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Uncertainty in Climate Change Projections

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Abstract

Twentieth century climate exhibits a strong warming trend. There is a broad scientific consensus that the warming contains a significant contribution from enhanced atmospheric greenhouse gas (GHG) concentrations due to anthropogenic emissions. The climate will continue to warm during the 21st century due to the large inertia of the Earth System and in response to additional GHG emissions, but by how much remains highly uncertain. This is mainly due to three factors: natural variability, model uncertainty, and GHG emission scenario uncertainty. Uncertainty due to natural variability dominates at short time scales of a few years up to a few decades, while at the longer centennial time scales scenario uncertainty provides the largest contribution to the total uncertainty. Model uncertainty is important at all lead times. Furthermore, our understanding of the Earth System dynamics is incomplete. Potentially important feedbacks such as the carbon cycle feedback are not well understood and not even taken into account in many model projections. Yet the scientific evidence is overwhelming that global mean surface temperature will exceed a level toward the end of the 21st century that will be unprecedented during the history of mankind, even if strong measures are taken to reduce global GHG emissions. It is this long-term perspective that demands immediate political action.

1. Introduction

The atmospheric carbon dioxide (CO_2) concentration has strongly increased since the start of industrialization (Fig. 1) in response to anthropogenic emissions and reached a level which is unprecedented in man's history. The present CO_2 concentration amounts to about

390ppm[1] as opposed to the pre-industrial concentration of 280ppm. Carbon dioxide is a greenhouse gas and known to warm the Earth's surface, as it is transparent for the short-wave solar but not for some of the long-wave infrared radiation emitted by Earth's surface. The globally averaged surface air temperature (SAT) of the planet has warmed by about 0.7°C during the 20th century (Fig. 1), global sea level has risen by just under 20cm, and many mountain glaciers and Arctic sea ice have considerably retreated. There is compelling scientific evidence that at least half of 20th century warming was forced by the increase of GHG concentrations (IPCC, 2007). They will continue to rise over the next years and possibly even decades, which together with the inertia of the climate system will support further global warming during this century. A global mean temperature rise implies higher warming over land than over oceans, with the tropical regions warming least and the northern polar region warming the most. But what else do we really know about the climate of the 20th and 21st century?

2. Natural variability

One source of uncertainty in climate change projections is natural variability. Surface air temperature during the 20th century displays a gradual warming and superimposed short-term fluctuations. The upward trend contains the climate response to enhanced atmospheric GHG levels but presumably also a natural component. The temperature ups and downs around the trend which are particularly pronounced in the Arctic (Fig. 2) largely reflect natural variability. Natural climate variations are of two types, internal and external. Internal variability is produced by the climate system itself due to its chaotic nature. External fluctuations need a forcing, a change in the boundary conditions. Climate fluctuations in response to volcanic eruptions and variations in solar radiation are examples. The eruption of the Philippine volcano Mt. Pinatubo in 1991, for instance, caused a relatively short-lived (one

[1] ppm: parts per million

year long) drop in global SAT of about 0.15°C in 1992 (Fig. 1); and an increase of the solar radiation reaching the Earth may have contributed together with other processes to the mid-century warming during 1930-1940 (Fig. 1). The anthropogenic influence on climate is also considered as external.

One way to estimate the external contribution to the 20th century SAT change is to run climate models with all (known) observed external (natural and anthropogenic) forcing in ensemble mode with different initial conditions. Fig. 2 shows such simulations of Northern Hemisphere (averaged over the latitude band 0-90°N, upper panel) and Arctic (averaged over the latitude band 60-90°N, lower panel) SAT. The average over all (IPCC[2]) models taken from the CMIP3[3] database (Meehl et al., 2007) is sometimes referred to as the "consensus" (black lines) and a measure of the externally driven climate change. It displays a clear gradual upward trend in both indices that is consistent with the observed trend (red lines). The spread (gray shading) about the "consensus", however, is large, partly because internal natural variability is also simulated by the climate models. A well-known example of such internal variability on interannual time scales is El Niño, a warming of the Equatorial Pacific occurring on average about every 4 years which is the warm phase of the El Niño/Southern Oscillation (ENSO). The record event of 1997/1998 "helped" to make 1998 the warmest year to date globally (Fig. 1)[4]. The year 2009 also happened to be an El Niño year, which supported, for instance, a weak Atlantic hurricane activity, as El Niño causes enhanced upper-level vertical wind shear over the Tropical Atlantic which is known to hinder hurricane development (e. g., Latif et al., 2007). The event persisted into 2010 and was partly responsible for the first half (January-June) of 2010 being the warmest on record globally. Different initial climate states yield different realizations of internal variability in climate

[2] IPCC: Intergovernmental Panel on Climate Change
[3] CMIP3: Coupled Model Intercomparison Project, 3rd collection
[4] According to the SAT analysis of the British Meteorological Office

models even under identical external forcing, one reason for the spread, as integrations are performed in ensemble mode with different start conditions.

Decadal-scale variability is also internally simulated by the models and evident in the data (e. g., Wang and Dong, 2010). In Figure 2, the deviation of the observed temperature evolution from the "consensus" reflects the internal variability, assuming the model-mean is a reliable estimate of the boundary-forced signal, and multidecadal changes are obvious in the residuals. Such multidecadal or even longer time scale natural variability, internally or externally driven, may mask anthropogenic climate signals which evolve on similar time scales. It has been concluded (e. g., Latif et al., 2006a) that the expected anthropogenic weakening of the Meridional Overturning Circulation (MOC), a prominent circulation in the Atlantic Ocean transporting large amounts of heat northward thereby contributing to the mild climate of Northern Europe, may not be detectable during the next decades due to the presence of strong internal multidecadal variability. This may not only apply to the MOC itself but also to other potentially related quantities such as surface air temperature in parts of Europe and North America, Sahel rainfall or Atlantic hurricane activity which are also characterized by pronounced multidecadal variability (e. g., Zhang and Delworth, 2006) and may hamper early detection of an anthropogenic signal.

To some extent, we need to "ignore" the natural fluctuations, if we want to "see" the human influence on climate. Had forecasters extrapolated the mid-century warming into the future, they would have predicted far more warming than actually occurred. Likewise, the subsequent cooling trend, if used as the basis for a long-range forecast could have erroneously supported the idea of a rapidly approaching ice age. The scientific challenge is to quantify the anthropogenic *signal* in the presence of the background climate *noise*. The detection of the anthropogenic climate signal thus requires at least the analysis of long records, because we can be easily fooled by the short-term natural fluctuations, and we need to understand their dynamics to better estimate the *noise level*. Sophisticated fingerprint methods (Hegerl et al.,

1996) maximizing the *signal-to-noise ratio* were applied to detect the anthropogenic signal in observations. The components of this strategy include observations, information about natural climate variability, and a model-derived "guess pattern" representing the expected time-space pattern of anthropogenic climate change. The expected anthropogenic climate change is identified through projection of the observations (say during the 20th century) onto the (model-derived) fingerprint. The latter can be optimized by weighting those components more strongly which are less "inflated" by natural variability. Furthermore, the relative contributions of different external drivers of climate have been quantified. The results appear to be sufficiently robust to conclude that the observed climate change during the last decades is consistent with a combined greenhouse gas and aerosol[5] forcing, but inconsistent with greenhouse gas or solar forcing alone (Hegerl et al., 1997).

It should be noted that internal natural variability such as El Niño and some decadal phenomena are predictable to some extent (e. g., Latif et al., 1998; Latif et al., 2006b; Smith et al., 2007; Keenlyside et al., 2008), and uncertainty in near-term climate projections can be potentially reduced by initialising climate models with the observed climate state.

3. Model uncertainty

The model spread seen in Fig. 2 also reflects model uncertainty, as different models simulate different climate responses even when forced by the same GHG concentration or emission scenario[6]. Climate models are grounded on basic physical principles. As such they are fundamentally different to empirical models which are used, for instance, in economic forecasting. Climate models, however, are far away from being perfect. Errors in annual mean SAT, for instance, typically amount to several degrees in some regions and internal variability

[5] These are small particles which are also produced by the combustion of fossil fuels and generally exert a net cooling effect on the Earth's surface.
[6] Emissions are prescribed if the climate model carries a carbon cycle module which calculates the fraction that remains in the atmosphere.

such as ENSO is not always consistent with data (IPCC, 2007). Limitations in computer resources dictate the use of either reduced or relatively coarse-resolution models. As a consequence many important processes cannot be explicitly simulated; they must be *parameterized*, the method of replacing them in the model by a simplified process. Some processes like cloud formation or some radiation processes are not completely understood and differently represented in the models, which adds to the uncertainty. Models, however, can be potentially improved and thus uncertainty stemming from model error reduced.

One way to compare models is by means of the *climate sensitivity* which is defined as the equilibrium change in globally averaged SAT in response to a doubling of the pre-industrial atmospheric CO_2 concentration (i. e. from 280 to 560ppm). IPCC AR4 stated that the value '...is likely to be in the range 2°C to 4.5°C with a best estimate of about 3°C, and is very unlikely to be less than 1.5°C'. In the IPCC definition *likely* refers to an outcome or result when its likelihood is greater than 66% probable. *Very unlikely* means a probability of less than ten percent. Thus there is a non negligible probability that the climate sensitivity is either considerably smaller or larger than the best estimate of 3°C. Obviously, just communicating the best estimate to the public is inappropriate.

The uncertainty in climate sensitivity itself is a good reason to demand reductions of global GHG emissions, because the possibility of 'a dangerous anthropogenic interference with the climate system'[7] cannot be ruled out with high confidence. That is we do not really know at which levels atmospheric GHG concentrations should be stabilized to prevent a dangerous climate change. Society may be lulled into a false sense of security by smooth model projections of global change. In some regions anthropogenic forcing on the climate system could kick start abrupt and potentially irreversible changes. For these sub-systems the term "tipping element" is commonly used (Lenton et al., 2008). Warming over the Greenland ice sheet, for instance, accelerates ice loss from outlet glaciers and lowers ice altitude at the

[7] United Nations Climate Convention, Rio de Janeiro (1992)

periphery, which further increases surface temperature and ablation. A complete meltdown would result in a rise of sea level of up to seven meters globally. The exact tipping point for disintegration of the ice sheet, however, is unknown, since current models cannot capture the complex dynamical deglaciation processes accurately. In a worst case scenario, global warming of more than 3°C could cause the ice sheet to disappear within 300 years. Other studies report that it would take an average global temperature rise of 6°C to push Greenland into irreversible melting (see the discussion by Ridley et al. (2009) and references therein). Similarly, global warming can potentially affect the stability of the West Antarctic Ice Sheet (WAIS, Pollard and DeConto (2009)), with ice volume equivalent to 5m of sea level. Protective ice shelves could shrink or even disappear and the WAIS would become vulnerable to melting. Again, the precise tipping point for complete disappearance of the ice sheet is highly uncertain.Thus the term “dangerous” is only loosely defined, and our models are not advanced enough to estimate the tipping points with high accuracy. A threshold may have been reached already in some regions such as in the Arctic, where rapid sea ice retreat has been observed during the recent decades, at a rate considerably faster than predicted by virtually all climate models, as shown by Stroeve et al. (2007).

4. Climate change projections

To predict the future climate we have to consider both natural variability and anthropogenic forcing. The latter is taken into account by assuming scenarios about future GHG and aerosol emissions. The scenarios (Fig. 3) cover a wide range of the main driving forces of future emissions, from demographic to technological and economic developments. While both natural variability (internal and external) and model error contribute the largest share to uncertainty when we consider the short-term climate evolution over the next years or few decades, the scenario uncertainty becomes the largest contributor when looking many decades or centuries ahead, as described by Hawkins and Sutton (2009) who analyzed the CMIP3 database.

IPCC AR4 published only climate projections based on several scenarios with no attempt to take account of the likely evolution of the natural variability. This by definition yields relatively smooth trajectories if the results are averaged over many realizations and models, which strongly filters internal variability. In the real world, the natural variations will introduce a large degree of irregularity (Figs. 1 and 2), and even short-term cooling may occur over the next years. It should be mentioned again that climate models do simulate internal variability and individual projections exhibit indeed a great deal of irregularity.

As can be clearly inferred from Fig. 3, it is the long-term strategy that we adopt which matters on the long time scales of many decades. Because of the long residence time of CO_2 of the order of 100 years in the atmosphere, climate response is governed by cumulative rather than current CO_2 emissions. Important is not the detailed emissions path, but that emissions are strongly reduced over a period of 50 to 100 years (Hasselmann et al., 2003). In order to stabilise the concentration of greenhouse gases in the atmosphere, GHG emissions would need to peak and decline thereafter. The lower the stabilisation level, the more quickly this peak and decline would need to occur. Stabilisation at lower concentration and related equilibrium temperature levels advances the date when emissions need to peak and requires greater emissions reductions by 2050. Climate sensitivity obviously is a key uncertainty for mitigation scenarios that aim to meet specific temperature levels, for instance the 2°C-target that is limiting global warming to 2°C by the end of the century above pre-industrial levels. The timing and level of mitigation to reach a given temperature stabilisation level is earlier and more stringent if climate sensitivity is high than if it is low (IPCC, 2008). Moreover, if the CO_2 concentration continues to strongly rise during this century, it will stay rather high throughout the millennium, as the removal of CO_2 from the atmosphere is a very slow process which is governed by the slow exchange between the surface and the deep ocean.

It is noted that approaching equilibrium can take several centuries, especially for sea level and scenarios with higher levels of stabilisation. Thermal expansion would continue for many centuries after GHG concentrations have stabilised, for any of the stabilisation levels assessed, causing an eventual sea level rise much larger than projected for the 21st century. If GHG concentrations had been stabilised at year 2000 levels, thermal expansion alone would be expected to lead to further sea level rise on the order of about half a meter. The eventual contributions from the Greenland and West Antarctic ice sheets is highly uncertain but could amount to several metres by the end of the millennium, and larger than from thermal expansion, should warming in excess of about 2°C above pre-industrial levels be sustained over many centuries.

5. Carbon cycle feedback

Finally, our understanding of the Earth System dynamics is incomplete. Many feedbacks such as the cloud or aerosol feedback in the atmosphere, the eddy feedback on the large-scale ocean circulation, or feedbacks from vegetation on regional and global climate are only poorly known. It is beyond the scope of this paper to review all important feedbacks in detail. The reader is referred for a comprehensive overview to Chapter 8 of IPCC (2007) and references therein.

Let us consider here in more detail the carbon cycle feedback, putting special emphasis on its marine component. As outline in Chapter 7 of IPCC (2007), about 80% of anthropogenic CO_2 emissions during the 1990s resulted from fossil fuel burning (including cement production), with about 20% from land use change (primarily deforestation). Almost 45% of combined anthropogenic CO_2 emissions have remained in the atmosphere. Oceans are estimated to have taken up approximately 30% (Sabine et al., 2004a), an amount that can be accounted for by increased atmospheric concentration of CO_2 without any change in ocean circulation or biology. Terrestrial ecosystems have taken up the rest through growth of replacement vegetation on cleared land, land management practices and the fertilizing effects of elevated CO_2 and Nitrogen deposition. According to more recent estimates, land takes up carbon at present at higher volumes than the ocean. However, error bars on these estimates are rather large (2.6 GtC[8], with a range of 4.3-0.9 GtC), while the ocean sink is much better constrained (2.2 GtC ± 0.4 GtC).

An important question related to future climate is that of how the two sinks will behave in response to global warming and elevated CO_2 levels. Uncertainty in the carbon cycle feedback creates uncertainty in the emissions trajectory required to achieve a particular CO_2 stabilisation level. The response of the land biosphere specifically the tropical rainforests, surface ocean warming or ocean acidification due to the marine uptake of anthropogenic CO_2 are examples of processes that can strongly impact the net carbon sink, eventually determining the level of enhanced greenhouse warming. Models generally predict that an increasing fraction of total anthropogenic CO_2 emissions will remain airborne through the 21st century and most also indicate a decline in the fraction of emissions absorbed by both the ocean and the land, but they strongly differ in the magnitude of the changes projected for the 21st century. Carbon cycle feedbacks could significantly accelerate climate change over the 21st century. In one particular simulation under a 'business as usual' scenario (Cox et al., 2000), the terrestrial biosphere acted as an overall carbon sink until about 2050, but turned into a source thereafter. By 2100, the ocean uptake rate of 5 GtC/yr was balanced by the terrestrial carbon source, and atmospheric CO_2 concentrations were 250ppm higher in the fully coupled simulation with interactive carbon cycle than in uncoupled mode, resulting in a global-mean warming of 5.5°C, as compared to 4°C without the carbon cycle feedback. A recent study, however, concludes that the carbon cycle feedback may not be as strong as previously estimated, with a likely range of only 1.7–21.4ppm/°C (Frank et al., 2010).

[8] GtC: gigatonnes (10^{12}kg) Carbon

Let us consider the marine component of the carbon cycle feedback in some more detail. The oceans hold around 38,000 GtC. They presently store about 50 times more CO_2 than the atmosphere and 10-20 times more than the terrestrial biosphere and soils (Sabine et al., 2004b; IPCC 2007). However, the ocean is not only an important CO_2 reservoir, but also the most important *long-term* CO_2 sink. Without oceanic uptake of anthropogenic CO_2, the relative CO_2 concentration in the atmosphere would presumably lie more than 55ppm above the present level (Sabine et al., 2004a). Using inorganic carbon measurements from an international survey effort in the 1990s and a tracer-based separation technique, the oceanic sink was estimated to account for about 48% of the total fossil-fuel and cement-manufacturing emissions during 1800-1994, implying that the terrestrial biosphere was a net source of CO_2 to the atmosphere. The terrestrial net source, however, represents a balance between CO_2 emissions from land-use change, and an uptake of CO_2 by the terrestrial biosphere, and emissions from land-use change are only poorly constrained. Furthermore, the results are sensitive to the airborne fraction, i.e., the fraction of the combined fossil-fuel and land-use emissions that remains in the atmosphere. Nevertheless the future development of the oceans as a CO_2 sink will be very important in determining how strongly anthropogenic CO_2 emissions are reflected as an increase in the atmospheric CO_2 concentration (Fig. 4).

Over very long times of several centuries, in which mixing takes place throughout the world's oceans, the ocean can take up about 65-80% of the anthropogenic CO_2, depending on the total CO_2 emissions. At even longer time scales this proportion can further increase due to the dissolution of carbonate sediments (Caldeira and Wickett, 2005). In the coming decades and centuries, however, only a portion of this great sink potential can be realized. The limiting factor is the transport of carbon taken up at the surface into the deep ocean. In fact, the oceans have so far only absorbed about 30% of the amount of anthropogenic carbon that they could take up over a long time period at present atmospheric concentrations.

When one compares the quantities of CO_2 taken up by the ocean with anthropogenic emissions, the efficiency of the ocean sink appears to be falling already. It has been shown (Sabine et al. 2004a) based on an analysis of observational data that from 1800 to 1994 the ocean absorbed nearly half of the total fossil-fuel emissions and 28–34% of the total anthropogenic emissions (fossil-fuel burning, cement production, and land use change), while from 1980 to 1999 this value was only 26%. Sabine and Tanhua (2010) extending the analysis of Sabine et al. (2004a) to 2006 recently reported that the ocean storage of carbon accounted for only 41% of the total fossil-fuel emissions since the preindustrial era. This percentage has dropped from 48% since the mid 1990s because the rate of ocean carbon uptake does not seem to be keeping pace with the rate of growth in CO_2 emissions. The land use change emissions are highly uncertain, but if they are included as part of the calculation, then the oceans are only absorbing about 25% of the current total anthropogenic emissions. Due to the large uncertainty in the determination of the global carbon balance, this decrease is not statistically significant, but expected on the basis of known physical and biogeochemical processes. In summary, estimates of decadal-scale ocean inventory changes consistently show increases in anthropogenic carbon in the water column, but have not been synthesized in a coordinated way to be able to confirm or deny a slowdown in the rate of carbon storage.

Global warming affects the capacity of the ocean sink, since the solubility of CO_2 in seawater decreases with rising temperature. An additional effect of global warming is increasing ocean stratification which reduces the vertical mixing and hence the transport of CO_2 from the surface to the deep ocean. Both reduced solubility of CO_2 and reduced vertical mixing, tend to reduce the efficiency of the oceanic carbon sink in a warming world. Another potentially significant impact on the oceanic CO_2 uptake is due to changes in the hydrological cycle at high latitudes in the North Atlantic: Here, reduced surface salinities, together with higher SSTs, would lower the density of surface waters and thereby may inhibit the formation of deep waters. This in turn would reduce meridional pressure gradients and tend to slow down the MOC and the carbon uptake. Climate model simulations indeed predict a weakening of the North Atlantic MOC for the 21st century when forced by increasing greenhouse gas concentrations, although the results strongly vary from model to model.

Complementary to the simulated weakening of the Atlantic MOC, climate models also predict an intensification of the ocean circulation in the Southern Ocean, resulting from a larger warming in mid and low latitudes compared with the waters around Antarctica. As a result, the meridional pressure gradients are predicted to increase both across the Antarctic Circumpolar Current (ACC) and in the atmosphere above the Southern Ocean. Consequently, the strength of both the surface westerlies and ACC increases in most models, which would lead to reduced carbon uptake in this region. Le Quere et al. (2007) find indeed that the Southern Ocean sink of CO_2 has weakened between 1981 and 2004 by 0.08 GtC/y per decade relative to the trend expected from the large increase in atmospheric CO_2. Estimates of the total impact of the circulation changes on the solubility pump differ considerably among different models, predicting a reduction in global oceanic carbon uptake by some 3-20%. A major part of the large uncertainty can be attributed to our incomplete understanding of the Southern Ocean's role as a carbon sink. Furthermore, the role of mesoscale eddies in stabilizing the Southern Ocean circulation in the presence of intensifying surface winds needs to be considered in this context (Böning et al., 2008).

The marine carbon uptake is also strongly affected by biological processes which, however, are very difficult to assess and therefore represent the greatest uncertainty in estimating the future development of the oceanic carbon sink. Our understanding of biological responses to ocean change is still in its infancy. Such responses relate both to possible direct effects of rising atmospheric CO_2 through ocean acidification (decreasing seawater pH) and ocean carbonation (increasing CO_2 concentration), and indirect effects through ocean warming and changes in circulation and mixing regimes. These changes are expected to impact marine ecosystem structure and functioning and have the potential to alter the cycling of carbon and nutrients in the surface ocean with likely feedbacks on the climate system. The long-term consequences of all these processes on marine life, however, are hard to quantify.

The global carbon cycle is both driven by and a driver of Earth's climate system. In this system, climate change therefore goes hand in hand with a change in carbon cycling and a redistribution of reactive carbon among the carbon reservoirs in the atmosphere, terrestrial biosphere, soil, and ocean. The distribution of carbon between these reservoirs is the result of a multitude of interconnected physical, chemical, and biological processes, many of which are sensitive to climate change themselves. As several of the underlying processes are not only interlinked but also highly nonlinear, the sign and magnitude of the ocean's carbon cycle feedback to climate change is yet unknown. Moreover, climate change projections themselves are highly uncertain even when considering only the evolution of the physical climate system (atmosphere, ocean, and sea and land ice) and neglecting biogeochemical feedbacks.

6. Conclusions

What are the implications of all this? First, uncertainty is an integral part of climate change projections. It arises from natural variability, model and scenario uncertainty, and from our incomplete knowledge of the Earth System dynamics. Impact studies and political decisions to mitigate climate change have therefore to be based on inherently uncertain climate change projections for the 21st century. It is important to communicate this to the wider scientific community and the public.

However, although the exact global warming to be expected by the end of this century cannot be predicted with great accuracy, there is a very high likelihood that globally averaged surface air temperature (SAT) will rise to a level which will be unprecedented during the history of mankind. Global SAT during the last major warm period, the Eemian Warm Period, peaked about 125,000 years ago and was about 0.5-1.0°C higher relative to present levels. We can expect an additional warming during the 21st century of 0.3-0.9°C assuming year 2000 constant GHG concentrations just due to the inertia of the Earth System, with a best estimate of 0.6°C (IPCC, 2007). Furthermore, we cannot expect global GHG emissions to rapidly decline soon, which will contribute to additional global warming. Thus the uncertainty in climate projections for the 21st century just reflects that we simply do not know by how much the Earth's climate will warm by the end of the century above levels which mankind has ever experienced in its history; and we do not know the exact trajectory climate will follow. Political action to cut global GHG emissions is thus imperative.

Yet we must improve our understanding of the Earth System dynamics. The mechanisms and predictability of natural climate variations which will be always superimposed on the long-term warming trend need to be better understood. This will improve our ability to detect anthropogenic climate signals against the background climate noise, especially on a regional scale and concerning the statistics of extreme weather events. Furthermore, some of the short-term natural climate fluctuations may be predictable, and climate models suitably initialized with the present climate state have the potential to predict these, which would be of enormous societal benefit. ENSO is a successful example at interannual time scales. Decadal timescale climate variations, especially those in the North Atlantic Sector, were also shown to be promising in this respect.

Moreover, climate models suffer from large biases. Improved global models will enable more reliable regional climate projections, in which society is mostly interested in. The Earth System exhibits a wide range of dynamical phenomena with associated physical, biological and chemical feedbacks that collectively result in a continuum of temporal and spatial variability. A new paradigm is emerging that of the *seamless prediction* (e. g., Palmer et al., 2008). In a nonlinear system such as the Earth System many time and space scales interact with each other. Certain weather patterns, for instance, such as blocking events are not well captured in state-of-the-art climate models. Drought conditions in Europe, for example, are often associated with blocking events, and their frequency could increase in response to global warming in certain regions. It is questionable whether global climate models can reliably predict regional precipitation changes in response to increased GHG concentrations, if they do not realistically simulate weather phenomena like blocking. Thus there is no scientific basis to draw artificial boundaries between mesoscale prediction, synoptic scale prediction, seasonal prediction, ENSO prediction, decadal prediction and climate change prediction. However, practical considerations of computing and of model complexity may require different prediction systems for different time scales. The simulation and prediction of mesoscale systems, synoptic scale disturbances, intraseasonal, seasonal and interannual variations are intimately linked, and therefore, future research on prediction of weather and climate should be carried out in a unified framework. For reliable prediction of regional climate change it is essential that climate models accurately simulate the modes of natural variability from diurnal to seasonal and decadal. Utilization of the insights gained from operational weather and seasonal prediction, and of the synergy between the weather and climate prediction communities is essential for the development of next-generation prediction systems.

Finally, we need to advance our understanding of how the Earth's biogeochemical cycles, including human actions, interact with the climate system by constructing Earth System Models (ESMs). “Pure” climate models are based on an atmospheric circulation model coupled with an oceanic circulation model, with representations of land and sea ice dynamics. These models have been devised by climate modelers to study weather, climate, and potential changes, both natural and anthropogenic. An ESM adds, to all of these components, the interactive carbon cycle, and associated chemical and ecological tracers, which determine nutrients, plant biomass and productivity. The ESM also captures numerous types of emissions, variations of land surface albedo due to both natural vegetation changes and land use history, including agriculture and forestry, and aerosol chemistry. Adding these different components to the ESM represents a major step towards simulating the Earth's ecological systems. The vision of global modeling is an integrated ESM, projecting not only climate variability on seasonal to centennial timescales, but also biogeochemical and ecosystem cycling and biological feedbacks on the climate system. It will allow, for instance, the study of coastal ocean ecosystems and is an important step toward ecological prediction. This is a comprehensive effort, requiring incorporation of climate dynamics, biogeochemistry, ecological processes and human activity.

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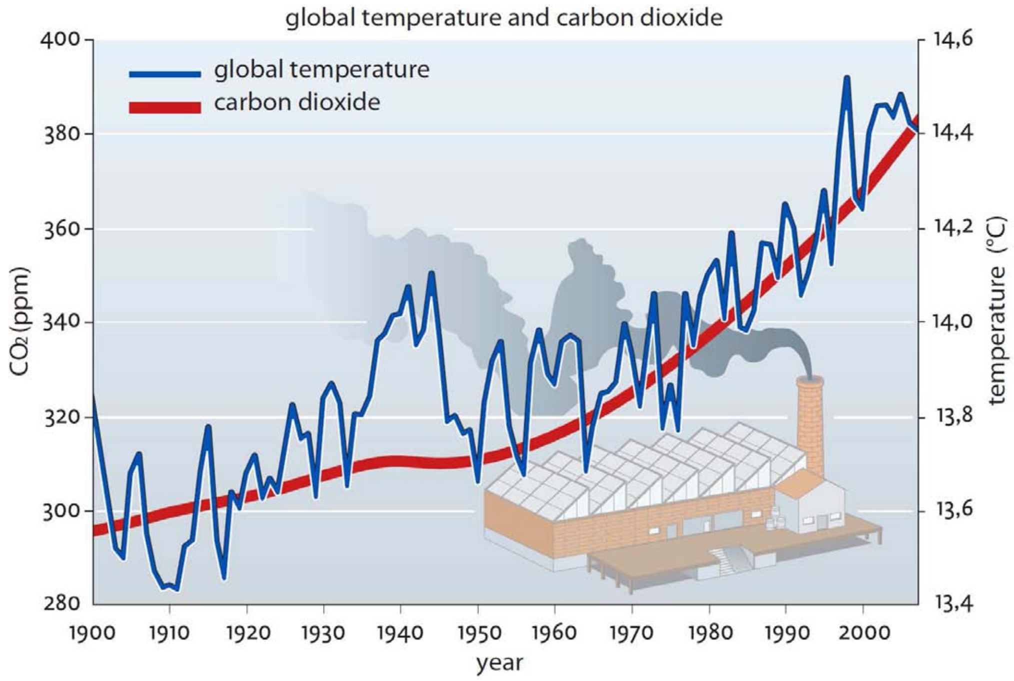
Figure Captions

Fig. 1: Observed annual globally averaged SAT (°C, blue line) taken from HadCRU3 and smoothed atmospheric carbon dioxide concentration (ppm, red line) during 1900-2008.

Fig. 2: a) Observed (HadCRU3) Northern Hemisphere averaged and b) Arctic (60-90°N) SAT (red lines) and the multi-model mean of the CMIP3 models. The shading displays the model spread. Please note that sampling is different in the models than in HadCRU3, which may explain part of the differences. After Semenov et al. (2010).

Fig. 3: Global equivalent CO_2 emissions (Gt CO_2/yr) for 1940 to 2000 and emissions ranges for categories of stabilisation scenarios from 2000 to 2100 (left panel); and the corresponding relationship between the stabilisation target (ppm) and the likely equilibrium global average temperature increase (°C) above pre-industrial levels (right panel). Coloured shadings show stabilisation scenarios grouped according to different targets (stabilisation category I to VI). The right-hand panel shows ranges of global average temperature change above pre-industrial levels, using (i) 'best estimate' climate sensitivity of 3°C (black line in middle of shaded area), (ii) upper bound of likely range of climate sensitivity of 4.5°C (red line at top of shaded area) (iii) lower bound of likely range of climate sensitivity of 2°C (blue line at bottom of shaded area). Black dashed lines in the left panel give the range of recent baseline scenarios published since the SRES (IPCC 2000). From IPCC (2008).

Fig. 4: (a) CO_2 emissions scenarios releasing from 1250 to 20,000 Pg C (4580–73,300 Pg CO_2) to the atmosphere after year 2000 (1Pg=1Gt). (b) CO_2 emissions specified for the Special Report on Emissions Scenarios (SRES) A1, A2, B1, and B2 pathways (IPCC, 2000) and allowable emissions calculated with an ocean model from WRE (Wigley et al., 1995) CO_2 stabilization scenarios. (c) Model-predicted atmospheric CO_2 contents (ppm) for the emission pathways shown in (a). (d) Atmospheric CO_2 (ppm) predicted for the SRES emission pathways and specified for the WRE stabilization scenarios. Please note that the upper scenarios in (a) and (c) are merely speculative ones. From Caldeira and Wickett (2005).



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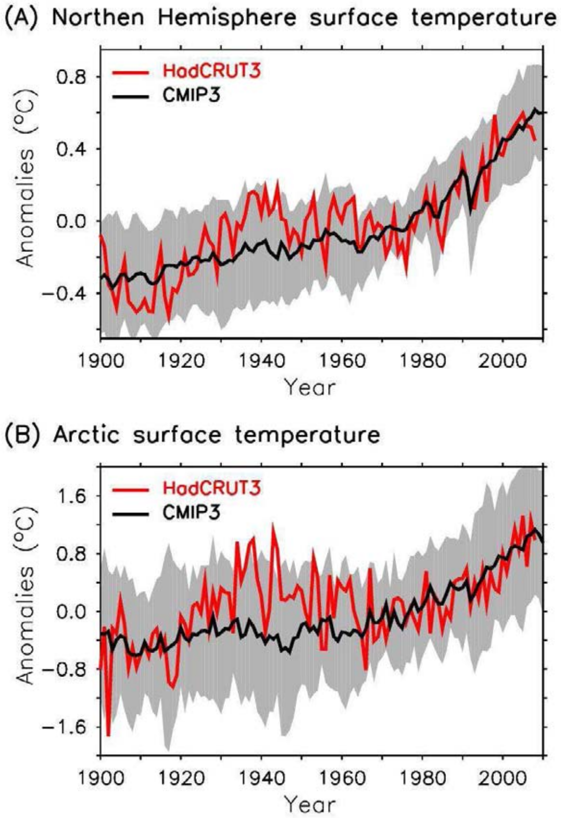

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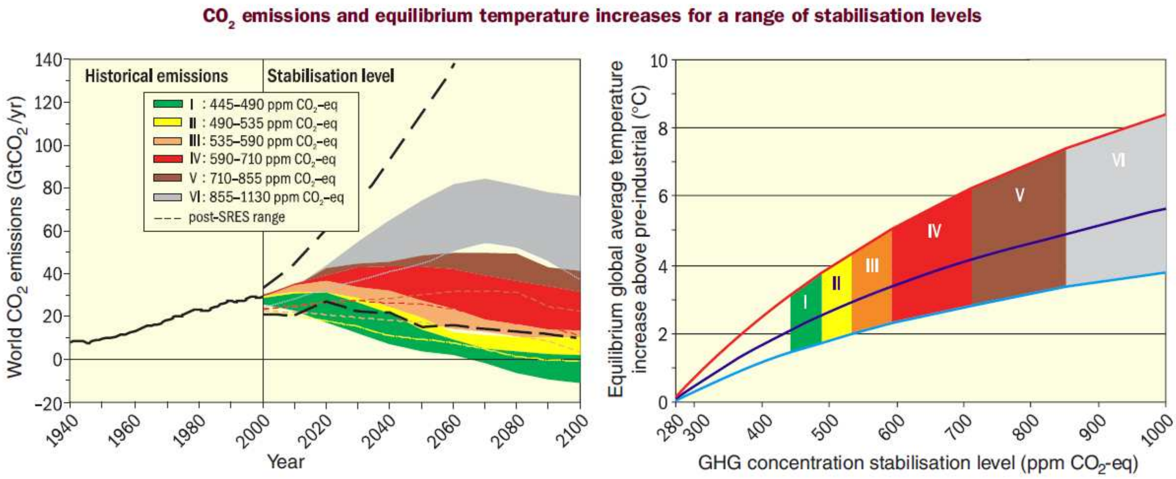

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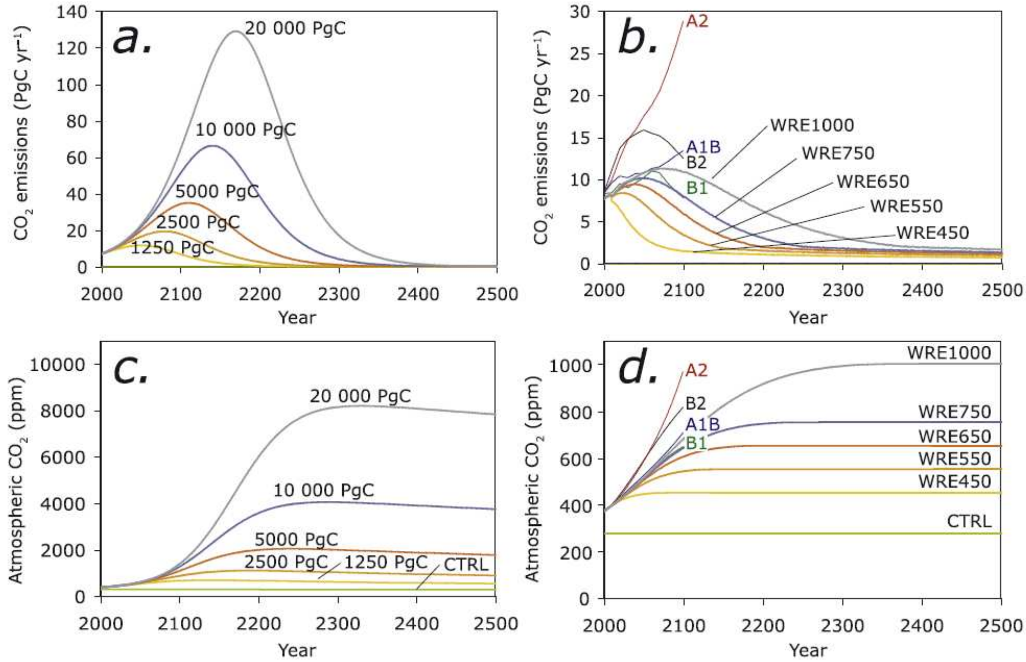

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