A Potential Disintegration of the West Antarctic Ice Sheet: Implications for Economic Analyses of Climate Policy

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Key objectives of international greenhouse gas (GHG) policy are to (i) "prevent dangerous anthropogenic interference with the climate system" and (ii) "enable economic development to proceed in a sustainable manner" (UNFCCC, 1992). One common interpretation of "dangerous anthropogenic interference" is to trigger a climate threshold or "tipping point" response – a nonlinear shift in the Earth system with the potential for abrupt, irreversible, or hysteresis effects (e.g., Alley et al., 2003). Examples of possible threshold responses include a disruption of the oceanic thermohaline circulation, sudden methane releases from the oceans or permafrost, or disintegrations of the Greenland or Antarctic ice sheets. The geological record shows that the Earth system can show such threshold responses, but the mechanisms, dynamics, and sensitivities are deeply uncertain (Alley et al., 2003).

A sound representation of these potential climate threshold responses and their consequences in integrated assessment models (IAMs) is important, for example, given the salience to agreed-upon policy objectives. IAMs are simplified representations of the coupled natural and human systems used to evaluate climate change scenarios and to inform policy decisions (e.g., by computing the US government's social cost of carbon (SCC) estimate). Because IAMs analyses face severe challenges (discussed below) in representing these complex and uncertain thresholds, decision-relevant metrics like the SCC may be biased (Stern, 2013). Here we explore one such threshold response, a potential disintegration of the West Antarctic Ice Sheet (WAIS) and consequent sea-level rise (SLR). We review current analytical approaches and the scientific understanding of WAIS, identify key methodological and conceptual issues, and demonstrate avenues to address some of them through a stochastic hazard IAM framework that combines emulation, expert knowledge, and learning. We conclude with a discussion of challenges and research needs.

I. Climate Thresholds and IAMs

Representing a potential threshold in an IAM typically requires drastic approximations in the form of simple emulators. Projected climate threshold responses are deeply uncertain and, once triggered, the response can be abrupt (i.e., faster than the forcing) and show hysteresis (Alley et al., 2003). These characteristics can amplify the marginal damages of the last unit of forcing that pushes the system over the tipping point.

The first IAMs to explicitly account for low-probability, high-consequence climate "catastrophes" (e.g., a 10 percent GDP loss) used an expected value or certainty equivalent approach (e.g., Nordhaus and Boyer, 2000; Hope, 2006), missing the stochastic nature and other complex threshold characteristics. While IAM analyses tend toward simple uncertainty methods like sensitivity or Monte Carlo analysis due to computational considerations, more advanced approaches to decision-making under uncertainty that incorporate risk directly into the IAM structure can identify optimal hedging strategies (Kann and Weyant, 2000).

An early effort to incorporate uncertain thresholds in an IAM with global stochastic optimization investigated the oceanic thermohaline circulation (Keller, Bolker and Bradford, 2004).

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Two recent studies applied stochastic dynamic programming and a hazard rate approach to represent climate thresholds (Lontzek et al., 2015; Lemoine and Traeger, 2014), while another integrated Bayesian updating of correlated uncertainty about both climate sensitivity and tipping point risk using approximate dynamic programming (Shayegh and Thomas, 2014). These studies broke important ground, but can still be considerably improved in aspects such as the representation of geophysical dynamics, diverse expert assessments, and the resulting impacts on the natural and human system (Diaz, 2015).

A. *Scientific Understanding of WAIS Threat*

The geological record and model simulations suggest a WAIS vulnerability to climate change. The WAIS is a marine ice sheet, with much of its base grounded below sea level with floating ice shelves exposed to warming subsurface ocean currents that cause basal melt (Church et al., 2013). A total WAIS disintegration would cause roughly 3.3 meters global SLR, on top of other effects such as thermal expansion of seawater (Church et al., 2013). Rising seas can affect tens of millions of people in low-lying coastal areas, as well as infrastructure, capital assets, and vulnerable ecosystems. The potential damages are driven, for example, by permanent land inundation, increased flooding from storm surges, saltwater intrusion, and accelerated erosion (Nicholls, 2011).

Current estimates of the sensitivity and timescale of a potential WAIS disintegration are deeply uncertain. This stems in large part from the limited ability to represent the complex processes and feedbacks on relevant spatial and temporal scales, the relatively sparse instrumental and geological record, and divergent expert assessments (Alley et al., 2005). Several positive feedbacks in ice-loss can contribute to a WAIS threshold response, including the "marine ice sheet instability" due to a reverse bedslope that compounds grounding line retreat, a "cliff instability" with increased ice-loss as the cliff height increases, and increased surface temperature with reduced ice sheet height (Schoof, 2007; Pollard, DeConto and Alley, 2015).

We focus on three expert assessments characterizing different aspects of the WAIS hazard. Bamber and Aspinall (2013) elicited expert opinion about ice sheet contributions to global SLR rates in 2100, Kriegler et al. (2009) surveyed the likelihood of WAIS disintegration occurring by 2200 for three temperature pathways, and Vaughan and Spouge (2002) assessed the probability of two WAIS melt rate scenarios.

II. Methods and Key Results

We explore the threat of WAIS disintegration in an approximate way in a stochastic optimization IAM. Our objective is to illustrate the relationships between scientific uncertainties, policy objectives, and (constrained) economically-optimal strategies in the face of a specific climate threshold response.

A. *DICE-WAIS IAM*

The DICE-WAIS IAM expands on the well-known Dynamic Integrated Climate-Economy (DICE) model.[1] DICE is a simple, globally-aggregated Ramsey growth model that maximizes the expected value of discounted utility. DICE-WAIS introduces additional variables to account for SLR and the associated economic damages from coastal impacts. It is formulated as a multistage stochastic program and uses a hazard rate approach to allow for a possible threshold response in any time period, as in Rutherford (2013). The hazard rate gives the conditional probability of triggering WAIS disintegration and is an endogenous function of global mean temperature change, calibrated to reflect the average of published expert opinions (Kriegler et al., 2009). This framework approximates the stochastic nature of the WAIS threat.

B. *Approach*

DICE-WAIS evaluates the Pareto optimal mitigation strategy that balances the uncertain climate damage outcomes across all possible states of the world with the costs of mitigation investments (see Diaz, 2015). In addition to the stochastic uncertainty about WAIS threat, here we also sample parametric uncertainty for climate sensitivity, the WAIS trigger temperature, and the annual rate of WAIS discharge in a

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[1] The DICE-WAIS documentation is available in the Supplementary Materials (SM); for details on the underlying DICE-2013R model, see Nordhaus and Sztorc (2013).

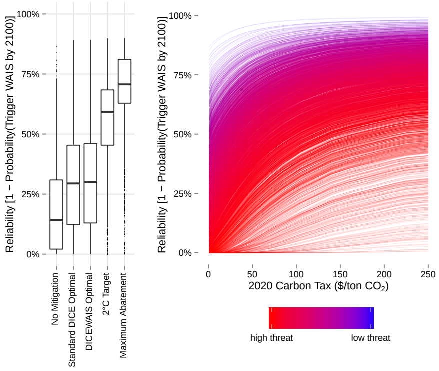

FIGURE 1. WAIS RELIABILITY BY CLIMATE POLICY.

Note: a) Distribution of WAIS reliability in 2100 under various climate policies given parametric uncertainty about climate sensitivity, WAIS trigger temperature, and rate of WAIS discharge. Boxes give the interquartile range with median, whiskers represent the 5th-95th percentile, and outliers shown as dots. b) The relationship between carbon tax policy and WAIS reliability outcome, depending on the parametric uncertainty threat (see Figure SM 1 for classification). Color saturation indicates the likelihood of uncertain parameters. Color gradient classifies parametric uncertainty from low threat (e.g., blue in upper left shows low climate sensitivity and high trigger temperature) to high threat (e.g., red in lower right shows high climate sensitivity and low trigger temperature).

Monte Carlo experiment with 5,000 runs. We consider a range of climate policies and also conduct sensitivity analysis on SLR damage severity and the social rate of time preference.

C. *Main Results*

The reliability of WAIS, defined as the probability of not triggering a WAIS disintegration by 2100, shows a characteristic and perhaps intuitive response surface across the uncertain parameter values (scenario map in Figure SM 1 classifies parametric uncertainty as low to high threat), with poor average reliability (e.g., 29 percent) under the optimal strategy. Despite this well-defined pattern for the reliability outcome, the threat of WAIS disintegration implies little motivation for additional mitigation, reflected in the near-term SCC, which rises by only 2 dollars per ton of carbon dioxide from the average of 19 dollars in the standard DICE model (Figure SM 2). This might be attributed to the assumption of modest economic costs (i.e., the SLR damage function) and a discount rate applied over a long time horizon. However, increasing coastal damages and decreasing the social rate of time preference causes relatively little increase in the SCC (Figure SM 2). Instead, we hypothesize that this weak sensitivity is driven by interactions between the persistent positive hazard rate and the irreversible nature of the threshold, which together ensure a relatively insensitive relationship between mitigation and damages, combined with a truncated model time horizon that captures only a fraction of the disintegration process.

Putting aside the economically-efficient results, increased reliability can be achieved through more aggressive mitigation (Figure 1a). For example, a 2°C climate policy or the limiting case of maximum abatement both raise WAIS reliability considerably. To analyze the implied shadow price for increased reliability we assess a range of carbon tax stringencies beginning in 2020 and rising at 4 percent per year (Figure 1b). The reliability increases with increasing carbon tax across all threat scenarios, with the largest responsiveness for realizations of parametric uncertainty with intermediate threat. There are decreasing returns as the carbon tax approaches the backstop abatement cost across all threat scenarios. Note that even maximum mitigation cannot ensure total reliability due to the applied hazard rate approach.

III. Discussion and Research Needs

Our simple model is designed for a transparent and numerically-efficient analysis of abatement strategies, but it relies on several strong assumptions and approximations that miss relevant aspects of the coupled natural and human systems. For example, we examine just one potential climate threshold response, apply simplistic biogeochemical and geophysical models, and consider a short time horizon relative to the WAIS response time. A more refined representation of WAIS geophysics and climate interactions is crucial to capture the potential feedbacks discussed earlier. Furthermore, our model only considers mitigation decisions in response to WAIS threat, whereas adaptation to the resulting SLR (or even geoengineering) may well be more relevant.

Beyond these important model refinements, there is a need to expand the framing of climate risk management analysis more broadly. The framework accounts for a relatively small subset of diverse preferences. For example, it has limited descriptive power in situations of deep or Knightian uncertainty (Budescu et al., 2014) and is silent on alternative ethical frameworks such as prioritarianism (Adler and Treich, 2015). In addition, this framework collapses the explicit multi-objective aims of UNFCCC Article 2 into a single objective using a priori defined preferences. More advanced decision-analytical approaches such as many objective robust decision-making can provide valuable insights in such situations (e.g., Hadka et al., 2015). Moreover, applying discount rates over the long time horizon of WAIS disintegration can reduce these impacts to negligible levels. Finally, the representation of endogenous learning is highly stylized and focuses on a subset of the relevant uncertainties.

In conclusion, we analyze optimal mitigation strategies in a stochastic optimization IAM with endogenous hazard of triggering a WAIS disintegration while also considering probabilistic uncertainty in several other dimensions. Adorned with numerous caveats (some discussed above), our findings suggest three main conclusions. First, the strategy that maximizes the expected value of discounted utility in our model leaves a sizable likelihood (over 70 percent) of triggering WAIS disintegration. Second, the risk of accelerated SLR from WAIS and consequent coastal damages alone has little impact on optimal policy stringency due to the weak sensitivity between mitigation and expected present value coastal damages within the considered framework. Third, increasing mitigation can considerably reduce the risk of triggering a WAIS disintegration, but with a decreasing marginal return.

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