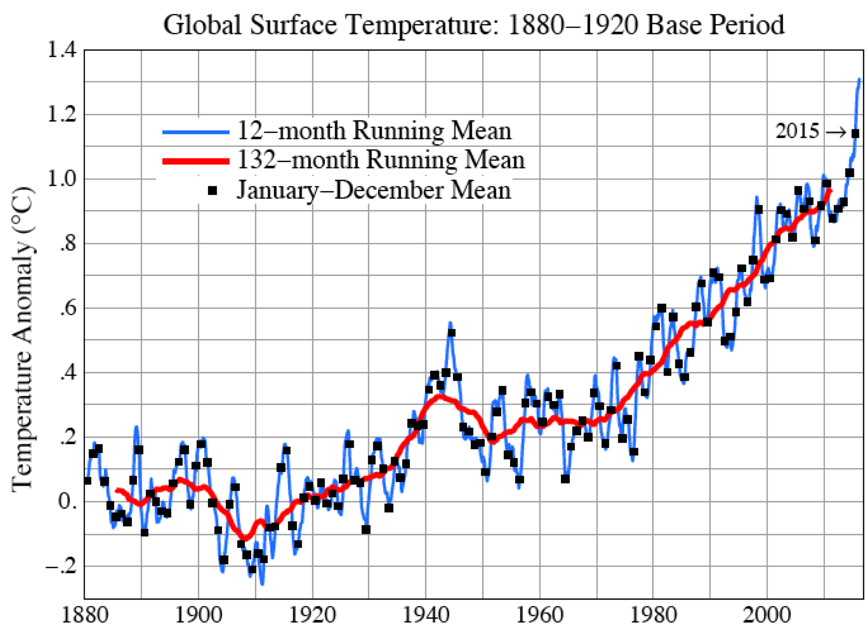

Figure 2. Change in Global Mean Surface Temperature since 1880.

temperatures have brought observations and model projections into greater agreement. Recent temperature observations show the world is already very close to the 1.5°C aspirational goal that came out of the Paris COP21 talks.

Emissions, Concentrations, Projections, and Climate Sensitivity

Emissions

Prior to the industrial revolution, the concentration of carbon dioxide in the atmosphere was about 280ppm for thousands of years back to the transition from the last Ice Age producing a relatively stable climate where agriculture and civilization flourished. The effect of the modern era of fossil use after World War II is striking. The noticeable increase in emissions after about 1950 is considered one of the great accelerations of human presence on Earth and one key marker of the Anthropocene.

Figure 3 here from Le Quéré et al. (2016) shows CO_2 emission sources (fossil fuel -gray, land-use change-tan) and how they are partitioned between carbon sinks (ocean-blue, atmosphere-purple, and land-green) in billions of tonnes of Carbon (GtC) per year. The symmetry is striking, but it is uncertain as more carbon is emitted, how the airborne fraction of CO_2 will change over time. The figure reveals the high level of interannual variability in the partitioning of emitted carbon particularly between the atmosphere and the land.

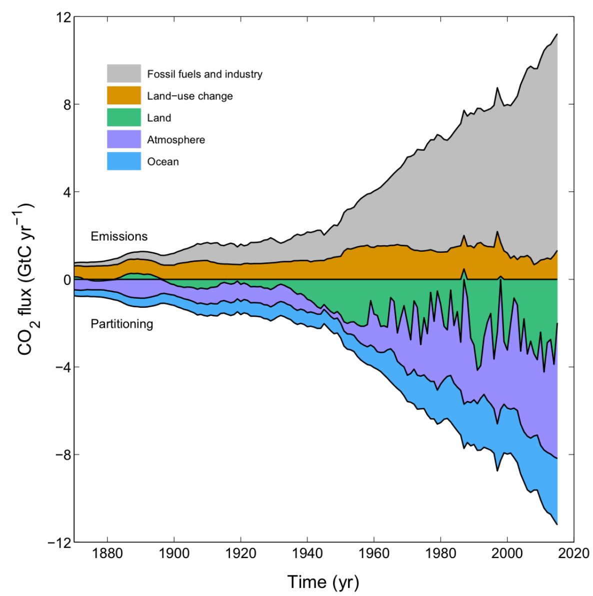

Figure 3. Partitioning of Carbon Sources and Sinks. Le Quéré 2016.

Table 1 from Friedlingstein (2015) shows two competing aspects of the carbon cycle response – one negative and one positive. The CO_2-carbon cycle feedback is negative, i.e. the increase in atmospheric emissions leads to a greater uptake of CO_2 by the land and ocean providing a carbon sink. How these relationships may change as emissions continue, is dependent on carbon cycle feedbacks.

Table 1. Partitioning of Carbon Sources and Sinks. Positive carbon values are to the atmosphere. Friedlingstein (2015)

Carbon Sources and Sinks in Billions of Tonnes of Carbon (GtC)	
Sources	
Fossil fuel emissions	375 ± 30
Net land-use change	180 ± 80
Sinks	
Atmospheric increase	240 ± 10
Oceanic uptake	-155 ± 30
CO_2 driven	-160 ± 30
Climate driven	+5 ± 5
Land uptake	-160 ± 90
CO_2 driven	-185 ± 90
Climate driven	+25 ± 10

Friedlingstein's findings in Table 1 indicate carbon uptake by the land and ocean from the atmosphere is dominant. However, the climate-carbon cycle feedback (climate driven) is positive for the land and the ocean. As the Earth warms, both the land and ocean will release more carbon to the atmosphere. The uncertainty in these estimates illustrates how the state-of-the-art quantitative estimates of the carbon cycle, while improving, are far from determined. For example, in a paper by Crichton et al. (2016), the role of melting permafrost carbon release as a positive feedback during the last deglaciation increased temperature and estimated 10 to 40% compared to simulations this team ran without the permafrost feedback. The total permafrost pool is estimated at 1000 to 1500 GtC (Hugelius et al. 2014). By contrast, there is a carbon budget of 1000 GtC of cumulative emissions since the industrial era, to remain below 2 deg C at better than even odds. We are set to exceed this budget within 20 years at current rates (Pearce 2016).

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CO2 Concentrations and Projections

The observed concentrations of CO_2 track the modeled range of concentrations from the first assessment report in 1990 through the fourth assessment. In Figure 4 from Fuss et al. (2014), emissions, concentrations, IPCC Representative Concentration Pathways (RCP 2.6-8.5), and resulting temperature in 2100 are all indicated. The actual emissions on the black curve are tracking close to the high emission scenario RCP8.5 (sometimes referred to as a "business as usual"). The blue curve (RCP2.6) has the best chance of achieving the 2°C goal. RCP2.6 dips below the zero line of net emissions around the year 2070. To achieve the desired result of this scenario (equivalent radiative forcing at the end of the century of 2.6 W/m^2), the Integrated Assessment Model team that produced the RCP2.6 scenario assumes massive Bio-energy Carbon Capture and Sequestration (BECCS) to achieve the necessary negative emissions.

The observed concentrations compared to the newest scenarios in the 2014 report (IPCC 2014) show that while they have steadily increased (43% over preindustrial) and are now over 400 ppm, there is little discrepancy between the observed concentrations and the various model scenarios for recent years. The divergence in the various IPCC RCP scenarios becomes striking after about 2020 indicating how the world is at the cusp of choosing a trajectory that will affect climate for generations to come.

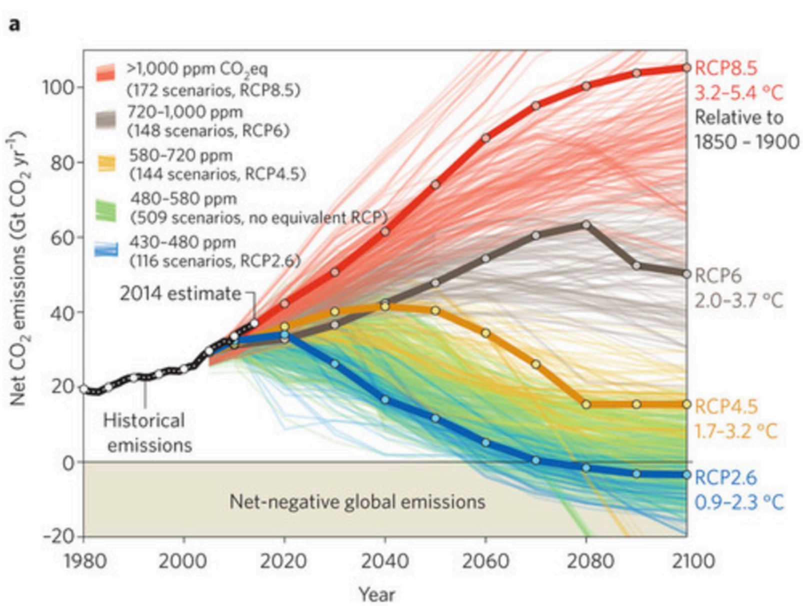

Figure 4. Historical Emissions vs. IPCC Representative Concentration Pathways. Fuss (2014)

The sum of the historical emissions shown in Figure 4 from Fuss et al. (2014) only track 1980-2014. Accounting for total emissions back to the beginning of the industrial era is shown in Figure 5 from the IPCC (2014). Here the gray bars are fossil fuel, cement, and flaring and the tan bars are land-use change such as forestry. Tracking cumulative emissions by country reveals the historical

role played by each and is increasingly important as an accounting concept able to be translated into policy for agreed upon temperature goals such as the Paris Agreement.

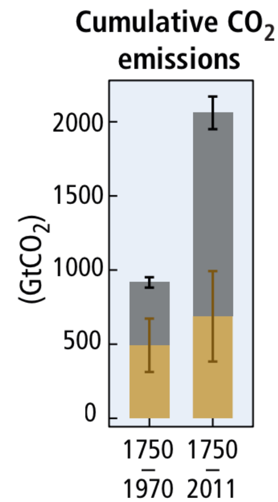

Figure 5. Cumulative CO2 emissions from land use change (brown) and industry including fossil fuels (grey). IPCC (2014)

Climate Sensitivity

In Figure 4, resulting temperatures are indicated as a range of values in 2100, illustrating the perennial question in the climate science community of how the Earth responds to a doubling of CO_2–the Earth's climate sensitivity. How sensitive the Earth is to a doubling of CO_2 (ie. Earth's Equilibrium Climate Sensitivity) is critical in understanding climate change and related impacts expected from increases in CO_2. The anticipated impacts of a 4°C world, for instance, are very different than those of a 2°C world. Confidence in climate sensitivity estimates are therefore critical in understanding how the fossil age will affect the Earth for hundreds to thousands of years.

The IPCC AR5 report states that the likely range for the Equilibrium Climate Sensitivity (ECS) is 1.5 to 4.5°C. This estimate has changed little since a report chaired by Jule Charney in 1979 for the National Academy of Sciences where by simple calculations and expert judgment, they came up with the same range (Charney 1979). The estimate has remained, but from the standpoint of the processes involved, there is higher confidence in the current estimate.

ECS is an abstract concept since the climate system will never be in equilibrium, and this metric is derived as a comparative quantity to calibrate climate model response only to increasing CO_2. ECS also does not include long-term feedbacks in the Earth system, some of which can unfold over thousands of years. From a climate modeling perspective, a more useful metric is the transient climate response (TCR) which is a measure of the climate system's warming at the time of CO_2 doubling in an experiment where CO_2 increases at the idealized rate of 1% per year compounded. These metrics are useful as a point of reference for new generations of climate models compared to previous generations.

Historically, observation-based estimates of climate sensitivity have had lower values for both ECS and TCR compared to those forecasted by climate models. In a recent paper by Armour the question of the Earth's climate sensitivity was reviewed (TCR on the left and ECS on the right in Figure 6). Armour

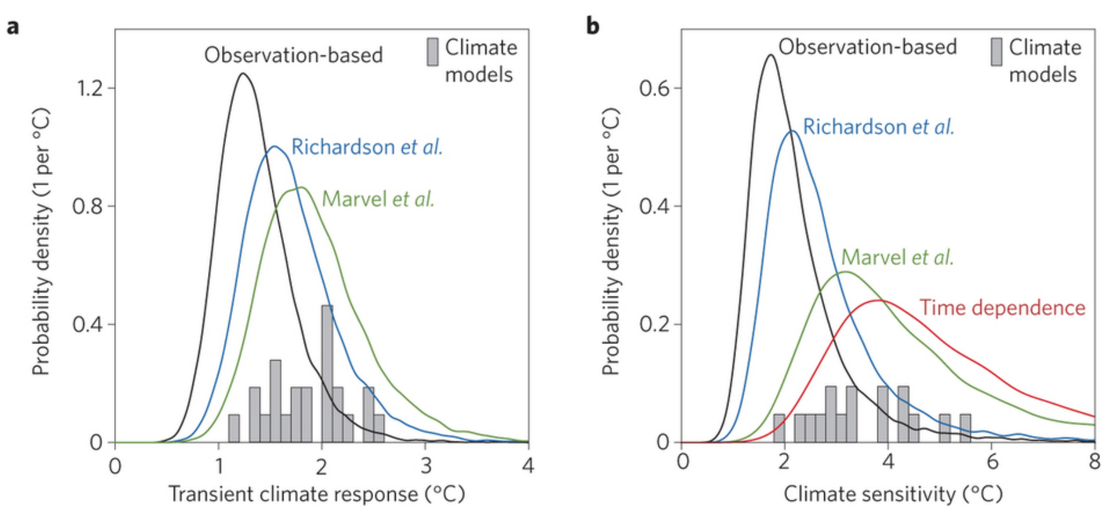

Figure 6. Recent studies are finding better alignment between observation- and model-based estimates of climate sensitivity. Armour (2016)

places the results of Richardson et al. and Marvel et al. in Figure 6 showing how these recent studies find better alignment between climate sensitivity from observations compared to the range estimated by climate models (Armour 2016).

Richardson's model considers the effect of ship-based ocean measurements underestimating the temperature of the air above the surface water by about 9%. Richardson's analysis also considers the poor spatial coverage of ocean observations leading to an additional upward correction of 15% (Richardson et al. 2016). These are additive, yielding a 24% correction. Marvel's analysis considers the effects of non-CO_2 GHGs and aerosols increasing the climate sensitivity with a 30% correction (Marvel et al. 2016). Also in Armour's figure, the probability distribution labeled "time dependence" is an adjustment that reflects the lag time of the ocean reaching a new equilibrium. Each of these adjustments raises the estimates of ECS to higher values more in alignment with modeled values.

Most climate models have an ECS in the 2 to 4°C range; however, there are more outliers on the warm side of the distribution than below 2°C. An earlier review study by Knutti and Hegerl (2008) considered many different approaches including paleoclimate studies and similarly found a likely ECS estimate of between 2 to 4.5°C. A new study by Friedrich et al. (2016) considers nonlinear aspects of ECS. By examining the ice core record of 784,000 years, they found that ECS for a CO_2 doubling is different during cold periods at 1.78°K compared to warm periods such as the present interglacial where they find the ECS to be 4.88°K.

Although the scientific bases for determining the ECS, both from observational and modeling studies, has improved considerably, the original central estimate and likely range of warming between 1.5°C to 4.5°C continues to hold up. The range represents uncertainties such as cloud feedbacks, limitations and uncertainties of temperature measurements, and uncertainties in other feedbacks in the climate system not measured.

Recent temperature observations show the world is already very close to the 1.5°C aspirational goal that came out of the Paris COP21 talks.

Climate Models

Model Development

Global climate models, Earth System Models, and their corresponding socioeconomic scenarios provided by Integrated Assessment Models, are used in concert to represent the general course of the Earth's climate based on different story lines of future human-caused emissions and land use. Climate models have progressed considerably over the last 30 years. At the time the IPCC got underway, a limited number of General Circulation Models (GCMs) had a fully-coupled ocean-atmosphere at coarse spatial resolution and a simple representation of sea ice. By the mid 1990s, aerosols from natural and human sources were added and the total number of climate centers capable of complex climate modeling grew. With aerosols, higher resolution and other improvements, models were better able to represent the observations of the 20th century. The more recent development of Earth System Models (ESMs) includes more processes such as the carbon cycle, atmospheric chemistry, dynamic vegetation, and land ice, to characterize a more complete representation of the Earth's components and dynamics. As a result, the capacity to represent how the Earth is changing due to human activities is steadily improving, both in terms of key Earth processes and resolution.

An important test of a climate model is to simulate the time evolution of 20th century climate in hindcast model experiments by including anthropogenic and natural factors (such as GHGs, land-use change, aerosols, solar inputs) in the simulations. By these measures modern climate models are able to

simulate most features of 20th century climate, and this builds credibility for how these models can be used to simulate future climate change.

Concurrent with model development has been the evolution of how to evaluate climate models. Model evaluation includes many other important variables in addition to temperature. For example, these include how well models represent zonal and meridional wind, atmospheric pressure at different altitudes, top of atmosphere outgoing shortwave radiation, mean sea level pressure, and precipitation. International model evaluation efforts are under the auspices of the World Climate Research Program and its Climate Model Intercomparison Project (CMIP) providing a common framework for standard model experiments and variables for comparison between models running experiments and in comparing model output to Earth observations. CMIP got underway in the 1990s to evaluate models among all of the major international modeling centers (Gleckler et al. 2016).

In addition to the massive modeling efforts in the GCMs and ESMs, simple and intermediate complexity climate and carbon cycle models have an essential role in exploring specific questions about the Earth system. One example is the Model for the Assessment of Greenhouse Gas induced Climate Change (MAGICC) which can be coupled with a regional climate Scenario Generator (SCENGEN) and run on a laptop. From a climate policy perspective, interactive modeling tools such as Climate Interactive's C-Roads enable users to consider various emission pathways and policies and their effect on future climate. Another example is Energy Innovation's Energy Policy Simulator that allows users to explore the cost and emission reductions achieved by various energy policies (MAGICC/SCENGEN, Climate Interactive C-Roads, Energy Innovation Policy Simulator).

Observations Informing Modeling

Deployment of major international observation networks such as the Argo network of ocean buoys and the Earth Observing System of satellites are providing more detail on how natural cycles and processes can amplify or dampen projected anthropogenic warming on interannual to decadal timescales. Looking to the future climate, there is still uncertainty – particularly in the representation of clouds and the carbon cycle; however, the gains in observations and modeling capability are offering decision-makers a viable set of tools for understanding how GHG emissions and land-use change are altering the Earth. The record of how well these models have performed in representing what has been observed over recent decades and the 20th century adds to their credibility.

One recent example of a critical observational global data set is the heat content of the ocean. Figure 7 from Gleckler et al. (2016) shows that ocean heat content has doubled in recent decades over the heat content that built up from the beginning of the industrial era (change over 1865-2012). An estimated 90% of the heat uptake of Earth responding to GHG warming since 1970 has gone into the ocean (Gleckler et al.

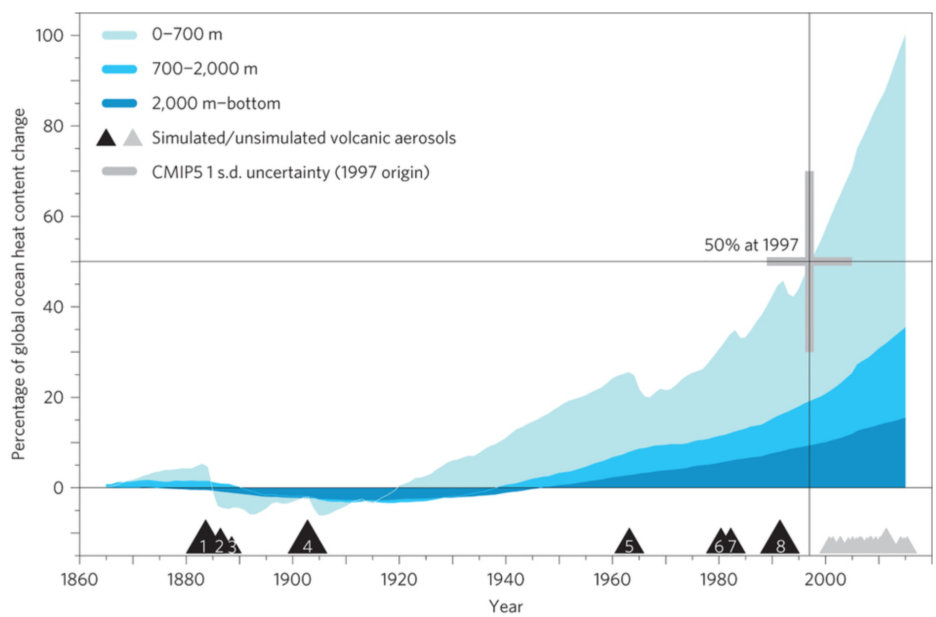

Figure 7. Ocean heat content is increasing in response to warming caused by greenhouse gases. Gleckler et al. (2016)

2016, Trenberth and Fasullo 2013). The eventual effect on surface air temperatures of ocean heat uptake since the mid-20th century has yet to be realized.

Interestingly, models can be used to inform observations. A paper by Massonnet et al. (2016) explores how models can be used to estimate the quality of observations. Just as models are imperfect representations of the real Earth, so too are observations because they are often so sparse in time and space as to give an incomplete picture of what is being measured. Because of this, a variable like ocean surface temperature can in some cases be better represented in a GCM than what can be obtained from sparse ocean measurements alone. Research into this type of analysis is critical for improving the information that can be extracted from global observational data sets. It is also critical to have data sets on the ocean state to assimilate into computer models—particularly in sorting out anthropogenic forcing versus natural variability in the Earth system at interannual to decadal timescales.

Observations Compared to IPCC Projections: Temperature Trends & Sea Level Rise

Temperature Trends

One challenge in sorting out human from natural drivers of change in the climate system is to adjust the observations to account for the effect of the El Niño Southern Oscillation (ENSO), volcanic eruptions, and solar influences. Generally, El Niño has a warming effect, La Niña a cooling effect, volcanic eruptions a cooling effect, and the solar cycle has a minor effect on radiative forcing depending on the solar minima or maxima of the 11 year sunspot cycle. Foster described one approach to this method to smooth out inter-annual variability and natural influences and thereby gain a clearer picture of the overall warming signal (Foster and Rahmstorf 2011).

Foster's approach is particularly useful in understanding climate variability at interannual to decadal timescales. At these scales, the influence of variability in natural phenomena can have a noticeable influence on the Earth's temperature year to year—dampening or augmenting the persistent radiative forcing that drives a temperature increase due to the steady increase of anthropogenic emissions of greenhouse gases. Thus it is this interplay between the internally generated naturally occurring climate variability and the response to human influences that produces the climate we experience in any given year or decade.

Using the method to remove the short-term natural variability effects, Figure 8 from Rahmstorf et al. (2012) shows (in pink) the unadjusted global mean surface temperature (GMST), and (in red) the adjusted temperature using Foster's method. The expanding lavender cone starting in 1990 represents the standard IPCC SRES socio-economic scenarios and their projected range of temperatures from the third IPCC assessment with a 1990 starting point. The green cone represents the projections from the 4th IPCC assessment starting in 2000.

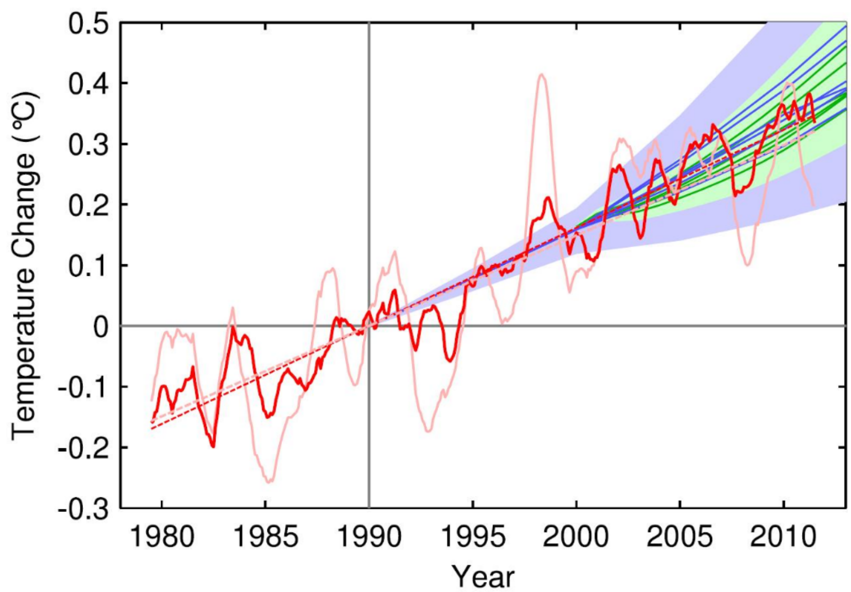

Figure 8. Observed global mean surface temperature unadjusted (pink) and adjusted using Foster's method to remove short-term natural variability effects (red), show agreement with projections from the IPCC 3rd and 4th assessments. Rahmstorf (2012)

A main conclusion from this paper is that through 2011, the adjusted GMST is consistent with the IPCC projections of the IPCC 3rd and 4th assessments (IPCC TAR and AR4) made with previous generation models and different starting points. If the answers from different models and different emission scenarios changed over time with each new generation of model, this would indicate some fundamental lack of understanding of the basic processes in the climate system. The consistency of these results is reassuring because comparable results from different generations of climate models with somewhat different future emission scenarios made with different start dates indicates that the climate model projections closely track what has been observed since 1990.

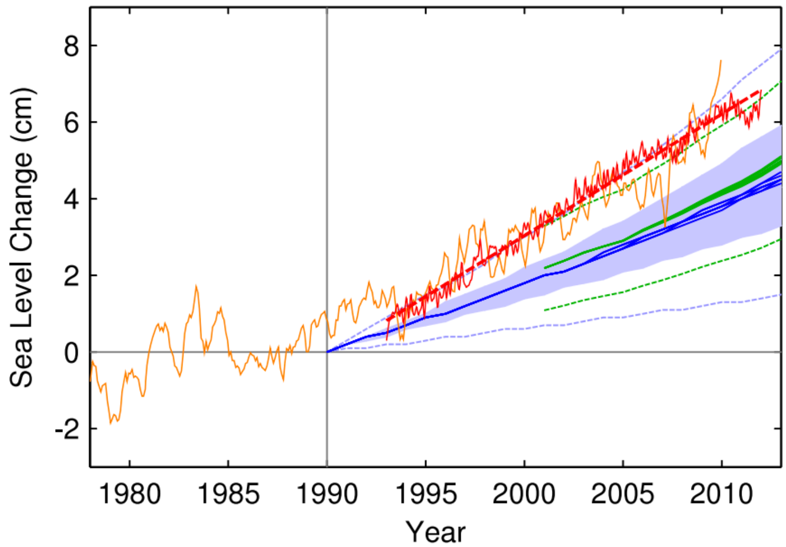

Figure 9. Sea level rise measurements taken by satellite (red) and tidal gauges (orange) are tracking higher than projections made in the 3rd and 4th IPCC Assessments. Rahmstorf et al. (2012)

Sea Level Rise

In the same paper by Rahmstorf et al. (2012), IPCC model projections from the third and fourth IPCC assessments (Figure 9, blue and green curves respectively) are compared to satellite altimeter measurements of sea level rise (SLR) in red and tide gauge measurements in orange. As of 2011, the satellite observations of the annual rate of change in sea level rise were 60% greater than the IPCC projections (3.2 mm/yr vs. 2.0mm/yr). The IPCC model projections for SLR in the IPCC fifth assessment chapter on sea level rise acknowledge the rapidly changing understanding of factors and processes that contribute to SLR and in this assessment the more recent generation of models are better at incorporating key processes. The improved process models in the AR5 better represent observations. Semi-empirical models informed by observations generally produce higher projections and are discussed in the AR5. For the AR5 50th percentile SLR value for Representative Concentration Pathway 4.5 (RCP4.5), the projected SLR for 2100 relative to 1986-2005 is 0.47m whereas in the same the semi-empirical results from various studies are up to twice as high. Potential surprises in ice-sheet dynamics are not captured in either the process based or semi-empirical methods. Even with the median AR5 projections for 2100 there would be considerable disruption to coastal settlements and ecosystems, and in all studies SLR continues after 2100 (Deconto and Pollard 2016, Fasullo et al. 2016).

Satellite observations of the annual rate of change in sea level rise were 60% greater than the IPCC projections.

Cumulative Carbon Budget

A positive sign in recent emissions data, and what it implies for the future, was recently released in a study by Le Quéré, et al. (2016), confirming that CO_2 emissions in 2014, 2015, and 2016 have been flat while the global economy continued to grow. This is a reminder to science and policy communities alike that the storylines of the IPCC RCP scenarios are only possible future emission pathways that may or may not come to pass. This decoupling of the global economy from carbon emissions is essential to

achieve the Paris Agreement and indicative of both low carbon emitting technologies and greater efficiencies emerging in the energy sector.

From a climate standpoint, one way to achieve the Paris goal with a 66% chance of staying below 2°C is to stay within a carbon budget of about 1000 GtC (to convert from GtC to $GtCO_2$ multiply by 3.67). The remaining budget as of 2011 described in the IPCC 2014 Synthesis Report is about 272 GtC (the IPCC in this case uses 1861-1880 as the baseline) (IPCC 2014).

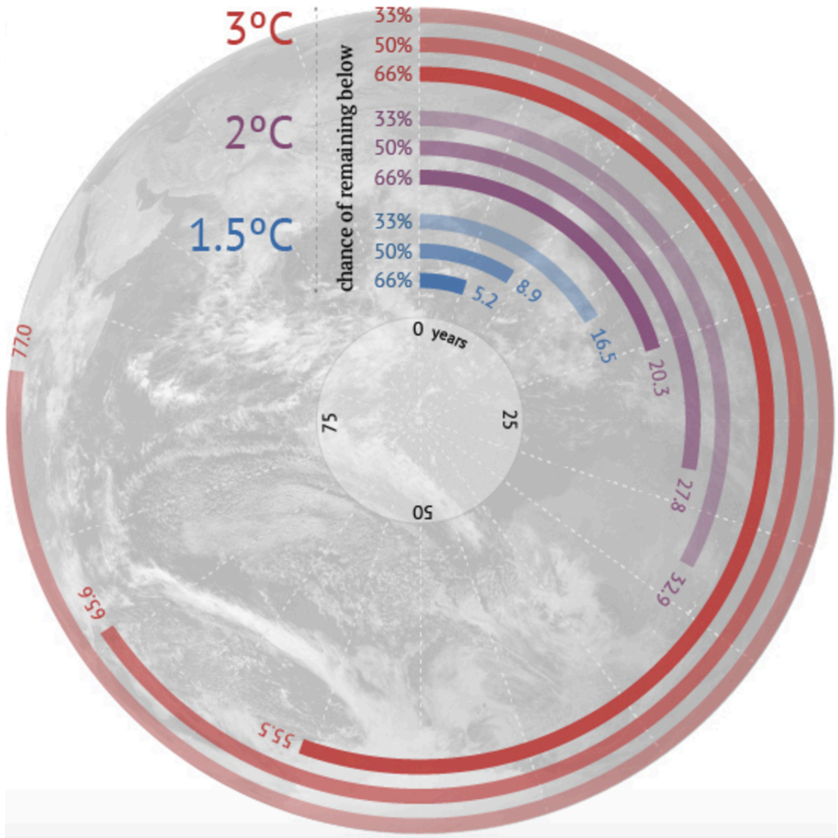

Figure 10. At current rates of emissions, we will exceed the carbon budgets for 1.5°C and 2°C in approximately 5 and 20 years, respectively (based on a 66% chance of certainty). Pearce (2016)

The remaining budget is limited, especially to secure better than even chances of meeting the intended target. Figure 10 from The Carbon Brief organization updated as of May 2016 shows the 3°C, 2°C and 1.5°C cases. The 2°C and 1.5°C cases allow for only 20 years and 5 years respectively of continued emissions at present rates based on a 66% chance of staying within each carbon budget (Pearce 2016).

In a recent paper by Rogelj et al. (2015), his team underscores just how great the need is for technologies that can achieve negative emissions ***unless*** substantial reductions occur between now and 2050. In other words, slow rates of reductions require greater amounts of negative emissions in the latter half of the century.

Non-CO2 GHGs

Figure 11 of radiative forcing shows the net effect of anthropogenic and natural forcing due to the full suite of GHGs, aerosols and factors such as the variation in solar output – all measured in W/m² relative to 1750. Figure 11 puts in perspective the importance of the various well-mixed greenhouse gases (WMGHGs) where CO_2 dominates. Next in importance is methane, the suite of halocarbons, and nitrous oxide. The total anthropogenic forcing is less than the WMGHGs because of the net cooling effect of aerosols. Natural influences, such as from variation in solar radiation, are negligible in

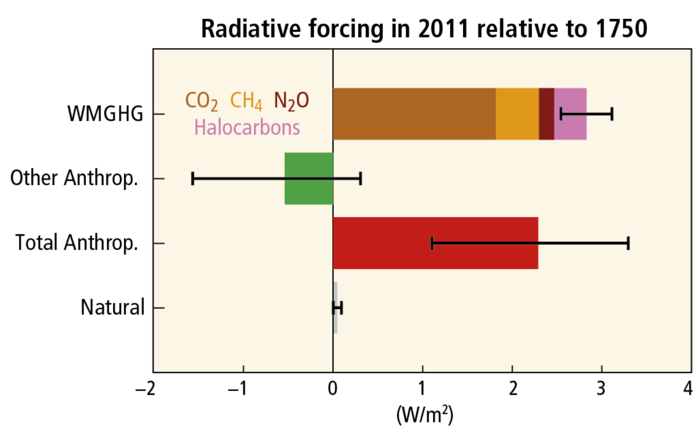

Figure 11. Net effects of anthropogenic and natural forcing due to the full suite of greenhouse gases, aerosols, and variation in solar output. IPCC (2013)

comparison. The net anthropogenic forcing relative to 1750 since 1950 has increased by a factor of four, from 0.57 in 1950 to 2.29 W/m^2 in 2011. The large error bars in the IPCC assessment of radiative forcing are due primarily to uncertainties in the effect of aerosols (volcanic eruptions mineral dust, SO_2, NH_3, organic and black carbon) which have both a positive and negative effect on radiative forcing, but overall a net negative effect (IPCC 2013).

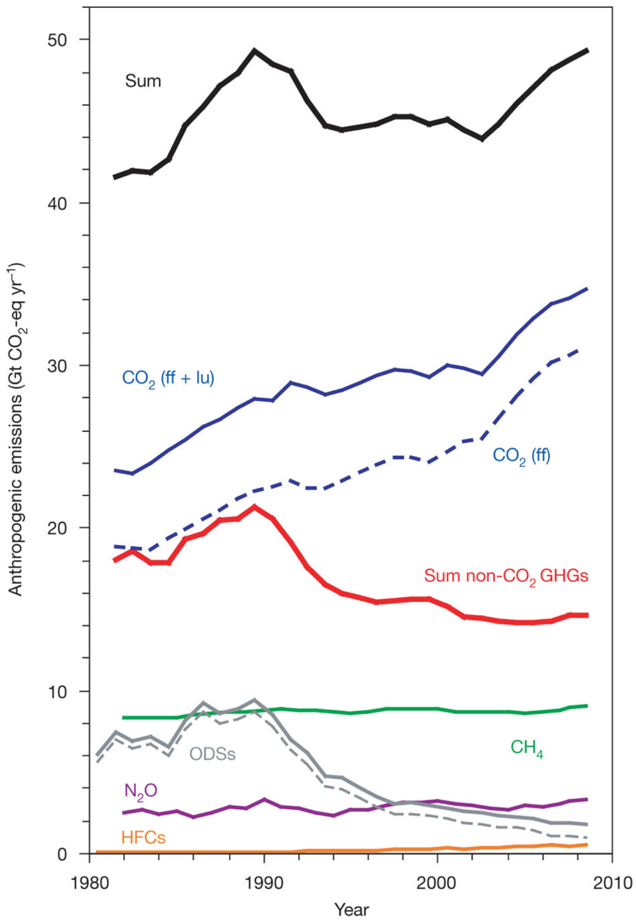

Figure 12. $GtCO_2$ equivalent of annual emissions of non-CO_2 greenhouse gases. The impact of the Montreal Protocol passed in 1989 to decrease the production of substances contributing to ozone depletion is evident. Montzka (2011)

NOAA reports in the Annual Greenhouse Gas Index (AGGI) the full suite of long-lived gases and how they alter the CO_2 concentration upward to achieve a CO_2 equivalent of 485 ppm (In 2015, CO_2 = 399 ppm, the AGGI was 1.37 relative to 1990, so the equivalent forcing considering all GHGs is 485ppm). Their analysis states that CO_2, CH_4, N_2O, and CFC 12 & 13 account for 96% of the radiative forcing from 1750 to 2015. The remaining 4% results from 15 minor long lived halogenated gases (CFC-113, CCl_4, CH_3CCl_3, HFCs 22, 141b and 142b, HFCs 134a, and 125, SF_6 and halons 1211, 1301 and 2402) (Butler and Montzka 2016).

As depicted in Figure 12 from Montzka et al. (2011), the total of all GHGs are shown as $GtCO_2$ equivalent per year since 1980 (black line). The sum of the non-CO_2 gases, shown in red, reveals the impact of the Montreal Protocol after about 1990. Some Ozone-Depleting Substances (ODSs), shown in gray are also GHGs. The recent internationally agreed upon upgrade to the Montreal Protocol—the Kigali accord (October 2016) in Rwanda, takes an important step in limiting HFCs which will further reduce GHG forcing of the climate. HFCs at baseline estimates (unchecked growth) would have an estimated CO_2 equivalent effect of 4.0 to 5.3 $GtCO_2$ per year by 2050 (Velders et al. 2015).

Sources of Methane

The major GHG after CO_2 from fossil fuel burning, cement, and land-use change is methane at 16% of the total emissions, followed by nitrous oxide at 6% and the suite of fluorinated gases such as HFCs, at 2% (IPCC 2014). Recent attention has been focused on obtaining better measurements on the contribution of methane from the fossil fuel industry, particularly given the substitution of natural gas for coal and new extraction technologies with poorly understood emission rates from leakage (fugitive emissions). A new study by Rice (PNAS 2016) shows how the partitioning between fossil fuel related methane and agricultural methane sources has

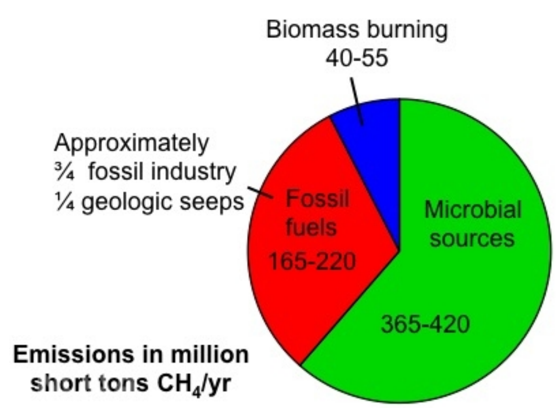

Figure 13. Fossil fuel activities contribute 20-25% of total global methane emissions. NOAA (2016)

...methane emissions from the fossil industry were 20 to 60% higher than recent inventory estimates by the EPA and the European Commission.

changed, particularly since 2000. This finding is contrary to other research on the sources of methane over the last several decades.

While the growth of methane in the atmosphere increased by more than a factor of two from 1750 to the late 1980s, the rate leveled off thereafter. Between 1999 and 2006 the rate was close to zero. By taking advantage of a global network of sampling flasks used to collect methane from 1979 to 1998, combined with more recent isotope retrievals in the interval 1984 to 2009, Rice's team was able to determine a 24 Tg per year increase in fugitive methane emissions from fossil fuel sources since 1984.

In terms of comparing recent increases for methane, NOAA reports a change from 5.7 ± 1.2 ppb per year between 2007 and 2013 to 11.5 ppb per year between 2014-2015. NOAA (2016) finds that the fossil fuel industry produces 20 to 25 percent of annual methane emissions as indicated in red in Figure 13.

Using an isotope method, Schwietzke et al. (2016) finds that methane emissions from the fossil industry were 20 to 60% higher than recent inventory estimates by the EPA and the European Commission. This is a reclassification of emission sources, not an increasing trend in emissions from fossil fuel operations. This study notes that while fugitive emission leakage rates have been reduced from 8% to 2% over the last 3 decades, the global expansion of the industry is a key factor in why these efforts do not show a reduction in total emissions from this source. Overall methane emissions have increased primarily from microbial activity and biomass burning.

So while natural gas is cleaner burning and less CO_2 intensive per unit of energy compared to coal, when the impact of fugitive emissions of methane from natural gas operations are included, the net gain from a GHG standpoint is diminished. While reducing non-CO_2 GHGs is important and necessary in achieving the Paris goals, the reduction of CO_2 emissions remains the critical objective for stabilizing climate.

Summary

Here we have reviewed a sampling of recent peer-reviewed literature on various aspects of the climate system, including contextual information on temperature and quantities associated with the carbon cycle and non-CO_2 GHGs. The projections made in 2013 by the IPCC AR5 WG1 for temperature, emissions, concentrations, and sources and sinks have improved since the earliest of these projections and, for the most part, fall within the range of the modeling results.

The warming slowdown (known as the hiatus) in the first decade of the 21st century dipped below the climate model projected warming and has been an active area of research. However the decade itself was the warmest in the temperature record. Most explanations rest upon the dampening effect of natural variability due to an ocean cool phase countering temporarily the persistent radiative forcing from elevated GHGs. The last few years of record breaking temperatures may indicate an end to the so-called hiatus and greater alignment between climate models and observations.

Of considerable importance is continued research into the carbon cycle and how carbon emissions are partitioned between the air, land, and ocean, as well as how these sources and sinks may change in a warmer world. Many other lines of evidence not considered here such as the loss of Arctic sea-ice, the rate of glacial melt, and extreme events, all point in the direction of a warming Earth, perhaps showing signs of warming faster than anticipated. Cumulative carbon emission studies and the remaining carbon budget to stay below 2°C indicate how critical it is to achieve sustained steep reductions in the near term and near zero net emissions as we move into the second half of the 21st century.

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