Challenges in Constraining Climate Sensitivity: Should IPCC AR5’s Lower Bound Be Revised Upward?

Guest blog John Fasullo

I would like to start by thanking the conveners of Climate Dialogue for their invitation to participate in this forum for discussing Earth’s climate sensitivity and the challenges involved in its estimation. The invitation provides a valuable opportunity to exchange perspectives on what I view as a critically important issue.

As outlined in the editors’ introduction, considerable challenges remain. Exchanges that highlight these, while also promoting potential solutions for dealing with them, are likely to be central to achieving a better understanding of climate. To provide context for my commentary I have taken the liberty of addressing the basis for the decision made in IPCC AR5 to reduce the lower bound of the estimated range of equilibrium climate sensitivity, asking whether the decision was justified at the time of the report and whether the reduction remains warranted given our improved understanding of climate variability since then. ***In short, I argue that although IPCC’s conservative and inclusive nature may have justified such a reduction at the time of their report, the evidence accumulated in recent years argues increasingly against such a change.***

The Challenge

As outlined in the introduction there are multiple approaches for estimating Earth’s equilibrium climate sensitivity (ECS) and transient climate response (TCR). All attempts to quantify climate feedbacks, changes in the climate system that either enhance (positive feedbacks) or diminish (negative feedbacks) the change in the amount of energy entering the climate system (the planetary imbalance) as a result of some imposed forcing (e.g. increased atmospheric concentrations of carbon dioxide).

To varying extents, the approaches all face common challenges, including uncertainty in observations and the need to disentangle the response of the system to carbon dioxide from the convoluting influences of internal variability and responses to other forcing, such as due to changes in aerosols, solar intensity, and the concentration of other trace gases. It is known that sensitivity estimates derived from both the instrumental and paleo records entail considerable uncertainty arising from such effects (1, 2).

For some approaches, uncertainty in observations is also a primary impediment. Efforts to estimate climate sensitivity from paleoclimate records are a good example. While benefiting from the large climate signals that can occur over millennia, these approaches face the additional challenge of a proxy record that contains major uncertainty (2). Nevertheless, the paleo record provides a vital perspective for evaluating the slowest climate feedbacks.

General circulation models (GCMs) offer a uniquely physical approach for estimating ECS and TCR and readily allow for controlled experimentation, yet their representations of key processes is often lacking (also for example the interaction of aerosols with clouds) and some processes, particularly those acting on low frequency timescales or for which observations are generally unavailable, contain additional uncertainty.

Climatological constraint approaches attempt to relate the spread in these uncertainties across GCMs for some simulated field to a key physical feedback or basic model sensitivity. This approach has led to the developing subject of ‘emergent constraints’ (3,4). Challenges for the approach include the difficulty of establishing statistical confidence in identified relationships, due to a lack of independence across GCMs, and the need to firmly establish a physical basis for why a climatological constraint should act as an indicator of future change. The degree of these challenges may relate to how strongly a given field is tied to surface temperature, as useful insight has been gained for some fields (e.g. snow cover and water vapor, 3,5) but not others (clouds, 6).

The relevance of perturbation studies to climate change are limited by the degree to which they can serve as analogues to climate change, the certainty with which their forcing can be known, and the potentially complex and poorly understood interactions between that forcing and nature (e.g. clouds). So-called combined approaches incorporate two or more of the above methods in an attempt to leverage the strengths of each, but in doing so are also susceptible to their weaknesses. Broadening the discussion to address TCR increases the range of relevant processes to include those governing the rate of heat uptake by various reservoirs, particularly the ocean.

To some extent, the distinctions between ECS estimation methods are artificial. All GCMs have used the instrumental record to select model parameter values that produce plausible climates, and similarly all observational constraints require some implicit ‘model’ of the climate, even if this is simply an energy balance approach. It is my perspective that ultimately further progress in estimating both ECS and TCR can best be made by a combined consideration of the individual approaches and the adoption of a physically-based perspective rooted in narrowing uncertainty in the individual feedbacks that govern sensitivity across a broad range of timescales.

The need for physical understanding

Irrespective of their complexity, all approaches are faced with the challenges of attribution and uncertainty estimation, for which the validity of observations, underlying model, and base assumptions are key issues. It therefore is inappropriate to place high confidence in any single approach. Given this, and the fact that they do not each lead to the same estimated range of sensitivity, undermines efforts to provide a single best-estimate.

A complicating factor is that definitions of ECS can vary somewhat within the context of each approach, with estimates of ECS being based on a rather limited set of feedbacks as traditionally defined in slab-ocean GCM experiments (so-called fast-physics feedbacks including those in clouds, water vapor, and temperature), an additional level of complexity in the context of fully coupled GCMs and the instrumental record (including changes in the upper ocean, cryosphere, and vegetation), and the influence of very low frequency processes on paleoclimate timescales (involving ice sheets, deep ocean). A focus on specific feedbacks, rather than on ranges for sensitivity, promotes an apples-to-apples comparison across these perspectives.

A challenge to the feedbacks-centric approach however is that existing multi-model GCM archives contain output that only allows for limited exploration of feedbacks on a process level. Computation of key diagnostics (e.g. atmospheric moisture and energy budgets) is not possible given the limited availability of the high frequency data required, and many aspects of model physics remain undocumented. There is also a need to include experiments that isolate individual feedbacks. It is anticipated that with additional improvements in these archives and strategic experimental designs, many of these issues will be addressed in coming years (7).

Simple models: when are they simplistic?

Simple models rooted in statistics can be powerful tools for interpreting complex systems, a potential that relates to understanding both GCMs and the instrumental record. Ideally, if the appropriate statistical “priors” can be found for the free parameters in the models and if the underlying model is adequate, there is the potential for significant insight. In practice however, the approaches can be severely limited by the assumptions on which they’re based, the absence of a unique “correct” prior, and the sensitivity of their methods to uncertainties in observations and forcing (8, 9).

Simple models are also problematic in that they are of limited use for hypothesis developing and testing. They do not resolve individual feedbacks and thus how to incorporate them in the approach for future progress mentioned above remains unclear. This is not to say however that they offer no potential for hypothesis building. In fact, one hypothesis that has been suggested based on simple models is that the climate record of the past 15 years or so argues for a reduction in the lower bound of our estimated range of ECS, due to the reduced rate at which the surface has warmed and the negative feedbacks it might be viewed as suggesting. Indeed, this hypothesis was found to be sufficiently compelling that IPCC AR5 lowered its lower bound estimate on the likely range for ECS (10). But in retrospect, was this change warranted?

The “Hiatus”: Evidence For Lower Sensitivity?

In the past decade or so there has been a slowdown in the rate of global surface warming. This so-called “hiatus” has been manifested with both seasonal and spatial structure, with greatest surface cooling occurring in the tropical eastern Pacific Ocean in boreal winter and little cooling apparent over land or at high latitudes (9). The apparent slowdown of global surface warming has led some to conclude that evidence for lower climate sensitivity is “piling up” (11). Some have even argued that global warming has stopped.

It is true that, under the assumption of all things being equal, simple models have provided a consistent message regarding the need to lower the likely estimated ranges of sensitivity in order to achieve a best fit to the observational record (12,13). However, per the discussion above, a more physical approach is also essential in order to test this hypothesis and evaluate whether or not the circumstances surrounding the hiatus are indeed suggestive of “all things being equal”. In essence, the physical assumptions underlying this interpretation merit further scrutiny.

If the argument is to be made that recent variability warrants lowering ECS estimates, then clearly a central tenet of that argument is that the planetary imbalance has been mitigated by feedbacks. To reasonably assert that global warming has stopped, the planetary imbalance should be shown to be zero. Such assertions are readily testable across a broad range of independent climate observations and, in fact, a growing body of work has aimed to do just this.

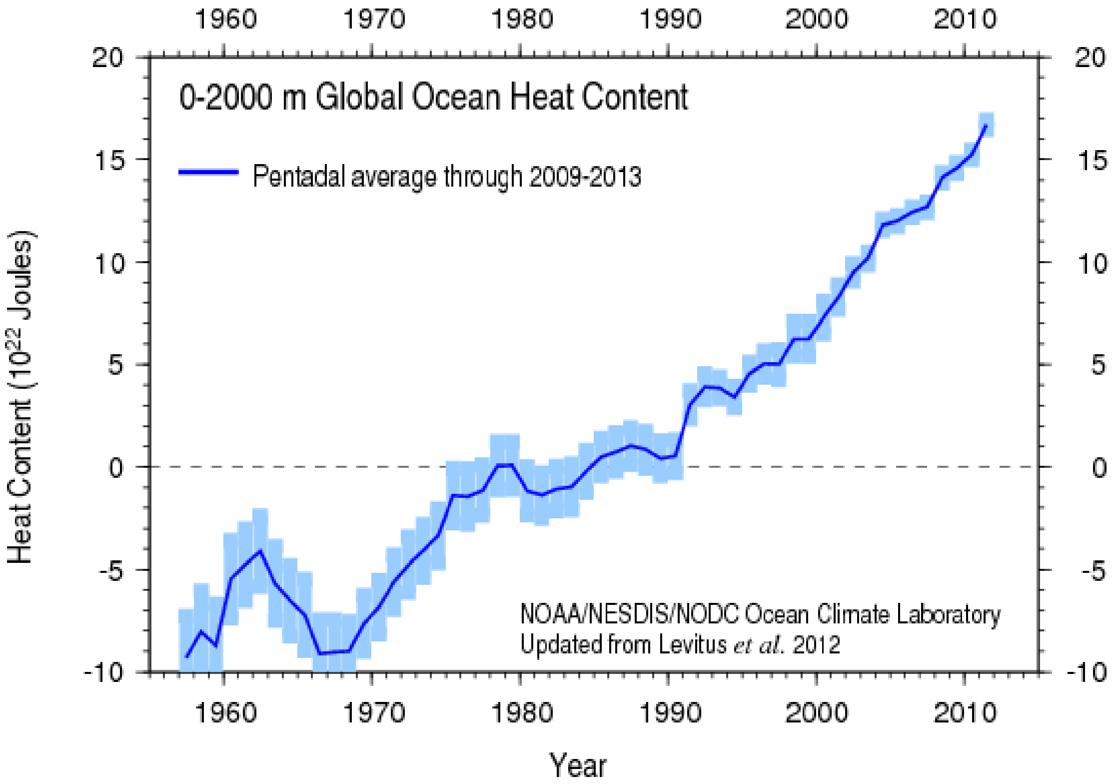

Figure 1: Global ocean heat content from the surface through a) 700 m and b) 2000m with error estimates (bars) based on data from the World Ocean Database (14).

The picture emerging from this work is that surface temperature during the hiatus has not been driven primarily by a reduction in the planetary imbalance due to negative feedbacks but rather by the vertical redistribution of where in the ocean the imbalance is stored. Specifically, the increase in storage in deeper ocean layers has led to a relative reduction in the rate of warming of the upper ocean.

When this vertical structure is averaged out, for example by considering the total ocean heat content (OHC) from the surface to 2000 meter (Figure 1) the data show remarkable constancy in the rate of warming from the 1990s through 2000s. They also show a dramatic shift in how that warming has occurred as a function of ocean depth between decades, with the uppermost layers warming little in recent years in conjunction with rapid warming at depth.

The general lack of strong decadal shifts in total OHC have recently been corroborated by estimates of global thermometric sea level rise from satellite altimetry, which show remarkable persistence in the rate of thermometric expansion since 1993 (15). Further, efforts to deduce variability in the planetary imbalance from the satellite record of top of atmosphere radiative fluxes also find little change between the 1990s and 2000s (Richard Allan, personal communication).

The consistent picture that emerges from these various lines of evidence is that any assumption of “all things being equal” with respect to internal variability during the hiatus is invalid and little evidence exists for a role played by reductions in the planetary imbalance due to climate feedbacks. In the context of this exceptionally persistent planetary imbalance, studies suggesting a role for reductions in net forcing as driving the hiatus (16) only heighten the challenge for hypotheses that the hiatus is evidence for a strong negative feedback.

Is such behavior surprising? Not really. As early as 2011, colleagues and I demonstrated that the NCAR CCSM4 reproduced periods analogous to the current hiatus, with hiatus periods accompanying changes in the vertical redistribution of heat driven by winds at low latitudes (17). Subsequent work has shown that similar behavior is evident across a wide range of GCMs. Recent observations have only reinforced the likelihood that the current hiatus is consistent with such simulated periods. The main question that persists relates mainly to the broader context for the hiatus, given the uncertainties surrounding internal variability, and just how unusual such an event may be.

Nature as an ensemble member, not an ensemble mean

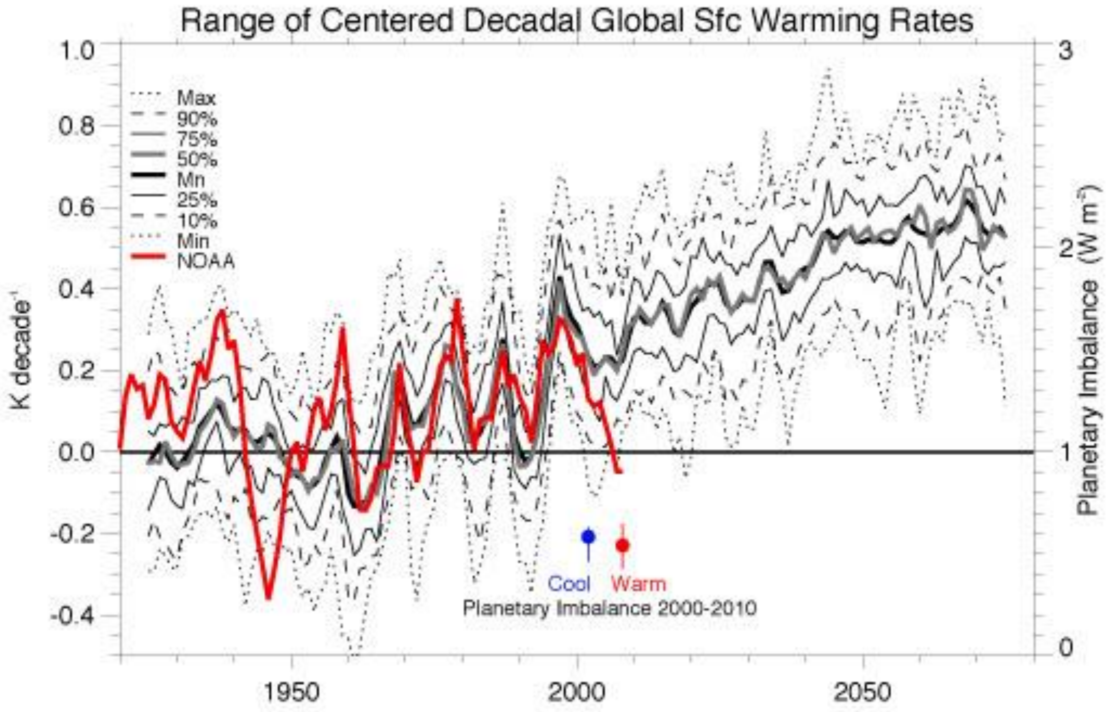

Figure 2: The range of decadal trends in global mean surface temperature from the CESM1-CAM5 Large Ensemble Community Project (LE, black and grey lines, 18) along with an observed estimate based on the NOAA-NCDC Merged Land and Ocean Surface Temperature dataset. Also shown are the mean (circle) and range (lines) of simulated planetary imbalance (right axis) from 2000 through 2010 for the 10 members of the LE with greatest cooling (blue) and warming (red)

The NCAR CESM1-CAM5 Large Ensemble (LE) Community Project provides a unique framework for understanding the role of internal variability in obscuring forced changes. It currently consists of 28 ensemble members in simulations of the historical record (1920-2005) and future projections (2006-2080) based on RCP8.5 forcing.

At 4.1°C, the ECS of the CESM1-CAM5 is higher than for most GCMs. Nonetheless, decadal trends from the model track quite closely with those derived from NOAA-NCDC observations (red line), with the model mean decadal trend (thick black line) skirting above and below observed trends about evenly since 1920. In several instances, decadal trends in observations have been at or beyond the LE range including intervals of exceptional observed warming (1945, 1960, 1980) and cooling (1948, 2009). The extent to which these frequent departures from the LE reflect errors in observations, insufficient ensemble size, or biases in model internal variability remains unknown. Nonetheless, there is no clear evidence of the model sensitivity being systematically biased high. Also noteworthy is the fact that the LE suggests that due to forcing, as indicated by the ensemble mean, certain decades including the 2000s are predisposed to a reduced rate of surface warming.

The LE also allows for the evaluation of subsets of ensemble members, such as in Fig 2, where the planetary imbalances for the ten ensemble members with the greatest global surface warming (red) and cooling (blue) trends from 2000-2010 are compared. It is found that no significant difference exists between the two distributions and the mean imbalance for the cooling members is actually greater than for the warming members. Thus the finding of a relatively unchanged planetary imbalance during the recent hiatus period is entirely consistent with analogous periods in LE simulations. While the LE does suggest that recent trends have been exceptional, this is also suggested by the instrumental record itself, which includes exceptional El Niño (1997-98) and La Niña events (2010-2012) at the bounds of the recent hiatus.

A Path Forward

In my view, a combined effort that makes use of various approaches for constraining sensitivity, with an emphasis on evaluating individual climate feedbacks with targeted observations, provides a viable path forward for reducing uncertainty. Process studies focusing on feedback related fields are also essential and recent efforts have shown consistently that low sensitivity models generally perform poorly and therefore should be viewed as less credible (4, 19, 20). Testing models with paleoclimate archives, where uncertainties in proxy data and forcings are adequately small, is also likely to be essential.

Often lost in the conversation of estimating climate sensitivity is the need for well-understood, well-calibrated, global-scale observations of the energy and water cycles and related analysis systems such as reanalyses to provide a global holistic perspective on climate variability and change. As the hiatus illustrates, such observations can be an invaluable tool for hypothesis testing. Lastly, there is a need to move beyond global mean surface temperature as the main metric for quantifying climate change (21). Improved estimates of ocean heat content have been made possible though data from ARGO drift buoys and improved ocean reanalysis methods. Similar advances are being made across a range of climate indices (e.g. sea level, terrestrial storage) and are likely to be fundamental in providing improved metrics of climate variability and change, evaluating models, and narrowing remaining uncertainties.

Biosketch

Dr. John Fasullo is a project scientist at the National Center for Atmospheric Research in Boulder, CO. He received his B.Sc. degree in Engineering and Applied Physics from Cornell University (1990) and his M.S. (1995) and Ph.D. (1997) degrees from the University of Colorado. Dr. Fasullo studies processes involved in climate variability and change using both observations and models with a focus on the global energy and water cycles. He has published over 50 peer-reviewed papers dealing with aspects of this work, aimed primarily at understanding variability in clouds, the tropical monsoons, and the global water and energy cycles. His work has centered on identifying strengths and weakness across observations and models, and has emphasized the benefits of holistic evaluation of the climate system with multiple datasets, theoretical constraints, and novel techniques. Dr. Fasullo is a member of various committees and science teams, and participated in the IPCC AR4 report that contributed to the award of the Nobel Peace Prize to IPCC in 2007.

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