https://doi.org/10.5194/tc-2021-175
Preprint. Discussion started: 21 June 2021

The Cryosphere
Discussions

Brief communication: A roadmap towards credible projections of ice sheet contribution to sea-level

Andy Aschwanden[1,*], Timothy C. Bartholomaus[2,*], Douglas J. Brinkerhoff[3,*], and Martin Truffer[1,*]
[1]Geophysical Institute, University of Alaska Fairbanks. Fairbanks, Alaska. USA
[2]Department of Earth and Spatial Sciences, University of Idaho. Moscow, Idaho. USA
[3]Department of Computer Science, University of Montana, Missoula, MT, USA
[*]These authors contributed equally to this work.
Correspondence: Andy Aschwanden (aaschwanden@alaska.edu)

Abstract.

Accurately projecting mass loss from ice sheets is of critical societal importance. However, despite recent improvements in ice sheet models, our analysis of a recent effort to project Greenland's contribution to future sea-level suggests that few models reproduce historical mass loss accurately, and that they appear much too confident in the spread of predicted outcomes. The inability of models to reproduce historical observations raises concerns about the models' skill at projecting mass loss. Here we suggest that the future sea level contribution from Greenland may well be significantly higher than reported in that study. We propose a roadmap to enable a more realistic accounting of uncertainties associated with such forecasts, and a formal process by which observations of mass change be used to refine projections of mass change. Finally, we note that tremendous government investment and planning affecting 10s to 100s of millions of people is founded on the work of several tens of scientists involved in a significantly volunteer effort. To achieve the goal of credible projections of ice sheet contribution to sea-level, we strongly believe that investment in research must be commensurate with the scale of the challenge.

1 Sea level rise predictions from ice sheet loss

Global sea level rose during the 20th century more than 3 times faster than at any time during the last 2,000 years (Kopp et al., 2016). Over the last several decades, mass loss from the Greenland Ice Sheet has been the fastest growing contributor to this rise (Chen et al., 2017; Rietbroek et al., 2016). Sea level rise driven by global warming is expected to continue over the coming century, potentially flooding 14–322 million people per year in 2100, and reducing annual global gross domestic production by as much as 9% (Hinkel et al., 2014).

To guide planning for and mitigation of anticipated damages, the Intergovernmental Panel on Climate Change (IPCC) is poised to make a new suite of sea level rise projections for the remainder of the 21st century: its sixth assessment report (AR6). Effective planning for coming sea level rise necessitates that these estimates be accurate, but also that they be accompanied by a defensible assessment of uncertainty (Moon et al., 2020).

Recently, the global ice sheet modeling community has come together through a largely volunteer effort to support the AR6 and meet the need for projections of ice sheet change and attendant sea level contribution. This effort, the Ice Sheet Model

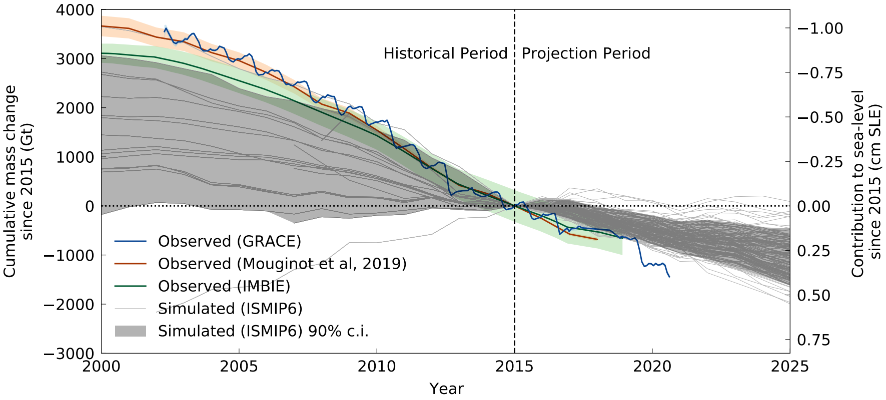

Figure 1. Observed and simulated historical mass changes from the Greenland Ice Sheet 2000–2020 in gigatons (Gt) and centimeters of sea level equivalent (cm SLE). GRACE and GRACE-FO JPL RL06Mv2 Mascon Solution (Wiese et al., 2020) (blue), reconstruction from Mouginot et al. (2019) (red) and a consensus estimate (The IMBIE Team, 2019) (green), and their respective uncertainties (shaded). ISMIP6 Goelzer et al. (2020) historical simulations and projection (gray lines) and the 90% credibility interval (light gray shading). The 90% credibility interval of ISMIP6 barely overlaps with observations.

Intercomparison for CMIP Phase 6 (ISMIP6) (Nowicki et al., 2016; Seroussi et al., 2020; Goelzer et al., 2020) represents the most impressive assembly of state-of-the-art models, initial conditions and boundary conditions to date. Through generous collaboration and leadership, 21 groups from around the world contributed 37 different models of Greenland and Antarctic Ice Sheet change through a set of core and optional experiments, and corresponding historical simulations. ISMIP6 produced probabilistic distributions of projected sea level contribution under the frequentist assumption that, with enough independent estimates of sea level contribution (i.e., different models and experiments), the sampled distribution of sea level contribution approximates the true distribution. Implicit in this approach is the assumption that the ensemble of ice sheet models perfectly spans, without bias, the range of potential sea level contribution. This ISMIP6 distribution has since been adopted as the foundation for the IPCC AR6 consensus estimate of sea level contribution from ice sheets. However, we believe that these results may not be accurate, and that the accompanying uncertainties do not reflect the true breadth of uncertainties associated with ice sheet change. We therefore argue that great care should be used in their practical application and in decision making.

Our skepticism regarding the ISMIP6 projections is based on the premise that accurate predictions of the cryosphere's contribution to sea level require that models:

1. Fully characterize uncertainties in model structure, parameters, initial conditions, and boundary conditions.
2. Yield simulations that fit observations within observational uncertainty.

If the first point is not satisfied, then predictive uncertainties are likely to be underestimated. If the second condition is not satisfied, then the distribution of model predictions are likely to be biased relative to reality. Our concern that the ISMIP6 ensemble satisfies neither condition is illustrated by comparing simulations of mass loss from the Greenland Ice Sheet be-

https://doi.org/10.5194/tc-2021-175
Preprint. Discussion started: 21 June 2021

tween 2000 and 2025 (Goelzer et al., 2020) with three independent observations of mass loss (Wiese et al., 2020; Mouginot et al., 2019; The IMBIE Team, 2019) (see Methods for details). A clear picture emerges (Figure 1): First, most simulations underestimate recent (2008–2020) mass loss. Indeed, the observed record of mass loss lies outside the 90% credibility interval of the ISMIP6 experiments, violating our second requirement. Underestimating recent mass loss likely translates into underestimating mass loss at 2100 as well. Second, observations and the ensemble are disjoint, implying that model uncertainty is underestimated both now and in the future, in violation of our first requirement. Lastly, the 90% credibility interval of the historical simulations is broader than that of the projections.

In an effort to guide future efforts, we recast the problem of ice sheet simulation through a probabilistic lens, and assess how our two conditions above relate to this viewpoint. We then sketch a path forward for robustly characterizing the potential ice sheet contribution to sea level over the coming century.

2 Quantifying uncertainties

For the practical problem of predicting the ice sheets' contribution to sea level, we find it useful to adopt a probabilistic framework. In that framework, we seek to establish a credibility bound (say 90%) for predictions, and to determine the range between which sea level contribution will fall with that pre-supposed probability. Such an interval can readily be constructed from a probability density function (PDF) for the cryosphere's contribution to global sea level, and thus this is the function that experiments aiming to quantify sea level contribution must correctly characterize. We write this predictive distribution as

$$P(\Delta z|\mathcal{F}), \tag{1}$$

where Δz is sea level contribution, and $\mathcal{F}$ represents climate forcings (i.e. greenhouse gas emissions) expressed as, e.g., Representative Concentration Pathways (RCP) or Shared-Socioeconomic Pathways, which should also be characterized by their own PDF. In this short communication we will not address the issue of uncertainty in the forcing $\mathcal{F}$ (Team et al., 2010) but concentrate on the uncertainties arising solely from ice sheet models.

While interpretation of $P(\Delta z|\mathcal{F})$ is straightforward, its accurate construction is a grand scientific challenge. The standard approach involves running computer programs that approximately solve mathematical equations describing our best understanding of ice sheet physics. In the best case, when all facets of a physical system are known (including initial and boundary conditions), the equations describing those systems are complete and deterministic, and the mechanism of solution is perfect, then uncertainty in the distribution collapses and sea level contribution, $P(\Delta z|\mathcal{F})$, can be characterized with a single model run. In practice, several types of uncertainties complicate the issue and introduce bias and variance in the predictions. In the following, we discuss these different categories of uncertainty as they pertain to the problem of sea level contribution.

Model uncertainty

The equations used to describe the physical processes in models are invariably an idealization of reality. Indeed, *all* models are subject to some degree of model error; some physical processes are represented incompletely, while others are omitted altogether. For example, the impact of subglacial hydrology on basal motion (e.g., Bueler and van Pelt, 2015) or the effect of ice mélange (Amundson and Truffer, 2010; Joughin et al., 2020) and iceberg calving (Amaral et al., 2020) on terminus position remain poorly represented in numerical ice sheet models, leading to potentially large model uncertainty (sometimes called structural uncertainty). On the other hand, the omission of frictional stresses from wind over an ice sheet surface yields a model that is incorrect yet the resulting error is negligible. Unfortunately, assessing the non-negligible drivers of model inadequacy is a long and arduous process. The different choices that modellers make in this regard leads to an implicitly defined probability distribution $P(\mathcal{M})$, where a particular model $\mathcal{M}$ is a random sample from that distribution. Such model error affects the distribution over sea level contribution as

$$P(\Delta z|\mathcal{F}) = \int P(\Delta z|\mathcal{F},\mathcal{M})P(\mathcal{M})\mathrm{d}\mathcal{M}. \tag{2}$$

Monte Carlo approximation of this integral is exceptionally challenging because drawing a single sample from $P(\mathcal{M})$ requires the development of a new and (ostensibly) independent ice sheet model, an effort which can take years. However, because many ice sheet models have been developed in parallel, it is now possible, through model intercomparison such as ISMIP6 and CMIP6, to try to approximate the distribution above.

Initial state uncertainty

Decade to century scale forecasts of ice sheet behavior are sensitive to the initial state, similar to numerical weather forecasts (Vaughan and Arthern, 2007; Aschwanden et al., 2013; Aðalgeirsdóttir et al., 2014). Unfortunately, observations alone are insufficient to define an initial state (set of all initial conditions), necessitating the use of data assimilation to combine sparse observational data with models of varying complexity.

Similar to model uncertainty, initial state uncertainty $\mathcal{I}$ affects the distribution over sea level contribution as

$$P(\Delta z|\mathcal{F}) = \int P(\Delta z|\mathcal{F},\mathcal{I})P(\mathcal{I})\mathrm{d}\mathcal{I}, \tag{3}$$

where $\mathcal{I}$ is an initial state.

Details vary from model to model, but generally include initial conditions for the conservation of mass (ice thickness and extent), momentum (basal stress distribution), and energy (temperature or enthalpy).

Parametric uncertainty

Due to computational and conceptual constraints, there are limits to the level of detail at which processes can be simulated in ice sheet models predicting sea level contribution. For example, the fracture processes that occur at a marine ice sheet's calving front are more complex than can be reasonably captured. This gives rise to parameters $\mathbf{k} = \{k_1,\ldots,k_N\}$, where N is the number of parameters. These parameters are explicit numerical values that act as the bridge between un-simulated small scale processes and their integrated effects at a practical computational scale. Unfortunately, accurate numerical values for such parameters do generally not exist. This lack of knowledge induces *parametric* uncertainty, for example, different values of thermal conductivity within firn might lead to different predictions of sea level contribution. The predictive distribution under parametric uncertainty is

$$P(\Delta z|\mathcal{F}) = \int P(\Delta z|\mathcal{F},\mathbf{k})P(\mathbf{k})\mathrm{d}\mathbf{k}, \tag{4}$$

where $P(\mathbf{k})$ is the probability distribution over a given model's parameter values, which we assume to be independent of scenario. Aschwanden et al. (2019) approximately evaluate the equation above using Monte Carlo simulation, which is computationally challenging but conceptually simple: sample a large number of parameter values from $P(\mathbf{k})$, and compute sea level contribution for each sample.

Aleatoric uncertainty

Ice sheet models additionally have *aleatoric* uncertainty, i.e. they are subject to irreducibly random processes, most notably the chaotic dynamics present in both atmospheric and oceanic forcings. The predictive distribution under this kind of uncertainty can be decomposed as

$$P(\Delta z|\mathcal{F}) = \int P(\Delta z|f)P(f|\mathcal{F})\mathrm{d}f, \tag{5}$$

where f represents a specific realization of a random forcing, and $P(f|\mathcal{F})$ is its probability distribution under scenario $\mathcal{F}$. Due to the relatively slow response time of the cryosphere to such forcings, aleatoric uncertainty often contributes little variance to predictions in sea level contribution over practical time scales of decades to centuries. However, in circumstances where these forcings may interact with a critical glaciological instability like the Marine Ice Sheet Instability (Mercer, 1978), aleatoric uncertainty has the tendency of producing ‘fat tails’, effectively biasing ice sheet evolution towards more extreme mass loss scenarios (Robel et al., 2019). While only a few studies have characterized the distribution over ice sheet responses to aleatoric uncertainty, and its influence is not precisely known, Monte Carlo simulation can be used to understand the effects of this kind of uncertainty when multiple realizations of forcings are available.

3 Assessing the ISMIP6 ensemble through the probabilistic lens

The response of an ice sheet to a given forcing $\mathcal{F}$ may be estimated with Earth System Models directly. At present, however, Earth System Models with built-in interactive ice sheets remain in their infancy (Vizcaino, 2014) and are not yet able to resolve ice sheet processes such as grounding line migration at the necessary resolution, requiring intermediate steps. A common approach, pursued by Goelzer et al. (2020), involves general circulations models to calculate how the global climate responds to a given forcing $\mathcal{F}$, regional climate models to downscale the global climate response to the ice sheet scale, and process models and parameterizations (e.g., surface energy balance models, calving models or frontal ablation models) to interface with ice sheet models.

To make the daunting task of estimating ice sheet response to different forcings a tractable community effort, a certain degree of standardization, streamlining, and simplification was necessary. The ISMIP6 steering committee and its working groups prepared data sets that could be used by individual modeling groups, including but not limited to, preparing oceanic

https://doi.org/10.5194/tc-2021-175
Preprint. Discussion started: 21 June 2021

(Slater et al., 2020) and atmospheric (Barthel et al., 2020) boundary conditions. To allow a wide range of modeling groups to participate, concessions had to be made, resulting in an experimental setup that does not always reflect advances in modeling practices since the Sea-level Response to Ice Sheet Evolution (SeaRISE Bindschadler et al., 2013; Nowicki et al., 2013) project, including calving and frontal ablation. These practical limitations contribute to an incomplete characterization of uncertainties.

Here we consider uncertainty within the Goelzer et al. (2020) experimental protocol through the probabilistic frame work outlined above.

Incomplete consideration of uncertainty

ISMIP6 integrates over the model uncertainties, including models of ice sheet dynamics, surface mass balance, and ice front position. However, the ISMIP6 predictive distribution does not integrate over uncertainty in parameters. Each group decided on the best parameter set for their simulations. This means that each model contributes a point estimate consisting of a single “best” model run to the larger ensemble. Despite that the parameters leading to this "best" run are often highly uncertain, this uncertainty is thus ignored in the multi-model ensemble leading to an underestimated variance. While it is difficult to gauge the magnitude of this underestimation, Aschwanden et al. (2019) suggest that the parametric uncertainty (inter-quartile range) at 2100 is 0.3 and 12.9 cm SLE for RCP 2.6 and 8.5, respectively, which is larger than the model uncertainty suggested by the ISMIP6 experiments (0.8 and 3.4 cm SLE, respectively). If one takes the Aschwanden et al. (2019) estimate of parametric uncertainty as reasonable, then the variance in ISMIP6’s predictive distribution is greatly underestimated with respect to the real variance. When comparing model predictions to observations, as in Figure 1, this has the effect of ascribing misfit between modeled predictions to model uncertainty, when parametric or aleatoric uncertainty may just as likely be the culprit.

Additional uncertainty emerges from model initial conditions. A strength of the ISMIP6 protocol was the independence of different modeling groups to select their model initialization protocol. However, one unintentional outcome of this protocol is that each modeling group’s simulations start with a markedly different ice sheet; for example, initial ice sheet extent varied among models by up to 17% (Goelzer et al., 2020). Given the strong control of subglacial topography on glacier retreat (Catania et al., 2018), those simulated ice sheets are unlikely to behave as the modern Greenland ice sheet does, or will.

A biased sample over models

The implicit hypothesis made when accounting for model error using an ensemble approach is that each model is an independent sample from $P(\mathcal{M})$, where the mode of $P(\mathcal{M})$ is the true data generating process (i.e. reality). However, the models included in the ensemble are not likely to be independent: they share many critical features like numerical methods, parameterizations, and a joint disregard *for potentially important physical processes that have not yet been discovered*. We emphatically note that this is not a methodological criticism: it is a challenge that exists generally in science, with analogous situations arising in climate modelling (Qian et al., 2016). We note also that such biases may also arise from incorrectly specified prior distributions over parameters and forcings. Nonetheless, the challenge remains real, as does its potential effect on the accuracy and uncertainty of sea level rise projections. As shown in Figure 1, ensemble predictions relative to contemporary observations of mass loss are strongly biased relative to present observations. While accurate reproduction of observed mass change was not a goal of Goelzer et al. (2020), credible projection of future mass change was. There is no reason to believe that the ensemble does not remain biased in its future predictions.

4 A Path Forward

While we do not consider the results of ISMIP6 and downstream analysis appropriate for use as the consensus estimate of the ice sheets' contribution to sea level over the next century, it remains a powerful blueprint for the collaborative efforts that the ice sheet modelling community is able to achieve. Building upon the multi-model ensembling approach of ISMIP6, below we offer suggestions on how to more completely account for uncertainties.

Accounting for all sources of uncertainty

While modelling efforts have captured aleatoric (Robel et al., 2019), parametric (Aschwanden et al., 2019), initial state (Aðalgeirsdóttir et al., 2014), and model (Goelzer et al., 2020) uncertainties independently, an effective projection of the ice sheets' contribution to sea level must do so simultaneously by approximately computing

$$\begin{aligned} P(\Delta z|\mathcal{F}) = \int & P(\Delta z|f,\mathbf{k},\mathcal{M}) \\ & \times P(f|\mathcal{F})P(\mathbf{k}|\mathcal{M})P(\mathcal{I}|\mathcal{M})P(\mathcal{M}) \\ & \times \mathrm{d}\mathbf{k}\,\mathrm{d}f\,\mathrm{d}\mathcal{I}\,\mathrm{d}\mathcal{M}. \end{aligned} \tag{6}$$

To do this, we envision a multi-model ensemble similar to the effort of ISMIP6, but with each model contributing an ensemble of simulations using random parameter values drawn from consensus estimates of the uncertainties associated with parametrically defined physics (cf. Aschwanden et al., 2019), and with random climate and ocean forcings developed in collaboration with their respective modelling communities (cf. Robel et al., 2019). We anticipate that such an effort will yield a distribution of sea level projections that is much broader, and thus less certain, than that presented in recent sea level rise projections (IPCC, 2019). However, we feel that only through modeling what may be considered "unlikely" projections will our community accurately quantify the *a priori* variance in the projections of numerical ice sheet models.

Conditioning simulations on observations

While accounting for all sources of uncertainty encourages a prior distribution over model projections that appropriately acknowledges the current limits of our scientific understanding, it does not ameliorate the problem of inherent biases in the sampled forcings, parameters, and models. Scientists can add specificity and value to the projected distribution by taking advantage of additional information, such as the observations illustrated in Figure 1. To address both of these problems simultaneously, we advocate for *conditioning* ensemble predictions on relevant observations. One way of doing this is through Bayes' theorem (often called Bayesian calibration), which states that

$$P(\Delta z|\mathcal{F},\mathcal{O}) = \frac{P(\mathcal{O}|\Delta z,\mathcal{F})P(\Delta z|\mathcal{F})}{\int P(\mathcal{O}|\Delta z,\mathcal{F})P(\Delta z|\mathcal{F})\,\mathrm{d}\Delta z}, \tag{7}$$

where $\mathcal{O}$ is a set of observations, $P(\mathcal{O}|\Delta z, \mathcal{F})$ is the likelihood that some simulation associated with sea level contribution prediction Δz agrees with observations, and $P(\Delta z|\mathcal{F}, \mathcal{O})$ is the *posterior predictive distribution* of sea level, which can be thought of as the prior ensemble (Eq. 6) filtered by relevant data.

All ice sheet models already perform this calibration for certain subsets of available observations, e.g. by calibration of basal traction or other parameters to yield observed surface velocity or ice geometry within observational uncertainty. In essence, we argue that the existing calibration for parametric uncertainty be moved out from under the purview of individual models, and become an explicit step in the assessment of ice model ensembles.

For the purposes of projecting ice mass change, we argue that the most salient observations on which to condition the prior distribution are measurements of mass change itself (Aschwanden et al., 2013; Aðalgeirsdóttir et al., 2014). Conditioning on observations also requires carefully accounting for the complicated relationship between the time scales of variability in model physics, forcings, and observational uncertainty; the appropriate time scale over which simulations need to show agreement with observations is not (yet) known. The further back in time, the more spatially and temporally sparse observations become, and the larger their associated uncertainties are. Nonetheless, reliable observations of mass change are now available on the decadal time scale (see Figure 1), reducing the likelihood of mistakenly fitting models to short-term fluctuations in weather and ocean conditions. Fortunately, the record of detailed accurate observations is growing continually, soon spanning a climatology (30 years).

By accounting for the broad range of potential *a priori* uncertainties in model projections, and then ascribing predictive weight only to those models that demonstrate skill at reproducing observations, the path towards realistic distributions of sea level contribution over the next century is within reach. Without a large, but realistic, spread of model outcomes it might well be possible that an insufficient number of models remain after fitting to observations.

Complementary efforts

Projections made with numerical "high-fidelity" models are computationally expensive and creating ensemble simulations of sufficient size are limited by the availability of computational resources. Training surrogate models ("emulators") with the output of the high-fidelity models can help better characterizing sea-level contribution probability distribution functions.

It is worth noting that recent efforts have used ISMIP6 as a basis for further analysis, in particular by training a surrogate model on the ISMIP6 and GlacierMIP output that effectively acts as an interpolant (Edwards et al., 2021). While this interpolant is an effective tool for quarrying the predictive distribution of sea-level contribution as a function of time and climate scenario *as quantified by ISMIP6*, it inherits the same challenges as its antecedent, namely a lack of accounting for all uncertainty types and a mechanism for bias correction.

Modern machine learning methods show promise to complement established numerical research tools in Earth system science in general, and ice sheet modeling in particular (Reichstein et al., 2019; Edwards et al., 2019; Brinkerhoff et al., 2021; Edwards et al., 2021; Jouvet et al., 2021). If numerical and statistical models are paired carefully and skillfully with structured expert judgment (Bamber et al., 2019), credible projections of ice sheet contribution to sea-level are within reach.

5 Meeting the challenge

The potential economic impact of rising sea level has been estimated at over a trillion US$ (Diaz and Moore, 2017). Similarly, the US government is considering investing trillions of US$ to prepare for and avert further climate change (Blumer, 2020) while other major world economies consider similar commitments. Contrasting these staggering numbers, the current funding for research related to sea level rise remains miserly. In 2019, the U.S. National Science Foundation allocated $123M to research funded by its Office of Polar Programs (National Science Foundation, 2021), only a small portion of which supports the projection of sea level rise. During an ISMIP6 planning effort in September 2018, participating modeling groups were polled as to how many simulations they could execute in support of projecting ice sheet contributions to sea level rise. Several groups, none of whom were receiving funding to support these simulations, estimated that they could run 5–10 simulations scheduled amongst their existing commitments. This effort is severely under-resourced to meet its mission and yet millions of lives and trillions of dollars depend on an accurate, reliable answer.

It is unconscionable that the only scientific basis for sea level contribution from the ice sheets stems from an essentially volunteer effort. Given the lack of investment, it is small wonder that ice sheet mass change validation deviates so severely from observations (Fig. 1). We urgently need more reliable assessments of the potential impacts of sea level rise, which includes a deliberate effort at quantifying and then systematically reducing uncertainties. Ice sheet modeling, like climate modeling before it, developed from efforts to address basic science questions. However, despite major advances in the capabilities of ice sheet models and expanding appreciation for the importance of their projections, the funding model of modest grants to address basic science and accomplish incremental model development along the way is unchanged. International governments directly support development, maintenance, and operation of the Earth System Models that serve as the foundation for CMIP6 (Eyring et al., 2016), and this financial support has contributed to a suite of models that now convincingly reproduce observed climate variability (Jones et al., 2013). It is time to similarly bring ice sheet modeling to an operational level and support it with the funding the problem deserves.

The ambitious characterization of uncertainties and ensemble conditioning we propose requires a massive international and inter-agency effort in both model development and improved observational capabilities. Similar to the manner by which American researchers conducting field work in Antarctica benefited in 2019 from $292M of investment in professional facilities, and operational and logistical support (National Science Foundation, 2021), we call for professional support for the largely computational sea level projection effort. These resources, in the form of dedicated developers and high performance computing time, will free up scientists to continue basic science, while the global community receives the applied science (i.e., reliable sea level projections) it needs.

The past two decades have shown that ice sheets react to climate far more rapidly than previously thought (Zwally et al., 2002; Rignot and Kanagaratnam, 2006; Joughin et al., 2014). The study of glaciers and ice sheets has moved from a fringe scientific exercise to a central question of major global economic significance. In response to COVID-19, 18 billion US$ flowed from the U.S. government to fund vaccine development (Tozzi et al., 2020). Appropriate resourcing is possible. While

https://doi.org/10.5194/tc-2021-175
Preprint. Discussion started: 21 June 2021

the emergent threat of sea level rise is less abrupt than that from COVID-19, a similarly serious effort is required to reduce uncertainties in sea-level projections.

Data availability

We downloaded the scalar time-series produced by ISMIP6 for the Greenland Ice Sheet from Zenodo with digital object identifier from https://doi.org/10.5281/zenodo.3939037 (last access: November 2020). The data is split into a historical period (pre-2015) and the projection period (2015–2100). The choice of the starting date of the historical simulation was left to the individual modeling groups and ranges from 1961 to 2008. Thus we only used historical simulations from 2008–2014 and projections from 2015–2020 for our analysis, for a total of 20 unique historical simulations and 165 projections. For the projections we used the version where the control simulation was removed (H. Goelzer, pers. comm., November 2020). Removal of the control simulation is intended to account for unforced model drift and mass loss committed as a result of non-equilibrium ice sheet conditions at the start of the simulations. Committed sea level rise is estimated to add an additional 6 mm to simulated sea level rise by 2100 (Price et al., 2011; Goelzer et al., 2020) and thus has little impact on the low bias of recent, simulated mass loss.

For observations, we used the following data sets: mass loss from GRACE and GRACE-FO JPL RL06Mv2 Mascon Solution from 2002 to 2020 (Wiese et al., 2020), a reconstruction based on a comprehensive survey of thickness, surface elevation, velocity, and surface mass balance from 1972 to 2018 Mouginot et al. (2019), and a multi-method consensus estimate (The IMBIE Team, 2019).

The analysis was performed using a Jupyter notebook which is available at https://github.com/aaschwanden/ismip6-ipcc.

https://doi.org/10.5194/tc-2021-175
Preprint. Discussion started: 21 June 2021

References

Amaral, T., Bartholomaus, T. C., and Enderlin, E. M.: Evaluation of Iceberg Calving Models Against Observations From Greenland Outlet Glaciers, Journal of Geophysical Research: Earth Surface, 125, 1–29, https://doi.org/10.1029/2019JF005444, 2020.

Amundson, J. M. and Truffer, M.: A unifying framework for iceberg-calving models, J. Glaciol., 56, 822–830, https://doi.org/10.3189/002214310794457173, http://openurl.ingenta.com/content/xref?genre=article&issn=0022-1430&volume=56&issue=199&spage=822, 2010.

Aschwanden, A., Aðalgeirsdóttir, G., and Khroulev, C.: Hindcasting to measure ice sheet model sensitivity to initial states, The Cryosphere, 7, 1083–1093, https://doi.org/10.5194/tc-7-1083-2013, 2013.

Aschwanden, A., Fahnestock, M. A., Truffer, M., Brinkerhoff, D. J., Hock, R., Khroulev, C., Mottram, R., and Khan, S. A.: Contribution of the Greenland Ice Sheet to sea level over the next millennium, Science Advances, 5, eaav9396, https://doi.org/10.1126/sciadv.aav9396, http://advances.sciencemag.org/lookup/doi/10.1126/sciadv.aav9396, 2019.

Aðalgeirsdóttir, G., Aschwanden, A., Khroulev, C., Boberg, F., Mottram, R., and Lucas-Picher, P.: Role of model initialization for projections of 21st-century Greenland ice sheet mass loss, Journal of Glaciology, 60, 782–794, https://doi.org/10.3189/2014JoG13J202, http://www.igsoc.org/journal/60/222/t13j202.html, 2014.

Bamber, J. L., Oppenheimer, M., Kopp, R. E., Aspinall, W. P., and Cooke, R. M.: Ice sheet contributions to future sea-level rise from structured expert judgment, Proceedings of the National Academy of Sciences of the United States of America, 166, 11 195–11 200, https://doi.org/10.1073/pnas.1817205116, 2019.

Barthel, A., Agosta, C., Little, C. M., Hattermann, T., Jourdain, N. N., Goelzer, H., Nowicki, S., Seroussi, H., Straneo, F., and Bracegirdle, T. T.: CMIP5 model selection for ISMIP6 ice sheet model forcing: Greenland and Antarctica, Cryosphere, 14, 855–879, https://doi.org/10.5194/tc-14-855-2020, 2020.

Bindschadler, R. A., Nowicki, S., Abe-Ouchi, A., Aschwanden, A., Choi, H., Fastook, J., Granzow, G., Greve, R., Gutowski, G., Herzfeld, U., Jackson, C., Johnson, J., Khroulev, C., Levermann, A., Lipscomb, W. H., Martin, M. A., Morlighem, M., Parizek, B. R., Pollard, D., Price, S. F., Ren, D., Saito, F., Sato, T., Seddik, H., Seroussi, H., Takahashi, K., Walker, R., and Wang, W. L.: Ice-sheet model sensitivities to environmental forcing and their use in projecting future sea level (the SeaRISE project), J. Glaciol., 59, 195–224, https://doi.org/10.3189/2013JoG12J125, http://www.igsoc.org/journal/59/214/j12J125.html, 2013.

Blumer, B.: To Cut Emissions to Zero, U.S. Needs to Make Big Changes in Next 10 Years, https://www.nytimes.com/2020/12/15/climate/america-next-decade-climate.html, Accessed: 2021-04-27, 2020.

Brinkerhoff, D., Aschwanden, A., and Fahnestock, M.: Constraining subglacial processes from surface velocity observations using surrogate-based Bayesian inference, Journal of Glaciology, pp. 1–19, https://doi.org/10.1017/jog.2020.112, https://www.cambridge.org/core/product/identifier/S0022143020001124/type/journal_article, 2021.

Bueler, E. and van Pelt, W.: Mass-conserving subglacial hydrology in the Parallel Ice Sheet Model version 0.6, Geosci. Model Dev., 8, 1613–1635, https://doi.org/10.5194/gmd-8-1613-2015, http://www.geosci-model-dev.net/8/1613/2015/, 2015.

Catania, G. A., Stearns, L. A., Sutherland, D. A., Fried, M. J., Bartholomaus, T. C., Morlighem, M., Shroyer, E., and Nash, J.: Geometric Controls on Tidewater Glacier Retreat in Central Western Greenland, Journal of Geophysical Research: Earth Surface, 123, 2024–2038, https://doi.org/10.1029/2017JF004499, 2018.

Chen, X., Zhang, X., Church, J. A., Watson, C. S., King, M. A., Monselesan, D., Legresy, B., and Harig, C.: The increasing rate of global mean sea-level rise during 1993–2014, Nature Climate Change, 7, 492–495, https://doi.org/10.1038/nclimate3325, http://dx.doi.org/10.1038/nclimate3325%0Ahttp://10.0.4.14/nclimate3325%0Ahttp://www.nature.com/nclimate/journal/vaop/ncurrent/abs/nclimate3325.html#supplementary-information%5Cnhttp://www.nature.com/doifinder/10.1038/nclimate3325http://www.nature.com/doi, 2017.

Diaz, D. and Moore, F.: Quantifying the economic risks of climate change, Nature Climate Change, 7, 774–782, https://doi.org/10.1038/nclimate3411, 2017.

Edwards, T. L., Brandon, M. A., Durand, G., Edwards, N. R., Golledge, N. R., Holden, P. B., Nias, I. J., Payne, A. J., Ritz, C., and Wernecke, A.: Revisiting Antarctic ice loss due to marine ice-cliff instability, Nature, 566, 58–64, https://doi.org/10.1038/s41586-019-0901-4, http://dx.doi.org/10.1038/s41586-019-0901-4, 2019.

Edwards, T. L., Nowicki, S., Marzeion, B., Hock, R., Goelzer, H., Seroussi, H., Jourdain, N. C., Slater, D. A., Turner, F. E., Smith, C. J., McKenna, C. M., Simon, E., Abe-Ouchi, A., Gregory, J. M., Larour, E., Lipscomb, W. H., Payne, A. J., Shepherd, A., Agosta, C., Alexander, P., Albrecht, T., Anderson, B., Asay-Davis, X., Aschwanden, A., Barthel, A., Bliss, A., Calov, R., Chambers, C., Champollion, N., Choi, Y., Cullather, R., Cuzzone, J., Dumas, C., Felikson, D., Fettweis, X., Fujita, K., Galton-Fenzi, B. K., Gladstone, R., Golledge, N. R., Greve, R., Hattermann, T., Hoffman, M. J., Humbert, A., Huss, M., Huybrechts, P., Immerzeel, W., Kleiner, T., Kraaijenbrink, P., Le clec'h, S., Lee, V., Leguy, G. R., Little, C. M., Lowry, D. P., Malles, J.-H., Martin, D. F., Maussion, F., Morlighem, M., O'Neill, J. F., Nias, I., Pattyn, F., Pelle, T., Price, S. F., Quiquet, A., Radić, V., Reese, R., Rounce, D. R., Rückamp, M., Sakai, A., Shafer, C., Schlegel, N.-J., Shannon, S., Smith, R. S., Straneo, F., Sun, S., Tarasov, L., Trusel, L. D., Van Breedam, J., van de Wal, R., van den Broeke, M., Winkelmann, R., Zekollari, H., Zhao, C., Zhang, T., and Zwinger, T.: Projected land ice contributions to twenty-first-century sea level rise, Nature, 593, 74–82, https://doi.org/10.1038/s41586-021-03302-y, http://www.nature.com/articles/s41586-021-03302-y, 2021.

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., and Taylor, K. E.: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, Geoscientific Model Development, 9, 1937–1958, https://doi.org/10.5194/gmd-9-1937-2016, 2016.

Goelzer, H., Nowicki, S., Payne, A., Larour, E., Seroussi, H., Lipscomb, W., Gregory, J., Abe-Ouchi, A., Shepherd, A., Simon, E., Agosta, C., Alexander, P., Aschwanden, A., Barthel, A., Calov, R., Chambers, C., Choi, Y., Cuzzone, J., Dumas, C., Edwards, T., Felikson, D., Fettweis, X., Golledge, N., Greve, R., Humbert, A., Huybrechts, P., Le clec'h, S., Lee, V., Leguy, G., Little, C., Lowry, D., Morlighem, M., Nias, I., Quiquet, A., Rückamp, M., Schlegel, N.-J., Slater, D., Smith, R., Straneo, F., Tarasov, L., van de Wal, R., and van den Broeke, M.: The future sea-level contribution of the Greenland ice sheet: a multi-model ensemble study of ISMIP6, The Cryosphere, pp. 1–43, https://doi.org/10.5194/tc-2019-319, 2020.

Hinkel, J., Lincke, D., Vafeidis, A. T., Perrette, M., Nicholls, R. J., Tol, R. S. J., Marzeion, B., Fettweis, X., Ionescu, C., and Levermann, A.: Coastal flood damage and adaptation costs under 21st century sea-level rise, Proceedings of the National Academy of Sciences, 111, 3292–3297, https://doi.org/10.1073/PNAS.1222469111, https://www.pnas.org/content/111/9/3292, 2014.

IPCC: Special Report: The Ocean and Cryosphere in a Changing Climate, p. in preparation, https://doi.org/https://www.ipcc.ch/report/srocc/, 2019.

Jones, G. S., Stott, P. A., and Christidis, N.: Attribution of observed historical near-surface temperature variations to anthropogenic and natural causes using CMIP5 simulations, Journal of Geophysical Research Atmospheres, 118, 4001–4024, https://doi.org/10.1002/jgrd.50239, 2013.

Joughin, I., Smith, B. E., and Medley, B.: Marine Ice Sheet Collapse Potentially Underway for the Thwaites Glacier Basin, West Antarctica., Science, 735, https://doi.org/10.1126/science.1249055, http://www.ncbi.nlm.nih.gov/pubmed/24821948, 2014.

Joughin, I., E. Shean, D., E. Smith, B., and Floricioiu, D.: A decade of variability on Jakobshavn Isbræ: Ocean temperatures pace speed through influence on mélange rigidity, Cryosphere, 14, 211–227, https://doi.org/10.5194/tc-14-211-2020, 2020.

Jouvet, G., Cordonnier, G., Kim, B., L\"uthi, M., Vieli, A., and Aschwande, A.: Deep learning speeds up ice flow modelling by several orders of magnitude, J. Glaciol., p. in review, 2021.

Kopp, R. E., Kemp, A. C., Bittermann, K., Horton, B. P., Donnelly, J. P., Gehrels, W. R., Hay, C. C., Mitrovica, J. X., Morrow, E. D., and Rahmstorf, S.: Temperature-driven global sea-level variability in the Common Era, Proceedings of the National Academy of Sciences, 113, E1434–E1441, https://doi.org/10.1073/PNAS.1517056113, 2016.

Mercer, J. H.: West Antarctic ice sheet and CO2 greenhouse effect: a threat of disaster, Nature, 271, 321–325, https://doi.org/10.1038/271321a0, http://www.nature.com/doifinder/10.1038/271321a0, 1978.

Moon, T., Scambos, T., Abdalati, W., Ahlstrøm, A. P., Bindschadler, R., Gambill, J., Heimbach, P., Hock, R., Langley, K., Miller, I., and Truffer, M.: Ending a Sea of Confusion: Insights and Opportunities in Sea-Level Change Communication, Environment: Science and Policy for Sustainable Development, 62, 4–15, https://doi.org/10.1080/00139157.2020.1791627, 2020.

Mouginot, J., Rignot, E., Bjørk, A. A., van den Broeke, M., Millan, R., Morlighem, M., Noël, B., Scheuchl, B., and Wood, M.: Forty-six years of Greenland Ice Sheet mass balance from 1972 to 2018, Proceedings of the National Academy of Sciences, p. 201904242, https://doi.org/10.1073/pnas.1904242116, http://www.pnas.org/lookup/doi/10.1073/pnas.1904242116, 2019.

National Science Foundation: FY 2021 Budget Request to Congress, https://www.nsf.gov/about/budget/fy2021/pdf/fy2021budget.pdf, Accessed: 2021-04-27, 2021.

Nowicki, S., Bindschadler, R. A., Abe-Ouchi, A., Aschwanden, A., Bueler, E., Choi, H., Fastook, J., Granzow, G., Greve, R., Gutowski, G., Herzfeld, U., Jackson, C., Johnson, J., Khroulev, C., Larour, E., Levermann, A., Lipscomb, W. H., Martin, M. a., Morlighem, M., Parizek, B. R., Pollard, D., Price, S. F., Ren, D., Rignot, E., Saito, F., Sato, T., Seddik, H., Seroussi, H., Takahashi, K., Walker, R., and Wang, W. L.: Insights into spatial sensitivities of ice mass response to environmental change from the SeaRISE ice sheet modeling project II: Greenland, J. Geophys. Res., 118, 1025–1044, https://doi.org/10.1002/jgrf.20076, http://doi.wiley.com/10.1002/jgrf.20076, 2013.

Nowicki, S. M. J., Payne, A., Larour, E., Seroussi, H., Goelzer, H., Lipscomb, W., Gregory, J., Abe-Ouchi, A., and Shepherd, A.: Ice Sheet Model Intercomparison Project (ISMIP6) contribution to CMIP6, Geoscientific Model Development, 9, 4521–4545, https://doi.org/10.5194/gmd-9-4521-2016, http://www.geosci-model-dev.net/9/4521/2016/, 2016.

Price, S. F., Payne, A. J., Howat, I. M., and Smith, B. E.: Committed sea-level rise for the next century from Greenland ice sheet dynamics during the past decade, P. Natl. Acad. Sci. USA, 108, https://doi.org/10.1073/pnas.1017313108, 2011.

Qian, Y., Jackson, C., Giorgi, F., Booth, B., Duan, Q., Forest, C., Higdon, D., Hou, Z. J., and Huerta, G.: Uncertainty Quantification in Climate Modeling and Projection, Bulletin of the American Meteorological Society, 97, 821–824, https://doi.org/10.1175/BAMS-D-15-00297.1, https://journals.ametsoc.org/doi/10.1175/BAMS-D-15-00297.1, 2016.

Reichstein, M., Camps-Valls, G., Stevens, B., Jung, M., Denzler, J., Carvalhais, N., and Prabhat: Deep learning and process understanding for data-driven Earth system science, Nature, 566, 195–204, https://doi.org/10.1038/s41586-019-0912-1, http://dx.doi.org/10.1038/s41586-019-0912-1, 2019.

Rietbroek, R., Brunnabend, S.-E., Kusche, J., Schröter, J., and Dahle, C.: Revisiting the contemporary sea-level budget on global and regional scales., Proceedings of the National Academy of Sciences of the United States of America, 113, 1504–9, https://doi.org/10.1073/pnas.1519132113, 2016.

Rignot, E. and Kanagaratnam, P.: Changes in the Velocity Structure of the Greenland Ice Sheet, Science, 311, 986–990, https://doi.org/10.1126/science.1121381, http://www.sciencemag.org/cgi/doi/10.1126/science.1121381, 2006.

Robel, A. A., Seroussi, H., and Roe, G. H.: Marine ice sheet instability amplifies and skews uncertainty in projections of future sea-level rise, Proceedings of the National Academy of Sciences, p. 201904822, https://doi.org/10.1073/pnas.1904822116, http://www.pnas.org/lookup/doi/10.1073/pnas.1904822116, 2019.

Seroussi, H., Nowicki, S., Payne, A., Goelzer, H., Lipscomb, W., Abe Ouchi, A., Agosta, C., Albrecht, T., Asay-Davis, X., Barthel, A., Calov, R., Cullather, R., Dumas, C., Gladstone, R., Golledge, N., Gregory, J., Greve, R., Hatterman, T., Hoffman, M., Humbert, A., Huybrechts, P., Jourdain, N., Kleiner, T., Larour, E., Leguy, G., Lowry, D., Little, C., Morlighem, M., Pattyn, F., Pelle, T., Price, S., Quiquet, A., Reese, R., Schlegel, N.-J., Shepherd, A., Simon, E., Smith, R., Straneo, F., Sun, S., Trusel, L., Van Breedam, J., van de Wal, R., Winkelmann, R., Zhao, C., Zhang, T., and Zwinger, T.: ISMIP6 Antarctica: a multi-model ensemble of the Antarctic ice sheet evolution over the 21st century, The Cryosphere, pp. 1–54, https://doi.org/10.5194/tc-2019-324, 2020.

Slater, D. A., Felikson, D., Straneo, F., Goelzer, H., Little, C. M., Morlighem, M., Fettweis, X., and Nowicki, S.: Twenty-first century ocean forcing of the Greenland ice sheet for modelling of sea level contribution, Cryosphere, 14, 985–1008, https://doi.org/10.5194/tc-14-985-2020, 2020.

Team, C. W., Knutti, R., Abramowitz, G., Collins, M., Eyring, V., Gleckler, P. J., Hewitson, B., Mearns, L., Stocker, T., Dahe, Q., et al.: IPCC Expert Meeting on Assessing and Combining Multi Model Climate Projections, Intergovernal Panel Climate Change, 2010.

The IMBIE Team, T. I.: Mass balance of the Greenland Ice Sheet from 1992 to 2018, Nature, 579, 233–239, https://doi.org/10.1038/s41586-019-1855-2, http://www.nature.com/articles/s41586-019-1855-2, 2019.

Tozzi, J., Griffin, R., and Stein, S.: Trump Administration Dips Into Protective Gear, CDC Funds to Fund Vaccine Push, https://www.bloomberg.com/news/articles/2020-09-23/how-much-is-the-trump-administration-spending-on-a-vaccine, Accessed: 2021-04-27, 2020.

Vaughan, D. G. and Arthern, R. J.: Why Is It Hard to Predict the Future of Ice Sheets?, Science, 315, 1503–1504, https://doi.org/10.1126/science.1141111, http://www.sciencemag.org/cgi/doi/10.1126/science.1141111, 2007.

Vizcaino, M.: Ice sheets as interactive components of Earth System Models: progress and challenges, Wiley Interdisciplinary Reviews: Climate Change, pp. 1–12, https://doi.org/10.1002/wcc.285, http://doi.wiley.com/10.1002/wcc.285, 2014.

Wiese, D. N., Yuan, D.-N., Boening, C., Landerer, F. W., and Watkins, M. M.: JPL GRACE and GRACE-FO Mascon Ocean, Ice, and Hydrology Equivalent Water Height RL06M CRI Filtered Version 2.0, https://doi.org/http://dx.doi.org/10.5067/TEMSC-3MJ62, 2020.

Zwally, H. J., Abdalati, W., Herring, T., Larson, K., Saba, J., and Steffen, K.: Surface melt-induced acceleration of Greenland ice-sheet flow., Science, 297, 218–22, https://doi.org/10.1126/science.1072708, http://www.ncbi.nlm.nih.gov/pubmed/12052902, 2002.