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The rapid disintegration of projections: The West Antarctic Ice Sheet and the Intergovernmental Panel on Climate Change

Jessica O'Reilly
Department of Sociology, College of Saint Benedict, Saint John's University, Collegeville, MN, USA

Naomi Oreskes
Department of History and Program in Science Studies, University of California San Diego, La Jolla, CA, USA

Michael Oppenheimer
Department of Geosciences and Woodrow Wilson School, Princeton University, Princeton, NJ, USA

Abstract

How and why did the scientific consensus about sea level rise due to the disintegration of the West Antarctic Ice Sheet (WAIS), expressed in the third Intergovernmental Panel on Climate Change (IPCC) assessment, disintegrate on the road to the fourth? Using ethnographic interviews and analysis of IPCC documents, we trace the abrupt disintegration of the WAIS consensus. First, we provide a brief historical overview of scientific assessments of the WAIS. Second, we provide a detailed case study of the decision not to provide a WAIS prediction in the Fourth Assessment Report. Third, we discuss the implications of this outcome for the general issue of scientists and policymakers working in assessment organizations to make projections. IPCC authors were less certain about potential WAIS futures than in previous assessment reports in part because of new information, but also because of the outcome of cultural processes within the IPCC, including how people were selected for and worked together within their writing groups. It became too difficult for IPCC assessors to project the range of possible futures for WAIS due to shifts in scientific knowledge as well as in the institutions that facilitated the interpretations of this knowledge.

Corresponding author:
Jessica O'Reilly, College of Saint Benedict/Saint John's University, Sociology, 205 Simons Hall, Collegeville, MN 56321, USA.
Email: jloreilly@csbsju.edu

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In September 2009, dozens of scientists who study the West Antarctic Ice Sheet (WAIS) met for their annual workshop at the Pack Forest Conference Center, close to Mt Rainier National Park in the state of Washington. Among the residential cabins and dining hall and in a stand of second growth Douglas firs sat a large log-hewn structure, formed like a gigantic one-room schoolhouse. Inside, fleece-garbed and predominately male Antarctic scientists sat at rows of tables facing the front of the room, listening to research updates from their colleagues.

One presentation hit a sore spot among WAIS scientists. It addressed the stability of the WAIS and whether it would grow (due to additional snowfall) or shrink (due to melting and iceberg formation) in a warming world, thus subtracting from or adding to future sea level rise. The most recent assessment from the Intergovernmental Panel on Climate Change (IPCC) omitted any specific prediction of whether WAIS would lose ice, and if so, how slowly or rapidly it would do so. (A rapid loss is sometimes labeled a 'collapse' in colloquial terms, although this is a bit of a misnomer since the fastest conceivable disintegration would stretch over hundreds of years.) In the third assessment report (IPCC, 2001; abbreviated as TAR), chapter authors cited high uncertainty, but they also provided long-term projections for the highest potential rate of ice loss (called an 'upper bound') during such a 'collapse'.[1] Based on the then-recent literature, they concluded that WAIS would be stable in the short term. However, in the Summary for Policy Makers (SPM) of the fourth and most recent IPCC assessment report (IPCC, 2007; abbreviated as AR4), the authors stated that although relatively rapid loss of ice was already observed from parts of WAIS (due to melting and iceberg formation as the ice flowed off the ice sheet into the ocean), they could not provide an estimate of long-term behavior and the resulting contribution to sea level rise. In addition, the authors decided to exclude from their tabulated, numerical estimates of 21st century sea level rise the possibility of any further changes in flow rate (called ice dynamics) from either Greenland or Antarctica (Oppenheimer et al., 2007). In short, in the TAR, WAIS was deemed stable in the short term (through 2100) and a highly uncertain numerical estimate was provided for rapid disintegration in the long term. While the AR4 was being written, new observations undermined the previous consensus that WAIS would not contribute significantly to short-term 21st century sea level rise. The great difficulty with coming up with a credible numerical estimate for the short term led to *no* WAIS prediction – in the short or long term – in AR4. How and why did the scientific consensus expressed in the third IPCC assessment disintegrate on the road to the fourth?

Due to the recent observations and the resulting challenge to the models, AR4 authors decided that there was not enough agreement in the broader expert community to provide an assessment of the likelihood of rapid disintegration. They wrote in the SPM: 'dynamical processes related to ice flow not included in current models but suggested by recent observations could increase the vulnerability of the ice sheets to warming, increasing future sea level rise. Understanding of these processes is limited and there is no consensus on their magnitude' (IPCC, 2007: 17). Rather than allowing the IPCC to

Table SPM.3. *Projected global average surface warming and sea level rise at the end of the 21st century. {10.5, 10.6, Table 10.7}*

Case	Temperature Change (°C at 2090-2099 relative to 1980-1999)[a]		Sea Level Rise (m at 2090-2099 relative to 1980-1999)
	Best estimate	*Likely* range	Model-based range excluding future rapid dynamical changes in ice flow
Constant Year 2000 concentrations[b]	0.6	0.3 – 0.9	NA
B1 scenario	1.8	1.1 – 2.9	0.18 – 0.38
A1T scenario	2.4	1.4 – 3.8	0.20 – 0.45
B2 scenario	2.4	1.4 – 3.8	0.20 – 0.43
A1B scenario	2.8	1.7 – 4.4	0.21 – 0.48
A2 scenario	3.4	2.0 – 5.4	0.23 – 0.51
A1FI scenario	4.0	2.4 – 6.4	0.26 – 0.59

Table notes:
[a] These estimates are assessed from a hierarchy of models that encompass a simple climate model, several Earth System Models of Intermediate Complexity and a large number of Atmosphere-Ocean General Circulation Models (AOGCMs).
[b] Year 2000 constant composition is derived from AOGCMs only.

Figure 1. Table SPM.3. IPCC AR4 Summary for Policy Makers (IPCC, 2007: 13). The 'A' and 'B' scenarios to the left are emissions scenarios expected to play out under various combinations of policy, population growth, and economic development.

estimate the potential rate of disintegration over the long term, as with the third assessment, the new observational information gave the authors pause on providing a numerical prediction.

For the near term (21st century, see Figure 1), AR4 does not explicitly present a numerical WAIS contribution (TAR did not do so either). Instead it assumed that the dynamical contribution to sea level rise from both the Greenland and Antarctic ice sheets would continue into the future at the same rate indicated by recent observations. The table (below) provides multiple sea level rise estimates based on several greenhouse gas emission scenarios, but notes that the numbers provided are a 'model-based range excluding future rapid dynamical changes in ice flow' (IPCC, 2007: 13). Though the later textual caveat suggests that the contribution of the ice sheet to a rise in sea levels could be significantly higher, this statement was overshadowed by the numbers, in the minds of many readers.

Using ethnographic interviews and analysis of IPCC documents, we trace the abrupt disintegration of the WAIS consensus. First, we will provide a brief historical overview of scientific assessments of the WAIS. Second, we will provide a detailed case study of the decision not to provide a WAIS prediction in AR4. Third, we will discuss the implications of this outcome for the general issue of scientists and policymakers using institutions as translational devices to make projections.

For WAIS scientists working on AR4, framing the decision to refrain from making estimates in light of new data was embedded in beliefs about what constitutes appropriate data for assessments, comfort with risk and prediction, and professional reputation. There is tremendous complexity in undoing previously published knowledge, particularly when it is replaced with increased uncertainty instead of new, 'improved' information, and this process is often slow, expensive, and politically difficult (Oreskes, 1999).

In addition to the normative scientific questions that surround the projections and lack of projections for WAIS, we consider the organisational culture of the IPCC as being integral to how scientific assessments are written. The IPCC institution is formed of people with varying levels of commitment to and interest in that institution: we refer to all of these people when we discuss 'the IPCC'. The structure and mission of the IPCC process is unprecedented, so that the actors involved must continually define and redefine their terrain. Further, the IPCC is not a traditional bureaucracy – it is largely populated by a shifting set of volunteer scientist-authors. Institutional cultures are productive – within the IPCC, the institutional culture enables authors to make climate science intelligible to policymakers. IPCC authors were less certain about potential WAIS futures than in previous assessment reports, in part because of new information but also because of the outcome of cultural processes within the IPCC, including how people are selected for and work together in their writing groups (see also Hulme and Mahoney, 2010).[2] It became too difficult for IPCC assessors to project the range of possible futures for the WAIS due to shifts in scientific knowledge and characteristics of the organization that facilitated the interpretations of this knowledge.

Assessing the WAIS

At first glance, the WAIS appears to be like the larger, contiguous East Antarctic ice sheet – a huge expanse of ice frozen over land, accumulating in a mass several kilometers high through snowfall, and then losing mass into the sea at its edge as the ice moves toward lower elevations under the influence of gravity and interacts with the warmer ocean and atmosphere. However, since the 1960s, glaciologists have raised the specter of WAIS instability. No ice sheet can survive indefinitely on a warming planet, but WAIS is particularly vulnerable because most of it sits on rock that lies below sea level. Lying so close to, and in part within, the warming Southern Ocean, the ice sheet could potentially disintegrate more quickly than other parts of the Antarctic or Greenland ice sheets that are perched further above sea level. If WAIS disintegrated completely, it would raise the global sea level by 3.3–6.0 m (Alley and Whillans, 1991; Bamber et al., 2009; Lythe et al., 2001). Setting aside questions about its impact on ecosystems and the global environment in general, such a sea level rise would have a profound effect on much of the world's human population: flooding cities and deltas, overriding levees, disrupting sewage and wastewater systems, and so on, as well as forcing the construction of sea defenses to facilitate adaptation to the higher sea level.

With these concerns, scientists try to make projections of how rapidly disintegration could occur and whether it could be tantamount to a collapse. These projections can be tracked through the four assessment reports of the IPCC, a massive and comprehensive effort by scientists to provide policymakers with information about climate change. There are two main ways by which an ice sheet can contribute to sea level rise: (1) surface melting and (2) dynamic effects, where parts of the ice sheet flow off the continent to form icebergs or melt from below after encountering warm ocean water. Ice experts understand surface melting, and they know that a cold ice sheet like WAIS sheds little ice in that way under current climate conditions. Rather, its greatest potential for losing volume rapidly comes from dynamic effects. Experts use gravity field measurements and radar and laser altimetry from satellites and airplanes to estimate current changes in ice mass and extent. However, by lacking understanding of the basic processes that cause the dynamic effect, and thus lacking a model with which to make predictions, AR4 authors had no way of estimating if the current rate of loss due to dynamic effects would grow, shrink, or stay constant in the future.

In these assessments, authors dealt with two WAIS timescales: one for this century, and another for the more distant future. In the TAR, the possibility of rapid ice loss from WAIS via dynamical processes before the year 2100 was essentially ruled out by projections of a sea level rise of 0.09–0.88 m (compared with the AR4 prediction of 0.18–0.59 m); but dynamical loss was considered as a possibility for long-term estimates of sea level rise over multiple centuries.[3]

The TAR estimates were based on physical, process-based models, which at the time had some credibility due to their ability to predict the behavior of the Antarctic ice sheet through the hundred-thousand-year glacial–interglacial cycles. Previous IPCC assessment reports had assumed these models provided a reliable basis for predicting behavior on the decadal and multi-century scales as well. This essentially allowed any WAIS contribution to be ignored for the near term (the 21st century) because the models indicated that this was too soon for significant dynamical responses to occur in WAIS. However, new observations shortly before and during AR4 raised questions about this assumption (Vaughan, 2008) and muddled the distinction between the short-term and long-term by suggesting that dynamical processes might already be playing a significant role in ice loss. AR4 authors tried to stick to the long-term/near-term dichotomy in their writing while also trying to work out the new relationship between near- and long-term projections for the ice sheet. After AR4 was completed, a variety of estimation methods for sea level rise were published that did not rely on ice-sheet models (Pfeffer et al., 2008; Rahmstorf, 2007a; Vermeer and Rahmstorf, 2009).

Glaciologists began studying the WAIS in a systematic fashion during the International Geophysical Year of 1957–1958, though there were some earlier observations from exploratory traverses. Expert concern about a potential collapse of the WAIS and accompanying sea level rise during a global warming did not emerge until the late 1960s, and the idea was slow to gain traction. Glaciologist John Mercer, while studying mechanisms for the changes of sea level possibly brought about by shrinkage of WAIS in the deep past, noted the potential for large and rapid change in a warming world (Mercer, 1968). Mercer's subsequent publication in *Nature* was ominously titled 'West Antarctic Ice Sheet and CO_2 greenhouse effect: a threat of disaster' (Mercer, 1978). In the 1980s, academic and governmental scientists began to publish findings from the earliest sea level rise workshops that considered the future of WAIS (Carbon Dioxide Assessment Committee, 1982; Hoffman et al., 1983; Institute for Energy Analysis, 1983; International Institute for Applied Systems Analysis, 1981). In 1982, Roger Revelle, well known for his long-standing interest in global warming from increased atmospheric greenhouse gases, convened a WAIS workshop at Scripps Institution of Oceanography at the University of California, San Diego. The material from this workshop was included in the 1983 National Research Council report *Changing Climate* (Carbon Dioxide Assessment Committee, 1983) and discussed in a Department of Energy report, *Carbon Dioxide – Science and Consensus* (Institute for Energy Analysis, 1983). But there was no consensus among the relevant experts, except to say that little was known about the WAIS, and that it would be very difficult to predict its future behavior (see also American Association for the Advancement of Science, 1980, Barnett, 1982; International Institute for Applied Systems Analysis, 1981; Hoffman et al., 1983; National Research Council, 1985; Smith, 1982). While WAIS was generally considered to be potentially unstable in a warming world, the timeframe of the instability was unknown beyond one crude estimate of its fastest possible rate by Bentley (1982).

These early scientific WAIS workshops were conducted in an ad hoc and informal style. An interested institution – a government agency or a university department – would sponsor the event, raise funds, and invite experts to attend a workshop for a few days. While there, scientists would present their latest research results, discuss their implications, and coordinate future research. These meetings were key to establishing a cohort of WAIS specialists, spanning continents, generations, institutions, and disciplines. The physical meeting of international WAIS experts and students gave participants an opportunity to learn what others outside their university, research team, or disciplinary specialty were doing in the way of research, and the meeting also afforded participants a chance to discuss each other's work. (This type of workshop continues to be held annually, with meetings of the US-focused WAIS Initiative and the European-based Forum for Research into Ice Shelf Processes (FRISP) and sometimes joint WAIS–FRISP meetings.)

In the 1980s, several brief meetings (over a weekend, for example) produced comprehensive statements about WAIS and resulted in published proceedings (Carbon Dioxide Assessment Committee, 1982; Hoffman et al., 1983; Institute for Energy Analysis, 1983; International Institute for Applied Systems Analysis, 1981). These reports were not put through formal peer review, though the writers solicited comments from their colleagues. The life of the document often ended there, except for the occasional thumb-through for a figure or citation. Some of the conclusions were used in broader climate change assessments, themselves one-off documents.

This changed in 1988 with the establishment of the Intergovernmental Panel on Climate Change (Bolin, 2007; Le Treut et al., 2007). The IPCC assessment era – from the late 1980s to the present – presents a different kind of scientific assessment than the ones described above. At their outset, IPCC chapter-writing meetings were much like those in the scientific workshops of the 1980s (Oerlemans, recorded interview, Utrecht, The Netherlands, 6 July 2009). Over time, however, IPCC assessments have become more formalized and influential. Most significantly, the IPCC requests that the assessors provide projections of future climate change, usually to the target date of 2100. This target date works well for policy planning but limits the ability to adequately characterize the WAIS due to the uncertainty on when and at what level of warming the dynamic processes would become important. By 2100, a spectrum of additional change could occur in the ice, ranging from very little to very significant (Pfeffer et al., 2008).

WAIS, models, and the IPCC

Climate modeling is a technological activity at the crux of the relationship of science and policy (for more on this relationship, see Edwards, 1999; Jasanoff and Wynne, 1998; Oreskes et al., 1994; Oreskes and Belitz, 2001; Parker, 2009; Petersen, 2006). Modelers constantly have to negotiate boundaries between producing computer programs based on parameterizations and other approximations that are used to mimic not yet well-understood ice dynamics, and interpreting the results in terms of outcomes in the real world (Edwards, 2010; Lahsen, 2005; Orrell, 2008; Sarewitz et al., 2000; Shackley and Wynne, 1996).

Understanding the shortcuts, approximations, and best guesses built into all predictive models becomes more difficult the further one is removed from model production. MacKenzie (1990), using his schematic 'certainty trough', has explained that while those directly involved in knowledge production and those alienated from it tend to have relatively high levels of uncertainty, those who are model users rather than producers of have *lower* uncertainty about the models (MacKenzie, 1990: 372). IPCC assessors may fall into this category of users who are somewhat removed from knowledge production, but also committed to the certainty of such knowledge. Modeling communities and their associated institutions, such as the IPCC, are self-governing, using peer review and other expert, insider oversight to produce results. Though model developers participate in the IPCC process, the IPCC does not create climate models; instead, it uses them, along with varying degrees of critical assessment of model findings. These usually informal techniques do not always translate well between nations, institutions, and cultural systems, though they appear necessary for the successful conduct of science (Edwards and Schneider, 2001).

Beginning in the 1970s, ice sheet modelers, along with field glaciologists, began contributing to the study of WAIS. Their models were rudimentary, limited by computing power and the scant amount of observational data available. Ice sheet models became more complex in the 1980s, when doctoral student Philippe Huybrechts introduced a thermomechanical ice sheet model. His three-dimensional model included for the first time calculations of heat flows within the ice. Aided by the efforts of his supervisor, Dutch glaciologist Johannes Oerlemans, and by increasing computer power to run a model with such a complex representation of an ice sheet, Huybrechts' project marked a pivotal shift in how the ice sheet could be modeled. The model could simulate conditions for a select number of centuries into the future, including the influence of warmer surface temperatures. The end results were a set of projections about what an ice sheet could look like in, say, 2100 (contingent on the assumption that the model represented the key physical processes more or less correctly, an enormous *if*). As one of a very few available three-dimensional, continental-scale ice sheet codes, the Huybrechts model became the standard model just as drafting of the first IPCC assessment report began.[4] In an interview, Huybrechts suggested that current observations that call the projections of his model into question, could be resolved as 'noise' when put in the context of slow, long-term ice sheet dynamics (recorded interview, Brussels, Belgium, 3 July 2009). Huybrechts' model is still widely used and his work remains heavily influential.

Among the possibilities considered by IPCC authors in their assessment reports are two extreme ones: (1) the potential for an incremental contribution of WAIS to sea level rise or fall through the year 2100 and beyond, resulting from a slow and steady ice loss or gain and (2) the potential for WAIS to undergo a geologically rapid disintegration, potentially already underway in parts of the ice sheet, whereby much of the ice sheet disintegrates into the sea, as initially suggested by Mercer (1968) and elaborated upon by Hughes, Weertman and others (Hughes, 1973, 1977; MacAyeal, 1989; Thomas and Bentley, 1978; van der Veen, 1985; Weertman, 1974). When glaciologists and ice modelers tried to explore and quantify the latter scenario, they came across many technical challenges: an incomplete understanding of ice dynamics, uncertainty about the details of external conditions in the atmosphere and ocean which could trigger a rapid disintegration, and the numerical challenge of modeling WAIS. The two futures also have different policy implications: in the first, the WAIS contribution is part of the larger sea level rise problem; in the second it is dominant and potentially catastrophic.

As noted above, WAIS models are now considered by many scientists to be unreliable either for 21st century or for long-term, multi-century predictions, because of the models' inability to reproduce recent observations. Huybrechts' model has been used in all of the IPCC assessment reports, though new models are slowly being developed. In an interview, Huybrechts spoke at length about the challenges of modeling the grounding line (the boundary between the part of the ice grounded on land and the part floating in the sea), which he characterized as a transition zone where it is difficult to differentiate between ice sheets (ice over the continent), ice shelves (ice attached to the ice sheet, but floating over the sea), and ice streams (faster moving portions of the ice sheet):

> That makes it complicated because the whole question is over what distance do you have like a transition zone. Is there a wide transition zone or is the flow regime just changing from one kilometer to the next? … in West Antarctica there is a whole zone in which you cannot really decide what it is. (Huybrechts, recorded interview, Brussels, Belgium 3 July 2009).

In his account, the literally and figuratively shifting nature of WAIS and its associated measurements and projections makes observations difficult (because no one region or time is representative of the whole), and therefore, reliable models are difficult to build for lack of sufficient measurements for comparison. In addition, WAIS experts simply do not feel confident that they understand the basic physical processes operating in the ice sheet. They are trying to build quantitative models of a phenomenon whose inner workings (the physics of ice flow) aren't fully characterized. To bridge this gap and simplify the numerical difficulties, Huybrechts' model contains a shortcut to solving the equations – called the 'shallow ice approximation' – which modelers have been unable to justify fully with observations.

The shallow ice approximation is an educated guess that stands in for a complete solution to the physical equations. It allows calculation of the forces (stresses) in the ice sheet based on the ice thickness and slope at individual points, by assuming that all stress is determined by interactions very near any given point in the ice. It works best when friction at the base of the ice is the dominant restraint on motion, but observations indicate that stress also comes from the interaction between ice streams and the static ice ridges between them, and from obstructions where the ice shelves (the front edge of the ice sheet floating on the sea) run into bedrock. As researchers learned from observations and began to suspect the utility of the shallow ice approximation, consensus became difficult to establish with regard to what to tell policymakers about the future contribution to sea level rise from WAIS for the 21st century or beyond.

Organizing and writing assessment reports

Each IPCC assessment report goes through a development and planning stage before the authors begin their work. This stage is conducted by people who work for the IPCC, government representatives, and volunteer scientists nominated by their governments to participate in the IPCC process. In a series of meetings with some of the past authors, IPCC coauthors and staff work out a proposed organization and order of chapters. The proposed organization must be approved in a formal process by the panel of government representatives who make up the IPCC. There had been a sea level rise chapter in each of the previous three assessment reports. While most of the chapters were broad, global assessments of processes and models of climate changes in the past, present, and future, the earlier sea level rise chapters instead focused on only one aspect of climate change. For the AR4, the IPCC decided to split this material into discussions of past, present, and future conditions of ice and sea level, which would be placed into the respective chapters on past, present, and future climate and ice conditions. As a result, the WAIS discussion also became split among the chapters.

Jonathan Gregory called each earlier sea level rise chapter a 'whole [IPCC] report in miniature'. He said that while the chapter reorganization did not end up working well in AR4, it was 'important to try it', in order to see if this approach would improve the report overall (Gregory, recorded interview, Reading, UK, 14 July 2009). When viewing it with hindsight, most participants who we interviewed thought that this chapter reorganization was a mistake and were relieved to know that the sea level rise chapter would be reinstated in the Fifth Assessment Report, due to be published in 2013 or 2014. However, most of them pointed to the workload burden that the chapter split piled upon the authors, and not to changes in the outcome of the assessment: it was logistically more difficult, but in the end, some of the scientists with whom we spoke believed that the scientific outcomes would have been the same if the sea level rise chapter had been intact. However, a consequence of dealing with sea level rise in different chapters that did not focus uniquely on sea level rise was that a different assortment of people sat around the table, including those who were experts on some other aspect of climate and who possibly had less inclination to include WAIS projections in sea level rise estimates. Under these conditions, the authors also had to grapple with the pressure of answering within a tight deadline a multitude of scientific questions across a variety of subject areas.

After the chapter organization was worked out for AR4, writing teams were chosen for each chapter. IPCC chapters have a new writing team for each assessment, although sometimes with some overlap with earlier assessment teams. Each chapter has two Coordinating Lead Authors (CLAs), who oversee the entire process, a number of Lead

Authors (LAs), who are given writing responsibilities for sections of the chapter, depending on their expertise, and Contributing Authors, who are asked to provide a section of text, a chart, or some numbers for a limited portion of the chapter. Each chapter of an IPCC report is written by a small group of experts and is put through two rounds of formal peer review, as well as one 'informal' round in most cases, before being accepted into the assessment report.[5] This is a rigorous process, to be sure, but while all authors subscribe to the outcome, only a handful consider themselves expert on any particular details.

Writing teams have enormous influence over the organization of their chapters. Each chapter's authors need to organize and assess information drawn from hundreds of sources, and accordingly are selected for their expertise and familiarity with the subject matter. There are IPCC diversity criteria to consider, which emphasize representation from developing and developed nations, as well as an IPCC goal to make sure that new people are contributing to the chapters, instead of maintaining entrenched leadership from assessment to assessment. However, the national diversity of the IPCC continues to be heavily skewed towards representatives from a few developed, usually English-speaking nations (Hulme and Mahoney, 2010). This lack of diversity is evident among the people interviewed for this specific case study.

Once a writing team is assembled, the assessing begins. The writing of scientific assessments is a unique procedure that requires information to be processed, organized, and communicated with attention to science as well as its importance for policymakers, but without overemphasizing either category or ignoring the implications of the other (Farrell and Jager, 2006; Jasanoff, 1990, 2005; Mayo and Hollander, 1994; Patt, 1999, 2007; Social Learning Group, 2000). It is a subtle balancing act that requires a skill set in which no author has been formally trained, so the art is learned (or not learned) almost entirely on the job and informally from others who have written previous assessments.

Writing a chapter takes at least 2 years, as it involves multiple drafts, and consideration of thousands of comments from independent and governmental expert reviewers. The scientific literature that is being assessed does not provide uniform methods, units of measurement, scale, writing style, or research questions across all the disciplines involved. From a large pile of publications, the authors must distill the ideas into a clear, orderly discussion of the matter at hand. This kind of work will be conducted differently depending upon the people working on it, and their subjective relationships to organization, workload, presentation of material, writing, communication, and so on. There are no strict rules to the process; it is produced by the writing team members, who bring to bear a range of backgrounds, conceits, passions, and concerns. Writing teams are composed of scientists chosen for their professional credentials, but they carry with them beliefs and opinions on how to manage the massive project of writing an IPCC chapter, as well as their individual and disciplinary approaches to risk and uncertainty.

There are gradations of formality in the writing process, and collaborations emerge among authors of different chapters and from different working groups, as the need arises. During the initial writing stage of AR4, scientists from the US and UK – Michael Oppenheimer, Richard Alley, David Vaughan, Jonathan Gregory, and Tony Payne – formed an informal writing collaboration focused on the WAIS. These scientists represented Working Group I – the physical science-oriented IPCC report, with which the present article is primarily concerned – as well as Working Group II, which dealt with adaptations to climate change, including risk management approaches. The collaboration was primarily focused on the long-term stability issue, and this group worked on 'scaling up' their projections during their informal conversations. However, in Jonathan Gregory's opinion it was apparent that they could not include these projections in the formal assessment report. 'We didn't add these estimates to the other terms because it wasn't achieved in the same kind of rigorous way', said Gregory, 'it wasn't scenario-based. It wasn't model-based. It's just a back of the envelope indication of order of magnitude. So I think it would have been misleading to add it on' (interview 14 July 2009). This is but one small example of the collaborations that can form during the IPCC writing process and the informal, casual, 'back of the envelope' calculations that experts produce and reject (or sometimes accept) during their conversations. Stefan Rahmstorf of the Potsdam Institute for Climate Impact Research (PIK), wrote a paper using semi-empirical (i.e. not based on process models) sea level rise projections. Rahmstorf's paper was inspired by his participation in the AR4 writing process, specifically, the phase when discussions from a cross-chapter meeting encouraged the writer-scientists to produce alternative, non-model based ideas for predicting sea level rise (Rahmstorf, recorded phone interview, Bremen, Germany and Albany, Minnesota, 30 August 2010). Instead of trying to make calculations of the separate contributions by WAIS, the East Antarctic Ice Sheet, and the Greenland Ice Sheet, Rahmstorf thought about the ice sheets in aggregate. He decided not to estimate the various contributions to sea level rise separately, including those from ice sheets, but instead tried to infer the sensitivity of past sea level rise to global mean temperature and scale up past rates of sea level rise in parallel with the projected temperature increases, to estimate future sea levels (Rahmstorf, interview 30 August 2010). This paper (Rahmstorf, 2007a) was published after the publication deadline required for inclusion in AR4. Since the paper could not be included in the report, Rahmstorf offered to provide some text and numerical estimates for sea level rise during the 21st century that would take into account changes in the ice sheets (interview, 30 August 2010). This offer was declined on the procedural grounds that it was new research, not an assessment of previously published material.

In contrast, the numbers ultimately presented by IPCC came from model-based projections of all components of sea level rise, adjusted to take account of recently observed dynamic behavior of the ice sheets. However, pressed by review comments, the authors made an additional correction to take into account the possibility of small increases in the combined dynamical contribution of ice from Greenland and Antarctica, but with no separate estimate for WAIS. This correction, which is not found in the Table SPM-3, was added to text of the Summary for Policy Makers.

Did developing such a number amount to new research, not previously published? It was clearly difficult to define the boundary between new research and what simply was a reorganization of previously published information. In general, IPCC numbers are held to particular standards, based on peer-reviewed literature and runs of elaborate models: there is a pedigree to these numbers that makes them acceptable for inclusion in a chapter. In IPCC reports, the standard scientific pedigree provided by peer review is combined with an IPCC-specific administrative deadline for publishing materials.

Moreover, with different writing groups focusing on different pieces of the complicated WAIS problem, it was difficult to achieve consistency among the chapters. Authors of different chapters informally worked with one another to tell a consistent story about ice sheets, but with many people involved and the coherence of several chapters at stake, making consistent decisions became difficult to manage.

Gregory is a renowned climate modeler at the University of Reading with a part-time appointment at the Hadley Centre, the UK's weather and climate research center. According to several of the scientists we interviewed, he was a pivotal actor, along with a few other lead authors, in the decision not to provide WAIS projections in AR4. Gregory was intimately involved in negotiations over the final text and table in the Summary for Policy Makers. We interviewed him in his office at the University of Reading, and he spoke quickly, covering rich technical and philosophical detail about the nuances of ice sheet modeling and the institutional machinations of the IPCC. He spoke about the break-up of WAIS and sea level rise into multiple chapters and the inordinate burden of work this put upon him: 'as a consequence of sea level being so many different places of course there was a new kind of coordination problem that hadn't existed in the previous reports in making sure that the right information was in all the chapters to tell a coherent story' (interview, 14 July 2009). IPCC authorships are notoriously work-heavy and this decision significantly increased that workload on the scientists covering the WAIS problem. For Gregory, one of the major consequences was that he ended up being a lead author, not only for chapter 10 on Global Climate Projections, but also for chapter 5 on Oceanic Observations, because he spent so much time working to make sure that the sea level rise stories told in different chapters were consistent with one another. He assumed an unofficial role as coordinator of sea level rise estimates, placing more work on him than either he or the IPCC had expected.

Susan Solomon, the co-chair of the AR4 Working Group I report, led the process that developed the proposed chapter organization for the report, later approved by the Panel. In an interview, she articulated her reasons for eliminating the sea level rise chapter, noting that 'there's no perfect way to slice the cake on any topic that has overlap.' She had hoped that the reorganization would help to articulate the specific research on sea level rise in various areas – modeling, oceans, and cryosphere. Solomon commented further that 'I think every assessment benefits by choosing to do that cross-cut [of chapter organization] in a slightly different way. So it was an experiment, maybe it was before its time and if so, then mea culpa, but it was done because I hoped it would allow us to really draw on the observation and build into the projections and in a sense that could have happened if the data and the physical understanding of rapid ice flow was stronger than it is' (recorded interview, Boulder, CO, 7 October 2010). In this statement, Solomon suggests that the weak data kept the experiment from working – ideally, her chapter organization structure would have led to a clearer picture of global sea level rise. We argue that the decision to reorganize assessment report chapters contributed to a reorganization of scientific content and the conclusions that the assessors are charged to develop and revise with each assessment report. This reorganization, coupled with leaps in knowledge about WAIS behavior, muddled the already highly uncertain characterization of projected WAIS futures.

A new view of the ice sheet

At the same time that the AR4 was being written, recent satellite remote sensing data radically changed the way the WAIS was perceived: despite earlier assertions by Mercer (1968, 1978), large parts of the ice community had considered WAIS to be a relatively stable feature. However, the balance shifted, and WAIS became generally viewed as more dynamic, and possibly on the whole or in part more unstable in the near term. Before it was possible to comprehensively retrieve and organize satellite imagery for Antarctica, it was difficult to 'know' the ice sheet in its entirety, though field glaciologists did their best. Between 1988 and 2001, Caltech glaciologists Barclay Kamb and Hermann Engelhardt, for example, selected a series of sites to drill boreholes down into the ice, taking samples and pictures down each hole (recorded interview, Pasadena, CA, 23 April 2009). Because a significant amount of the ice discharged from WAIS moves via ice streams, Kamb and Engelhardt selected their drill sites in relation to those features, in an effort to determine the speeds of particular ice streams, the materials at their base, and the speed and amount of water flowing underneath them. The samples and photographs documented the state of the ice stream at each borehole, close-up and at a particular moment, which was crucial for understanding how and why the ice moved on its bed. But, the next season or even the next week, the behavior of and ice stream and its under-ice water could change significantly, so that their measured properties would vary widely from location to location.[6]

Using satellites to take images of WAIS provided a new way to know the ice sheet. With these images, scientists could view the ice sheet in its entirety, examine complex systems of ice streams, and infer the location beneath the surface of interconnected watercourses as they repeatedly filled and drained (Fricker et al., 2007). Research programs were put into place to view and measure the ice streams and subglacial water day to day and year by year. Field glaciology research continues, building upon the pioneering work of Kamb, Engelhardt, and others, and complementing the bigger picture afforded by satellite remote sensing with an intimate look at the behavior of ice at specific locations.

Satellite images also showed observers that, to some extent, they were looking in the wrong place. Many of the rapid changes were occurring in the Amundsen Sea area, where no nation had permanent bases. David Vaughan described the consequences of viewing the first satellite results in the late 1990s:

> Everything changed, then, from not knowing where the changes were occurring and trying to battle on with understanding the processes, and just overnight it started to change. The interesting thing from the West Antarctic Ice Sheet point of view, was that unfortunately we'd all been working in the wrong areas … the US programme was essentially focused on the Siple Coast and the UK–European programme was based – focused – on the Filchner–Ronne Ice Shelf, areas around there. The one area we weren't looking at was the ice that flows out into the Amundsen Sea … it was a really sad thing because we had been missing it, because all of the action, essentially, most of the ice water was clearly coming from the Amundsen Sea. And there were good reasons why, it's a really hard place to get to, it's a long way from any of our logistic stations, it's – the weather is worse than it is on the Siple Coast, Filchner–Ronne, it was just

> hard to get there. But almost as soon as those results came out, we became convinced that we have tried to change the emphasis and get over into that Amundsen Sea embayment area. (Vaughan, recorded interview, Cambridge, UK, 17 July 2009)

These results now suggested areas of rapid change in the ice sheet where models had depicted its behavior as generally stable. Through the early 2000s, more information poured in, depicting an accelerating rate of change in the Amundsen Sea area. This had profound ramifications for how the ice model projections were perceived. Tony Payne said:

> Up until about ten years ago, there wasn't much data to test the ice sheet models, so everyone kind of assumed that they were going to be right. So, all of a sudden, more or less overnight, there was this huge amount of data from interferometry to radar altimetry to test the models. So when you looked at the models, you realised that none of the observations could be reproduced by the models, the large-scale, whole ice sheet models. (Payne, recorded interview, Bristol, UK, 10 July 2009)

More data led to more uncertainty, as observers gained an appreciation of how complex the system was and how much remained unexplained. This shift in thinking about the standard-bearing models was not universally accepted. Philippe Huybrechts put forward an alternative explanation for the failure of current observations to match his model: 'it may well be the weather of the ice sheets that no model can ever be expected to predict accurately' (recorded interview 3 July 2009). With the phrase, 'weather of the ice sheets', Huybrechts was referring to the smaller scale variabilities that occur anywhere, without producing longer-term patterns (which might be called the 'climate' of the ice sheets). But while Huybrechts defended his models, the net result of the new data was less overall confidence on the part of WAIS scientists that they understood what was going on with the ice sheet and that the models were reliable as predictive tools.

As the AR4 chapters were being finalized (and past the official publication inclusion deadline of 24 July 2006), WAIS experts were writing up their most recent research. Their articles contained findings from satellite-sensing studies of ice sheets and new projections of sea level rise that shifted previously held understandings of both, including that of WAIS (Pfeffer et al., 2008; Rahmstorf, 2007a; Rignot et al., 2008; Vaughan, 2008; Velicogna, 2009; Wingham et al., 2009). This new information was dramatically different from the projections provided by the continental-scale models, which were based on the shallow-ice approximation, and suggested that parts of the ice sheet were already transforming rapidly and that the risk of disintegration for a substantial part of the ice sheet was higher than indicated in recent assessments.

These new findings missed the deadline to be included in the assessment report, so the numbers given in Table SPM-3 and the companion text mentioned previously, the caveat in the table, and the related chapter material, reflect a state of very high uncertainty in scientists' understanding of WAIS. As is clear from the interviews with the participants, the decision not to address emerging findings was far from simple, but it hinged on maintaining IPCC protocols. Jonathan Gregory summarized:

> So it seemed to us that we just couldn't do it because the IPCC depends on using peer-reviewed results … so we've always had to do the projections, but we had to do the projections as far as possible, well entirely based on peer-reviewed, published methods. And there is no peer reviewed published method for making rapid dynamical change, the projected dynamical changes in ice sheets, so we couldn't do it. That was our judgment. So we had to say we can't do it, and we're not doing it, and they're not included. (Gregory interview, 14 July 2009)

According to Gregory, IPCC authors had to piece together sea level rise projections from an assortment of numbers, methods, and timescales available in the published, peer-reviewed literature (a situation replicated throughout the IPCC process as a standard task in scientific assessments). The IPCC authors were creating new numbers from numbers that were required to have a specific pedigree in order to be included. In Gregory's opinion, the textual caveat included with the table in the SPM was a strong statement suggesting that sea level rise could indeed be very high in the future, but he also acknowledges that 'of course, people like to look at numbers' (interview, 14 July 2009).[7]

Rahmstorf was asked by the German government to sit in their delegation during the negotiation of the SPM. In an interview, he remembered the negotiation process differently from Gregory and Solomon. The German delegation decided to speak forcefully against the text as it stood. However, Rahmstorf considered other SPM meeting participants to be actively working against German intervention in this case. In his account, there were 'procedural tricks and delays that [kept the German governmental delegation] stonewalled until the last night before the meeting concluded, when it was blocked with the argument that it was now too late to recalculate those numbers' (interview, 30 August 2010).[8] His concern was that the sea level rise estimate of 0.18–0.59 m by 2100, accompanied by the note that those numbers excluded rapid dynamical ice flow, was unclear. The exclusion wasn't a wholesale omission of all contributions from Antarctica and Greenland; instead, it omitted just what now looked like a significant part–future *changes* in the dynamical component.[9] Rahmstorf explains:

> We asked for that table to list the range completely without ice sheet contribution. And the reason for that was to make it more transparent what this range actually is, because in the discussions in Paris, it became evident that it is very unclear what is actually meant by excluding future rather dynamical changes in ice flow. Because it doesn't actually exclude all changes in ice flow, it just excludes kind of some part of it. And when, as the German delegation were asking Jonathan Gregory and the authors on the podium there, what actually is included technically and what is not, the answer was basically 'what is in the models', but nobody would tell us exactly what is in the models versus what is not in the models. (Rahmstorf, interview, 30 August 2010)

Note that Rahmstorf's key issue was not with the numbers, but with how the numbers were presented in the SPM text. In his account, the German governmental delegation provided alternative ways of presenting the information (or lack thereof) in ways that may have been more clear to the policymakers – the intended readers of the document.

Most of the scientists interviewed agreed that the way ice sheets were handled in AR4 was 'the right thing to do', and several went so far as it call the decision 'brave', or 'courageous' (Alley, interview 14 December 2009; Payne, interview 10 July 2009; Vaughan, interview 17 July 2009). They considered it brave because the authors were working against the unspoken expectation, from the IPCC community and the governments that supported it, to provide clear, ever-improving numerical projections reflecting the latest evidence.

Solomon was more matter-of-fact about the issue, stating that 'if the science doesn't allow you to give a number that means anything then you have no business giving it' (interview, 17 October 2010). She recalled that some governmental reviewers did indeed ask for more specific sea level rise numbers, and she joked about the vague comments: '"Please give us a number" – well thanks, but is it one or a million?' While surely the range was not as great as she suggested, for Solomon there was simply not enough information to pull any sort of realistic number into the text.

Glaciologists and ice modelers who were more removed from the Working Group I (WGI) SPM noticed ramifications of this decision as well. David Vaughan cited concerns about the 'legacy' left in the wake of this issue, particularly in the way it was interpreted in the media: that scientists could become less certain about serious concerns than they had been previously (interview, 17 July 2009). Modeler Tony Payne saw the outcome as an opportunity: once the IPCC authors claimed that they could not make projections involving dynamical ice changes, researchers suddenly were able to use that uncertainty to garner support for ramping up their modeling capabilities. The IPCC had proven that there was still a major, as-yet-unsolved problem (interview, 10 July 2009). In short, the people involved simply did not agree on how to interpret the decision to exclude a prediction from the report: it was courageous, it was a problem, or it was simply how it was.

Conclusions: Collapsing projections

The disintegration of WAIS projections in the AR4, compared with previous IPCC assessment reports, was the result of multiple forms of novelty colliding with one another: new data, new writing teams, higher visibility for the IPCC, and new structure for the report made an epistemic and institutional jumble for IPCC authors to try to deal with. While the authors agreed that the new data were the primary impetus for the collapse of consensus in this case, the ways in which people and chapters were organized accentuated the high degree of uncertainty surrounding WAIS.

IPCC reports have a specific sort of documentary life (Riles, 2006), as well as a specific and developing relationship with policymakers. IPCC assessment reports are written with the understanding that there will be subsequent IPCC reports. In this sense, IPCC reports are provisional. In addition, the ways in which chapters are organized, writing teams are formed and managed, and even how the various deadlines are set are as integral to the IPCC process as are the scientists and their publications.

As described in this paper, IPCC authors also sometimes *chose* to enable some projections while inhibiting others. Other writing teams had been able to make projections of some sort even when consensus was limited. For example, in the case of climate sensitivity, the authors showed the full, wide, divergent spectrum of plausible outcomes (Meehl et al., 2007: Box 10.2; Randall et al., 2007) and associated probabilities. Similarly, when assessing the combined ice sheet contribution to long-term sea level rise, Working Group II presented a range of potential outcomes and characterized its confidence in this assessment (Schneider, 2009). In contrast, the approach taken by Working Group I was to step back from presenting a wide range of possibilities. It would be necessary to study many more such cases and also to undertake a deep analysis of the way these assessments are taken up by the policy community to decide which approach is more efficacious.

The decision by the AR4 authors not to make a WAIS prediction emerged from the complex arrangements needed to write a scientific assessment, including the translational tuning necessary for relating data to models and for situating uncertain science into a policy-relevant document. Foucault (1977: 189) suggests that individuals within institutions become emplaced into a 'network of writing', becoming entrenched in practices and habits that create policies and other official documents. While the AR4 authors formed such a network, this configuration did not account for institutional misteps – states, bureaucracies, and chapter organization in scientific reports (Abrams, 1988; Ferguson, 1999; Mosse, 2004; Scott, 1998). In the WAIS example, the 'network of writing' struggled when the practices and habits of the institution changed, as well as when a radical shift occurred in the subject matter being written about.

The people interviewed about this case never mentioned pressure to come to a consensus, though they suggested various strategies for trying to come to an agreement. Perhaps the authors were correct in not trying to enforce consensus about the rapid disintegration of WAIS when it was clear that there was none (see Sarewitz, 2011). Alternately, the authors could have considered publishing the range of possible numbers and scenarios, highlighting their lack of consensus and the high uncertainty surrounding the rapid disintegration of WAIS.

How are models, assessments, and projections translated from science into policy-relevant documents? We argue that the institutions, such as the IPCC, are acting as the translators and mediators. By examining WAIS projections in IPCC reports – particularly the omission of a prediction in the most recent report – translation from science to policy is enabled as well as hindered by the IPCC institution, an important actor in this drama. In AR4, expert authors unmade WAIS projections, citing new data, a lack of consensus, and sheer ignorance. The authors also had to grapple with significant organizational challenges. The IPCC exists to enable production of climate change assessments in a credible manner, and it generally succeeds in doing so. However, the assessment reports shape and are shaped by processes meant to streamline and organize the writing process. Shackley (1997: 79) noted that concern over IPCC chapter writing groups and the IPCC peer review process mimics an 'enclave' with a tendency to 'close ranks' when faced with criticism. Elzinga (1996) stated that the IPCC's apparently closed assessment process can lead to epistemic and paradigmatic skewing. These processes have been subject to critique and review, most notably in the InterAcademy Council review published in 2010, following some errors detected in AR4 (Committee to Review the Intergovernmental Panel on Climate Change, 2010). The IPCC is an institution in the service of science and policy, and it borrows an admixture of organization styles from both.

Within the IPCC, authors, delegates, and IPCC employees use management strategies from both international diplomacy and scientific practice to create each assessment report, using hybrid management to deal with the complexities of research and policy-making in international governance (Miller, 2001, following Guston, 2001). Hybridizing the powerful regimes of international policy and science, though, requires significant translation between the subjective and contingent understandings of each. Such hybridization also falls under the mantle of 'science diplomacy', where scientific information is applied to policy goals (Skodvin, 2000).

These understandings are often particular to each chapter, despite the assumed cosmopolitanism of global governance and environmental science. The specific requirements upon participants within the IPCC institution – such as a prediction horizon of 2100 and publication deadlines – allow coherence among chapters but can also limit the ability to characterize the current state of the science.

Notes

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1. In the TAR, the potential importance of ice sheet dynamics in the 21st century was not anticipated. The potential contribution from the Greenland and Antarctic Ice Sheets to sea level rise in the 21st century was calculated using a model that does not represent such dynamical changes.
2. The reconciliation of the findings of Working Group I on sea level rise with those of Working Group II is beyond the scope of this article. While we chose to focus this case study on the decision by Working Group I not to include numerical estimates for sea level rise that include the WAIS, Working Group II came up with 'radically stronger conclusions' about this matter (Schneider, 2009: 194). Steve Schneider, a Working Group II author, spoke about this problem in his popular book, *Science as a Contact Sport*. In it, he says that he and Susan Solomon, the co-chair for Working Group I, finally worked out some text for the IPCC Synthesis report that rectified the two diverging outcomes. Much of their 'negotiations' were worked out 'at dinner at writing team meetings, and usually over a good bottle of red wine' (Schneider, 2009: 194). While the agreed-upon text was formally approved, this passage in Schneider's book underscores the usefulness of collegiality, friendship, and sociality in finding consensus.

   In an interview (Boulder, Colorado, 7 October 2010), Susan Solomon discusses the impact of less formal meetings such as the one described above: 'usually conversations on a less formal scale don't really solve issues. What they do is allow people to understand [the] other's point of view, at least in my own mind. Nothing changed, but maybe he understood me better about why I thought there was nothing in the literature and maybe I understood him better about where he was going to draw the boundary and what he was planning to do.'

3. The AR4 SPM put more emphasis on the potential long-term contribution from Greenland. The possibility of such a contribution from Antarctica as a whole is also noted, but no numerical estimate is provided.

4. M.A.W. Mahaffy wrote another very early three-dimensional continental-scale ice model code in the 1970s.
5. The Summary for Policy Makers (SPM) follows a slightly different schedule and involves a plenary session to approve the document.
6. Kamb and Engelhardt did use satellite imagery to avoid crevasses and choose study sites.
7. Gregory also was expecting more of a fight in getting the statement and table approved at the SPM Plenary, but the item came up quite late in the evening and was, surprisingly to Gregory, happily endorsed by the US and the UK.
8. In reviewing his quotations, Rahmstorf added (interview, 30 August 2010):

   This specifically concerned our proposal to communicate the uncertainty differently, namely to take the ice sheets out of the numerical range altogether. This actually would not have changed the numbers all that much – the ice sheet contribution is near zero in the IPCC range. But it would have been much clearer to say: this much is what you get without the contribution of ice sheets. Other suggestions by the German delegation that just concerned specific wording were taken up in the plenary, e.g. including in the heading of Table SPM.3 the words 'excluding future rapid dynamical changes in ice flow', and footnote 15 on page 14 (which was necessary to make the point that the AR4 models do not give lower SLR values than the TAR models).

9. Rahmstorf also wrote a detailed blog post on realclimate.org explaining how the AR4 came to the numbers that it did, and the problems with them (Rahmstorf, 2007b).

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Biographical notes

Jessica O'Reilly is an Assistant Professor of Anthropology in the Sociology Department at the College of Saint Benedict and Saint John's University. She is the author of 'Tectonic History and Gondwanan Geopolitics in the Larsemann Hills, Antarctica', in *PoLAR: Political and Legal Anthropology Review* (34(2), 2011) and is continuing her research on Antarctic environmental management and negotiations over climate science in the IPCC assessment process.

Naomi Oreskes is Professor of History and Science Studies at the University of California, San Diego. Her research focuses on the historical development of scientific knowledge, methods, and practices in the earth and environmental sciences, and on understanding scientific consensus and dissent. Her most recent work, *Merchants of Doubt: How a Handful of Scientists Obscured the Truth on Issues from Tobacco Smoke to Global Warming* (2010), co-authored with historian Erik M. Conway, was awarded the Watson-Davis prize of the History of Science Society and was a finalist for the *Los Angeles Times* book prize.

Michael Oppenheimer is the Albert G. Milbank Professor of Geosciences and International Affairs at Princeton University. He has been a contributing author, lead author, or/and coordinating lead author on the Second, Third, Fourth, and Fifth Assessments Reports of IPCC as well as a 2012 special report assessing adaptation to climate extremes and disasters.