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Atmospheric Chemistry and Physics Discussions

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Interactive Comment

Interactive comment on "Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2 °C global warming is highly dangerous" *by* J. Hansen et al.

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First, I complement all of the authors for providing insightful context to the on-going climate change discussion. This paper demonstrates how in the face of significant uncertainties some models can be used to progressively bound, and iteratively characterize, the range of probable Earth System responses to continued anthropogenic radiative forcing.

Second, I note that your curve for the 20-year doubling rate of sea level rise, SLR,

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shown in panel (b) of Figure 8 of your paper aligns between the Intermediate – High – 1.2m and the Intermediate – Low - 0.5m curves shown in Figure ES1 for the global mean sea level rise scenarios from Parris et al. (2012). Furthermore, Parris et al. (2012) states that its curve labeled Highest – 2m is based on Pfeffer et al. (2008), and further states: "The Highest Scenario should be considered in situations where there is little tolerance for risk (e.g. new infrastructure with a long anticipated life cycle such as a power plant)." Thus, it appears that your 20-year doubling scenario is close to the 50% confidence level of the most recent published NOAA SLR guidance. Further, per Parris et al. (2012), the design of new coastal infrastructure with a long service-life should consider a 2100 sea level between your 10-year doubling, and your 20-year doubling, projected sea level values. Therefore, to maintain consistent guidance, United States government supported climate model projections used for the design of significant coastal infrastructure should introduce sufficient ice sheet meltwater (and if appropriate icebergs) into the adjoining modeled oceans in order to simulate the levels of SLR from the most recent NOAA guidance on this topic (Parris et al. 2012).

Third, as current ice sheet model forecasts may underestimate associated SLR contributions this century, it is understandable why the Parris et al. (2012) Highest – 2m SLR guidance curve, that is based on Pfeffer et al. (2008), cite values that are above the highest Intergovernmental Panel on Climate Change - Fifth Assessment Report (IPCC - AR5), projected SLR values. Furthermore, the National Research Council, NRC, (2013), Abrupt Impacts of Climate Change Anticipating Surprises, states: "A retreat of Thwaites Glacier in West Antarctica could give a much wider and deeper calving front than any observed today, so the "speed limits" suggested by Pfeffer et al. (2008) may not apply (Parizek et al., 2013)." Therefore, it is understandable why your paper would consider SLR values higher than 2m by 2100. Nevertheless, most SLR experts (e.g. Jevrejeva et al., 2014) believe that consideration of higher SLR values this century requires further justification by additional lines of evidence.

Fourth, it is useful to understand that the majority of expert opinion (including Pfeffer et al., 2008, Pfeffer 2011 and Jevrejeva et al., 2014) on SLR frequently come from extrapolations based on:

(a) Limited, and uncertain, paleo-evidence;

(b) Modern data, dominated by satellite information, which was gathered primarily during the so-called "hiatus" period and thus is not likely to fully characterize long-term behavior; and

(c) Ice sheet model projections that may underestimate associated ice mass losses. I note that while insightful, the positive feedback mechanisms cited in your paper are not likely to be sufficient proof to convince most SLR experts that abrupt SLR will be initiated within the next few decades. Therefore, it is suggested that you add new supplemental information listing recommended lines of future investigation that would justify the use of climate model projections utilizing the introduction of ice sheet meltwater in the range between your 5-year doubling, and 10-year doubling rates of SLR. In this regards the following recommended lines of future investigations (it is noted that researchers, including Pollard et al. 2015, have already demonstrated that abrupt sea level rise can occur if modern Earth Systems were to be subjected to Pliocene-like conditions) are presented for your consideration and are sub-divided into categories of investigations related to:

(a) Additional paleo-evidence of synchronized Earth System responses that have contributed to past abrupt sea level rise, and which could be currently occurring;

(b) Early accelerated ice mass contributions to SLR from both marine-terminating glaciers in Greenland and from marine glaciers in the Amundsen Sea Embayment, ASE, West Antarctica;

(c) Rapid ice mass contributions to SLR suitable to sustain rates of between 5-year and 10-year doubling rates over the next few decades;

(d) Documentation of increased probabilities of relatively high climate sensitivities.

Lines of Investigation of Paleo-Evidence of Earth System Synchronicity that Could Occur During the Balance of this Century:

While your paper provide considerable, and relevant, evaluations of paleo-evidence supporting your conclusions; nevertheless, your evaluation of non-linear Earth Systems responses could benefit from addition investigations of the following matters:

(a) Coletti et al. (2015) provides paleo-evidence including information showing how Marine Isotope Stage, MIS, 11c exhibited unusually high climate sensitivity. Praetorius and Mix (2014) show that synchronization of North Pacific and Greenland climates preceded the last two abrupt deglacial warming periods during Termination I; which indicates that dynamic coupling of North Pacific and North Atlantic climates may lead to critical transitions in Earth's climate system. Maher et al. (2014) provide evidence that Earth Systems naturally produce hiatus periods followed by periods of greater than usual Earth System responses.

It is therefore, recommended that future modeling efforts recognize both the periodicity and synchronicity of key Earth Systems; which could demonstrate that the Earth is now entering a multi-decadal period of higher than average climate sensitivity (such as likely occurred during MIS 11c), including a synchronization of the North Pacific and Greenland climates.

(b) Marino et al. (2015) present evidence that a bipolar seesaw temperature response during the Eemian produced heat gains at high southern latitudes; which accelerated Antarctic ice-sheet melting contributing to the sea level high-stand in this period. As it is probable that comparable bipolar seesaw effect could accelerate Antarctic ice mass loss due to a short-term surge in ice mass loss from Greenland, it is recommended that future modeling effort evaluate this impacts of this phenomena in the coming decades.

(c) Orsi et al. (2012) demonstrated that based on WAIS-Divide ice borehole temperature information, from the Little Ice Age, that the West Antarctic Ice Sheet, WAIS, can be subject to relatively rapid surface temperature increases during warming phases

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such as the Earth Systems are currently experiencing. Therefore, both field and numerical investigations should seek to better characterize the phase relationship of both atmospheric, and oceanic, advection of heat energy from the Tropical Pacific to the WAIS.

Lines of Investigation for Possible Early Accelerated Ice Mass SLR Contributions This Century:

While your paper provides insightful information about the possible abrupt acceleration of SLR over the coming decades, these discussions could benefit from addition investigations of the following matters:

(a) Dutrieux et al. (2014) demonstrate strong basal ice mass loss sensitivity of ice shelves in the ASE to climatic variability including ENSO events, due to associated fluctuations in the advected warm circumpolar deep water, CDW, at intermediate water depths in the central ASE. NOAA (among all other international meteorological institutions) are currently projecting relatively high probabilities of from strong to super El Nino conditions until late in the austral Fall of 2016; which will likely advect higher than average CDW into the central ASE area.

In this regards, in July 2015 the ice calving face for the Pine Island Ice Shelf, PIIS, has retreated to the furthest upstream position in the modern era and is roughly aligned with the location of the confluence of the PIIS and what MacGregor et al. (2012) have call the Southwest Tributary Glacier. Thus it is recommended that additional field, and numerical, investigations evaluate the probability that a further retreat of the PIIS ice calving face could sufficiently reduce the buttressing on the Southwest Tributary Glacier so that within the next decade that its ice flow velocities may increase by between five and eight times as occurred to the various tributary glaciers when the Larsen B Ice Shelf collapsed. Furthermore, MacGregor et al. (2013) have provided evidence that an increase in the ice flow rate of the Southwest Tributary Glacier may decrease the shear restraint for the Thwaites Glacier's Eastern Shear Margin; which if it were to

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occur would contribute to the near-term destabilization of the Thwaites Glacier.

Furthermore, regarding the short-term stability of Thwaites Glacier, the following image from Logan et al. (2013) shows the fractured condition of the floating, and grounded, ice at the base of the Thwaites Ice Tongue, TIG, in January 2013 (see the figure caption for the location of the grounding line, calving front, ice flow direction, facture spacing and tabular iceberg widths). Kim et al. (2015) provides evidence that since 2000 both the Thwaites Eastern Ice Shelf, TEIS, and the TIG, have experienced accelerating degradation associated with CDW advection and basal ice melting. Currently, two grounded icebergs are shielding the mélanges of tabular icebergs in the vicinity of the base of the TIG. However, Logan et al. (2013)'s Fig. 6 (my Figure 1), shows that if an above average intrusion of CDW into the central ASE reduces the shielding by the grounded icebergs then the mélanges of tabular icebergs will be free to float away, exposing the calving front to accelerated activity in the area around the base of the TIG.

Unfortunately, the mechanisms that generated the TIG in the first place (including a subglacial trough with a channel that drains basal meltwater from the Byrd Subglacial Basin, BSD) will likely promote relatively rapid calving of both floating and grounded glacial ice in this area. Therefore, if/when the mélanges of tabular icebergs float away the residual local ice shelf could degrade relatively rapidly which would likely result in cliff failures of the adjoining fractured ice grounded in the trough at the base of the TIG. Also, if such cliff failure calving events manage to clear all of the ice out of this trough area, within the next decade or so, then this would allow warm CDW to penetrate deeper into the BSB via a submarine canyon near the southern end of the trough; which leads directly into the heart of the BSB. Therefore, it is recommended that field, and numerical, investigations be undertaken to better determine the risk that the areas about the base of the TIG will degrade rapidly over the coming decade.

(b) Rignot et al. (2015) present evidence that several marine-terminating glaciers in Greenland may be more sensitive to ice mass loss than previously understood. Also, NASA will lead the six-year Oceans Melting Greenland (OMG) in order to better project the risk, and rates, of ice mass loss from Greenland. Early ice mass loss from Greenland would raise sea levels in the Southern Ocean; which together increasing local sea levels due Southern Ocean water freshening and with higher storm surge from the increasing cyclonic activity in the Southern Ocean, could help to destabilize Antarctic ice shelves and grounded icebergs. Therefore, it is recommended that future modeling effort should consider scenarios that result in early regional SLR in the Southern Ocean and the influence of such an early regional SLR on the stability of Antarctic ice shelves and grounded icebergs.

(c) Sung et al. (2015) show that there is an asymmetric impact of the Atlantic Multidecadal Oscillation, AMO, on the behavior of the ENSO, resulting in more strong El Nino events; while have less impact on La Nina events. Rahmstorf et al. (2015) show that the last century's slow-down of the AMOC occurred at an exceptionally high rate, and that this slow-down may accelerate this century. Cai et al. (2015) show that continued radiative forcing would increase the frequency of extreme ENSO events. Latif et al. (2015) show that continued radiative forcing would resulting in increasing numbers of Super El Nino events.

As both a slow-down of the AMOC and an increase in the number and intensity of extreme El Nino events, can both accelerate ice mass loss from Antarctica, it is recommended that future model runs be initiated so as to match our current unfavorable conditions, rather than using averaged conditions.

Lines of Investigation for Possible Rapid Ice Mass SLR Contributions Sufficient to Sustain Doubling rates of Between 5-year and 10-year Doubling Rates for the Next Few Decades:

While your paper provides insightful information about the possible high rate of SLR over the coming decades, these discussions could benefit from addition investigations of the following matters:

(a) Lee et al. (2015) present evidence that the Tropical Pacific Ocean was significant source of the ocean heat content, OHC, that transported into the Southern Ocean during the "hiatus" period. Also, the hiatus period was characterized by increased numbers of La Nina events that helped to sequester heat that is now warming the Southern Ocean, and as the next several decades should see an increasing frequency of intense El Nino events (see Latif et al. 2015 and Cai et al. 2015). Therefore, it is recommended that future evaluations of ice mass loss from Western Antarctica in the coming few decades consider both atypically warming ocean and atmospheric conditions.

(b) Both Schroeder et al. (2014) and Damiani et al. (2014) present evidence of relatively high geothermal heat flux in the BSB. Therefore, it is recommended that future evaluations of ice mass loss from the BSB in the next few decades include not only the influence of this basal heat on basal ice viscosity, but also of the influence of the associated high basal meltwater discharge rates on the stability of the glacial ice at the base of the TIG.

(c) Turney et al. (2015) present evidence that future increasing tropical warmth will strengthen meridional circulation; which will in-turn increase the telecommunication of energy from the Tropical Pacific Ocean to Antarctica (and particularly to the WAIS). Therefore, it is recommended that future ice mass evaluations for the WAIS explicitly consider the influence of this increased telecommuted energy, particularly on the risk of surface ice melting contributing to hydrofracturing of both marine glaciers and ice shelves.

(d) Harig and Simons (2015) present ice mass loss/gain data for Antarctica, for the period from January 2003 to June 2014, as summarized in their Fig.1 (my Figure 2). This figure makes it clear that West Antarctica accounts for most of the ice mass loss in Antarctica, followed by the Antarctic Peninsula and the Wilkes Land Region; while the Dronning Maud Land region accounts for the majority of Antarctica's ice mass gain in this period. Thus when extrapolating nonlinear ice mass change trends it is

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advisable to develop individual nonlinear ice mass change relationship for each of the different regions of Antarctica; rather than averaging these different trends together as is done in your paper. Furthermore, per Gorodetskaya et al. (2014) nine atmospheric rivers that hit Dronning Maud Land (DML), East Antarctica between 2009 and 2011. As atmospheric river events are historically rare in Antarctica it is recommended that consideration be made of the probable biasing influence of including these precipitation from these atmospheric river events on long-term ice mass change calculations.

Lines of Investigation for Documenting the Increased Probabilities of Relatively High Climate Sensitivities:

While your paper provides insightful information about the response rate of various Earth Systems through the rest of this century, these discussions could benefit from addition investigations of the following matters:

(a) Schneider von Deimling et al. (2015) present evidence that by the middle of this century thermokarst activity could cause a spike in Arctic methane emissions. Also, Wang et al. (2014) present evidence of a two-fold increase of carbon cycle sensitivity subject to tropical temperature variations. Therefore, it is recommended that the influence of such rapid response carbon-cycle feedback mechanisms be included in future modeling efforts.

(b) Krasting et al. (2014) cite numerical evidence that anthropogenic radiative forcing has now entered a period on increasing Transient Climate Response to cumulative Emissions (TCRE); which means until society reduces its greenhouse gas, GHG, emissions below 2014 levels, all GHG resident in the atmosphere is cause higher climate response than at any time in recent decades. Therefore, as positive carbon-cycle feedback mechanisms may make it difficult to prevent future GHG concentrations from rising; it is recommended that the influence of high GHG emission rates on TCRE should be evaluated.

(c) Both Tian (2015) and Sherwood et al. (2014) present evidence that current equilibrium climate sensitivity, ECS, values may be significantly higher than those values indicated by the IPCC AR5. Therefore, it is recommended that future modeling efforts carefully evaluate the possible consequences of calibrating for emergent ECS values in the 4 to 5 C range.

(d) It is not clear to me that the practice cited in your paper of injecting fresh water into the Southern Ocean at -15 C is equivalent of having an armada of icebergs circling Antarctica for decades while they slowly melt (which could be the case after about 2040). It seems to me that the iceberg armada scenario would result in warmer sea surface temperatures; therefore, it is recommended that future modeling efforts consider the latent heat of melting ice separately from the temperature of the fresh water injected into any given model, as this could affect the modeled Earth Systems sensitivities.

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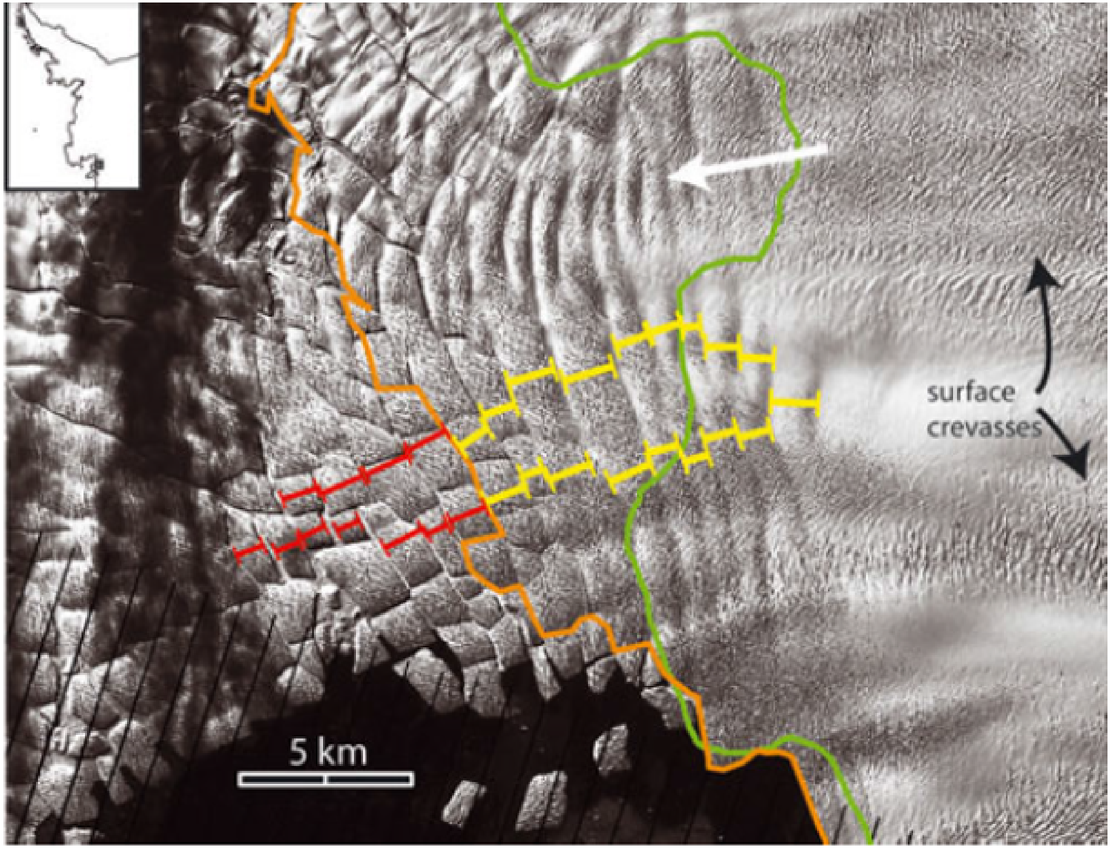

Fig. 1. Fig. 6. Landsat-7 ETM+ band 8 (15 m resolution) image of Thwaites Glacier (from January 2013) and MOA-derived grounding line (green line). Ice velocity is indicated by the thick white arrow. Surface

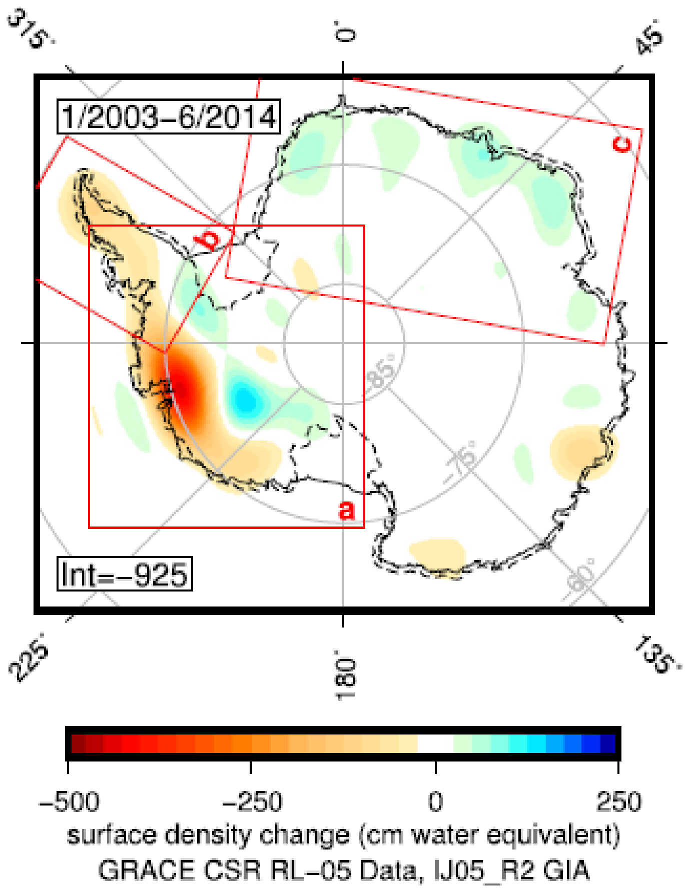

Fig. 2. Fig.1. Ice mass change (mass corrected using the GIA model by Ivins et al., 2013) over Antarctica for the period January 2003 to June 2014. This solution is from a localization over the whole of Antar