PROJECTIONS OF FUTURE CLIMATE CHANGE

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INTRODUCTION

We now know that the surface of the Earth is warming as a result of Mankind's activities. The obvious question then is "can we predict changes in climate that will happen in the future"? The chaotic behaviour of the atmosphere, which limits our ability to predict weather to only a week or so, also limits our ability to predict detailed variations in climate. It is impossible to predict, for example, the actual UK precipitation for winter 2050. However, we can make *projections* of climate change - that is we can examine scenarios or "parallel universes" of possible climate change that can come about because of our continuing emissions of greenhouse gases and other radiatively important substances. Such projections are very helpful for politicians and policy makers when assessing what to do about the problem of anthropogenic climate change, as they give an estimate of the likelihood of change given certain pollution scenarios.

The main tools we use for making projections of climate change are climate models. These usually consist of three-dimensional dynamical and physical models of the atmosphere, ocean, land surface and cryosphere, which are coupled together and run on powerful supercomputers. Worldwide there are many such models, all with different formulations, strengths and weaknesses, and this leads to one of the major uncertainties in climate change projections – it is almost impossible to choose which model is the best. Hence it is usual to examine all the different climate models for their respective projections of climate change and form levels of certainty based on the degree of consensus between the models. The IPCC has defined four levels of certainty in projections: Virtually certain to very likely (established projections which most models agree on), very likely (new projections which most newer models agree on), likely (new projections which a smaller number of models agree on) and medium likelihood (models are unresolved but changes are physically plausible). These provide the basis for the sections below.

In addition to uncertainties in the climate models we use to make projections, there are also uncertainties in the future levels of greenhouse gases in the atmosphere and in the radiative forcing associated with these levels. The latter is a scientific problem and is subject of the article by Haigh in this issue. The former is not only a problem for scientists to solve but has very significant socio-economic and political aspects regarding the future polluting habits of the human race. Hence it is usual to use scenarios of future levels of greenhouse gases etc. based on different global situations. However we shall see that because of time-lags in the climate system associated with the large heat capacity of

the ocean, much of the global warming over the next few decades has already been determined by our emissions of the last few decades – we are already committed to future climate change.

The following represents a summary of the main findings of Chapter 9 of the IPCC report "Projections of Future Climate Change".

GLOBAL MEAN CHANGES

It is useful to examine projections of globally averaged quantities in order to highlight the uncertainties in climate change over the next 100 years. Figure 1 shows projected surface air temperature from 1990 to the year 2100 for a range of scenarios and including uncertainties in the climate models (in fact this figure has been made using a simple energy balance climate model tuned to reproduce the response of the full dynamical climate models). The range of global mean temperature warming at 2100 (relative to 1990) is 1.4°C to 5.8°C and the level of uncertainty in the global mean temperature resulting from the uncertainty in the emission scenario is approximately the same as that due to the uncertainty in the climate model response. To put these changes in context, the approximate global temperature change corresponding to the last ice age is approximately 5-10°C. In addition to the magnitude of the change, the projected *rate* of warming is likely to be unprecedented in the last 10,000 years.

It can also be seen from fig. 1 that the range of uncertainty for projections of global mean temperature change in, for example, 2020 and 2050 are less than those in 2100 (being 0.3-0.9°C, 0.7-2.6° rising to 1.4-5.8°C respectively). While this is partly due to smaller uncertainties in emissions at these times, there is a significant effect of time lags in the climate system associated with the relatively slower rate of uptake of excess heat by the ocean in comparison with the atmosphere and land surface. This "committed warming" is estimated to be in the range 0.1°C to 0.2°C per decade over the next few decades regardless of uncertainties in model sensitivities.

While global mean quantities are useful for measuring the gross characteristics of climate change and for comparing models, society is more sensitive to regional changes that can vary significantly from the global mean value. The following sections give a summary of the different aspects of climate that, according to the IPCC, are likely to change in the next century.

VIRTUALLY CERTAIN TO VERY LIKELY CHANGES

The following are projections in which most climate models agree and have agreed in the past leading to greater certainty:

- As the surface warms, the troposphere will also warm and stratosphere will cool. The stratospheric cooling occurs because of the reduction in upward long wave radiation from the troposphere.

- Land areas warm faster than ocean regions, due to the smaller heat capacity of the land in comparison with the ocean, and high-latitude regions warm faster than low latitude regions because of a feedback between temperature and snow and ice cover.
- The cooling effect of tropospheric aerosols mitigates part of the future surface air temperature warming, although this effect is reduced in comparison with previous IPCC estimates.
- Due to deep mixing in the ocean , there are minima in warming in the North Atlantic and in the Southern Ocean circumpolar regions.
- Northern Hemisphere snow cover and sea-ice extent decrease.
- Global mean water vapor, precipitation and evaporation increase. An increase in temperature implies the atmosphere can hold more water vapour leading to a more vigorous global hydrological cycle.
- Most tropical and high latitude regions show increased mean precipitation, while most subtropical regions have decreased mean precipitation.
- The intensity of rainfall events increases, and this increase is greater than that expected from a simple change in the mean rainfall.
- Increased evaporation leads to soil moisture decreases in mid-continental regions in the summer.
- The mean state of the tropical Pacific becomes more “El Nino-like” with greater warming in the east in comparison with the west and a corresponding eastward shift in precipitation.
- Interannual variability in the northern summer monsoon increases.
- Models show more frequent extreme high maximum temperatures and less frequent extreme low minimum temperatures with a decrease in the diurnal temperature range in many areas with a greater increase in night-time lows than in day-time highs.
- There is more confidence in temperature changes that in precipitation changes.
- The Thermohaline Circulation (THC) weakens causing reduced warming in the North Atlantic. The rate of weakening is different in different models but in no model is the THC weakening strong enough to counter greenhouse warming in Europe.
- Heat penetrates the ocean most efficiently at high latitudes where vertical mixing occurs.

VERY LIKELY CHANGES

The following are projections that are agreed upon by a smaller number of newer models:

- The direct radiative effect of sulphate aerosols (a reduction in solar heating) leads to a reduction in mid 21st century warming in comparison to the case with no direct effect.
- For global mean temperatures in the next 100 years, uncertainties in emission scenarios are of the same order as uncertainties in model sensitivities.

- An initially weakened Thermohaline circulation can recover to present day values on a time-scale of centuries when greenhouse gas levels are stabilizes. Among present day models there is no scenario of a permanently shutdown THC in the next 100 years.
- An increase in temperature and humidity leads to greater values of the "heat index" – a measure of discomfort on hot days.

LIKELY CHANGES

The following are projections are agreed upon by many models and are physically plausible:

- Extremes of warm temperatures are more likely to occur in regions of reduced soil moisture and extremes of cold temperatures are more likely to occur in regions of snow and ice retreat.
- Precipitation extremes increase more than the mean and the return time for extreme precipitation events decrease nearly everywhere.

MEDIUM LIKELEHOOD CHANGES

The following are results that are less certain and there is no consensus across models or they are unresolved. They remain physically plausible.

- It is unclear whether changes in heat or fresh water fluxes play the dominant role in weakening the THC.
- A complete irreversible collapse of the THC by 2100 is less likely than previously thought. However it is still possible beyond 2100 and if the forcing is large enough.
- The cause of the El Nino like change in the tropical Pacific is unclear.
- Some models show an increase in the amplitude and frequency of El Nino events, but there is no consensus across models.
- There is no consensus on changes in mid-latitude storms nor on changes in the frequency and intensity of tropical cyclones
- There is no consensus on changes in modes of variability such as the North Atlantic Oscillation.

SUMMARY

The above is a rather brief tour of the potential for climate change over the next 100 years and beyond. The projections are summarized graphically in fig. 2 together with their uncertainty indicators. The reader is referred to Chapter 9 of the IPCC TAR for further information, references and figures.

While it may appear that there is a heavy reliance on the climate models for projections of climate change, many of the potential changes above are consistent with sound physical principals which gives us increased confidence. Also climate models are

continuously improved by the addition of more realistic physical processes and validated against observed records of recent climate (see the article by Stott et al. – detection and attribution is a powerful method of model validation) and of palaeo climate. Climate models remain the most powerful way to combine our knowledge of the observations, physics and dynamics of the climate system in order to produce the best estimates of future climate change.

The challenge in climate projection is to quantify many of the uncertainties in future climate and thus produce climate *predictions* with robust estimates of the probability of changes occurring.

REFERENCES

The reader is referred to Chapter 9 of the IPCC report for a full list of references.

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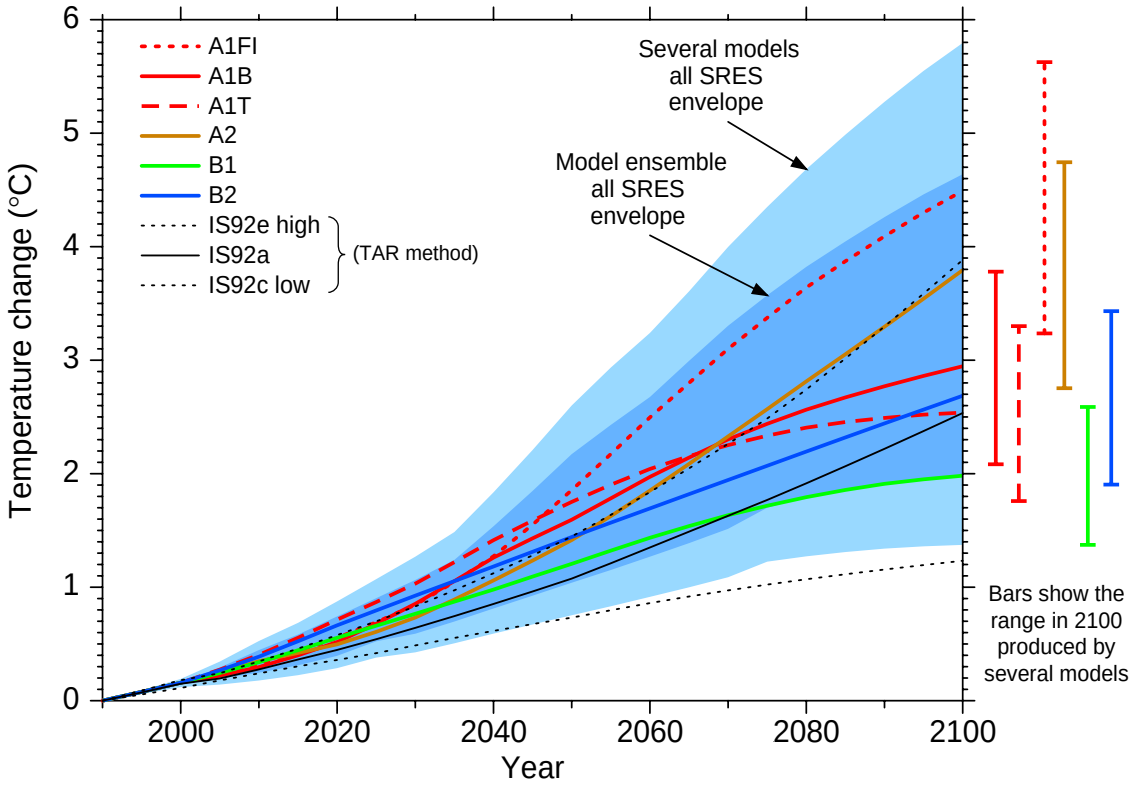
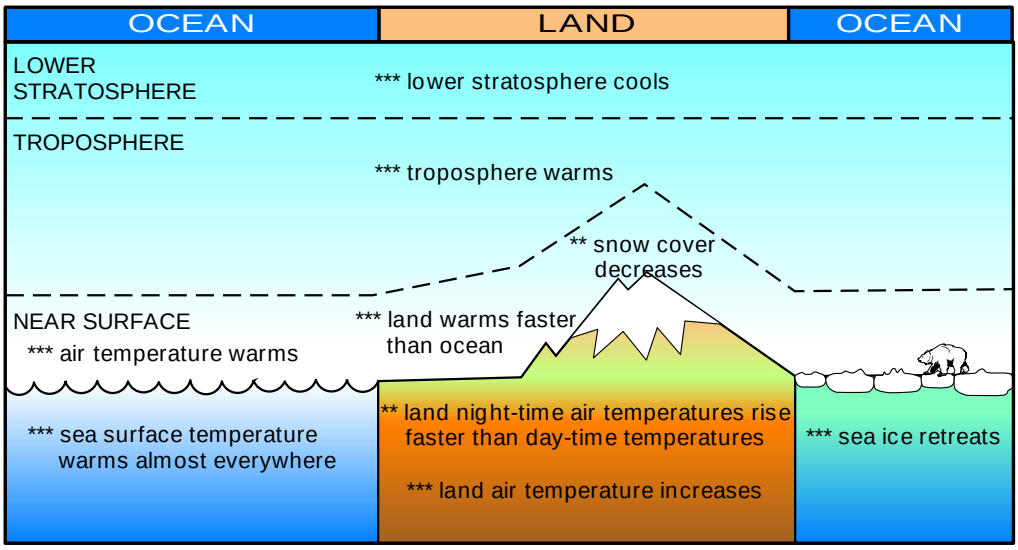
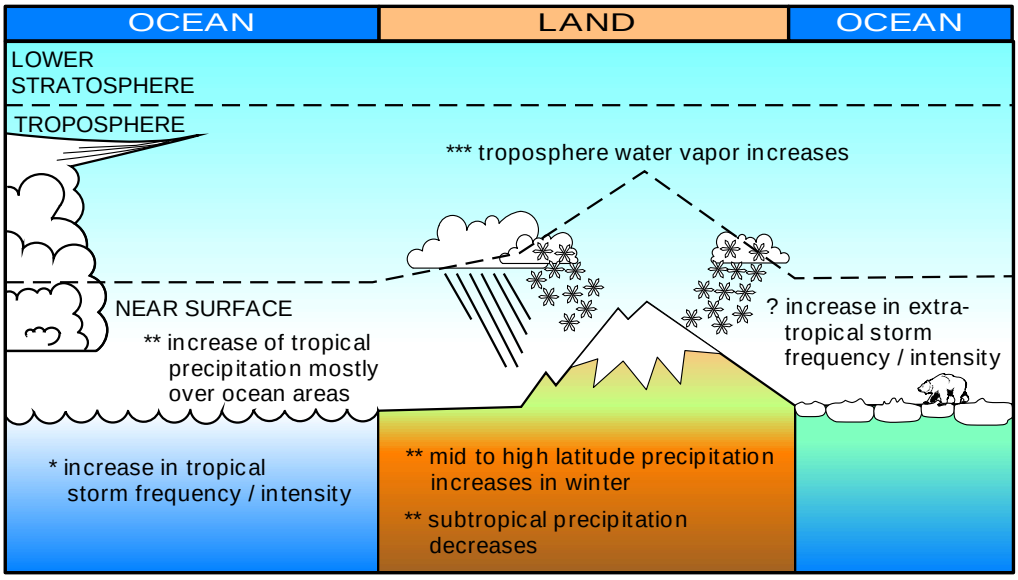


FIGURE 1: (fig 9.14 of IPCC – global SAT 1990-2100). Projected global temperature change 1990-2100. Lines show the mean response of all models for different emission scenarios. Blue shading highlights the uncertainty from the combined effects of uncertainty in scenarios and model sensitivity.

(a) Temperature indicators



(b) Hydrological and storm-related indicators



*** virtually certain
(many models analysed and all show it)
** very likely
(a number of models analysed show it, or change is physically plausible and could readily be shown for other models)
* likely
(some models analysed show it, or change is physically plausible and could be shown for other models)
? medium likelihood
(a few models show it, or results mixed)

FIGURE 2: (fig 9.31 of IPCC – summary of projections). A schematic summary of projected changes in climate, together with their uncertainties. To be compared with the observed changes (fig. 4 of Folland et al.).