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Complete List of Authors:	Wolff, Eric; University of Cambridge, Earth Sciences Shepherd, John; University of Southampton, Ocean and Earth Science Shuckburgh, Emily; British Antarctic Survey, Watson, Andrew; University of Exeter, College of Life and Environmental Sciences
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Feedbacks on climate in the Earth system: introduction

Eric W. Wolff[1], John G. Shepherd[2], Emily Shuckburgh[3] and Andrew J. Watson[4]

1. Department of Earth Sciences, University of Cambridge, Cambridge CB2 3EQ, UK
2. Ocean and Earth Science, University of Southampton, Southampton SO14 3ZH, UK
3. British Antarctic Survey, Cambridge CB3 0ET, UK
4. College of Life and Environmental Sciences, University of Exeter, Exeter EX4 4QE, UK

In the past century the Earth has undergone a very fast and unusual change in the radiative forcing of its climate, resulting from human actions. This change in forcing has resulted mainly from rising concentrations of greenhouse gases, particularly carbon dioxide (CO_2), but also from changes in the nature of the land surface and changes in the concentrations of aerosol particles in the atmosphere and of ozone-destroying chemicals in the stratosphere. If the changes in forcing continue on their current trajectory, then very substantial changes in climate are predicted by the end of the century [1].

It is reasonably straightforward to calculate the equilibrium change in temperature at global scale that would result from a particular change in forcing if the Earth behaved as a simple black body and there were no additional effects [2]. For example it can be calculated that a doubling of CO_2 concentration results in a long-wave forcing of about 3.7 W m^{-2}, which by itself would cause an equilibrium warming of about 1.2°C.

However in practice the initial perturbation causes a range of other feedback effects, which may weaken or strengthen the global temperature response. These effects are substantial, and it is the net effect of such feedbacks that determines the overall sensitivity of the planet to forcing. Negative feedbacks (such as that due to the change in atmospheric lapse rate, i.e. changes in the vertical temperature gradient of the atmosphere) cause the climate to be less sensitive to changes of forcing, while positive feedbacks like the ice-albedo feedback cause it to be more sensitive. The most recent IPCC synthesis report concludes that the combined effects of all feedbacks is likely to be significantly positive [1].

Importantly, the nature and magnitude of these feedbacks is the principal cause of uncertainty in the response of Earth's climate (over muitidecadal and longer periods) to a particular emissions scenario or greenhouse gas concentration pathway. Moreover, although feedbacks are often discussed at a global scale, and in terms of single global numerical feedback parameters, feedbacks also play a key role in inducing regionally variable responses to climate forcing, both in terms of temperature and other key variables such as rainfall and the occurrence of extreme events. For these reasons, improving understanding of feedback processes is an urgent priority.

Because the emphasis in climate change research has often been on the next few decades, up to a century, most discussions of climate feedbacks have focussed on the fast feedbacks, such as those caused by changes in water vapour, clouds and sea ice extent, which are included in the traditional definition of climate sensitivity [3]. However, the eventual response of the planet, and the one that is observed in records of past climate changes, includes some feedbacks with a much longer timescale. These include changes in ice sheet extent, and carbon cycle feedbacks. A final group of effects, often discussed under the umbrella of abrupt events, but representing highly non-linear feedbacks, may also be considered: these would include hypothesised releases of high latitude methane, or rapid changes in ocean circulation resulting from climate change.

In designing this discussion meeting, we included work on a deliberately broad range of feedbacks, taking into account feedbacks with timescales ranging from instantaneous up to thousands of years. We split the topic broadly into three categories: feedbacks involving water in the atmosphere, as water vapour, clouds and aerosol; feedbacks involving ice (on both land and the sea); and feedbacks involving greenhouse gases and the carbon cycle. Presenters were asked to consider the processes, modelling studies and the palaeo-records of past climate change. Process studies contribute the detailed knowledge needed to improve models. Modelling studies indicate how the different processes combine to produce observed large-scale behaviour. Palaeo-records contains numerous examples of the response of the climate system to natural forcings such as volcanic eruptions, changes in the distribution of solar energy due to changes in Earth's orbit and axial tilt, and natural emissions of greenhouse gases. These can be investigated [4, 5] to challenge and support our understanding of feedbacks in the present and the future.

The papers in this volume represent contributions from the three broad topics, delving into the past, present and future, and into process studies, modelling work and palaeo-climate analysis. The contributions outline the current state of knowledge and highlight future directions of research. Some of the papers take a more general look at the overall impact of feedbacks [3, 6], and the variability of that impact over time [7] and space [8]. In the two days following the discussion meeting, a satellite meeting considered some of the issues raised in more detail, basing discussion around a set of questions, paraphrased here as:

"Which feedbacks (and what aspect of them) provide the most uncertainty in response, (a) for global response by 2100, (b) for regional variations of temperature, precipitation, extreme events and (c) for long term outcomes and commitments beyond 2100?" The following paragraphs draw on the conclusions of both meetings.

The response from water vapour itself and from the lapse rate feedback are considered to be reasonably well-understood, but that from clouds [9, 10] remains the major known cause of uncertainty in both short term (decadal) and long-term (multi-centennial) climate prediction. Improvements in the understanding of processes affecting a number of different cloud types have been made in recent years. An approach involving multi-model comparisons, cloud process modelling and ground-based observations offers a path to further reduce uncertainty, but it appears to remain challenging to translate new knowledge into more skilful practicable representations of the effects of clouds (parameterisations) in GCMs.

For aerosols a first concern has been to determine whether the forcings assessed in the historical period due to aerosols are accurate, as this affects the correct assessment of the forcing-response relationship. However beyond that, there remains much work to be done on the role of aerosols in a range of feedbacks (including those involving clouds). The meeting heard about new experimental facilities, that are starting to have a major impact on our understanding of the complex chemistry determining the rate of formation and growth of cloud condensation nuclei (particles on which cloud condensation can occur).

The presence of absence of sea ice causes a range of feedbacks, starting with the change in albedo (reflectivity), but encompassing a wide range of physical and chemical effects. Along with changing snow cover, this is a crucial component in producing the biggest regional contrast in the response to climate change: Arctic amplification. The Antarctic differs from the Arctic in a number of respects: not least, one is a continent surrounded by ocean, and the other an ocean surrounded by continent. Amplification and sea ice retreat have not yet emerged around most of the sectors of Antarctica. Overall, there is still some way to go in understanding how ice dynamics and thermodynamics, and other factors involving atmospheric and ocean dynamics and atmospheric chemistry, interact to determine the way in which feedbacks are manifested in the polar regions. The possible impact of Arctic sea ice changes on mid-latitude weather patterns is a topical example of the processes that are not yet properly explored and are still poorly understood.

The ice sheets on land react on much longer timescales, and are not included in the traditional short-term definition of climate sensitivity, but of course were the dominant feature of glacial-interglacial changes and some other past climate changes. Their dynamic behaviour is one of the most important uncertainties for the commitment beyond 2100, as there are good reasons to believe that there is a threshold (whose value remains uncertain) beyond which the loss of much of the Greenland ice sheet becomes inevitable. Additionally the processes that can destabilise a marine ice sheet such as most of West Antarctica are now much better understood, but not to a level where an accurate prognosis of their contribution to the future rates of sea level change can yet be given. The role of the cryosphere was extensively discussed at the meeting, and is considered in some contributions here, but is not represented by a dedicated paper in the volume.

The feedbacks discussed so far describe the amplifiers and attenuators of climate change in response to a given change in a forcing (such as CO_2). However there are further feedbacks within the carbon cycle itself. More than half of anthropogenic carbon emissions are currently absorbed by the ocean and the land biosphere and it is critical to climate projections to accurately understand how this proportion may evolve in response to changes in CO_2 concentration and climate. The palaeo-climate record suggests that large changes in concentrations of greenhouse gases are possible, and were a major amplifying feedback in glacial cycles. Remote sensing and measurement networks are transforming our ability to understand carbon fluxes but much more needs to be done. Promising approaches include the study of “emergent constraints” – the evidence of recent variability in the ocean and land sinks of CO_2, responding to climate variations such as the El Niños [11], and detailed data-constrained models of major unknowns, such as the response of permafrost soils to climate warming [12].

Finally, discussion of the economic benefits of narrowing the uncertainties in the strength of feedbacks [13] reminds us that a whole new set of feedbacks between the climate and the human response to it will play a major role in defining the trajectory of emissions and climate change in the next few decades.

The papers in this volume review what is known about many of the major feedback processes that have affected past, and will affect future, climate change. They also identify the issues that we know still need to be addressed, and demonstrate how they may be approached. Even so, it remains possible that there are additional feedback processes that have yet to be discovered and may prove to be significant; to avoid surprises, we must continue to use improved process understanding along with the palaeo-record to identify missing feedbacks that should be included in models.

References

[1] IPCC. 2013 *Climate Change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge and New York, Cambridge University Press; 1535 p.

[2] Knutti, R. & Hegerl, G.C. 2008 The equilibrium sensitivity of the Earth's temperature to radiation changes. *Nature Geoscience* **1**, 735-743. (doi:10.1038/ngeo337).

[3] Knutti, R. & Rugenstein, M.A.A. 2015 Feedbacks, climate sensitivity, and the limits of linear models. *Philosophical Transactions of the Royal Society A*.

[4] Braconnot, P. & Kageyama, M. 2015 Shortwave forcing and feedbacks in Last Glacial Maximum and Mid-Holocene PMIP3 simulations. *Philosophical Transactions of the Royal Society A*.

[5] Kennedy, A.T., Farnsworth, A., Lunt, D.J., Lear, C.H. & Markwick, P.J. 2015 Atmospheric and oceanic impacts of Antarctic glaciation across the Eocene-Oligocene transition. *Philosophical Transactions of the Royal Society A*.

[6] Gillett, N.P. 2015 Weighting climate model projections using observational constraints. *Philosophical Transactions of the Royal Society A*.

[7] Gregory, J.M., Andrews, T. & Good, P. 2015 The inconstancy of the transient climate response parameter under increasing CO2. *Philosophical Transactions of the Royal Society A*.

[8] Sutton, R., Suckling, E. & Hawkins, E. 2015 What does global mean temperature tell us about local climate? *Philosophical Transactions of the Royal Society A*.

[9] Bretherton, C.S. 2015 Insights into low-latitude cloud feedbacks from high-resolution models. *Philosophical Transactions of the Royal Society A*.

[10] Webb, M.J., Lock, A.P., Bretherton, C.S., Bony, S., Cole, J.N.S., Idelkadi, A., Kang, S.M., Koshiro, T., Kawai, H., Ogura, T., et al. 2015 The impact of parametrized convection on cloud feedback. *Philosophical Transactions of the Royal Society A*.

[11] Friedlingstein, P. 2015 Carbon cycle feedbacks and future climate change. *Philosophical Transactions of the Royal Society A*.

[12] Koven, C.D., Schuur, E.A.G., Schädel, C., Bohn, T.J., Burke, E.J., Chen, G., Chen, X., Ciais, P., Grosse, G., Harden, J.W., et al. 2015 A simplified, data-constrained approach to estimate the permafrost carbon-climate feedback. *Philosophical Transactions of the Royal Society A*.

[13] Hope, C. 2015 The $10 trillion value of better information about the transient climate response. *Philosophical Transactions of the Royal Society A*.