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Ringberg15: Earth's Climate Sensitivities

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Executive Summary

To assess gaps in understanding of Earth's climate sensitivities a workshop was organised under the auspices of the WCRP *Grand Science Challenge on Clouds, Circulation and Climate Sensitivity* (Ringberg15). The workshop took place in March 2015 and gathered together over thirty experts from around the world for one week. Attendees each gave short presentations and participated in moderated discussions of specific questions related to understanding Earth's climate sensitivities. Most of the time was focused on understanding of the equilibrium climate sensitivity, defined as the equilibrium near-surface warming associated with a doubling of atmospheric carbon dioxide. The workshop produced nine recommendations, many of them focusing on specific research avenues that could be exploited to advance understanding of climate sensitivity. Many of these dealt, in one fashion or another, with the need to more sharply focus research on identifying and testing story lines for a high (larger than 4K) or low (less than 2 K) equilibrium climate sensitivity. Additionally, a subset of model intercomparison projects (CFMIP, PMIP, PDRMIP, RFMIP and VolMIP) that have been proposed for inclusion within CMIP were identified as being central to resolving important issues raised at the workshop; for this reason modelling groups were strongly encouraged to participate in these projects. Finally the workshop participants encouraged the WCRP to initiate and support an assessment process lead by the *Grand Science Challenge on Clouds, Circulation and Climate Sensitivity* on the topic of Earth's Climate Sensitivities, culminating in a report that will be published in 2019, forty years after the seminal report by Charney and co-authors.

Preface

How sensitive is Earth's surface temperature to radiative forcing? This simple question has intrigued scientists for more than a century. A particular instance of this question arises in the context of rising concentrations of greenhouse gases. Over the industrial era long-lived greenhouse gases in the atmosphere have perturbed Earth's radiative budget to a degree equivalent to a 70% increase in CO_2 alone. How much warmer would Earth be, *ceteris paribus*, if concentrations of atmospheric CO_2 rose to twice their preindustrial level? This question, rephrased as 'what is Earth's equilibrium climate sensitivity' remains for many the holy grail of contemporary climate science. But like the purported search for the holy grail, an attempt to answer this question might be obscuring the point that for many important practical questions other measures of Earth's climate sensitivities may be more relevant, and better constrained by data. For example, it appears that the peak warming for a given cumulative release of carbon dioxide depends more on the transient climate response (TCR, defined below) than it does on the equilibrium climate sensitivity.

To assess current understanding, or rather gaps in understanding, of Earth's climate sensitivity a workshop was organised, under the auspices of the WCRP *Grand Science Challenge on Clouds, Circulation and Climate Sensitivity* (Ringberg15). The one week workshop brought together just over thirty experts from around the world to discuss what we know, what we don't know, and most importantly, what we think we could know if we are clever in how we organise our research, or in how we pose our questions. The discussion of these points fed into a series of workshop recommendations and a suggested implementation plan for the World Climate Research Programme.

Background

Ringberg15 was organised under the auspices of the *Grand Science Challenge on Clouds, Circulation and Climate Sensitivity*. One of the objectives of this new initiative of the World Climate Research Programme is to narrow uncertainty in estimates of Earth's Climate Sensitivities (Bony et al., 2015). The best known of these sensitivities is the Equilibrium Climate Sensitivity, or ECS (Knutti and Hegerl, 2008). The ECS is defined as the change in the globally averaged near-surface temperature that would arise at equilibrium from a doubling of the concentration of atmospheric carbon dioxide, neglecting changes in the biosphere, land cryosphere (ice sheets) or lithosphere (Charney et al., 1979; Bony et al., 2013). Other sensitivities include the transient climate response (TCR) and the hydrological sensitivity, which describes the response of globally averaged precipitation to warming. There are a number of lines of argument, ranging from better use of the historical temperature record to its socio-economic relevance, as to why the TCR might be more relevant to understand than ECS (Allen and Frame, 2007). Nonetheless, much of the discussion at the workshop focused on ECS because scientifically the open issues that it raises are central to understanding Earth's other climate sensitivities.

Although within the *Grand Science Challenge on Clouds, Circulation and Climate Sensitivity* the question as to the magnitude of the ECS focuses more specifically on the role of clouds and convection, Ringberg15 took a broader perspective. One reason for doing so was the perception that the periodic assessments of quantities like the ECS, which are normally undertaken by the IPCC, would be more effective in advancing the science if they were complemented by an autonomous effort that co-evolved with the science. By organising a workshop to explore the possibility of engaging the community in a more continual and forward looking process the organizers of Ringberg15 hoped to launch such a process, and in doing so accelerate the advancement of the science.

A further backdrop to the meeting was the perception, arising in part out of the organizers' experiences in the last IPCC assessment report, that different lines of argument were pulling estimates of the ECS (and TCR) in different directions. Recent work using simple models to interpret the historical temperature record, in light of estimates of anthropogenic forcing and estimates of imbalances in Earth's energy budget, has pointed to lower estimates of ECS. This class of studies was influential in reassessing the change in the lower range of the confidence interval of ECS between the fourth and fifth assessment report. Some of these estimates appeared inconsistent with inferences drawn from more comprehensive models, but the timeline of the IPCC process made it difficult to reconcile these differences within the framework of the assessment.

Ringberg15 was thus organised to revisit the question of Earth's climate sensitivities – with a focus on Earth's Equilibrium Climate Sensitivity and its Transient Climate Response. Through coordinated experiments, an assessment of apparently contradictory lines of evidence, and critical tests of story lines for a surprisingly large (or small) climate sensitivity, the workshop aimed to more clearly summarise the current state of understanding as to how Earth responds to forcing, and identify fruitful research directions for further narrowing uncertainty.

The Workshop

Schloss Ringberg, a scientific meeting facility maintained by the Max Planck Society, was chosen as the meeting venue. Because it integrates meeting and lodging facilities in a single venue its capacity is limited to about three dozen individuals. Such a size was well suited to an aim of the workshop, which was to collectively and critically examine the foundations upon which current understanding is based. Toward this end about half of the time during the week of the meeting was devoted to short (15 min) talks to introduce the participants and their ideas, and the rest of the time was spent in moderated discussions on specifically chosen topics.

Workshop participants (listed in Table 2) were invited based on their ability to contribute to the different themes, elaborated upon below, that the workshop wished to address. In selecting participants consideration was also given to national background, career stage, gender and diversity of opinions. Regarding the latter, the workshop strove to identify and bring together leading representatives of very different lines of thought regarding Earth's climate sensitivities, with the hope that doing so would better clarify gaps in understanding. The response to the workshop invitation was overwhelmingly positive, and most participants financed their own participation. For those with insufficient support from their own institutions, supplemental funding was also provided by the WCRP and the Max Planck Institute for Meteorology.

Themes

Concepts and Terminology Several of the workshop presentations, including introductory talks by Steve Sherwood, Reto Knutti and Jonathan Gregory, and a later talk by Michel Crucifix, addressed some of the basic concepts and frameworks that have been introduced to understand Earth's response to externally imposed perturbations, or forcing (see also Bony et al., 2006; Knutti and Hegerl, 2008; Stevens and Schwartz, 2012; Sherwood et al., 2015, for a review of concepts).

The equilibrium climate sensitivity, or ECS, is defined as the equilibrium near-surface warming that results from a doubling of atmospheric CO_2. It allows one to define a ratio between the radiative forcing, $F_{2\times}$, from the change in the CO_2, and the ECS,

$$\lambda_{2\times} \equiv \frac{F_{2\times}}{\mathrm{ECS}}. \tag{1}$$

This ratio, $\lambda_{2\times}$, has units of $\mathrm{W\,m^{-2}\,K^{-1}}$ and is called the climate feedback parameter (e.g.,

Figure 1: Participants (at least most of them) on the way to town.

Bony et al., 2006; Knutti and Hegerl, 2008).[1] The generality of $\lambda_{2\times}$, and its ability to scale the response of the systems to other perturbations, is a matter of some discussion, and likely depends on how one estimates the radiative forcing. Although the forcing in Eq. (1) is not well defined, it has come to be quantified using a model described below, which results in a value of $F_{2\times} \approx 3.7$ W m^{-2}.

To estimate $\lambda_{2\times}$ from data, or diagnose differences in estimates of $\lambda_{2\times}$ that emerge from the integration of more complex models, requires an interpretive framework. Perhaps the simplest and most widely used such framework is one that expresses the net power, N, into the system from space in terms of T and other bulk (or global) quantities, such that

$$N = N(Y_i, T, X_i(Y_i, T)). \tag{2}$$

Here the vectors Y_i and X_i differ to allow X_i to depend on both Y_i and T. As an example, a Y_i might be the solar insolation, or a temperature independent perturbation to an atmospheric greenhouse gas, while an X_i might describe the albedo or atmospheric stratification, which we would expect to depend on temperature. Given this model it follows that

$$\mathrm{d}N = \left(\frac{\partial N}{\partial Y_i} + \frac{\partial N}{\partial X_j}\frac{\partial X_j}{\partial Y_i}\right)\mathrm{d}Y_i + \left(\frac{\partial N}{\partial T} + \frac{\partial N}{\partial X_i}\frac{\partial X_i}{\partial T}\right)\mathrm{d}T, \tag{3}$$

where repeated indices implies summation. The first term on the rhs of Eq. (3) is usually defined

[1]Terminology in the literature can be confusing. Some authors use the symbol α instead of $\lambda_{2\times}$ and call this quantity the climate response parameter (Gregory, 2004) or even the climate sensitivity parameter (Gregory and Forster, 2008). The latter may be confusing because other studies (Sherwood et al., 2015) use the phrase 'climate sensitivity parameter' to denote the inverse of what we here call the climate feedback parameter.

as the forcing, $\mathrm{d}F$; the second term the radiative response, $-\lambda \mathrm{d}T$. With these definitions,

$$\mathrm{d}N = \mathrm{d}F - \lambda \mathrm{d}T. \tag{4}$$

Allowing for the X_i to also depend on the Y_i generalises the concept of forcing by allowing for 'adjustments', i.e., changes to the energy balance that can be indirectly attributed to a perturbation Y_i but which are independent of T. The parameter λ which scales the radiative response to temperature changes can be interpreted in terms of a basic radiative response, $-\partial_T N$, usually called the Planck Response, and feedback factors, $\partial_{X_i} N \, \partial_T X_i$. In practice, differences in the timescale of the response of the system can also be used to separate feedbacks from forcings or adjustments. This can be a source of some confusion when there is not a clear separation of timescales. An instance of this, discussed below, occurs in the distinction of climate sensitivity and Earth system sensitivity. Some components of the Earth system are regarded as boundary conditions for climate sensitivity, in which case changing them produces a forcing or adjustment; the same components may be regarded as interactive for Earth system sensitivity, in which case changes in them may be feedbacks.

In the case that Eq. (2) is an adequate model, and if λ does not depend on the state of the system, then $\lambda = \lambda_{2\times}$. Much of the discussion of the workshop focused on the adequacy of Eq. (2) as a model of the climate system, raising the question as to whether globally averaged surface temperature is the most appropriate state variable, and, even if it is, the extent to which λ depends on the state of the system, either as measured by T or by hidden parameters encapsulated as noise. Because as a matter of practice it is difficult to determine λ from infinitesimal changes it is useful to define

$$\lambda_{\mathrm{eff}} = \frac{\Delta F - \Delta N}{\Delta T} \tag{5}$$

so as to allow for the possibility that λ may be state dependent. To the extent that λ depends on the state of the system, λ_{eff}, and hence the difference to λ, may also depend on the nature of the forcing. Different forcings can be expected to induce different adjustments. Because λ_{eff} can (given an estimate of the forcing) be estimated from data, the question then becomes whether or not $\lambda_{2\times}$ is well approximated by λ_{eff} and if not, whether there might be better theories for how $\lambda_{2\times}$ relates to quantities that can be constrained by theory or data (Winton et al., 2010; Geoffroy et al., 2013).

The idea of an effective climate feedback parameter λ_{eff} also arises in discussions of the transient climate response, which is usually defined as the change in T that arises from a steady ($1\%\ \mathrm{yr}^{-1}$) increase in atmospheric CO_2 at the time when CO_2 has reached twice its preindustrial value (after approximately seventy years). As such, from Eq. 5, TCR implies a particular value of λ_{eff}. The TCR is useful for indicating the response of the Earth system to complex perturbations, rather than an idealised increase in CO_2 imposed in isolation, only in so far as the TCR λ_{eff} is a good indicator of the λ that applies in the situation of interest.

To the extent one is only interested in TCR it might be argued that differences between $\lambda_{2\times}$ and λ_{eff} are immaterial. But if one is interested in understanding how the Earth system responds to complex perturbations, rather than an idealised increase in CO_2 imposed in isolation, then it will again be necessary to understand the origin, if any, of differences between $\lambda_{2\times}$ and λ_{eff}.

The workshop addressed some nuances in the language describing climate sensitivity. ECS (and to a lesser degree TCR) is often used to mean slightly different things in the published literature, which can confuse attempts to reconcile different estimates of their magnitude. The historical definition of ECS is influenced by how scientists defined the climate system when first attempting to quantify it. ECS as used by Charney et al. (1979) does not incorporate changes in the biosphere, elements of the cryosphere, nor lithosphere.[2] Others have come to use ECS

[2]Those authors never used the term equilibrium climate sensitivity, but rather speak of the 'equilibrium surface global warming due to a doubled CO_2'.

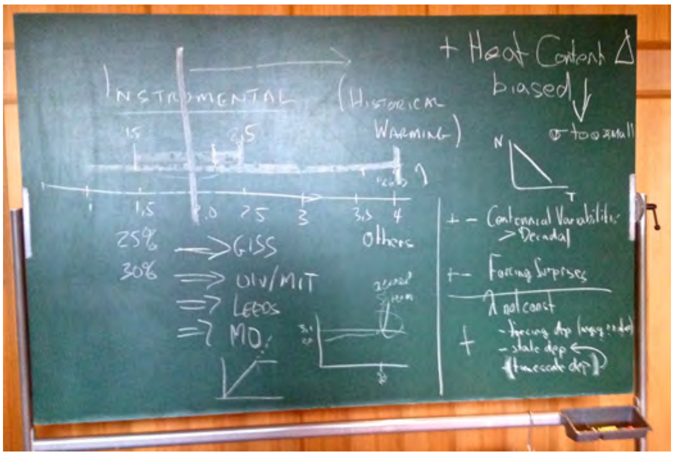

Figure 2: A snapshot of the board during a discussion of how to interpret the historical temperature record.

in a more general sense, to simply mean the equilibrium response of some representation of the climate system to a doubling of CO_2, and have introduced the phrase Charney Sensitivity to link to ECS estimates from a system similar to that studied by Charney et al. (1979). More recently the idea of an effective climate sensitivity has emerged as $\lambda_{\rm eff}^{-1}F_{2\times}$. The effective climate sensitivity is the same as the ECS only in so far as either $\lambda_{\rm eff} = \lambda_{2\times}$, or $F_{2\times}$ is adjusted to compensate for differences between the two climate sensitivity parameters.

The idea of Earth System Sensitivity has also been introduced as a way to discuss systems that incorporate many slow feedback processes (e.g., the land-cryosphere), as for instance arises when looking at some systems in the palaeo record. In an effort to avoid constructing an overly elaborate jargon it was agreed that the workshop would retain the original meaning of ECS, e.g., in the sense of Charney et al. (1979). As good practice researchers were encouraged to be specific as to the properties of the system they were using to define the climate sensitivity. In practical terms this means distinguishing between λ, or $\lambda_{\rm eff}$ or $\lambda_{2\times}$ and specifying which feedback processes are being considered art of the system.

Although an understanding and quantitative estimate of the ECS, equivalently $\lambda_{2\times}^{-1}$, has long been a goal of climate science, one presentation asked to what extent further precision in the estimate of $\lambda_{2\times}$ has implications for policy. The question was motivated by economic modelling (with all its caveats which the workshop participants did not have the expertise to judge), which suggests that the TCR (rather than ECS) determines the social cost of carbon. An implication of this is that because TCR is more tightly constrained than ECS, uncertainty in ECS – though large – may have less implications for policy than is usually assumed.

The Instrumental Record Given estimates of the historical warming ΔT, the forcing F and the change in ocean enthalpy uptake, which due to the low thermal inertia of the atmosphere is equal to ΔN, it has been proposed to estimate $\lambda_{\rm eff}$ from Eq. 4. To the extent that one can equate $\lambda_{\rm eff}$ with $\lambda_{2\times}$, these records appear to constrain ECS to a value of between 1 and 4 K, (Fig. 2). Likewise, using the satellite record, it is conceivable that short-term fluctuations in N, when related to fluctuations in T, can similarly be used to estimate λ. The implications of estimating λ in this fashion, and the validity of assuming that $\lambda_{2\times} = \lambda_{\rm eff}$ were a topic of substantial discussion.

Comprehensive modelling suggests that during the initial response to a perturbation $\lambda \geq \lambda_{2\times}$, so that when one plots the imbalance in the top-of-atmosphere irradiance versus T, the relationship often describes a convex, rather than a linear curve. One study, using two versions of the Hadley Centre model, has also found a marked sensitivity of λ to the pattern of SSTs during warming. If SSTs are constrained to match the historical pattern of SST evolution, a value of λ much larger than the same model's $\lambda_{2\times}$ arises. These studies suggest that the magnitude of the ECS from estimates of λ during an initial period of warming, or for warming with the observed pattern of SST changes, could be biased low – perhaps considerably so. But physical hypotheses are only beginning to be developed as to why, in many GCMs, λ departs from $\lambda_{2\times}$, or why SSTs have evolved in a way that, at least in some models, implies a value of λ much larger than would arise for a different warming pattern. Improved understanding is necessary to make better use of the historical temperature record and present day measurements of Earth's energy budget for constraining estimates of climate sensitivity.

Further themes that emerged in the interpretation of the instrumental record included the possible dependence of λ on the nature, and perhaps magnitude, of the forcing (e.g., Volcanic versus CO_2) and the influence of unforced variability. These are thought to be related to differences between λ_{eff} estimated over the instrumental record, which documents a period with a rich mix of forcing, and $\lambda_{2\times}$. A poor understanding of variability on timescales longer than a decade further complicates interpretations of the instrumental record. Work was presented suggesting centennial scale variability of the ocean enthalpy uptake, associated with changes in the southern ocean on the one hand, and the role of coupling between the atmosphere and upper ocean enthalpy (in association with changing patterns of winds and clouds) in generating multi-decadal variability. This research, and these discussions, highlighted an unsatisfactory understanding of the role of ocean dynamics in mediating variability in the surface temperature records on timescales longer than a decade.

The Palaeo Record The palaeo-record offers appealing opportunities to look for constraints on ECS because the consideration of long timescales allows for the comparison of stationary states, and thereby the use of an equation of the form of Eq. (5), with $\Delta N = 0$, to estimate λ_{eff} and, by inference, $\lambda_{2\times}$. Attempts to infer the ECS from the palaeo record have focused on different epochs, ranging from the mid-holocene, to glacial interglacial periods, to the time period at the transition from the Palaeocene to Eocene (55 Myr ago) when Earth was much warmer than it is at present. A recent summary of the palaeo evidence supports a range of ECS between 2.2 and 4.8 K (68 % probability, Rohling et al., 2012). Recent, unpublished work linking the Palaeocene-Eocene Thermal Maximum (55 M yr ago) to the Early Eocene Climatic Optimum (50 M yr ago) showed how, by looking simultaneously at two related periods, one can say something about state-dependence of climate sensitivity; in particular, the data provides support for the idea that ECS increases with increasing temperature, although such effects may only become important at much warmer (295 K or more) global temperatures. Overall there was less consensus on the extent to which the palaeo record constrains the upper and lower bounds of ECS. Estimates of palaeoconstraints on the lower bound of ECS ranged from 2-2.5 K and estimates of the upper bound ranged from 4.5 - 6 K.

Discussions pointed out that it might not be appropriate to consider the Earth system in stationarity on any timescale, although the implications of departures from stationarity on estimates of ECS from the palaeo record are not clear, and did not seem to be the major limitations of such approaches. The issue of state dependence, which could also underlie differences in λ and $\lambda_{2\times}$, likely plays an even larger role in interpreting the palaeo record, as a cold planet with large ice-sheets may respond differently to forcing than a planet with small or no surface ice. Large differences in the state of the planet thus complicate efforts to relate estimates of $\lambda_{2\times}$ from the palaeo record to those appropriate for the present state of the planet. One idea to receive considerable discussion was the hypothesis that $\lambda_{2\times}$ is a decreasing function of temperature. But this remains controversial as there are clear reasons, ranging from less negative temperature feedbacks and more positive surface albedo feedbacks as to why one might expect exactly the opposite (i.e., a smaller $\lambda_{2\times}$) for colder climates.

Fingerprints of Earth's Climate Sensitivities Other studies explored the ability of constraining $\lambda_{2\times}$ by constraining its specific components. This work, which summarises a great many past studies, suggests that only accounting for robust and well understood feedbacks not associated with clouds yield a value of $\lambda_{2\times}$ of approximately $1.8\,\mathrm{W\,m^{-2}\,K^{-1}}$ implying an ECS of about 2 K. An increasing body of evidence suggests that clouds change with warming in a way that amplifies the warming (a positive feedback), but the magnitude of these changes are uncertain. Some of these feedbacks are well understood, for instance a positive long-wave feedback associated with the deepening troposphere with warming has been estimated to be about $0.4\,\mathrm{W\,m^{-2}\,K^{-1}}$ which would imply an ECS of about 2.6 K assuming all other cloud feedbacks were neutral. Mechanisms were presented whereby a reduction in high-cloud amount with warming, which would naively constitute a negative feedback, could be ineffective in increasing $\lambda_{2\times}$. Both modelling and observational evidence suggested that an increase in $\lambda_{2\times}$ associated with changes in terrestrial radiation from a reduction in high clouds is largely offset by a decrease in $\lambda_{2\times}$ due to compensating changes in the budget of solar radiation. These lines of investigation generally found it difficult to reconcile present day understanding of the individual feedback terms with an ECS substantially less than 2 K, or much greater than 4 to 5 K. That said, debate on the lower bound was lively, and a few individuals felt that a lower bound of 1.5 or 1.7 K cannot yet be ruled out by these lines of analysis, likewise an upper bound of 6 K or more.

Arguments for values of ECS larger than 3 K have a number of origins. A variety of investigations that have attempted to link a model's representation of the present climate state, or cloud-related climate processes, have concluded that models with an ECS less than about 2.5-3.0 K generally give a poorer representation of the present state, or of critical cloud processes. In addition the argument for a positive feedback from low maritime clouds has been bolstered by theoretical studies that outline robust mechanisms for such feedbacks. Many of these ideas are related to the vigour of convective mixing and its link to surface evaporation which will increase with warming via mechanisms that are well understood. At the same time it was pointed out that the links between radiative cooling in the atmosphere, the convective heating which balances it, and the clouds through which the convective heating is realised is poorly represented by models. As a result, there is the perception that modelled cloudiness may be more sensitive to the atmospheric mean state than clouds in nature. Support for this line of thinking was provided by global analyses of Earth's albedo, made possible by improved satellite measurements. Then again, other studies suggested that the representation of clouds within comprehensive models were insufficiently sensitive to changes in the climate state. In either case it was also pointed out that these ideas are reaching a state of refinement where they stand a chance of being tested using in situ measurements, for instance using aircraft and ground based remote sensing, opening new and exciting possibilities for constraining cloud feedbacks.

Because estimates of radiative forcing, and ocean enthalpy uptake are fundamental for interpretations of the historical temperature record it was pointed out that better use could be made of comprehensive modelling to constrain these estimates. For instance, new ideas have been recently developed to constrain aerosol forcing and suggest that forcings more negative than about $-1\,\mathrm{W\,m^{-2}}$ are implausible (Stevens, 2015). Working through these and related hypotheses for large or small forcings, or large or small ocean enthalpy uptake offers a chance for rapid progress on what seemed before to be intransigent questions. Similar approaches can be taken to understand variability, and increased computing power makes the use of large ensemble, or large number of single forcing runs more feasible, thereby better constraining estimates of the forcings actually applied to the models, which would greatly facilitate an interpretation of their output.

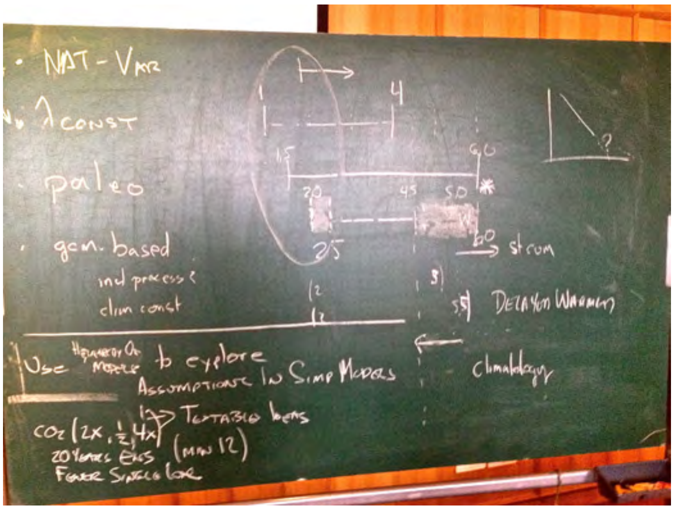

Figure 3: A snapshot of the board during a discussion of ways for reconciling different lines of evidence.

Combining multiple constraints One of the leitmotifs of the workshop was how to reconcile multiple constraints. It was pointed out that overlapping, but independent, estimates may provide an opportunity to narrow uncertainty. The implication being that estimates of ECS that are seemingly at odds with one another might actually provide a source of insight and tighter constraints on the likely value of ECS. Discussions of how to combine multiple constraints addressed formal issues that arise in statistical frameworks, trade-offs among different statistical approaches, as well as the impact of the choices being made as to what was being estimated. The value of combining analyses of perturbed parameter ensembles with multi-model ensembles was explored as a means of improving understanding and sharpening the inferences that can be drawn from models.

At the same time the workshop entertained very fruitful discussions (Fig. 3) as to how ECS could possibly be less than 2 K, or greater than 4 to 5 K. The weight of evidence for a positive water vapour feedback, and the robustness of non-cloud feedbacks generally meant that what participants considered to be extreme sensitivities could only be realised by clouds. This type of thinking was supported by the fact that deliberate attempts to alter a basic feedback process like the water vapour feedback, generally engendered compensating responses. For example, it is hard to dry out the atmosphere, thereby reducing the water vapour feedback, without reducing cloudiness, which in turn would increase the cloud feedback and offset any gains that would, in the absence of cloud changes, have otherwise been realised.

Ringberg15 in the public sphere

Ringberg15 was actively followed by the media, particularly social media. It featured prominently on twitter, under the hashtag Ringberg15, was discussed on many of the most active climate blogs and even mentioned in articles by major news outlets. Cognisant of the public interest in the subject, the organisation of the workshop also emphasised transparency. Photographs of board shots, publications, most presentations and other information were and continue to be made available on the conference website, which will also contain a link to this report. The conference website also maintains a running list of post AR5 publications that touch on central themes raised during Ringberg15.

Figure 4: A snapshot of the tracking statistics from the Ringberg15 hashtag. Ringberg15 featured prominently in the social media.

Recommendations

Discussions of the various themes also lead to a broader reflection on the assessment process. Specifically how should the science be shaped so as to reduce uncertainty, and how should the assessment process be structured so as to reap the most from existing research. Past experience has shown that a more thorough and critical review of the existing literature can be effective in both guiding future research, and resolving what might only appear to be contradictory findings. These types of meta-scientific discussions occupied much of the free time of workshop participants. From these discussions, as well as the more moderated plenary discussions in which half of the scheduled time was spent, the following recommendations emerged.

1. The climate sensitivity is not a quantity that can be measured, but must be inferred from models, constrained by observations and knowledge of the climate system. All models have potential flaws or oversimplifications that could alter the results. We therefore recommended focusing attention on the possible biases or shortcomings of the models employed in making estimates of climate sensitivity. This can include the use of perturbed parameter ensembles, which provide a useful testbed for relating feedbacks to model biases, and 'perfect model' experiments to explore the implications of simplifications, e.g., in how one defines the state of the system (see second recommendation). Because different models are adapted to different types of observational constraints, a focus on model biases and shortcoming should be adopted across the model hierarchy (e.g., Held, 2014), from fully interactive general circulation models at one end, to the simple one equation models, e.g. Eq. (4), at the other.

2. An opportune instance of the strategy outlined in the first recommendation would be to focus research on how various factors influence estimates of λ, or more practically λ_{eff}. To address this question, model calculations should be designed to better understand how λ depends on the nature or magnitude of the forcing (e.g., aerosols versus carbon-dioxide), detailed state of the climate system (such as represented by differences in ice-sheets, or

patterns of SST), and the role of internal variability and ocean enthalpy uptake in mediating the transient response of surface temperatures to forcing. Fuller participation by modelling groups in the idealised VolMIP experiments, and CFMIP offers opportunities to test these ideas, as does participation in PMIP and PDRMIP, both of which have suggested coordinated numerical experiments to help address these issues.

3. A poor characterisation of the forcing used in CMIP models has been a major weakness of all past phases of CMIP. For CMIP6, it is essential to have a diagnosis of forcing in each model's CMIP historical simulations. Mechanisms for diagnosing a models historical forcing are incorporated as part of RFMIP and these should be adopted by all models performing historical simulations in CMIP6. Modelling centres that can do so should also perform these diagnostic runs retroactively, for their CMIP5 and even CMIP3 models. Modelling centres are strongly encouraged to participate in RFMIP.

4. Because the response of general circulation models is susceptible to their representation of unresolved physical processes, focusing attention on how the representation of these processes influences estimates of ECS would be fruitful. There was a broad consensus for the need for increased attention being devoted to the representation of turbulence, convection and cloud processes, and their numerical implementation.

5. By focusing research on the construction and evaluation of physical hypotheses leading to a low ($< 2\,\mathrm{K}$) or high ($> 4\,\mathrm{K}$) ECS it should be possible to greatly improve estimates of Earth's Climate Sensitivities. Generally it is believed that to offset a positive feedback from rising high clouds and achieve an ECS $< 2\,\mathrm{K}$ it is necessary for the cloud feedback from other cloud changes to be modestly negative ($-0.4\,\mathrm{W\,m^{-2}\,K^{-1}}$), or for there to be a strong negative cloud adjustment to forcing. Likewise, the most plausible scenario for an ECS $> 4\,\mathrm{K}$ involves the desiccation of marine low-level clouds, either in response to warming or as an adjustment process. To the extent that a physically plausible model with a surprisingly high or low ECS can be constructed, an argument for its physical plausibility should be evaluated in reference to the observed record for different climate states, e.g., for instance through simulations of the last glacial maximum as well as the instrumental (1850-2015) record. Systematically exploring these high and low feedback hypotheses aligns well with the goals of both CFMIP and PMIP and these projects would benefit from modelling centres submitting models constructed to have very different climate sensitivities, but the best possible representation of the present climate.

6. Uncertainty in aerosol forcing hampers attempts to use the instrumental record to estimate the amount of warming attributable to greenhouse gases. For this reason, and because historical forcings are (in a relative sense) as uncertain as future forcings, more attention should be devoted to systematically evaluating different forcing scenarios for the historical period – for instance by developing and evaluating specific hypotheses as to how the historical aerosol forcing could be weaker (less negative) or stronger than presently thought. Here harmonising the capabilities of global aerosol models in terms of species included (e.g., nitrate and secondary organic aerosols) and radiative forcing mechanisms represented (notably deposition on snow and ice) would greatly improve their interpretation. It is expected that stronger constraints on aerosol forcing will emerge from the fuller use of available observational constraints beyond the aerosol optical depth, by considering measurements and retrievals of aerosol absorption, vertical profiles, and radiative fluxes (e.g., from CERES and GEBA/BSRN) to constrain different aerosol radiative forcing scenarios. More attention devoted to narrowing forcing estimates within activities such as AEROCOM and AerChemMIP is encouraged.

7. Because of pronounced variability and changes in aerosol forcing, the first-half of the twentieth century offers great potential for unravelling the relative role of forcing and internal variability. The use of the approaches being developed in DAMIP and RFMIP to explore these issues could provide stronger constraints on understanding aerosol forcing. Large ensembles of the historical period, also for individual forcings, would be beneficial for such studies. By systematically addressing the impact of internal variability such simulations would also aid the interpretation of observations of sea-level rise and ocean enthalpy uptake.

8. Above all the development of physical hypotheses for some of the key questions related to estimates of Earth's climate sensitivity should be done in a manner that is mindful of opportunities for observational tests that can be performed either on the basis of existing data, or through present and emerging measurement capabilities, including carefully designed field studies.

9. Given that Earth appears to have many climate sensitivities, a focused workshop involving climate scientists and economists with the goal of better understanding which climate sensitivities most influence economic projections and why, could be opportune. The WCRP or the *Grand Science Challenge on Clouds, Circulation and Climate Sensitivity* are encouraged to consider organizing such a workshop.

10. WCRP, through the *Grand Science Challenge on Clouds, Circulation and Climate Sensitivity* , should endorse and promote a community assessment of ECS. Discussions at the workshop demonstrated that such an assessment, if started now, can help spawn studies and syntheses that will greatly accelerate progress in understanding Earth's Climate Sensitivities.

In the course of preparing this report these recommendations were circulated among all the participants to ensure that they accurately reflected the workshop discussions and the sense of the participants. In this sense they are recommendations of the workshop itself.

Implementation within WCRP

To implement these recommendations, it would be helpful if the WCRP would:

- Highlight and circulate these recommendations within their core projects and working groups. For instance recommendations regarding modelling could be communicated to the modelling groups through WCRP, the *Grand Science Challenge on Clouds, Circulation and Climate Sensitivity*, or the WGCM which is responsible for CMIP. The role of ocean state in modulating ECS or TCR would be an important focus for the forthcoming CliVAR Open Science Conference.

- Initiate and support an assessment process led by the *Grand Science Challenge on Clouds, Circulation and Climate Sensitivity* on the topic of Earth's Climate Sensitivities, culminating in a report that will be published in 2019, forty years after the Charney Report.

- Communicate to funders the importance and opportunity of coordinated efforts to enhance understanding of Earth's climate sensitivities.

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References

Allen, M. R., and D. J. Frame, 2007: Call off the quest. *Science*, **318 (5850)**, 582–583.

Bony, S., and Coauthors, 2006: How Well Do We Understand and Evaluate Climate Change Feedback Processes? *J. Climate*, **19 (15)**, 3445–3482.

Bony, S., and Coauthors, 2013: Carbon Dioxide and Climate: Perspectives on a Scientific Assessment. *Climate Science for Serving Society*, J. W. Hurrell, and G. Asrar, Eds., Springer Netherlands, Dordrecht, 391–413.

Bony, S., and Coauthors, 2015: Clouds, circulation and climate sensitivity. *Nature Geoscience*, **8 (4)**, 261–268.

Charney, J. G., and Coauthors, 1979: Carbon Dioxide and Climate: A Scientific Assessment. Tech. rep., National Academy of Sciences, Washington DC.

Geoffroy, O., D. Saint-Martin, G. Bellon, A. Voldoire, D. J. L. Olivié, and S. Tyteca, 2013: Transient Climate Response in a Two-Layer Energy-Balance Model. Part II: Representation of the Efficacy of Deep-Ocean Heat Uptake and Validation for CMIP5 AOGCMs. *J. Climate*, **26 (6)**, 1859–1876.

Gregory, J. M., 2004: A new method for diagnosing radiative forcing and climate sensitivity. *Geophys. Res. Lett.*, **31 (3)**, L03 205–4.

Gregory, J. M., and P. M. Forster, 2008: Transient climate response estimated from radiative forcing and observed temperature change. *Journal of Geophysical Research: Atmospheres*, **113 (D23)**.

Held, I., 2014: Simplicity amid Complexity. *Science*, **343 (6176)**, 1206–1207.

Knutti, R., and G. C. Hegerl, 2008: The equilibrium sensitivity of the Earth's temperature to radiation changes. *Nature Geoscience*, **1 (11)**, 735–743.

Rohling, E. J., and Coauthors, 2012: Making sense of palaeoclimate sensitivity. *Nature*, **491 (7426)**, 683–691.

Sherwood, S. C., S. Bony, O. Boucher, C. Bretherton, P. M. Forster, J. M. Gregory, and B. Stevens, 2015: Adjustments in the Forcing-Feedback Framework for Understanding Climate Change. *Bulletin of the American Meteorological Society*, **96 (2)**, 217–228.

Stevens, B., 2015: Rethinking the lower bound on aerosol radiative forcing. *J. Climate*, 150319112745003.

Stevens, B., and S. E. Schwartz, 2012: Observing and Modeling Earth's Energy Flows. *Surv Geophys*, **33 (3-4)**, 779–816.

Winton, M., K. Takahashi, and I. M. Held, 2010: Importance of Ocean Heat Uptake Efficacy to Transient Climate Change. *J. Climate*, **23 (9)**, 2333–2344.

Appendix A: Organisational Acronyms

Table 1: Brief overview of the acronyms mentioned in the implementation plan. Most projects live within the WCRP organisational structure, the exceptions being THORPEX and its daughter programme T-NAWDEX, both of which are organised by the WWRP.

Acronym	Brief Description
AEROCOM	Aerosol comparison between observations and models
AR5	Fifth Assessment Report of the IPCC
AerChemMIP	Aerosol and Chemistry Model Intercomparison Project
BSRN	Baseline Surface Radiation Network
CERES	Clouds and Earth's Radiant Energy System
CFMIP	Cloud-feedback model intercomparison project
CMIP	Coupled Model Intercomparison Project
DAMIP	Detection and Attribution Model Intercomparison Project
ECS	Equilibrium Climate Sensitivity
GCM	General Circulation Model
GEBA	Global Energy Balance Archive
IPCC	Intergovernmental Panel on Climate Change
PMIP	Palaeoclimate Modelling Intercomparison Project
PDRMIP	Precipitation Driver Response Model Intercomparison Project
RFMIP	Radiative Forcing Model Intercomparison Project
SST	Sea Surface Temperature
TCR	Transient Climate Response
VolMIP	Model Intercomparison Project on the climatic response to volcanoes
WGNE	Working Group on Numerical Experimentation (joint WCRP-CAS)
WGCM	WCRP Working Group on Coupled Modelling
WCRP	World Climate Research Programme
WWRP	World Weather Research Programme

Appendix B: Workshop Organisation

Table 2: Scientific participants and presentation titles.

Name	Institution	Title
Allen, Myles	Oxford Univ.	Do we actually need better probability distribution functions for equilibrium and transient climate response?
Andrews, Tim	Met Office	Feedbacks and SST patterns (presented by Mark Webb)
Annan, James	Blueskies Res.	How to synthesise multiple constraints.
Armour, Kyle	MIT	Robust increase in effective climate sensitivity with transient warming.
Bellouin, Nicolas	U. Reading	Fast Adjustments
Bengtsson, Lennart	Unaffiliated	A more robust method for climate sensitivity studies
Bony, Sandrine	LMD	Do models over-estimate cloud feedbacks?
Caballero, Rodrigo	MISU	What do we learn about climate sensitivity from deep-time warm climates?
Church, John	CSIRO	Estimates of Ocean warming since 2006.
Crucifix, Michel	Univ Louvain	(Palaeo-)Climate sensitivity: definitions and ideas from the NPG literature
Dessler, Andres	Texas A&M	What can we learn about ECS from short-term inter-annual variations.
Edwards, Tamsin	Milton Keynes	Whatever happened to PalaeoQUMP?
Fasullo, John	NCAR	Understanding Sea Level as a Constraint on Climate Variability and Sensitivity
Forster, Piers	U. Leeds	Climate sensitivity and aerosol forcing diagnosed from near past and near term future surface temperature and energy budget changes
Geoffroy, Olivier	UNSW	Tropical fingerprints of low and high sensitivities in CMIP5 models
Golaz, Chris	NOAA, GFDL	Tuning the indirect effect, engineering the climate sensitivity: what should modellers do with these newly found powers?
Gregory, Jonathan	U. Reading	Non-stationary relationship between tropical TOA fluxes and surface temperatures in a model.
Hargreaves, Julia	Blueskies Res.	The LGM and Climate Sensitivity (presented by James Annan, with Contributions from Ayako Abe-Ouchi)
Hegerl, Gabi	U. Edinburgh	What observed and reconstructed climate change can and can't tell about equilibrium and transient climate sensitivity.
Latif, Mojib	GEOMAR	The Challenge of Climate Model Verification
Lewis, Nic	Unaffiliated	Pitfalls in climate sensitivity estimation.
Knutti, Reto	ETH, Zřich	Limitations of forcing feedback frameworks
Mauritsen, Thorsten	MPI	What if Earth had and adaptive iris?
Schmidt, Gavin	NASA/GISS	Use of GCMs in constraining sensitivity
Sexton, David	UKMO	The key principles in dealing with multiple observational constraints and imperfect models, and their implications for constraining equilibrium climate sensitivity.
Sherwood, Steven	UNSW	Trends in tropical troposphere temperatures, winds, and a possible forcing on recent climate.
Stephens, Graeme	NASA, JPL	Prospects for observational constraints on climate sensitivity.
Stevens, Bjorn	MPI	Some (not yet entirely convincing) reasons why $2.0 < \mathrm{ECS} < 3.5$
Sutton, Rowan	NERC	TCR and near-term climate change.
Vial, Jessica	LMD	On the role of convection and circulation in cloud feedbacks.
Webb, Mark	UKMO	Investigation of the mechanisms underlying differing cloud feedbacks in climate models.
Yu, Kosaka	U. Tokyo	Earth's energy budget in the presence of internal climate variability
Zelinka, Mark	DOE, PCMDI	Don't count on it: Reasons to doubt a strong negative cloud feedback.