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Brief communication: Sea-level projections, adaptation planning, and actionable science

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Abstract.

As climate scientists seek to deliver actionable science for adaptation planning, there are risks in using novel results to inform decision-making. Premature acceptance can lead to maladaptation, confusion, and practitioner "whiplash". We propose that scientific claims should be considered actionable only after meeting a confidence threshold based on the strength of evidence as evaluated by a diverse group of scientific experts. We discuss an influential study that projected rapid sea-level rise from Antarctic ice-sheet retreat but in our view was not actionable. We recommend regular, transparent communications between scientists and practitioners to support the use of actionable science.

1 Introduction

Increasingly, climate research published in scientific journals is guiding adaptation planning and public discourse. Many communities are evaluating their vulnerability to climate change and identifying the actions needed to adapt. The stakes are high, since adaptation solutions can be expensive, politically difficult, socially inequitable, and ecologically disruptive. Meanwhile, scientific understanding of the impacts of climate change on humans and ecosystems is ever-changing, driven by advances in climate models, observations, and computing. Progress can be slow because of the complexity of interactions among the atmosphere, ocean, land, and cryosphere. Understanding comes in fits and starts, as replication of novel results leads to wider agreement. All predictions carry some uncertainty, which cannot always be quantified.

It is unsurprising, then, that interactions between scientists and practitioners[1] have been fraught with difficulties. For example, a recent global survey of practitioners (Hirschfeld et al., 2023) revealed widely varying approaches to identifying sea-level projections for planning, showing confusion in translating science into action. Practitioners are eager to use the best available science, but not all published research is actionable—that is, adequate for use in decision-making, in particular for adaptation planning and action. Acting prematurely on novel claims can lead to costly maladaptation and policy chaos. Scientists can lose credibility by too frequently modifying the information sought by practitioners; this is known as the "whiplash effect" (Revkin, 2008).

[1]We define practitioners as governments and other entities (or their representatives) that are responsible—legally or otherwise—for developing, implementing, and managing adaptation measures to protect people, infrastructure, assets, and communities. Practitioners include local, state/provincial, and national governments, land managers, corporations, and other public or private sector entities with assets at risk.

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Actionable science was first defined in the climate context in 2009 by members of the Water Utility Climate Alliance to explain to the scientific community the importance of distinguishing novel hypotheses in research literature from information appropriate to drive adaptation. They defined actionable science as "data, analysis, and forecasts that are sufficiently predictive, accepted, and understandable to support decision-making, including capital investment decision-making" (Behar, 2009). This term has been widely adopted in the science, government, and adaptation communities (e.g., U.S. Army Corps of Engineers, 2012). The definition hints at the kind of knowledge appropriate for driving adaptation action ("sufficiently accepted"), but does not guide practitioners in how to identify this knowledge.

Our goal is to offer such guidance and thus reduce the possibility of harm (financial, aesthetic, social, and environmental) from the misinterpretation of science. We first discuss science and epistemology—the study of how we know what we know. Drawing on ideas from the philosophy of science, we describe the creation of knowledge as a community process of which peer review is only one element. We propose epistemic criteria for identifying actionable scientific claims. We then present a case study, describing an influential paper (DeConto and Pollard, 2016) that projected rapid sea-level rise from Antarctic ice-sheet retreat but in our view fell short of being actionable, both in real time and in retrospect. We conclude with recommendations for scientists and practitioners.

2 Science and epistemology

How do scientists create knowledge? Popular accounts often describe a series of discoveries by lone geniuses. This is an inaccurate description of scientific practice, especially since the emergence of large-scale, publicly funded science in the second half of the 20$^{\text{th}}$ century. Furthermore, many philosophers of science—including Helen Longino, from whose work (Longino, 1990) we draw here—would say that this picture fails to explain how science can be objective. She has argued that if scientists were not organized in communities, they would not be able to evaluate hypotheses in a way that leads to greater understanding and more reliable predictions over the long run.

Longino (1990) emphasizes that scientific knowledge is social knowledge; it is created by many people working together through "the clashing and meshing of a variety of points of view" (p. 69). Publication in a peer-reviewed journal does not make an idea "a brick in the edifice of knowledge" (p. 69). The critical treatment of ideas after publication is just as important, because it allows other scientists to challenge background assumptions, assess how well the current evidence supports a hypothesis, and gather new evidence that can confirm or refute it. This critical treatment requires cognitive diversity—that is, a wide range of disciplinary backgrounds, research skills, and problem-solving strategies (Rolin et al., 2023). As different points of view are offered and heard, the community can sift out individual biases and reach a more objective consensus.

Longino asserts that this process is essential to building knowledge but is "de-emphasized in a context that rewards novelty and originality" (p. 80). In other words, the professional rewards for publishing bold claims often exceed the rewards for determining whether those claims are justified. She argues that "critical activities should receive equal or nearly equal weight to 'original research' in career advancement" (p. 76).

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Although space does not allow us to defend these arguments in detail, they are consistent with recent work in the philosophy of science (see, e.g., the overviews by Longino (2019) and Rolin et al. (2023)) and with our own experience of doing science and observing scientists. We think Longino's analysis is especially relevant for climate science and adaptation planning.

The peer-reviewed journals that publish leading-edge climate research can be roughly divided into two groups. First are the disciplinary journals overseen by geoscience organizations such as the European Geosciences Union and the American Geophysical Union. Second are the "high-impact" multidisciplinary journals, including *Nature* and *Science*. Both sets of journals prioritize substantial, original research. There are greater professional rewards, however, for publishing in high-impact journals, which have wider audiences and favor work that is seen as novel and newsworthy. These journals are less likely to publish negative results—for example, the finding that a certain climate feedback is insignificant—even when the results are scientifically important and methodologically sound (Mehta, 2019).

Practitioners typically learn of scientific advances through media coverage of new studies in high-impact journals. These studies are often accompanied by press releases casting the work in a dramatic light. This creates risks for practitioners. If they rely on media accounts for the "best available science", they may give undue weight to worst-case scenarios. And if they regard high-impact claims as immediately actionable, they short-circuit the critical process needed to transform novel hypotheses into accepted knowledge.

For adaptation planning, the scientific assessments of the Intergovernmental Panel on Climate Change (IPCC) are more reliable than single studies. These assessments are directed mainly to policymakers but are read by practitioners with an eye toward what is actionable. IPCC policies and procedures (IPCC, 2013) have evolved over several assessment cycles to determine the state of knowledge on climate change as accurately as possible. In particular, the IPCC gives voice to many viewpoints. Author teams are assembled with a range of scientific opinions and expertise, incorporating geographic diversity and gender balance. These teams carry out open, transparent reviews of all available literature. As a result, it is less likely that questionable assumptions will go unchallenged or pertinent evidence overlooked.

The IPCC has also developed consistent ways to describe scientific uncertainty. The guidance note of Mastrandrea et al. (2010) sets forth two metrics for communicating uncertainty: (1) quantified measures, expressed probabilistically, and (2) "confidence in the validity of a finding", expressed using the qualitative descriptions "high", "medium", and "low". Confidence derives from two sources: the "type, amount, quality, and consistency of evidence (e.g., mechanistic understanding, theory, data, models, expert judgment) and the degree of agreement" [2].

According to this guidance, evidence is most robust when there are "multiple, consistent independent lines of high-quality evidence"—e.g., evidence from a combination of global climate models, detailed process models, paleoclimate proxy data, and historical observations. Winsberg (2018) gives the example of equilibrium climate sensitivity (ECS). Two climate models computing a similar ECS might not be independent; they might agree, for example, because they have similar but erroneous

[2] Unlike Mastrandrea et al. (2010), we will refer to evidence but not agreement as a source of confidence. As Rehg and Staley (2017) have pointed out, "agreement" could refer either to a social consensus among scientists or the degree to which different research findings converge in supporting a hypothesis. These authors argue that social consensus is neither necessary nor sufficient for confidence and that in practice, the IPCC defines agreement in the second sense. For this reason, we have taken "consistency" to imply convergence of findings, instead of treating agreement as separate from evidence.

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cloud feedbacks. In this case, paleoclimate data and instrumental records are valuable independent constraints, because their uncertainties are distinct from model uncertainties. If three independent methods agree that ECS is within a certain range, it is hard to explain why all three would have large errors in the same direction.

The IPCC guidance states further that the presentation of low-confidence findings "should be reserved for areas of major concern, and the reasons for their presentation should be carefully explained". One reason to present a low-confidence claim might be that it has gained currency in the scientific community despite a lack of high-quality evidence. It is better to discuss such a claim, including the gaps in the evidence, than to disregard it. Based on philosophical accounts of knowledge creation from Longino and others, along with the risks of acting prematurely without robust evidence, we suggest that in most cases, the low-confidence findings in IPCC reports are not actionable. This suggestion is not absolute: Given two possible actions with similar costs—for example, building a new facility either 2 m or 3 m above current sea level—it might be prudent to guard against unknown risks by opting for higher ground. But we caution against basing broad policies on low-confidence science; we give some examples in Section 3.

These philosophical accounts, combined with IPCC practices, point the way toward an epistemic criterion for actionable science. We propose the following: *A scientific hypothesis is sufficiently accepted for use in decision-making when it is supported by multiple, consistent independent lines of high-quality evidence leading to high or medium confidence, as determined by a diverse group of experts in an open, transparent process.* This criterion reflects Longino's view that scientific knowledge is created by communities and that peer-reviewed hypotheses must be scrutinized by a diverse group of scientists before they can be considered robust. The criterion also gives practitioners a clear and consistent way to evaluate whether claims are actionable. It is based on existing practices and does not require scientists to learn new ways to assess the literature.

In the next section we show how this criterion might be applied in practice. We discuss a hypothesis that was deemed actionable for practitioners but lacked community confidence, resulting in confusion and backtracking.

3 Ice-sheet and sea-level projections

Global mean sea level is rising by about 3.7 mm yr^{-1}, mainly because of ocean thermal expansion and the loss of land ice, including the Greenland and Antarctic ice sheets (GrIS and AIS) and mountain glaciers (Fox-Kemper et al., 2021). Uncertainty in long-term sea-level projections is dominated by the AIS, which contains marine-grounded ice that is vulnerable to retreat under climate warming. If melted, this ice could raise sea level by several meters.

The IPCC Fifth Assessment Report (AR5; Church et al., 2013) projected global mean SLR of 0.52–0.98 cm by 2100 in a scenario with high greenhouse gas emissions (RCP8.5). The authors cautioned that the high end of this range was not an upper bound, because it excluded the possible collapse of marine-based sectors of the AIS. A few years later, DeConto and Pollard (2016) (hereafter DP16) published a study in Nature arguing that AIS mass loss alone could raise global sea level by more than 1 m by 2100 and more than 15 m by 2500. They were motivated by paleoclimate records showing that mean sea level during the mid-Pliocene (3 million years ago, when temperatures were about 3°C above present-day values) was 5–20 m higher than today (Fox-Kemper et al., 2021). They proposed mechanisms that could account for Pliocene SLR and possibly drive future

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SLR: atmospheric warming leading to hydrofracture of floating ice shelves, followed by the failure of marine-terminating ice cliffs (also known as Marine Ice Cliff Instability, or MICI). In simulations of the past and future[3], they found rapid SLR in runs with MICI, but not without. In high-warming scenarios with MICI, the rate of global SLR due to West Antarctic Ice Sheet (WAIS) collapse reached 20 mm yr^{-1} by 2100 and more than 40 mm yr^{-1} by 2150. In runs with ocean warming only—i.e., without strong atmospheric warming followed by cliff failure—WAIS retreat and GMSL rise were more than an order of magnitude slower.

DP16 has been highly influential. It received more news and social media attention in 2016 than any other climate paper published that year (McSweeney, 2017) and has been cited more than 1000 times in peer-reviewed journals. Since the paper was published, it has drawn scientific criticism—appropriately so, since this is part of the scientific process. It has also figured prominently in adaptation planning—less appropriately, since it was treated as actionable before receiving broad critical treatment from other scientists. Here, we contrast the reception of DR16 by scientists with the way it was communicated to practitioners.

The DP16 argument can be summarized as follows: Hydrofracture and MICI can explain large Pliocene SLR; therefore we can expect large, rapid SLR in a future climate similar to the Pliocene. Several background assumptions are at work here: that Pliocene SLR is not explained by other processes; that the DP16 ice sheet model accurately simulates hydrofracture and MICI; and that ice shelves could collapse quickly (before 2100) in a warming climate. Each assumption has come under scrutiny. MICI has not been observed for present-day Antarctic ice shelves, and thus the collapse rate in the model is poorly constrained. Reese et al. (2018) argued that the model's treatment of the grounding line (the boundary between grounded and floating ice) is inaccurate for most ice shelves. Edwards et al. (2019) showed that for Pliocene SLR up to 15 m—within the uncertainty range—processes other than MICI could explain the paleo record. Bassis et al. (2021) developed a mechanistic model in which cliffs collapse catastrophically only over a restricted range of ice configurations. In a follow-up to DP16, DeConto et al. (2021) revised the atmospheric forcing, delaying hydrofracture and lowering the projected 21st century SLR contribution, even if MICI is active.

Initial media reports, on the other hand, glossed over the uncertainties in DP16, with dramatic headlines such as "Climate Catastrophe, Coming Even Sooner?" (Kolbert, 2016) and "Scientists nearly double sea level rise projections for 2100, because of Antarctica" (Dennis and Mooney, 2016). The latter headline is misleadingly ambiguous, since "Scientists" could refer either (correctly) to the authors of the paper or (incorrectly) to the broader scientific community. The *New York Times* compared the results to "the plot device of a Hollywood disaster movie" (Gillis, 2016). The general message was that a new peer-reviewed study had overturned the community consensus.

Publications aimed at coastal adaptation planners soon adopted the DP16 projections. Perhaps the most influential was Sweet et al. (2017) (hereafter S17) a multi-agency U.S. government report on future SLR. S17 sought to "support a wide range

[3]In addition to the Pliocene, DP16 simulated the AIS during the Last Interglacial (LIG), when global mean air temperatures were similar to today and GMSL was 5–10 m higher. Since the LIG atmosphere was too cool to trigger shelf collapse, these simulations required Southern Ocean warming of at least 3°C to drive WAIS retreat. DP16 suggested that regional ocean warming might have warmed the overlying atmosphere and thereby amplified ice loss, but in this case the atmosphere was not the primary driver.

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of assessment, planning, and decision-making processes", signaling the aim to influence practitioners. To be consistent with "recent updates to the peer-reviewed scientific literature", they issued an "Extreme" global mean sea-level projection of 2.5 m by 2100 for RCP8.5, exceeding the previous upper bound of 2.0 m based on Pfeffer et al. (2008). Their Extreme projection relied on a large AIS contribution, based primarily on DP16 [4].

DP16-based projections also were included in several reports commissioned by local and state jurisdictions for use by adaptation planners: "Climate Ready Boston" (Boston Research Advisory Group, 2016), "Rising Seas in California" (Griggs et al., 2017), and the "Unified Sea Level Rise Projection: Southeast Florida, 2019 Update" (Southeast Florida Regional Climate Change Compact Sea Level Rise Work Group (Compact), 2020). The Boston report relied on DP16, published just a few months earlier, for its "maximum possible" regional projection of 3.2 m SLR by 2100 under RCP8.5. In the recent global survey of more than 250 jurisdictions (Hirschfeld et al., 2023), this was the highest figure recommended for planning. The California report recommended use of a 2100 high-end projection of 3.1 m for San Francisco, based on 2.5 m of GMSL rise plus regional factors. This projection was incorporated a year later in official guidance (California Ocean Protection Council, 2018); the high-end estimate was to be applied to any assets whose failure "would have considerable public health, public safety, or environmental impacts". The Southeast Florida report did not cite DP16 but relied on S17 to develop its high-end, 2100 SLR projection of 2.61 m, calling it "the best available research" and "a reliable source of data from the national effort on sea level rise projections".

Recent community assessments have taken a broader view, citing DP16 but also considering subsequent critiques and recent modeling studies. The IPCC Sixth Assessment Report (AR6; Fox-Kemper et al., 2021) included two sets of high-end sea-level projections: one based on models with physical processes that are understood with at least medium confidence (e.g., Levermann et al., 2020, Edwards et al., 2021), and the other including low-confidence processes such as MICI. AR6 classified MICI as a deeply uncertain, low-confidence process because there is no accepted theory of its exact mechanism and limited evidence that MICI has taken place in the past or present. Similarly, AR6 ascribed low confidence to the Structured Expert Judgment (SEJ) study of Bamber et al. (2019) because it was unknown how many experts included low-confidence processes in their estimates. The low- and medium-confidence projections differ considerably. Under a high-emissions scenario (SSP5-8.5), the 95^{th} percentile upper bounds of SLR by 2100 are 1.6 m and 2.4 m for medium-confidence and low-confidence processes, respectively. The gap between medium and low confidence widens by 2150, with respective 83^{rd} percentile upper bounds of 1.9 m and 4.8 m. We suggest that in most cases, the low-confidence projections are not actionable.

Notably, AR6 does not rule out large 21^{st} century SLR contributions from low-confidence processes; the medium-confidence projections exclude MICI but do not assess its likelihood. The study of van de Wal et al. (2022) made a stronger and possibly

[4] The 2.0 m upper bound of Pfeffer et al. (2008) assumed large contributions from both ice sheets: 0.54 m from the GrIS and 0.62 m from the AIS. In AR5, Church et al. (2013) estimated a likely upper bound of just 0.21 m for the GrIS, since process models do not support "the order of magnitude increase in flow" in Pfeffer et al. (2008). To reach an upper bound of 2.0 m or more, S17 therefore needed an increased AIS contribution of ∼1.0 m or more. To support this increase, they cited DP16 along with the expert-judgment assessment of Bamber and Aspinall (2013). However, the latter study gave a high-end (95^{th} percentile) estimate of 0.84 m SLR from the two ice sheets, less than Pfeffer et al. (2008). Other studies cited by S17 did not give independent evidence of a large AIS contribution. Thus, both the "High" projection of 2.0 m and the "Extreme" projection of 2.5 m in S17 relied on DP16's claim that the AIS could contribute at least a meter of SLR by 2100.

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more helpful claim: that under 5°C of warming, as might occur under SSP5-8.5, there are no physically plausible processes that would raise sea level by more than 1.27–1.55 m before 2100. The higher value is the sum of contributions from thermal expansion (0.36 m), glaciers (0.27 m), the GrIS (0.29 m), the AIS (0.59 m), and land water storage (0.04 m), assuming perfect correlation between all contributions, while the lower value assumes independent contributions. These estimates are based on a variety of physical arguments, including a judgment that large ice shelves are unlikely to collapse during this century, and therefore widespread MICI before 2100 can be ruled out. The authors did not assign a confidence level, but drew on multiple lines of evidence suggesting medium confidence.

Figure 1 shows a number of high-end sea-level projections going back to 2012, drawn from community assessments and practitioner-oriented reports. "High-end" does not have the same meaning in all cases, but typically refers to scenarios judged to be physically plausible (though not likely) and/or with an estimated probability of ∼1–5%, assuming high emissions and warming (e.g., RCP8.5 or SSP5-8.5). The projections are shown in three groups: (1) assessments and reports published before 2016, (2) S17 and other reports that were published in 2016–2020 and relied on DP16 for the AIS contribution, and (3) reports and assessments since 2020. Group 2 stands out with projections of well over 2 m, which were excursions from a relatively stable base of projections near or below 2.0 m. For example, the two broad surveys by Horton et al. (2014, 2020) gave similar high-end projections of 1.5 m and 1.65 m. The smaller values in Group 3 reflect lower confidence in MICI and (in van de Wal et al. 2022) a desire to reduce chaos for practitioners by basing high-end estimates on physical plausibility supported by multiple lines of evidence. The steep rise and fall linked to DP16 illustrate the whiplash effect, which ill serves adaptation planners (Boyle et al., 2022).

Sweet et al. (2022), the successor report to S17, removed the Extreme projection of 2.5 m because it is now "less plausible" but retained a High projection of 2.0 m, based in part on DeConto et al. (2021) and Bamber et al. (2019). The latter study projected high-end SLR of 1.78 m from ice sheets by 2100, with an unquantified but probably substantial contribution from MICI [5]. Since these studies relied significantly on low-confidence processes, we think the High projection of Sweet et al. (2022) should not be considered actionable. Practitioner guidance that will apply to a broad range of assets will be more defensible if it adopts a high-end value closer to 1.5 m, as in AR6 and van de Wal et al. (2022).

[5] The experts surveyed by Bamber et al. (2019) did not identify the specific processes leading to ice loss, but a majority (14 of 22) of their high-end estimates for WAIS discharge by 2100 were at least 0.5 m, suggesting a primary role for MICI. This study, we would argue, also does not meet our diversity criterion, since the published projections were based on only eight surveys, with two surveys receiving a combined weight of 58%. The other surveys were culled based on responses to "seed questions" whose relationship to projection skill is unclear.

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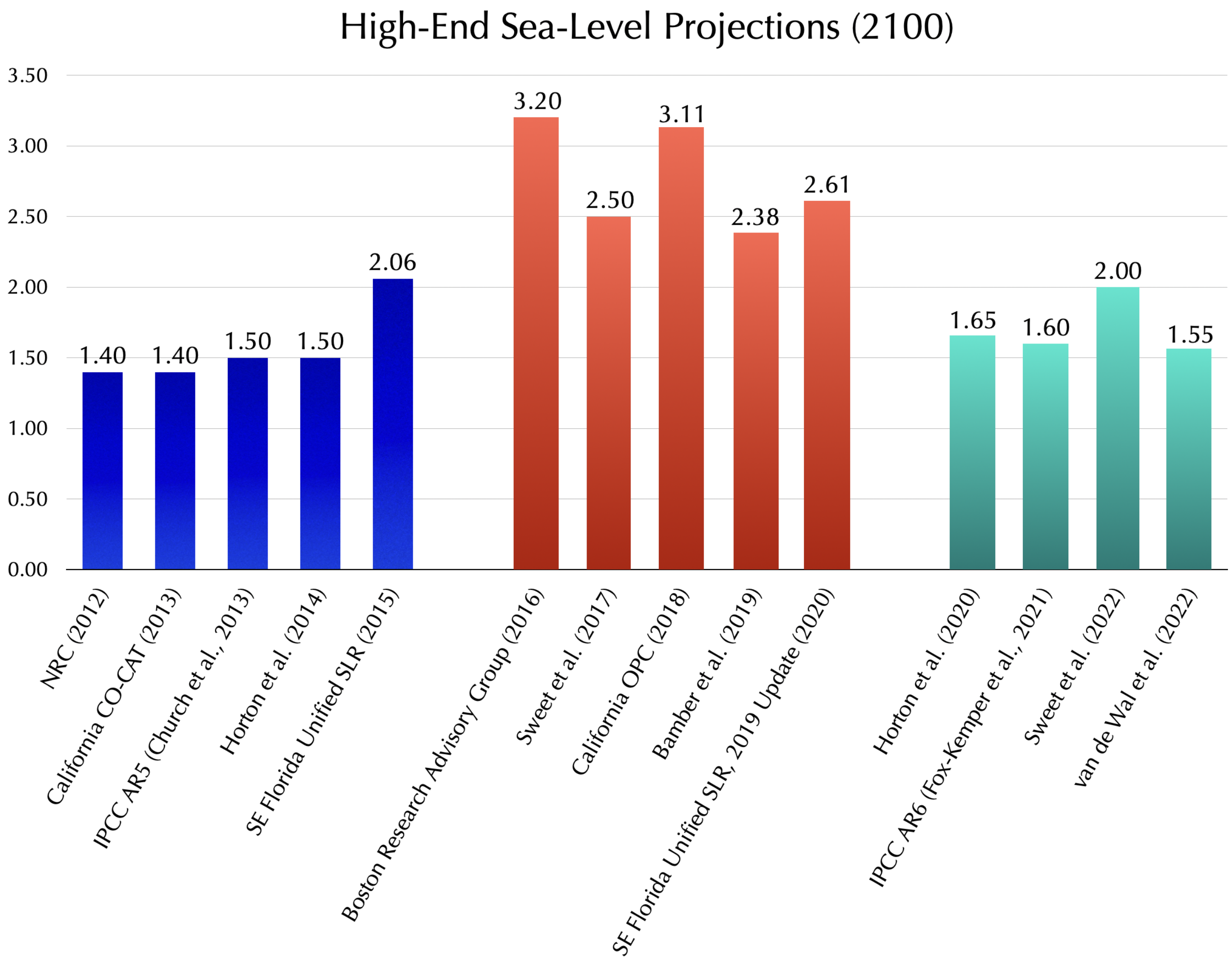

Figure 1. High-end projections for sea-level rise (m) by 2100, arranged chronologically: (1) community assessments and practitioner-oriented reports published before 2016 (blue), (2) reports and assessments that were published in 2016–2020 and relied on DP16 (red), and (3) recent reports and assessments (green) that either did not use DP16 or placed lower confidence in its projections. (Sweet et al. (2022) included MICI at a reduced rate, as described in the text.) Most projections are for global sea-level rise, although some jurisdictional reports (e.g., the 2016 Boston and 2018 California reports) include regional effects as well. The 2018 California value is for the San Francisco tide gauge. The AR6 value is the 95th percentile upper bound based on medium-confidence processes. The van de Wal et al. (2022) value is the upper value in their high-end range, assuming perfect correlation between components. Baseline dates vary but typically are around the year 2000.

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4 Recommendations

We have proposed an epistemic criterion for actionable science: A scientific hypothesis is sufficiently accepted for use in decision-making (i.e., is actionable) when it is supported by multiple, consistent independent lines of high-quality evidence leading to high or medium confidence, as determined by a diverse group of experts in an open, transparent process. This criterion is informed by IPCC practices and by philosophical arguments that scientific knowledge is social knowledge.

We think that scientists have a professional duty, when presenting new results, to put them in context and acknowledge uncertainties. When reporting on new results, journalists should seek a range of opinions to identify what remains unsettled. Journalists should also be mindful that not all breakthroughs are communicated through single studies in high-impact journals with bold press releases. Some breakthroughs emerge from multiple independent studies that support one another. Others are not evident at the time of publication, but only in hindsight with community corroboration of novel results.

We recommend that practitioners view novel peer-reviewed claims with caution, especially those that contradict the scientific consensus. They should be aware of these claims but not treat them as actionable before they are vetted by the science community. Practitioners can reduce the risk of maladaptation and whiplash through careful reading of IPCC reports and other community assessments, focusing on findings that are affirmed with confidence after critical review. We suggest that the IPCC medium-confidence sea-level projections are actionable, but not the low-confidence projections that include deeply uncertain processes such as MICI.

We seek to make the sea-level assessment process as objective as possible, insulated from social or political pressure to make projections that are higher or lower than justified by scientific knowledge. There may be pressures to reduce sea-level projections to minimize adaptation costs and political difficulties. We have also observed pressures to adopt extremely high projections, perhaps to motivate mitigation action or get practitioner attention. Divorcing the development of actionable science from both of these dynamics can prevent multiple risks, including maladaptation, loss of scientific credibility, and undermining of the adaptation enterprise.

We recommend that scientists and practitioners work together to better manage the boundary between research and decision-making. Regular and intentional communication between these groups can reduce confusion and minimize the risk of maladaptation. Organizations such as the Practitioner Exchange for Effective Response to Sea Level Rise (PEERS), formed in part to create practice-centered collaboration with a diverse group of scientific experts, can promote understanding of actionable science where that understanding is most needed. There is a careful dance between research and practice that can succeed with clear ground rules and open communication.

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