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Sources of knowledge and ignorance in climate research

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Abstract Ignorance is an inevitable component of climate change research, and yet it has not been specifically catered for in standard uncertainty guidance documents for climate assessments. Reports of ignorance in understanding require context to explain how such ignorance does and does not affect understanding more generally. The focus of this article is on dynamical sources of ignorance in regional climate change projections. A key source of ignorance in the projections is the resolution-limited treatment of dynamical instabilities in the ocean component of coupled climate models. A consequence of this limitation is that it is very difficult to quantify uncertainty in regional projections of climate variables that depend critically upon the details of the atmospheric flow. The standard methods for quantifying or reducing uncertainty in regional projections are predicated on the models capturing and representing the key dynamical instabilities, which is doubtful for present coupled models. This limitation does not apply to all regional projections, nor does it apply to the fundamental findings of greenhouse climate change. Much of what is known is not highly flow-dependent and follows from well grounded radiative physics and thermodynamic principles. The growing field of applications of regional climate projections would benefit from a more critical appraisal of ignorance in these projections.

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1 Introduction

In the study of any complex system such as the climate system it is inevitable that there will always be pockets of knowledge and ignorance (Bolin 1994). By ‘ignorance’ here we mean simply lack or want of knowledge. In a series of guidance notes (Moss and Schneider 2000; IPCC 2006; Mastrandrea et al. 2010) the Intergovernmental Panel on Climate Change (IPCC) has made significant progress in providing a framework in which to characterize the level of certainty and uncertainty in results from climate research. The most problematic and least well embraced aspect of that framework is the reporting of ignorance. The climate research community has not been systematic in circumscribing active areas of ignorance and formalizing its description.

Note that the admission of ignorance is different from admitting uncertainty more generally. There has been a relatively frank reporting of climate uncertainties in the literature and IPCC reports. The IPCC guidance documents on uncertainty are a testament to the more general embrace of uncertainty (van der Sluijs 2005). However, these documents and the reporting of uncertainties in the literature have generally shied away from the border with ignorance (Funtowicz and Ravetz 1990).

One reflection of the avoidance of ignorance is the categorization of the level of certainty of changes in climate variables in the IPCC uncertainty guidance. In the IPCC guidance documents (IPCC 2006; Mastrandrea et al. 2010) the degree of precision or knowledge of changes in climate variables can be expressed on a scale from “ambiguous” at the low certainty end through to quantification via a probability distribution at the high certainty end of the scale. There is no scope in the IPCC scale for professing less certainty than ‘ambiguity’. In the original schemes that the IPCC scale was based on [Risbey et al. (2002), Kandlikar et al. (2005), Risbey and Kandlikar (2007)] there is an additional category to represent “ignorance” (Risbey et al. 2002) or “effective ignorance” (Risbey and Kandlikar 2007) at the low end of the certainty scale.

One could argue that there is no great need for a category of ‘ignorance’ in summarizing and categorizing findings in the IPCC. If the goal is to summarize what we know, then by definition there is no need for a category that connotes that we don’t know. We just wouldn’t report such things in a summary. However, the IPCC is also there to address relevant questions of the science for policy, and has a mandate to assess potential environmental and socio-economic impacts. This requirement poses hard questions, as for example the task of describing climate changes in specific regions for long term regional planning. Sometimes the best answer to some of the questions of the science asked by policy may be “we don’t know”, and that is why we have need for a category of ignorance. It would be nice just to dispense science advice where we know all the answers, but that would mean ignoring some of the most critical questions.

This work provides an exploration of the role of ignorance through a focus on regional climate change projections. Regional projections of climate change require descriptions of the spatial field of climate variables such as temperature, wind, and rainfall at some specified point in the future (Giorgi et al. 2001). The main tool for providing detail about spatial fields is three dimensional (3d) general circulation coupled atmosphere-ocean climate models (CGCMs) (Meehl et al. 2007). In general, the reliability of regional projections depends on the reliability of CGCMs. If

CGCMs are unreliable at regional scales that does have consequences for regional projections. However, it would not follow that greenhouse climate change as a theory were compromised if CGCMs were unreliable, as some have asserted (Paltridge 2009). For that to be true, then CGCMs would have to be compromised in deriving fundamental properties of greenhouse climate change and would have to be the main source of knowledge and understanding of these properties. We show here that neither of these conditions is true.

Before describing the way in which CGCMs contribute to ignorance in regional projections, we outline their role in understanding greenhouse climate change more generally. This is necessary to provide context in viewing model errors. When admitting areas of ignorance one should try to be clear which areas of research are affected and which ones aren't. Because there is popular confusion about the role of CGCMs it is worth trying to clarify this issue. This paper is divided as follows. Section 2 briefly reviews sources of knowledge for greenhouse climate change and seeks to describe the role of CGCMs in the generation of this knowledge. Section 3 describes (from a purely dynamical perspective[1]) why CGCMs are (currently) a source of ignorance in the generation of regional climate change projections. Section 4 outlines why some common methods to improve regional projections are not sufficient to overcome the dynamical limitations of CGCMs. Section 5 discusses some of the consequences of CGCM limitations and Section 6 provides some guidance on incorporating ignorance into uncertainty assessments.

2 Sources of greenhouse knowledge

A comprehensive analysis of sources of knowledge of greenhouse climate change is beyond the scope of this work. Rather, we select only a few key quantities from the vast body of greenhouse research (Houghton et al. 1990, 1996, 2001; Solomon et al. 2007) and provide only brief arguments on each. The point here is to outline a general argument about the relative role of different sources of knowledge, but not to settle that argument. We are seeking to provide context on the role of CGCMs, not the last word. We discuss the climate sensitivity, temperature response, and the global hydrological response. For each of these features we are interested in asking: How do we understand the concept, how do we quantify it, and what are the main sources of understanding and support.

In each case we attempt to describe only those processes that are of prime importance. We try to say what the climate sensitivity, gross temperature pattern, and global hydrological response depend on to first order. The argument is that the first order controls on these fundamental features are determined by more straightforward physics, which are well understood independently of GCMs, as

[1]The term 'dynamics' is used here to refer to model instabilities and flow simulated from the model primitive equations as distinct from 'physics' represented by radiation, convection, and other model processes.

well as represented in GCMs. Of course these features are sensitive to dynamical processes and parameterizations too; just not to first order.

2.1 Climate sensitivity

The most fundamental parameter of greenhouse climate change is the climate sensitivity; usually expressed for a doubling of CO_2. The size of the global mean temperature response to a change in radiative forcing provides the main expectation for the magnitude of the greenhouse problem. Climate sensitivity is broadly understood via radiative theory and thermodynamic principles (Hansen and Takahashi 1984; Dickinson 1985).

The quantification of climate sensitivity can not be done from first principles. That is to say that we can't explicitly model every process and feedback in the climate system to calculate a net sensitivity. GCMs do only a shorthand version of the climate sensitivity calculation. They omit some processes and parameterize some of the major ones (such as moist convection and cloud processes). The climate sensitivity obtained from GCMs is dependent on the parameterizations, which can be tuned to produce a range of different sensitivities (Lal and Ramanathan 1984; Cunnington and Mitchell 1990; Senior and Mitchell 1993; van der Sluijs 1997; van der Sluijs et al. 1998). As such, GCMs can play only a supporting role in quantifying climate sensitivity. The main role is played by empirical studies of the response of the climate system to forcing over a range of different time scales. This includes an assessment of changes between glacial and interglacial periods (Lorius et al. 1990; Hansen et al. 2008), the response over the past century, and the response to volcanic perturbations (Hegerl et al. 2006).

The various empirical estimates of climate sensitivity are supported by work in simpler models (Wang et al. 1976; Ramanathan and Coakley 1978) and GCMs in isolating the key physics and feedbacks. However, if one could only know climate sensitivity empirically or from GCMs, many/most of us would choose the empirical estimates. They are based on imperfect analogues, but because it is the real system, they do contain the relevant physics and feedbacks in all their complexity. If we only had GCMs (and no empirical estimates) we would always be worrying that our cloud and water schemes weren't good enough to trust the particular model sensitivity. Estimates of climate sensitivity are reasonably robust because they are based on independent information from a variety of sources. GCMs are useful, but not critical, to the overall assessment of climate sensitivity.

2.2 Pattern of temperature change

The four dimensional (3d in space, plus time) pattern of temperature change is another fundamental measure of greenhouse climate change. The pattern of change is used to help differentiate a response to greenhouse and solar forcing for example and has provided the foundation of detection and attribution studies (Mitchell et al. 2001). GCMs are used extensively in detection and attribution studies to set the pattern and magnitude of forcing response. In most cases though, the models are representing relatively straightforward physics for this purpose.

The coarse spatial pattern of the temperature response is set largely by the land/ocean contrast and distribution and relies to first order on getting the heat capacities of these media right. The models of course do this well. The latitudinal temperature response features polar amplification (at least in the northern hemisphere; the southern hemisphere is complicated by ocean circulation and the vast ice sheet), which is largely set by ice-albedo physics and the gravitational stability of the lower atmosphere (Held 1993). These processes are reasonably well simulated in simpler models and GCMs. The vertical pattern of greenhouse temperature response features warming in the lower troposphere and cooling aloft. This response is set by the distribution of radiatively-active gases and understood from radiative physics and chemistry (Ramanathan et al. 1987; Pierrehumbert 2011). These processes can be simulated with fidelity in 1d vertical models (Manabe and Wetherald 1967; Wang et al. 1976; Ramanathan and Coakley 1978) and GCMs, with much of the basic understanding derived from the former simpler models.

GCMs would not be needed to obtain a qualitative understanding of the pattern of temperature change. Most of the elements of that pattern were available from radiative theory and simpler models. GCMs are required to provide estimates of the magnitudes of these patterns, but where they do so, they are relying on reasonably well understood physics within the models. The main features of the spatial pattern of surface temperature change, the latitudinal pattern of change, and the vertical pattern of change depend on radiative physics and chemistry of trace gases and other relatively well simulated physics. This is not to say that other physical processes (which may not be well simulated) are not relevant to the temperature pattern responses, but they are not the dominant processes in a first order assessment.

2.3 Global hydrological cycle

Greenhouse warming produces increases in lower tropospheric water vapour, global precipitation, and horizontal moisture transports, and enhances the pattern of evaporaton minus precipitation (Held and Soden 2006; Schneider et al. 2010; Seager et al. 2010). These results have all been documented in GCMs and follow early GCM work on midlatitude continental drying (Manabe et al. 1981) and enhancement of the wet and dry extremes of the hydrological cycle (Hansen et al. 1989; Seager et al. 2010). As noted by Held and Soden (2006), these results are "robust reponses of the hydrological cycle to global warming". These results are considered robust only in part because they occur across different GCMs. They are consistent across GCMs because they are features of the hydrological cycle that follow from the physics and thermodynamics of moisture as represented in fundamental relationships such as Clausius-Clapeyron (Held and Soden 2006).

Some of the gross features of the hydrological response have been deduced from GCMs, but they are considered to be robust because these features can be traced back to more fundamental thermodynamical relationships. As we consider more detailed circulation responses we start to lose the ability to trace changes back to fundamental relationships. When changes must be referenced to a specific place (as in regional projections) the dynamics of atmosphere and oceans come more strongly into play. The details of any mutual readjustments of these fluids (shifts in jet streams or storm tracks for example) does matter from the perspective of a particular location. That requires simulation of the 3d circulation, as is the province of CGCMs.

2.4 Summary

In this brief review of sources of understanding of greenhouse climate knowledge we have considered the climate sensitivity, the gross pattern of temperature response, and the global hydrological cycle. These are all fundamental features of greenhouse climate change and are generally held to be fairly robust. Understanding of these features is gained from observations of the climate system (present and past), radiative theory and chemistry of trace gases, thermodynamic principles, 1d and 2d models, and GCMs. GCMs play a supporting role in understanding these features, but not more than that.

3 Sources of greenhouse ignorance

GCMs do provide robust support in understanding the fundamental features of greenhouse climate change. We argue that that support is robust because it relates to features of the climate system that are substantially determined by radiative theory and fundamental thermodynamic relationships. These processes are well represented in GCMs. In moving to the domain of regional climate projections we face a substantially more difficult problem. Regional climate depends on the details of atmosphere and ocean circulation and thus on the dynamics of the climate system. CGCMs are required for generating regional projections. Because regional projections require information at points or regions in a spatial domain, we generally must use a 3d model.

In this section we argue that CGCMs are a source of ignorance when applied to this task. We focus only on dynamical sources of ignorance in regional projections, leaving aside physics and other issues. The advantage of focusing on dynamical sources is that one can make a direct connection from the dynamics through to regional flows. With errors in the physics it is harder to know which ones matter for regional scale flows and which ones don't. For example, the earliest weather models contained mostly dynamics, effectively no physics, but were capable of simulating regional flows in the extratropics (Lewis 1998). If one does not simulate the dynamical instabilities key to growth, then one is guaranteed not to get the eddies (regional flows) right, but one can miss out some fundamental physics and still do a good job of simulating the eddies. That is, the dynamics are necessary to make the case, but the physics are not. To understand more about the shortcomings of the dynamics in CGCMs it is useful to contrast them with current Numerical Weather Prediction (NWP) GCMs, which contain a substantially more complete representation of their dynamics.

3.1 NWP GCMs

The development of CGCMs is the culmination of a near century long research effort that started with the development of the first numerical weather predictions (Lynch 2006). CGCMs follow a lineage from NWP GCMs to atmosphere GCMs and ocean GCMs for climate, resulting in coupled ocean-atmosphere GCMs for climate. NWP GCMs were pioneered by Richardson (1922). Richardson's project for NWP has been substantially realized (Lynch 2006) in what must be one of the greatest science achievements of the 20th century (even if not widely recognized as such). With comprehensive observational networks, advanced data assimilation (Kalnay 2002), appropriate ensemble initialization (Toth and Kalnay 1997), and high resolution, contemporary NWP models are approaching Lorenz (1969)'s limit of deterministic predictability in the atmosphere.

The success of NWP GCMs is demonstrated routinely in forecast validations by the world's major weather forecast centres (Simmons and Hollingsworth 2002). Though these models are not perfect, they do contain the essential dynamics and they are not hampered over weather time scales by slowly evolving model errors. Their predictability is set by deterministic chaos. The instability time scales associated with that are relatively short (a few weeks). Over this time scale model bias and model error is generally not so critical that it comes into play during the forecast period.

NWP GCMs resolve and explicitly model the key dynamical processes in the atmosphere. This is apparent from consideration of the kinetic energy spectra in the atmosphere (O'Kane et al. 2009). Figure 1 shows the spectra for mean and transient (eddy) fields in an atmospheric GCM. The mean energy field is dominated by Rossby waves and jets at low wave numbers and decays at higher wave numbers. The transient energy spectrum peaks at about wave 10, where it crosses the mean spectrum. Interactions between eddies and the mean flow peak near wave 10, as does the maximum growth rate in baroclinic instabilities. NWP GCMs must (and do) resolve the flow field to wave 10 in order to capture eddy-mean flow interactions and the growth of baroclinic instabilities. A modern NWP GCM runs at resolutions well beyond wave 100. Because the eddies in the atmosphere are explicitly resolved,

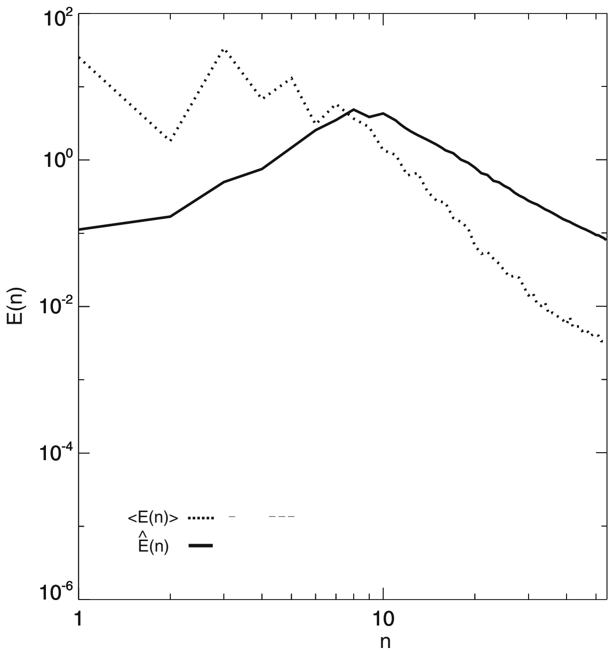

Fig. 1 Mean $< E >$ and transient $\hat{E}$ kinetic energy spectra in the atmosphere for January in m^2s^{-2} from simulations with the CSIRO Mk3 GCM. Adapted from O'Kane et al. (2009). The spectra are plotted as a function of wave number

the higher wave number eddy–eddy interactions can be parameterized with homogeneous approaches (Frederiksen and O'Kane 2008).

Deterministic NWP is so successful because NWP GCMs resolve and appropriately parameterize the dynamical instabilities that matter on the scale of their forecasts. The dynamics are well represented and the physics and errors in the physics generally play a secondary role to the dynamics over the relevant weather forecast time scales. By following the growth of the dominant dynamical instabilities, NWP models can provide accurate forecasts of the evolution of eddies and other regional details of the flow field.

3.2 CGCMs

Knowing why NWP GCMs are so successful also provides the key to understanding why CGCMs are not yet successful at regional scales. CGCMs simulate much longer time scales than weather and must therefore include an ocean component. In contrast to NWP GCMs, CGCMs have sparse observational data (in the ocean component), less advanced data assimilation, no ensemble initialisation, and resolutions that are grossly inadequate to represent the key dynamical instabilities in the ocean.

In contrast to the atmosphere, the key instability scale in the ocean is more like wave 100 than wave 10 (Smith 2007; Zidihkeri and Frederiksen 2010). This is because the oceanic radius of deformation is only about 50 km. Hence the scale of baroclinic instability is unresolved at mid-latitudes in a typical CGCM with resolution 1–3° ($\sim$100–300 km). It has recently been shown that successful large eddy simulation whereby changes in resolution do not affect small scale kinetic energy spectra power laws can be achieved using stochastic approaches to subgrid-scale parameterizations (Zidihkeri and Frederiksen 2010), consistent with statistical dynamical closure theory (O'Kane and Frederiksen 2008). These mathematically sophisticated methodologies are predicated on representing the respective roles of stochastic backscatter (energy injection from the subgrid to retained scales) and eddy viscosity (energy drain from the retained to the subgrid scales). Currently the ocean component of CGCMs include only deterministic damping (eddy viscosity), with no account taken of the random nature of the interactions with the subgrid scales (stochastic backscatter) necessary for a dynamically consistent subgrid-scale parameterization scheme.

The failure to appropriately represent stochastic backscatter in a CGCM will affect the large scale flows. Frederiksen et al. (1996) used the phrase "tail wagging the dog" to describe the dependence of energy spectra on resolution and dissipation in atmospheric GCMs. They noted that, even when the total kinetic energy is conserved, small changes in the spectra of the smallest resolved scales will cause reciprocal quantitative modifications of the large scale kinetic energy spectra. Thus, even the Rossby waves at low wave numbers in Fig. 1 [the peaks at low wave numbers for the mean flow spectrum] are modified when resolution is increased or when frictional dissipation is applied at the smallest resolved scales. The stochastic subgrid-scale parameterizations cited above are necessary to overcome the sensitivity of the larger scales to resolution and dissipation.

In the oceans the mesoscale eddies provide the primary mechanism by which information is transferred through eddy–mean, eddy–topographic and eddy–eddy interactions. However, as mesoscale eddies are typically not resolved in CGCMs, mixing is poorly represented and grossly unrealistic eddy viscosities are required for numerical stability. In ocean GCMs frictional dissipation is employed in a dual role, partly to parameterize subgrid scale processes, but more importantly to ensure numerical stability. Griffies and Hallberg (2000) point out that frictional viscosity is essential in an ocean model to suppress not simply an accumulation of enstrophy at the smallest resolved scales, but also to suppress spurious instabilities due to grid Reynolds number and western boundaries.

Whereas current atmospheric GCMs resolve the dominant eddy–mean flow interactions and can employ appropriate statistical parameterizations of subgrid scale backscatter, current ocean climate GCMs don't resolve mesoscale eddy–mean flow interactions and don't include subgrid scale backscatter. The unrealistic dissipation schemes used in ocean GCMs to suppress spurious instabilities also have the effect of killing instabilities associated with eddy–eddy and other interactions that are critical to simulation of the growth of instabilities in the flow. In short, the dynamics of the ocean component of CGCMs are severely compromised by lack of resolution. These models are not representing the growth of dynamical instabilities that are critical for simulation of 3d flows on climate time scales.

This point is critical but is not always comprehended and absorbed. Regardless of what timescale one is forecasting, a model must represent the key instabilities that manifest and govern the flow on the time scales of the forecast (Palmer et al. 2008). In the language of chaos theory, a model must remain on the dynamical attractor if it is to successfully forecast deterministic transitions in attractor regimes (as in weather forecasting) or capture the statistics of attractor regimes if representing climate. The baroclinically unstable modes are critical to error growth in synoptic eddies in NWP GCMs as they are to mesoscale eddies in ocean GCMs. If these growth modes are not adequately represented (as in current ocean GCMs), a model falls off the dynamical attractor and is compromised in its ability to capture regime transitions in the flow. Thus, the detail in shifts in dynamical features such as jet streams (Frederiksen and Frederiksen 2007) will be difficult to capture, and such detail is often critical in assessing climate change in regions (Risbey and Stone 1996).

The inability of CGCMs to adequately represent the key dynamical instabilities in the ocean must degrade the simulation of regional climate in these models. The failure to represent growth modes in the ocean will degrade the simulation of ocean circulation, which in turn degrades the simulation of atmospheric circulation. Though these errors originally manifest on small scales, they ultimately degrade the large scale circulation, which means that all regions are affected. Palmer (2010) notes that one can evaluate the regional performance of CGCMs by testing their simulations of the regional effects of the annual cycle. These effects are systematically misrepresented (Guilyardi et al. 2009; Palmer 2010). To add to the difficulty of projecting regional climate changes, model errors do become important on the time scales over which the projections are made. These are manifest as drifts and changes in the mean states of the models. The representation of slow physics (processes longer than the deterministic forecast limit) also increases the difficulty of regional projections, though we leave aside discussion of that, as our focus is on direct dynamical limitations.

The good news is that the failure to adequately represent key dynamical instabilities in CGCMs is largely a function of their inadequate resolutions. Once their resolutions have increased beyond wave 100 (in the ocean), then the key instabilities can be resolved and we can expect improvements in the dynamics (Shukla et al.

2010). The bad news is that we are not there yet and must come to terms with the limitations of current CGCMs.

4 Insufficient remedies

The inability to resolve and appropriately parameterize the key dynamical instabilities in CGCMs does not affect every aspect of the simulation (as noted in Section 2), but it must have some consequences for regional projections. Any regional scale variable that depends on the dynamics and details of the circulation (e.g. wind, rainfall) will not be reliably simulated.

The task of simulating regional climate in a CGCM at current resolutions (an order of magnitude cruder than that needed to resolve mesoscale ocean eddies) is the equivalent of asking NWP GCMs to run at a resolution an order or magnitude cruder than that needed to resolve atmospheric synoptic eddies. A NWP GCM running at that resolution (wave 1 or 2) would have no hope of producing detailed regional forecasts with any skill, and we wouldn't expect it to. The problem in this case is that many people do think the proposition is reasonable for CGCMs [e.g. Solomon et al. (2007) Box TS.8]. That in turn must reflect some failure on our part to communicate the scope of the regional projection problem and the deep uncertainties underlying it.

The uncertainty associated with regional projections of flow-dependent variables (wind and rainfall) in CGCMs is difficult to quantify. The spread of regional results across different CGCMs is sometimes used as a proxy or indicator of uncertainty in regional projections (Christensen et al. 2007). This kind of approach works in representing uncertainty when models represent well the essential dynamics or processes (as in quantifying uncertainty in weather forecasts). Since all CGCMs lack resolution in capturing the essential dynamics, it is very unlikely that the spread of CGCM results per se is telling us anything meaningful about the size of regional projection errors (Palmer et al. 2008). Model spread tells us something about model differences, but not about the effect of the common model limitation of not representing the key instabilities in the ocean. That component of the uncertainty is presumably large and unknown.

The quantification of uncertainty of regional projections in the literature usually separates out sources of error due to internal climate variability, model uncertainty, and scenario uncertainty (Hawkins and Sutton 2009). Model uncertainty is then quantified via a measure of model spread, ignoring the unknown contribution from common model limitations (Hawkins and Sutton 2009). This approach will be misleading where all the models fail to represent dynamical instabilities that are fundamental to the regional variables of interest.

Another approach that is sometimes employed is to place weights on the outputs of different CGCMs (Maxino et al. 2008; Hawkins and Sutton 2009) in order to ostensibly reduce the uncertainty in regional projections. As with the model spread issue, this approach is predicated on having at least some models that do capture the essential dynamics or processes. When none of the models do that, then weighting may reduce model spread, but that spread has no meaningful relationship to the size of regional projection errors. In such circumstances model weighting creates only the illusion of enhanced precision.

Yet another approach to regional climate projections is to downscale climate projections from the large scale circulation down to regional scales using a nested high resolution climate model (Giorgi et al. 2001; Solomon et al. 2007). This approach is predicated on a successful simulation of the large scale flow fields. Though the larger scale fields are resolved in CGCMs, the errors on smaller scales propagate up into the larger scales (Frederiksen et al. 1996; Palmer 2010) as outlined in Section 3.2. Scale separation does not hold in the atmosphere or ocean, despite the fact that approaches such as downscaling implicitly assume that it does. Large scale features such as blocking, which is critical to regional circulation in midlatitudes, is not well simulated in CGCMs (Scaife et al. 2010), nor is ENSO (Vecchi and Wittenberg 2010). Downscaling may have some utility in situations and regions where the flow changes are more robust (Held and Soden 2006) or where there is a predictable interaction with topography. However, for many regions we have neither a robust expectation of flow changes nor a predictable interaction with topography, and it is unclear what the utility of downscaling is.

In many cases the question of the adequacy of models for a particular task (Risbey 2002) is one of degree rather than a declaration of being adequate or inadequate per se (Sherwood and Schmidt 2011). While we agree with this sentiment, the exceptions can be important. For some details of regional climate projections the models are simply not appropriate to the task because they don't (yet) represent the dynamical processes that are required. This isn't a question of degree. It would be inappropriate (and potentially misleading) to rate models as partly suited to a task when we know that the task requires a set of physics or dynamics which are not present in the model.

5 Consequences

The claim made here is that *some* details of regional climate projections are highly uncertain to the point of ignorance. This is not so for all variables in all locations. As described in Section 2, gross temperature patterns are easier to project than other variables (being less sensitive to errors in the dynamics and details of the circulation), some aspects of the hydrological cycle are robust (following more directly from thermodynamic forcing), and some locations may have more predictable flow changes than others. However, features such as rainfall (in a given location) are often dependent on subleties of the flow, and we have no reliable way to characterize the likely error in that flow in present CGCMs. Thus, sometimes the appropriate answer to how the rainfall is likely to change in some regions may be "we don't yet know—and we may not know".

There is surely room to debate the *degree* of ignorance embedded in regional climate change projections. However, it is not unreasonable to assert that such ignorance exists. Palmer (2010) concludes similarly that "current global models represent the equations of motion of climate rather poorly on the regional scale". The question then is are we successfully communicating the ignorance underlying regional climate change projections (where it exists) to the impacts community that use these projections? The question is important because a considerable fraction of the total research effort on climate change is devoted to assessing impacts on the basis of regional projections (Parry et al. 2007).

Part of the communication task is to allow for the characterization and expression of ignorance in our knowledge base. That brings us back to the uncertainty guidance for the IPCC (Mastrandrea et al. 2010). Ignorance is not an explicit part of the guidance and the guidance thus provides no aid in confronting it. By including 'ignorance' as one of the categories describing the level of uncertainty and precision with which some changes in climate are understood, we open space to discuss it. Ravetz (1986) notes that we must become aware of our ignorance in order to avoid encountering "disastrous pitfalls in our supposedly secure knowledge or supposedly effective technique".

The open discussion of ignorance in the science would represent a departure from the "consensus approach" to uncertainty in the IPCC (van der Sluijs et al. 2010). As noted by van der Sluijs et al., the dominant consensus approach tends to underexpose "issues over which there is no consensus". The lack of discussion and attention to ignorance creates a situation where there cannot be consensus on areas of ignorance, as consensus requires the presence of a discussion. Thus areas of ignorance become marginalized in the consensus approach. van der Sluijs et al. pose a strategy of "openness about ignorance" to complement the consensus approach. Paradoxically, this may ultimately foster a more robust policy response as the science and its process becomes more transparent (Shackley et al. 1999). However, if the admission of ignorance is not to be exploited, then it requires context in educating the media and the public that greenhouse science can be robust even when areas of ignorance remain. One can't understand complex science problems without understanding something of the process of science itself (Risbey 2010). Thus an education in the process of science is also important. The alternative of not educating and not confronting ignorance (where it exists) in regional projections is unfair to the impacts and policy communities.

The fact that the poor representation of dynamical growth modes in current CGCMs corrupts regional projections does not imply anything about the sign of errors in projections. In any given region, changes may be less severe or more severe than implied by current model projections (Oppenheimer et al. 2007). The ignorance underlying regional projections is not a source of comfort in what is to come, but a reminder that we need to take into account a much broader range of possibilities than represented by the models.

6 Incorporating ignorance

The incorporation of ignorance in the IPCC uncertainty guidance could be accomplished by including a category for ignorance in the scheme characterizing key findings and expectations [Section 11 in Mastrandrea et al. (2010)]. Selection of the 'ignorance' category to describe a finding means only that a finding is characterized by "lacking or weakly plausible expectations" (Risbey and Kandlikar 2007). Selecting this category is appropriate when we don't know what changes to expect, even when we are otherwise well informed about a variable. Risbey and Kandlikar (2007) note that:

> "In most cases we know quite a bit about the outcome variable. Yet despite this, we may not know much about the factors that would govern a change in the variable of the type under consideration. As such, it may be difficult to outline

plausible arguments for how the variable would respond. If the arguments used to support the change in the variable are so weak as to stretch plausibility, then this category is appropriate. Selecting this category does not mean that we know nothing about the variable. Rather, it means that our knowledge of the factors governing changes in the variable in the context of interest is so weak that we are effectively ignorant in this particular regard."

An example using this categorization would be the projection of changes in rainfall over many tropical ocean and midlatitude continental areas. Rainfall changes in the latter regions may depend on changes in the amplitude and pattern of hemispheric stationary waves and jet streams, on shifts in blocking amplitude and frequency, on shifts in Hadley circulations and the subtropical ridge, and on changes in the El Niño/Southern Oscillation and tropical–midlatitude teleconnection processes, for example. We know something about all these processes, but can only characterize expected changes in these large scale features in gross terms in most cases (for all the reasons outlined in Section 3) (Risbey et al. 2002). Because rainfall in a region can be sensitive to the details of changes in these features, we may be effectively ignorant of how rainfall may change. Thus we might characterize rainfall change in some of these continental areas as follows:

Changes in rainfall over some midlatitude continental regions can not be reliably projected because they depend on the detailed response of governing processes that are still not reliably simulated in coupled models. The confidence level for quantifying such changes is currently best characterized by 'effective ignorance'.

This kind of language would alert users to the need for greater caution and openness in interpreting scenarios. It may also encourage users to identify alternative sources of information about expected changes. For example, the text could be accompanied by a summary of what is known about rainfall changes in the region from a variety of different sources (models, recent climate variability and trends, paleoclimate history, and climate analogues). Taken together, that information might raise the confidence level from 'effective ignorance' to a higher (more precise) category, but the lower category should be available if more consonant with the level of precision on expectations.

The IPCC AR4 report does indicate that confidence is "weak" in some regional precipitation projections (Working Group 1, chapter 11) and that the climate responses of some of the processes important for regional projections are "still poorly known" (Working Group 1 Technical Summary, box TS.10). This language is consistent with a categorization of 'effective ignorance' in some regional projections. However, the AR4 report also frequently describes regional projections in relative terms, where the relative benchmark is the IPCC Third Assessment Report (TAR). For example, chapter 11 of AR4 notes that precipitation projections are characterized by model agreement over "more and larger regions" (relative to TAR results). The AR4 synthesis report states that "there is now higher confidence than in the TAR in projected patterns of warming and other regional scale features, including changes in wind patterns, precipitation ... ". The evaluation of projections in relative terms obscures the fact that the coupled climate models in AR4 [the CMIP3 series (Meehl et al. 2007)] are no more free of the critical dynamical deficiencies discussed here than those of the TAR [the CMIP2 series of CGCMs]. The same is true for the CMIP5 models for the upcoming fifth IPCC assessment for that matter. There is less scope to evaluate the level of uncertainty in projections when they are assessed relative to past model projections. The relative evaluations don't provide much guidance for users either, who normally require some evaluation of the absolute uncertainty, not its trend.

Confidence in large scale and regional circulation changes is hard to characterize in absolute terms, which may promote the tendency to evaluate models in relative terms (relative to past performance). That in turn avoids the need to characterize deeper levels of uncertainty, and may contribute to overconfidence in model projection capabilities.

7 Conclusions

We have argued here that some aspects of regional climate projections are shrouded in ignorance. That conclusion itself is not entirely novel and is sometimes acknowledged (Palmer 2010). On the other hand, it is not generally appreciated, nor is it well communicated. The lack of communication is apparent in uncertainty guidance documents which don't include options to associate levels of uncertainty as deep as 'ignorance'.

While there are many robust elements of regional projections, some features such as rainfall at a location can be very sensitive to relatively small changes in large scale and regional flow patterns. Rainfall at a location is one of the most sought after variables in applying regional climate change projections, and yet it is one of the most uncertain.

The ability of CGCMs to simulate changes in the 3d flow in the atmosphere is severely hampered by the lack of resolution in the ocean component of current CGCMs. The ocean models in CGCMs used for climate projections do not resolve mesoscale eddies. This means that they don't resolve the main source of dynamic instability of the flow in these models and only very crudely parameterize *some* of the components of that instability (Section 3.2).

Incomplete parameterization of mesoscale eddy effects in ocean models does not reflect any lack of skill of ocean modellers. It is a consequence of not resolving scales in the ocean's kinetic energy spectrum where baroclinic instabilities are important. As such, homogeneous (and/or isotropic) approaches to parameterization of subgrid scale eddies that have been so successful in the atmosphere are invalid in an ocean context. Current ocean subgrid schemes do not account for eddy–eddy interactions and must compromise mixing and the resolved flow. Unrealistic eddy viscosity is employed in ocean GCMs to damp spurious instabilities at subgrid scale, but that in turn kills the transfer of energy from subgrid to resolved scales and neutralizes the key role played by mesoscale eddies in ocean climate. The shortcomings of ocean models are readily apparent in the form of poor mixing, the requirement to use unrealistic viscosities, poor representation of density fields, and poor validation of basic components of the annual cycle.

The deficiencies of ocean GCMs can be understood in contrast with the more mature NWP GCMs (Section 3.1). These deficiencies reflect the fact that ocean modelling is a more difficult problem. There are a number of reasons for this, but the relevant one for the purpose of this discussion is that the critical instability scale in the ocean occurs on spatial scales an order of magnitude finer than in the atmosphere and we simply don't yet have powerful enough computers to resolve these scales.

Poor simulation of the dynamically unstable component of ocean models will not affect every aspect of the coupled simulation. Many features of climate change simulations are set by radiative physics and basic thermodynamics, and are well represented in CGCMs (Section 2). However, errors in the flow in the ocean do matter from the perspective of the atmosphere, which exchanges fluxes of heat, moisture, and momentum with the ocean. Errors in these fluxes, even at small scale, lead to errors at all scales in the simulation of atmospheric flows. Over all time scales longer than a weather forecast (two weeks), these errors cause demonstrable degradation of atmospheric flow. Errors in the atmospheric models are important on these time scales too, but their source is different. The main sources of dynamic instability are resolved or can be appropriately parameterized in atmospheric models (Section 3.1). On time scales beyond weather, errors in the parameterization of physical processes (e.g. moist convection) become increasingly important in the atmospheric models.

Note that errors in physical parameterizations in CGCMs are likely to remain important long after more powerful computers are able to resolve mesoscale instability processes in the ocean. The point when dynamical instabilities are properly represented in ocean models in CGCMs will constitute a major source of improvement, but it does not mean that there won't still be major sources of ignorance in regional projections. We have simply focused here on dynamical instabilities (and their representation) as sources of ignorance as their connection to regional climate is more direct (Section 3).

So long as the key dynamical instabilities are not well represented in ocean models we will be stuck with errors in the atmospheric flow (at large scale and regional scale) which we cannot quantify in climate change simulations. For those regional variables that are sensitive to the details of the flow there will be some ignorance in quantifying changes for regional projections. That ignorance can not be eliminated by use of model ensembles, model weighting, or downscaling. These techniques only reduce uncertainty for regional variables and applications that are not flow sensitive (Section 4).

Dynamical limitations in CGCMs are potentially important for some regional climate applications. In particular, applications relying on regional rainfall projections in specific locations should be critically assessed. Some projected changes in regional precipitation are not likely to be meaningful. It is important to keep this result in context too. Not all climate variables are sensitive to the details of flow changes as mentioned. In particular, gross temperature patterns are likely fairly robust (Section 2.2). Some of the features of the hydrological cycle also follow directly from fundamental thermodynamical principles and are less sensitive to flow simulations (Section 2.3).

Features like the gross temperature response to greenhouse forcing do depend on the dynamics, but mostly in the details. Temperature in the lower troposphere is mostly just rising (assuming due allowance for decadal variability). Further, it will rise faster over land than over the oceans because it can't do much otherwise because of the respective heat capacities of land and ocean and the ocean's ability to remove heat from the surface. Temperature will rise faster in northern high latitudes as sea ice is removed, and cool aloft due to the radiative properties of the atmosphere and vertical distributions of trace gases. These gross responses are almost guaranteed and don't depend on details of model parameterizations or on knowing the dynamical response in detail. Of course this gross temperature pattern response won't be true everywhere and some local circulations (in atmosphere or ocean) will temporarily change this picture, but those regions will be the exception, not the rule.

The main elements of greenhouse climate change (climate sensitivity, gross temperature response, global hydrology) are supported by multiple independent sources of knowledge. Empirical observation of past and present climates, radiative theory, simple models and theory, and thermodynamical principles provide independent support for the understanding of the key elements of greenhouse theory (Section 2). GCMs provide a further source of understanding and support for these features. However, one doesn't need a GCM for this support precisely because these features are derivable from fundamental physics.

In short, of course there is ignorance in greenhouse climate science. That is a fundamental and constant property of the study of any complex system. We need to describe that ignorance in the context of the knowledge base and as a normal component of the process of science. The uncertainty guidance documents are an appropriate place to develop these aspects of the science. The delineation of ignorance may contribute to a deeper understanding of the science and its robustness.

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