PERSPECTIVES

CLIMATE CHANGE

How high will the seas rise?

Coastal defense measures must be flexible in the face of rising sea level estimates

By **Michael Oppenheimer**[1] *and* **Richard B. Alley**[2]

Recent estimates suggest that global mean sea level rise could exceed 2 m by 2100. These projections are higher than previous ones and are based on the latest understanding of how the Antarctic Ice Sheet has behaved in the past and how sensitive it is to future climate change. They pose a challenge for scientists and policy-makers alike, requiring far-reaching decisions about coastal policies to be made based on rapidly evolving projections with large, persistent uncertainties. An effective approach to managing coastal risk should couple research priorities to policy needs, enabling judicious decision-making while focusing research on key questions.

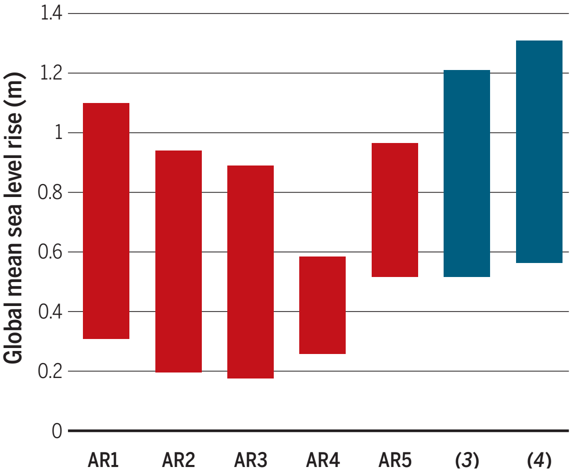
In a recent study, DeConto and Pollard used a model that combines ice-fracture processes with inferences from paleoclimatic data to estimate the Antarctic contribution to global sea level rise by 2100. For a high emissions scenario, they found this contribution to be as high as 78 to 150 cm (mean value 114 cm) (*1*). For the same scenario, the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) gave an Antarctic contribution of only –8 to +14 cm (mean value 4 cm) (*2*). Combining AR5 estimates for thermal expansion, mountain glaciers, the Greenland Ice Sheet, and land water storage with the Antarctic contribution from (*1*) yields a mean value of 184 cm for the total global sea level rise and an uncertainty range that extends above 2 m. Additional processes may increase or decrease local changes, but major coastal effects would occur almost everywhere (*3*).

These and other scientific developments (*1*, *3*, *4*) are emerging too fast to be captured by the comprehensive IPCC assessments, which are published every 6 to 7 years. Policy-makers are left without a means to contextualize recent estimates, which remain highly uncertain. Taking an engineering approach and defending against the highest projections available at a given time, plus a margin of error, can be prohibitively expensive. But ignoring such estimates could prove disastrous.

Furthermore, flood defenses take a lot of time and political will to implement. The construction of the Thames storm surge barrier and the ongoing strengthening of the Netherlands' sea defenses were both stimulated by a catastrophic 1953 storm in which more than 2000 people perished. Yet, the process of political consensus building, planning, finance, and construction took almost 30 years before the Thames barrier was complete (*5*)—and that was fast compared with some large infrastructure projects. Waiting another few decades to decide on specific adaptations in the hope that scientific predictions will become firmer may put completion off until the last quarter of this century. At that time, actual sea level rise could be approaching 2 m, with a much larger rise still to come.

The fall and rise of projected sea level rises

Sea level projections from models for year 2100 have changed markedly since the IPCC published its First Assessment Report (AR1) in 1990. Recent projections (*3*, *4*) are based on ice models and other approaches that may capture the ice sheet contribution better than in the past, but large uncertainties remain. For details see (*15*).



GRAPHIC: G. GRULLÓN/SCIENCE

CHANGING ESTIMATES

In the early 1980s, U.S. EPA projected a sea level rise of 144 to 217 cm by 2100 (*6*). From the late 1980s to the late 1990s, developments in numerical modeling of ice sheets undercut the notion that ice sheet instability would cause such rapid ice loss and sea level rise (*7*). Other sources of sea level change, particularly thermal expansion and mountain glacier retreat, dominated projections. The resulting estimates of total sea level rise were lower than before, as reflected by the projection in IPCC's AR1 of 31 to 110 cm (see the figure).

Fast forward another decade to IPCC's Fourth Assessment Report (AR4), and the field was in chaos due to emerging observations of the ice sheets. These led AR4's authors to refrain from a complete estimate of sea level rise because they could not constrain the effect of warming on ice sheet flow (*8*). Improved remote sensing and on-the-ground capability captured spectacular episodes of change, such as the collapse of most of the Antarctic Peninsula's floating Larsen B Ice Shelf and resulting acceleration of its tributary glaciers, acceleration of West Antarctica's Thwaites and Pine Island Glaciers, and ice loss in Greenland. These events were driven by similar dynamical processes that were not represented in ice sheet models, confounding attempts to project. Also troubling was the discovery that a few glaciers and ice streams on the periphery of East Antarctica are vulnerable to warming, adding additional meters to potential sea level rise beyond 2100 (*1*). These findings drove rapid improvements in ice sheet modeling and a renewed interest in paleoclimate analogs of a warming world, enabling IPCC to begin to quantify these uncertainties in AR5, although the models were still evolving. Since AR5, various improvements have been proposed for representing the ice sheet contribution to global mean sea level projections (*3*, *4*).

SOLVING THE ICE FLOW PROBLEM

The main reason for the difficulties in predicting sea level change is a limited understanding of ice flow. In many locations on the Greenland and Antarctic ice sheets, ice that is too thick to float rests on a bed below sea level. The ice thins as it flows toward the coast until it crosses the grounding line to form floating ice shelves. The latter, still attached to the main ice sheet, are restrained from flowing faster by friction at their sides or by local seafloor highs. Warming ocean water or air can thin ice shelves, reducing this lat-

Model projections suggest that global sea level could rise by 2 m or more by 2100. Such a rise would permanently submerge parts of coastal cities and regions unless costly defensive action, such as building sea walls, is taken. It would also vastly increase the area flooded temporarily during coastal storms. The image shows water crashing over the seawall in downtown Cedar Key, Florida, during Tropical Storm Andrea in 2013.

PHOTO: PAT BONISH/ALAMY STOCK PHOTO

eral and basal friction and speeding the flow of nonfloating ice into the ocean. This may trigger an unstable retreat of the grounding line in some cases. Recent advances in theory and modeling have produced credible descriptions of aspects of this behavior, which are now routinely incorporated into regional- and continental-scale ice sheet models used in projections. But the complexities of the ice sheet bed and ice interaction with the neighboring ocean make reliable prediction of unstable retreat very challenging.

At the same time, improved analyses of paleoclimate proxies indicate strongly that the sea surface was 6 to 9 m higher than today during the Last Interglacial (~130,000 to 116,000 years ago) (*9*). These high sea levels can only be explained through mass loss from the ice sheets in response to a sustained forcing that is likely to be exceeded before 2100 under high emissions pathways. The rate of this rise was geologically rapid but cannot be resolved to the century-or-less scale that is of greatest economic concern today.

Projections that sea level rise over the course of this century would remain below 1 m (*2*) hinged on the assumption that ice-shelf friction and other processes will continue to limit the rate of ice loss. However, beyond some threshold, especially if surface meltwater wedges open crevasses, the ice shelves may break off entirely to leave cliffs that calve icebergs directly. Taller cliffs are less stable. The tallest modern ice cliffs often persist months or longer between major calving events, but the larger stresses from taller cliffs might cause faster failure and retreat (*10*). Retreat of Thwaites Glacier in West Antarctica after future ice-shelf loss could generate such a high and potentially very unstable cliff. The study by DeConto and Pollard projected the onset of rapid ice sheet retreat around much of West Antarctica during this century after warming caused abundant meltwater in surface crevasses; the maximum retreat rate in these projections depends on uncertain assumptions, and a faster sea level rise might be possible (*1*).

RESEARCH PRIORITIES

Measurements of the Antarctic Ice Sheet and its surroundings continue to be sparse and difficult. Insufficient data limit physical understanding, in turn preventing accurate modeling. And, even under idealized conditions, efficiently solving the full fluid dynamic (Stokes) equations for ice flow presents numerical challenges. Recent reports (*11*, *12*) outline an integrated research program that targets these large uncertainties to understand by how much and how fast the sea level may rise. The Thwaites Glacier region appears to be the most likely place for rapid ice loss to drive sea level rise, motivating a combined modeling and observation effort to accurately characterize its bed, ice, ocean, and atmosphere.

Major retreat of Thwaites Glacier might not occur, or it might occur while maintaining an ice shelf at a rate that would be geologically rapid but not necessarily fast compared with societal ability to plan and adjust. But it is also possible that very fast retreat occurs, challenging adaptation capacity worldwide. High emissions scenarios foresee climate forcing well beyond that which occurred over the time span of the instrumental record. Models constrained against this record may therefore not capture future behavior. Even the paleoclimatic record may not capture both the size and rate of future warming, motivating the need for process understanding. Ice-shelf loss and cliff failure are most evident now along the Antarctic Peninsula and in Greenland. Process studies should also be conducted in these places.

POLICY IN THE INTERIM

There are better options for policy-makers than to play wait-and-see. Measures specifically designed with an eye toward evolving predictions include building defenses such as those in the Netherlands, which can be augmented over time (*13*); building structures resilient to periodic flooding; and retreat from exposed areas combined with enhancement of natural defenses such as wetlands. In flood-prone areas, perverse incentives, such as submarket insurance premiums, should be eliminated while substituting reduced premiums and other incentives contingent on property owners taking adaptive measures before disaster occurs. These measures would reduce the large expense now incurred for disaster relief and rebuilding.

Scientists can contribute to improving the basis for policy judgments by presenting policy-makers with projections that are as fully probabilistic as possible while also characterizing deep uncertainties, rather than just them handing the worst-case or most-likely estimates. Coastal protection is a risk management issue, and risks cannot be fully managed outside a probabilistic context. ■

REFERENCES AND NOTES

1. R. M. DeConto, D. Pollard, *Nature* **531**, 591 (2016).
2. J. A. Church *et al.*, in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. F. Stocker *et al.*, Eds. (Cambridge Univ. Press, Cambridge/New York, 2013), chap. 13.
3. R. E. Kopp *et al.*, *Earth's Future* **2**, 383 (2014).
4. M. Mengel, A. Levermann, K. Frieler, A. Robinson, B. Marzeion, R. Winkelmann, *Proc. Natl. Acad. Sci. U.S.A.* **113**, 2597 (2016).
5. O. A. Sayvetz, "A decision-making framework to support flood adaptation policy in New York City," thesis, Princeton University (2015).
6. S. J. Hoffman, D. Keyes, J. G. Titus, *1983, Projecting Future Sea Level Rise: Methodology, Estimates to the Year 2100, and Research Needs* (Environmental Protection Agency, Washington, DC, 1983).
7. J. A. Church, J. M. Gregory, in *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on*

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[1]*Department of Geosciences and the Woodrow Wilson School, Robertson Hall 448, Princeton University, Princeton, NJ 08544, USA.* [2]*Earth and Environmental Systems Institute and Department of Geosciences, 517 Deike Building, Pennsylvania State University, University Park, PA 16802, USA. Email: omichael@princeton.edu*

Climate Change, J. T. Houghton *et al.*, Eds. (Cambridge Univ. Press, Cambridge/New York, 2001), chap. 11.
8. IPCC, 2007: Summary for Policymakers, in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon *et al.*, Eds. (Cambridge Univ. Press, Cambridge/New York, 2007).
9. R. E. Kopp, F. J. Simons, J. X. Mitrovica, A. C. Maloof, M. Oppenheimer, *Nature* **462**, 863 (2009).
10. R. B. Alley *et al.*, *Annu. Rev. Earth Planet. Sci.* **43**, 207 (2015).
11. National Academies of Sciences, *A Strategic Vision for NSF Investments in Antarctic and Southern Ocean Research* (National Academies of Sciences, Washington, DC, 2015).
12. Royal Society London Workshop Report from West Antarctica and future sea-level rise: A workshop to identify priorities for research and collaboration in West Antarctica (Royal Society, London, 2016); www.istar.ac.uk/wp-content/uploads/sites/5/sites/5/2016/05/West-Antarctica-Royal-Society-Meeting-Report-final.pdf.
13. Delta Commission, "Working together with water. A living land builds for its future" (Findings of the Deltacommissie, 2008); www.deltacommissie.com/doc/deltareport_full.pdf.
14. S. Jevrejeva, A. Grinsted, J. C. Moore, *Environ. Res. Lett.* **9**, 1 (2014).
15. Model-based ranges of sea level projections by 2100 for high emissions scenarios from each IPCC assessment report were derived from figure 1 of (*14*). The upper end of the bar for AR1 has been modified to reflect the values actually published in AR1, rather than a sensitivity test published subsequently. The upper end of the bar for AR2 has been modified to reflect aerosol emissions in the IS92e scenario, rather than the constant-aerosol sensitivity test published in AR2 and reproduced in (*14*). In AR4, the numerical range given was qualified by the phrase "model-based range excluding future rapid dynamical changes in ice flow" to indicate that the value at the upper end of the AR4 bar is not a reasonable approximation of an upper bound to sea level rise. For AR5, the bar represents the 17 to 83% probability range. AR1 to AR3 used 1990 as the base year, whereas AR4 and AR5 used base periods 1980 to 1999 and 1986 to 2005, respectively. Two other recent estimates are shown (*3*, *4*), both using the 1986 to 2005 base period and an ice sheet treatment differing from AR5; neither account for the findings of DeConto and Pollard (*1*). Both estimates are for the 5 to 95% probability range. For (*3*), the 17 to 83% range is 62 to 100 cm. AR5 did not report a 5 to 95% range, and (*4*) did not report a 17 to 83% range.

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PLANT IMMUNITY

Starving the enemy

Plants respond to pathogen infection by relocalizing sugar from bacterial colonization sites

By **Peter N. Dodds** *and* **Evans S. Lagudah**

Plants are energy storage factories. Photosynthetic cells convert energy from sunlight to sugars that are transported to growing tissues via both extracellular and intercellular trafficking pathways. Many pathogens have evolved mechanisms to infect the nutrient-rich niche of plant tissues and exploit these sugar pipelines. Some pathogens manipulate sugar transport to enhance their access to carbohydrate. For example, *Xanthomonas* bacteria deliver transcription-activator–like effector proteins into leaf cells. These proteins induce expression of SWEET family sugar transporters to release sucrose into the apoplastic (extracellular) space where the bacteria grow (*1*). On page 1427 of this issue, Yamada *et al.* (*2*) show that, in return, plants can also regulate sugar transporters, to redistribute the sugars away from the infection niche, removing the pathogens' energy source and limiting their proliferation.

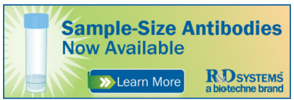
Plants respond to infection through an innate immunity system that uses both extracellular and intracellular receptors to detect pathogen components and trigger responses (*3*). Pattern recognition receptors (PRRs) expressed on the cell surface include flagellin-sensing 2 (FLS2), which recognizes bacterial flagellin, and chitin elicitor receptor kinase 1 (CERK1), which responds to chitin, a component of fungal cell walls (*4*). These receptor kinase molecules signal through interaction with the helper receptor kinase brassinosteroid insensitive 1–associated receptor kinase 1 (BAK1), which initiates a mitogen-activated protein kinase cascade and leads to responses including induction of defense gene expression, reactive oxygen species production, and stomatal closure.

Yamada *et al.* treated *Arabidopsis* plants with flg22, a fragment of bacterial flagellin recognized by FLS2, and found that hexose uptake from the apoplast increased as part of the induced defense response. This was mediated by the plasma membrane hexose sugar transporter 13 (STP13). Indeed, the *STP13* gene was expressed in leaf epidermal and mesophyll cells after flg22 treatment, but in addition, the transporter seems to be directly activated by phosphorylation. The authors observed STP13 interaction with several PRRs, including FLS2, as well as with the co-receptor BAK1, suggesting that it may be targeted by PRR signaling complexes. Indeed, the STP13 carboxyl-terminal cytoplasmic domain was an in vitro phosphorylation substrate of BAK1. A phosphomimic mutation of the target residue (threonine 485) resulted in enhanced glucose and fructose uptake rates for the transporter.

Yamada *et al.* further found that mutation of STP13 (and the constitutive hexose transporter STP1) increased hexose concentrations in leaf apoplast after flg22 treatment and enhanced growth of the pathogen *Pseudomonas syringae*. This was true even for a nonpathogenic *hrc* mutant strain that is incapable of delivering effectors into host cells. Expression of STP13–green fluorescent protein decreased bacterial growth, demonstrating the defensive value of induced hexose uptake in response to infection. However, an STP13 mutant with an altered BAK1 phosphorylation site failed to complement this phenotype, suggesting the importance of direct protein activation in the response. Overall, these findings show STP13-mediated hexose uptake as a basal pathogen resistance induced as part of pattern-mediated immunity. Cell wall invertase activity, which converts apoplastic sucrose into hexoses (glucose and fructose), was also induced by flg22, so the overall effect of this response is to remove a sugar source from the pathogen environment by sequestering it inside the host cells (see the figure). In addition to the nutritional effect on bacteria, Yamada *et al.* also observed increased induction of the type III secretion system in *P. syringae* infecting double *stp1stp13* mutant plants, suggesting that STP13 function may also contribute to suppressing bacterial virulence.

Partitioning of sugars between the leaf cell and apoplast may also be important for other pathogen interactions. One example is the enhanced infection of an *Arabidopsis stp13* mutant by the fungus *Botrytis cinerea* (*5*). Overexpression of STP13 reduced infection levels, suggesting a reliance on apoplastic sugars by this pathogen. However, no effects were observed for another fungus, *Alternaria*

Commonwealth Scientific and Industrial Research Organisation, Agriculture and Food, Canberra, ACT 2601, Australia. Email: peter.dodds@csiro.au



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Michael Oppenheimer and Richard B. Alley (December 15, 2016)

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