

Interactive comment on “Delaying future sea-level rise by storing water on Antarctica” by K. Frieler et al.

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Please find the authors’ answer below in red.

Some technical comments about your idea :

- How can you transport water in pipelines with a temperature of -80°Celsius in winter (-89°C has been measured in Vostok, -93°C measured by satellite between Dome Argus and Dome Fuji). On one year, the average temperature is -57°C. Moreover with powerful winds (catabatic winds with a speed of 200 km/h (possible until 300km/h)). Even with a good insulation, it seems not possible. If water freeze in the pipeline, the pipeline explodes. If water freeze in the pipeline and the pipeline doesn’t explode, how can you unfreeze kilometers of pipeline?

- You talk about the transalaskan pipeline. During the building of this pipeline, more than 30 people died. Alaska is cold. But compared to Antarctica, it’s nothing. In Antarctica, during winter, as far as I know, in the inland, there are only 3 bases with people living in (Amundsen-Scott, Vostok, Concordia) (some others have been used exceptionally). And those people only stay in the bases, they don’t go for a walk outside. Bases are inhabited during winter only near the shores. How people can work in winter to build pipelines ? It seems almost impossible. The Amundsen-Scott base has been built during the summer (with a warm temperature of -30°C), using a lot of C-130 Hercules planes. The cost of the construction of this base was huge, but it’s nothing compared to the building of a pipeline in Antarctica. Planes can’t fly in Antarctica during winter, etc. Summer in Antarctica is very short.

- Glaciers are moving, and sometimes are moving fast near the shores. How pipelines can be used on moving glaciers ?

- On the economic point of view. Even if water can be transported in the Antarctic inland, what will be the price for each cubic meter of water transported (including: building the pipeline and using the pipeline) ? And who will pay this huge bill ? On my point of view, that’s a very theoretical idea. It seems impossible to have something really functioning, and moreover something that can solve the problem of sea level

Answer:

Even if the associated risks, efforts, and costs were known we as scientists are not in the position to decide whether they are justified in comparison to the gain of a comprehensive protection of global coastlines.

We are not able to provide the answers to the technical questions associated the considered measure. The problem has many facets that may have to be addressed by researchers from different disciplines. As scientists we have to make explicit which components we address and which critical issues are unresolved. We do this throughout the text.

Regarding the technical issues we explicitly say that “The scope of such a project is unprecedented and would require major technical innovations, if possible at all.” We provide some further discussion in the SI explicitly mentioning the issue of extremely low temperatures.

We also mention that even “Based on simple upscaling of the costs of the Trans Alaska Pipeline with height, length and throughput (see section S1 of the SI), the costs will be orders of magnitude higher than the costs associated with local adaptation measures (Hinkel et al., 2014).”

Nevertheless, facing the problem of a sea level commitment of more than 2m per °C of global warming we consider it important to discuss a measure that may be the only option for a comprehensive protection of global coastlines although it seems to be technically unfeasible or too expensive to provide this protection.

- You are considering that putting salted water in Antarctica is not a problem. But the Madrid treaty is very strict on that point, it's not allowed.

Answer:

We now mention the Madrid treaty in a new section of the manuscript discussing the ethical problems of the approach:

“The Protocol on Environmental Protection to the Antarctic Treaty (Secretariat of the Antarctic Treaty, 1991) declares a clear intention to minimize human influences on the Antarctic continent. The signing parties “commit themselves to the comprehensive protection of the Antarctic environment and dependent and associated ecosystems and hereby designate Antarctica as a natural reserve, devoted to peace and science.” The measures proposed here (if at all feasible) mean a major human intervention putting the ecosystems of Antarctica and of the surrounding ocean at a high risk. Thus, the protection of global coastlines and associated natural and human would not only have to be weighted against the enormous efforts but also against the loss of Antarctica as a unique natural reserve.”

Moreover, when glaciers in the world will have melt (in a near future), the only place where pure water will available will be in Antarctica, and Greenland (maybe). And we can't destroy those ultimate pure water stock.

Answer:

The ice of Antarctica is as pure as the precipitation there or elsewhere. We do not expect that the problem of water availability due to melting of glaciers or other reasons will have to be resolved by transporting water from Antarctica to the affected regions. Under climate change precipitation is only expected to decline in some regions while it will increase in others. Thus, if water will have to be transported to regions affected by water scarcity, Antarctica seems to be the least efficient way to go.

1 Delaying future sea-level rise by storing water on 2 Antarctica

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8

9 Abstract

10 Even if greenhouse gas emissions were stopped today, sea level would continue to rise for
11 centuries, with the long-term sea-level commitment of a two-degree-warmer world
12 significantly exceeding 2m. In view of the potential implications for coastal populations and
13 ecosystems worldwide, we investigate, from an ice-dynamic perspective, the possibility to
14 delay sea-level rise by pumping ocean water onto the surface of the Antarctic Ice Sheet. We
15 find that due to wave propagation ice is discharged much faster back into the ocean than
16 would be expected from a pure advection with surface velocities. The delay time depends
17 strongly on the distance from the coastline at which the additional mass is placed and less
18 strongly on the rate of sea-level rise that is mitigated. A millennium-scale storage of at least
19 80% of the additional ice requires placing it at a distance of at least 700 km from the coast
20 line. The pumping energy required to elevate the potential energy of ocean water to mitigate
21 the currently observed 3mm yr^{-1} will exceed 7% of the current global primary energy supply.
22 At the same time, the approach may be the only way to protect entire coastlines or specific
23 regions that cannot be protected by dikes.

24

25 :

26 1 Introduction

27 Anthropogenic emissions of carbon into the atmosphere have increased global
28 temperatures by almost one degree during the past two centuries (IPCC, 2013). Even after a

1 | complete cessation of carbon emissions, temperatures are not expected to drop significantly
2 | for several centuries. Although the reduction of short-lived forcing agents has the potential to
3 | reduce the near-term warming by about 0.5 degrees, global mean temperatures are not
4 | projected to decline significantly, even under the strongest mitigation scenario, RCP2.6,
5 | which is already accounting for reductions in black carbon, methane, and other short-lived
6 | forcings (van Vuuren et al., 2011). As a consequence of the climate system's inertia and the ice
7 | sheets' response, mitigating greenhouse-gas emissions in the future can reduce, but will not
8 | stop, sea-level rise for centuries to come (Gillett et al., 2011; IPCC, 2013; Meehl et al., 2005;
9 | Solomon et al., 2009; Wigley, 2005). Conservative estimates for this so-called sea-level
10 | commitment are of the order of 2m per degree of global warming above pre-industrial
11 | temperatures over a time period of two millennia (Levermann et al., 2013); estimates of sea-
12 | level sensitivity to warming from paleo-records of earlier warm periods are even higher
13 | (Rohling et al., 2008, 2013). In addition, there is recent evidence from observations (Rignot et
14 | al., 2014) and numerical models (Favier et al., 2014; Joughin et al., 2014a) that the West
15 | Antarctic Ice Sheet has entered a state of irreversible ice discharge that would cause a sea-
16 | level contribution even without any additional warming. The associated long-term sea-level
17 | rise is estimated to be 1.1m from the Amundsen-Sea sector, or 3.3m if the entire marine part
18 | of West Antarctica ~~was~~ affected (Bamber et al., 2009).

19 | As a consequence, global coastal adaptation to ~~an~~ ongoing sea-level rise will be
20 | required unless water is taken back out of the ocean. Such local protection may not be
21 | physically possible or economically feasible everywhere. In South Florida in the USA, for
22 | example, the base rock is limestone, which makes the construction of levees very difficult
23 | (Strauss et al., 2014). In addition, dams may not be acceptable for some regions that ~~rely~~
24 | on tourism ~~associated with~~ attracted by natural beaches. Local protection will most likely only
25 | be done for areas ~~where valuable~~ with high assets ~~are~~ at risk, and will not cover entire coast
26 | lines including poor areas and ecosystems.

27 | Here, we evaluate, ~~from an ice-dynamic perspective,~~ the option of delaying global sea-
28 | level rise for three idealized scenarios of linear increases over the 21st century. Mitigating the
29 | currently observed rate (Cazenave and Dieng, 2014) of $\sim 3\text{mm yr}^{-1}$ is considered in
30 | comparison to the mitigation of 1mm yr^{-1} and a rate of 10mm yr^{-1} within the “likely range”
31 | for the end of the century under the high emission scenario RCP8.5 (IPCC, 2013). ~~Since~~
~~As~~ it

1 might be difficult to store such large water masses in liquid form on land due to adverse
2 effects on population, regional ecosystems, and expected changes in the hydrological cycle,
3 we explore ~~here~~ whether it is possible to store it ~~can be stored~~ as ice on Antarctica from the
4 perspective of ice dynamics.

5 The Antarctic ice sheet is situated on the coldest continent on Earth with most of its
6 surface temperatures far below the freezing point of ocean water throughout the year. The
7 water volume ~~that is~~ equivalent to one meter of global sea-level rise would elevate the
8 Antarctic ice sheet by ~25m if distributed uniformly. The currently observed ~3mm yr⁻¹ of
9 global average sea-level rise due to thermal expansion, additional water added from glaciers
10 and ice sheets, and changes in land water storage, corresponds to about 10¹² m³ yr⁻¹ of ocean-
11 water ~~volume. Solely in terms of throughput mitigating a sea-level rise of 3 mm yr⁻¹ would~~
12 ~~require 90 of the largest pump stations currently under construction in New Orleans each~~
13 ~~assumed to pump ~360 m³ s⁻¹ which corresponds to ~11·10⁹ m³ yr⁻¹ (Alyeska Pipeline Service~~
14 ~~Company, 2013). The height of the ice sheet of about 4000m means that it would require a~~
15 ~~constant power of 1275 GW to elevate the potential energy of the associated ocean water.~~
16 ~~This is equivalent to ~7% of the global primary energy supply of the year 2012 (International~~
17 ~~Energy Agency, 2014). The power required for the actual pumping may even be higher and~~
18 ~~reach 2300 GW under optimistic assumptions (see SI). It will have to be generated by~~
19 ~~renewable resources to avoid the additional climate change and sea-level rise associated with~~
20 ~~fossil fuels. The Antarctic continent is windy enough to support such pumping through wind~~
21 ~~energy, with around 16.7 TW available in a 200km wide band along the coast of East~~
22 ~~Antarctica (Archer and Jacobson, 2005) (see SI). Around 8% of that energy would need to be~~
23 ~~extracted to compensate the potential energy increase of the pumped water alone, which is~~
24 ~~equivalent to 850,000 wind energy plants of 1.5 MW running on full capacity. Although the~~
25 ~~approach may be the only way to protect entire coast lines it will not be feasible without~~
26 ~~major technical innovations solving the fundamental energy problem. In the following we~~
27 ~~explore the option from an ice dynamical point of view.~~ Antarctica's currently observed
28 ice loss occurs near the coast (Shepherd et al., 2012), while the surface in its interior is
29 moving at a speed of less than 0.1m yr⁻¹ per year (Rignot et al., 2011). Because the ice is
30 continually moving, ocean water put on the ice sheet will only delay sea-level rise. Here we

1 estimate the associated delay time and its dependence on the distance from the coast and the
2 application rate.

3 4 **2 Ice sheet simulations**

5
6 Using the Parallel Ice Sheet Model (PISM) (Bueler and Brown, 2009; Winkelmann et al.,
7 2011) we estimate the ice sheet's response to different ~~scenarios of~~ ice addition scenarios. To
8 this end we ran the model to equilibrium in a 100ky spin-up under constant present-day
9 atmospheric and oceanic boundary conditions. Surface air temperature (Comiso, 2000) and
10 mass balance (Arthern et al., 2006) are taken from observations made available in the
11 ALBMAP data set (Le Brocq et al., 2010). We apply sub-shelf basal melting and refreezing
12 rates from a 20th century simulation of the Finite Element southern ocean model (FESOM)
13 (Timmermann et al., 2012). The modeled equilibrium ice sheet state compares well to the
14 currently observed ice sheet in terms of surface elevation and grounding line position
15 (supplementary Fig. S2) and ice velocities (supplementary Fig. S3 and S4). Total modeled ice
16 volume deviates less than 0.5% from the observed state (Fretwell et al., 2013).

17
18 In our forcing simulations we disturb this equilibrium state with 100 year-long pulses of
19 increased surface mass balance (SMB) in selected bands (see Fig. 1). The added surface mass
20 compensates a $1\text{mm}/\text{y}^{-1}$, $3\text{mm}/\text{y}^{-1}$ and $10\text{mm}/\text{y}^{-1}$ sea level rise ($\Delta\text{SMB} = \text{rate of sea level rise}$
21 $\ast \text{ global ocean area} / \text{area of mass addition}$). The maximum sea level drop is therefore 1m. We
22 construct the bands of surface mass addition by drawing lines with distances of 200, 300, 400,
23 500, 600, 700, and 800 km from the coast, and use these as the center lines of 200 km wide
24 bands. The bands are limited to longitudes between 20°W and 165°E to only cover the East
25 Antarctic ice sheet because of the currently observed imbalance in West Antarctica. The rate
26 is applied for 100 years and then set to zero in order to better estimate the sea-level delay
27 time. Whether the pumping should be limited needs to be decided by society if such measure
28 is ever to be implemented.

29 ~~By adding the ice to the surface of an equilibrium simulation we do not account for any~~
30 ~~drift that might have been caused by previous variations in the boundary conditions such as~~
31 ~~the last deglaciation or the medieval warm period or anthropogenic warming. Although a~~

1 ~~possible drift within the present-day ice sheet could potentially alter the ice export as reported~~
2 ~~here, it can be assumed that the drift is negligible at distances of several hundred kilometres~~
3 ~~away from the coast.~~

4 By adding the ice to the surface of an equilibrium simulation we do not account for any
5 drift that might have been caused by previous variations in the boundary conditions, such as
6 the last deglaciation, or the medieval warm period or anthropogenic warming. Although a
7 possible drift within the present-day ice sheet could potentially alter the ice export as reported
8 here, it can be assumed that the drift is negligible at distances of several hundred kilometers
9 away from the coast.

10 To represent the large-scale dynamics reasonably well, we use a 12 km horizontal
11 resolution for the ice sheet simulations. Our hybrid shallow approximation ensures stress
12 transmission across the grounding line and a smooth transition between regimes of fast
13 flowing, sliding and slowly deforming, bedrock-frozen ice. The grounding line can freely
14 evolve ~~even at a~~ lower resolution due to a local interpolation of the grounding-line
15 position, ~~which~~ affects the basal friction and a new driving stress scheme at the grounding
16 line. The interpolation leads to ~~a~~ reversible grounding-line dynamics ~~that is~~ consistent with
17 Full-Stokes simulations ~~at~~ high resolution (Feldmann et al., 2014). Although the model is
18 capable of simulating the coastal dynamics of the ice sheet within limitations, it is important
19 to note that the results obtained here are predominantly dependent on the ice flow
20 representation in the interior of the ice sheet, for ~~which~~ large-scale continental ice-sheet
21 models like PISM and others (Bindschadler et al., 2013; Calov et al., 2010; Greve et al., 2011;
22 Huybrechts and Wolde, 1999; Pollard and Deconto, 2009; Swingedouw et al., 2008) have
23 been designed.

24
25 In the standard simulation we do not alter the surface air temperature during ~~the~~ mass
26 addition. To estimate the effect of surface warming due to the latent heat release of the sea
27 water, we conduct a second set of simulations that keeps the surface temperature at the
28 freezing point of sea water (-1.9 °C) during ~~the~~ surface mass addition. This imitates the
29 situation in which the ice surface remains in a mixed state of ice and water. Since Antarctica's
30 inland-surface temperatures are far below zero, this constitutes a strong warming signal that
31 diffuses down into the ice body and causes ice to soften and flow faster. The maximum
32 injection of latent heat occurs for the 10 mm yr⁻¹ sea-level-mitigation scenario and the 800km

1 band, which has the smallest area. The corresponding addition of 3.2 m yr^{-1} liquid sea water is
2 equivalent to a latent heat injection of about 35 Wm^{-2} . A warming from -20°C to -1.9°C
3 would increase the long-wave radiative loss to the atmosphere by 70 Wm^{-2} , according to the
4 Stefan-Boltzmann law, assuming an emissivity of 0.95. If open water areas are sustained on
5 the ice sheet, a sensible-heat-dominated loss can remove heat at a rate of 100 Wm^{-2} or more as
6 observed in ocean polynyas (Launiainen and Vihma, 1994). The maximum rate of latent heat
7 injection of 35 Wm^{-2} is much smaller than the potential of the atmosphere to remove the heat.
8 Thus, keeping surface ice temperatures at freezing point underestimates the atmospheric heat
9 loss so that the simulations provide an upper bound for the induced warming of ice.

11 3 Results

12 The ratio of the volume added during the first 100 years and the volume that is lost
13 again after 1000 years depends strongly on the distance from the coast (Fig. 2 and Fig. 3).
14 Consistent with earlier studies (Huybrechts and Wolde, 1999; Winkelmann et al., 2012), an
15 ice volume equivalent to 10-15% of the added ice is already lost at the end of the forcing
16 period, when the ice is added at a distance of 200km from the coastline, while the sea-level
17 contribution is strongly delayed at a distance above 500km from the coast (Fig. 2). In order to
18 minimize the return flow of the ice into the ocean, the specific positioning of the ice addition
19 could be varied spatially making use of slow-moving ice regions. Here we apply a simplified
20 spatial distribution in order to demonstrate the main process and ~~enable~~ allow for a conceptual
21 analysis of the simulations.

22 The time after which ~~the a certain~~ equivalent of a certain equivalent of the added ice has
23 been discharged into the ocean, is much shorter than would be expected from a mere
24 advection of the added ice mass with the surface velocities of the ice sheet (Fig. S52 of the
25 SI). ~~This is~~ because the ice thickness anomaly creates an imbalance between the driving
26 stress and the viscous ice flow. As a consequence, the ice transport occurs in waves from the
27 strip of perturbation to the coast (Winkelmann et al., 2012) (Fig. 1), ~~where~~ ~~th~~ the ice ~~being~~
28 discharged to the ocean ~~is not~~ ~~not being~~ the same ice that was added to the ice sheet earlier.

1 Even though the ice wave also travels partially inland, it is possible that more ice is
2 transported out of the continent than was initially added. ~~However, t~~This ice-loss exceedance,
3 ~~however,~~ occurs only several millennia after the perturbation (Fig. S52 of the SI). Whether it
4 is directly related to the perturbation or a manifestation of a localized multistability of the ice
5 dynamics is difficult to identify, because the differences between the initial and final ice
6 topography are within the uncertainty range of the model performance.

7 ~~The freezing of ocean water that is pumped onto the ice surface will release latent heat that~~
8 ~~will heat up both the atmosphere and the upper ice layer. The maximum injection of latent~~
9 ~~heat occurs for the 10 mm yr⁻¹ sea level mitigation scenario and the 800km band, which has~~
10 ~~the smallest area. The corresponding addition of 3.2 m yr⁻¹ liquid sea water is equivalent to a~~
11 ~~latent heat injection of about 35 Wm⁻². In order to estimate the effect of the surface warming~~
12 ~~on the ice dynamics, we conduct a second set of simulations in which the surface temperature~~
13 ~~is held at the freezing point of sea water of -1.9 °C during the forcing. This imitates the~~
14 ~~situation in which the surface of the ice remains in a mixed state of ice and water. As~~
15 ~~Antarctica's inland surface temperatures are far below zero, this constitutes a strong warming~~
16 ~~signal that diffuses down into the ice body and causes ice to soften and flow faster.~~

17 ~~A warming from -20°C to -1.9°C would increase the long wave radiative loss to the~~
18 ~~atmosphere by 70 Wm⁻² according to the Stefan Boltzmann law assuming an emissivity of~~
19 ~~0.95. If open water areas are sustained on the ice sheet, a sensible heat dominated loss can~~
20 ~~remove heat at a rate of 100 Wm⁻² or more as observed in ocean polynyas (Launiainen and~~
21 ~~Vihma, 1994). The maximum rate of latent heat injection of 35 Wm⁻² is much smaller than the~~
22 ~~potential of the atmosphere to remove the heat. Thus keeping surface ice temperatures at~~
23 ~~freezing point underestimates the atmospheric heat loss so that the simulations provide an~~
24 ~~upper bound for the induced warming of ice.~~

25 For perturbation areas ~~farwith large distance~~ from the coast, the discharge rates ~~of the~~
26 ~~ice sheet in the sensitivity simulation accounting for latent heat release~~ (Fig. 4, thin lines)
27 ~~areis~~ nearly identical to the response without warming (Fig. 4, thick lines) on the millennial

1 time scale considered. Within the first millennium, the latent heat release of freezing sea
2 water only alters the discharge when placed near the coast. After 2000 years, the additional
3 warming can induce a discharge exceeding 100% of the added ice in the 200-km simulations
4 (Fig S1 of the SI).

5 ~~It is possible that ice dynamic effects which are not included in these simulations (such~~
6 ~~as ice fractures or basal sliding conditions) alter the results quantitatively, but the shallow ice~~
7 ~~approximation which dominates the ice dynamics in the model in the interior of Antarctica~~
8 ~~has been shown to represent the interior ice sheet flow on multi-centennial and longer time~~
9 ~~scales (Greve and Blatter, 2009).~~

10

11 **4 Discussion**

12 All scenarios considered here assume that the only perturbation of the ice sheet is the
13 addition of ice mass in bands of the interior of East Antarctica. At the same time, Antarctica's
14 coastal regions are out of balance in a number of regions predominantly in West, but also in
15 East Antarctica. In this study it is assumed that the addition of ice in the interior will not
16 interfere with the imbalance at the coast. This might be an over-simplification, but currently
17 available modeling studies (Favier et al., 2014; Joughin et al., 2014b; Mengel and Levermann,
18 2014) indicate that perturbations near the coast will not reach as far inland over time periods
19 of several centuries. ~~However, a~~ possible interference between the interior of the ice sheet
20 and its coastal regions, ~~however,~~ needs further investigation, possibly with higher-resolution
21 regional ice sheet models.

22 It is possible that ice dynamic effects, which are not included in these simulations (such
23 as ice fractures or basal sliding conditions), alter the results quantitatively. However, the
24 shallow-ice approximation that dominates the ice dynamics in the model in the interior of
25 Antarctica has been shown to represent the interior ice sheet flow on multi-centennial and
26 longer time scales (Greve and Blatter, 2009).

1 We assume that it would be best to add the additional ice in the form of snow as
2 opposed to adding it as water which will then freeze. In this context it has to be noted that the
3 additional ice that is added to the ice sheet is made of sea water and thereby will have salinity.
4 The rheological effects of a “salt-ice” layer within an ice sheet are currently unknown and
5 need further investigation. While initially the “salt-ice” will be at the surface of the ice sheet,
6 the dynamic effect will be dominated by its gravitational effect which is covered by the
7 modelled ice dynamics modelled. However, ~~since~~while snow is falling onto the “salt-ice”
8 layer, this layer’s rheology will become relevant for the ice dynamics. At current and future
9 snowfall rates (Frieler et al., 2015) this will take several centuries.

10 The ~~conducted~~-simulations conducted here suggest that pumping ocean water onto the
11 interior of the Antarctic ice sheet can impose a significant delay of future sea-level rise.
12 However, as an option to mitigate the sea-level rise to which we are already committed, ~~to~~ a
13 substantial energy problem ~~must~~has to be overcome. Solely in terms of throughput, mitigating
14 sea-level rise of 3 mm yr⁻¹ would require 90 of the largest pump stations currently under
15 construction in New Orleans, each assumed to pump ~360 m³ s⁻¹, which corresponds to
16 ~11·10⁹ m³ yr⁻¹ (Alyeska Pipeline Service Company, 2013). The height of the ice sheet of
17 about 4000m means that it would require a constant power of 1275 GW to elevate the
18 potential energy of the associated ocean water. This is equivalent to ~7% of the global
19 primary energy supply of the year 2012 (International Energy Agency, 2014). The power
20 required for the actual pumping may even be higher and reach 2300 GW under optimistic
21 assumptions (see section S1 of the SI). It will have to be generated by renewable resources to
22 avoid the additional climate change and sea-level rise associated with fossil fuels. The
23 Antarctic continent is windy enough to support such pumping using wind energy, with around
24 16.7 TW available in a 200km wide band along the coast of East Antarctica (Archer and
25 Jacobson, 2005) (see section S2 of the SI). Around 8% of that energy would need to be
26 extracted to compensate the potential energy increase of the pumped water alone, which is
27 equivalent to 850,000 wind-energy plants of 1.5 MW, running on full capacity

1 ~~The scope of such a project is unprecedented~~It goes far beyond the scope of existing
2 ~~projects~~ and ~~would~~~~it~~ require major technical innovations, if ~~at all~~ possible at all. Therefore,
3 costs cannot be reliably estimated. Based on simple upscaling of the costs of the Trans Alaska
4 Pipeline with height, length and throughput (see section S1 of the SI), the costs will be orders
5 of magnitude higher than the costs associated with local adaptation measures (Hinkel et al.,
6 2014). However, it is important to note that in ~~this~~~~current~~ studies on sea-level adaptation³²,
7 protection is only installed if considered economically favorable. In contrast, storing water on
8 the Antarctic Ice Sheet would offer ~~a~~ general protection for entire coast lines and poor regions
9 that would otherwise be left unprotected. The associated investment could change the
10 mitigation costs by significantly increasing the demand (thereby technical progress) ~~for~~~~of~~
11 renewable energies significantly. By ~~generating~~~~creating~~ an additional demand for renewable
12 energies of the order of 10% of the global energy supply, this ~~approach offers~~~~measure~~
13 ~~thereby constitutes~~ a link between the mitigation and adaptation problem of climate change.

14 This study ~~must~~~~has to~~ be complemented by investigations on possible consequences of
15 the procedure. To name just a few, ~~it~~ is likely that construction of the pipelines, pump
16 stations, the energy generation, and the water extraction will induce disturbances in the
17 coastal ecosystems. It should also~~has to~~ be investigated how the water extraction will
18 influence the small- and large-scale ocean circulation. The ice-rheological changes ~~that are~~
19 induced by the addition of salt water should~~have to~~ be investigated together with potential
20 effects on the basal conditions of the ice.

21 The heat released from freezing and the pumping process itself is in the order of 10 TW
22 (latent heat) + 1TW (heat released from pumping). This corresponds to about 10% of the
23 maximum increase in latent heat transport in high northern latitudes under an SRES A1B
24 transient simulation (Held and Soden, 2006). The latent heat release is considered ~~as~~ a
25 major~~it~~ contribution to the Arctic amplification of global warming. ~~From~~~~Put into~~ this
26 perspective, the pumping-induced energy over Antarctica is not negligible but significantly

1 smaller than the warming induced latent heat released in northern high latitudes. Potential
2 consequences for the atmospheric and oceanic circulation ~~need~~ have to be further explored.

3 5 Ethical Considerations

4 The Protocol on Environmental Protection to the Antarctic Treaty (Secretariat of the
5 Antarctic Treaty, 1991) declares a clear intention to minimize human influences on the
6 Antarctic continent. The signing parties are “Convinced that the development of a
7 comprehensive regime for the protection of the Antarctic environment and dependent and
8 associated ecosystems is in the interest of mankind as a whole;“ and “commit themselves to
9 the comprehensive protection of the Antarctic environment and dependent and associated
10 ecosystems and hereby designate Antarctica as a natural reserve, devoted to peace and
11 science.” The measures proposed here (if at all feasible) mean a major human intervention
12 putting the ecosystems of Antarctica and of the surrounding ocean at a high risk. It will add to
13 the changes by human induced climate change itself (IPCC, 2013; Rignot et al., 2008; Ritz et
14 al., 2015). Thus, the protection of global coastlines and associated natural and human would
15 not only have to be weighted against the enormous efforts but also against the loss of
16 Antarctica as a unique natural reserve.

17 Storing water on the Antarctic continent also raises questions of inter-generational
18 justice. When ~~the~~ pumping is stopped, the additional discharge from Antarctica will increase
19 the rate of sea-level rise even beyond the warming-induced rate. In this way, ~~sense~~ the
20 ~~presented~~ approach presented here means taking out ~~raising~~ a loan on Antarctica that future
21 generations will have to pay back. In all simulations considered here, pumping ~~ceases~~ ~~is~~
22 ~~stopped~~ after 100 years, i.e. it is investigated as an option to delay part of the sea-level rise we
23 are already committed to, but not as a permanent measure that may induce further responses
24 of the ice sheet not captured here.

25 If at all feasible, the considered scenarios do not at all represent an alternative to the
26 mitigation of carbon emissions, because the method does not address any ~~other~~ climate-
27 change impact other than sea-level rise. Furthermore, unmitigated emission might induce a
28 sea-level rise of 10 mm yr⁻¹ and beyond, which increases the impacts on Antarctica and the

1 burden for future generations when mitigated by pumping of ocean waters. AndThirdly, after
2 ~~the~~ pumping is stopped, ~~the~~ sea level will accelerate quickly towards the rate that corresponds
3 to the warming level, plus that induced by the addition of ice onto Antarctica.

4 Although a potential way to delay the committed sea-level rise from an ice dynamical
5 perspective, ~~it represents an open engineering problem~~ whether it is at all possible to locally
6 generate the required energy poses an open engineering challenge.

10 Acknowledgements

11 We thank Hans-Joachim Schellnhuber for very fruitful discussions related to the development
12 of this manuscript and particularly associated with the problem of the energy requirements.

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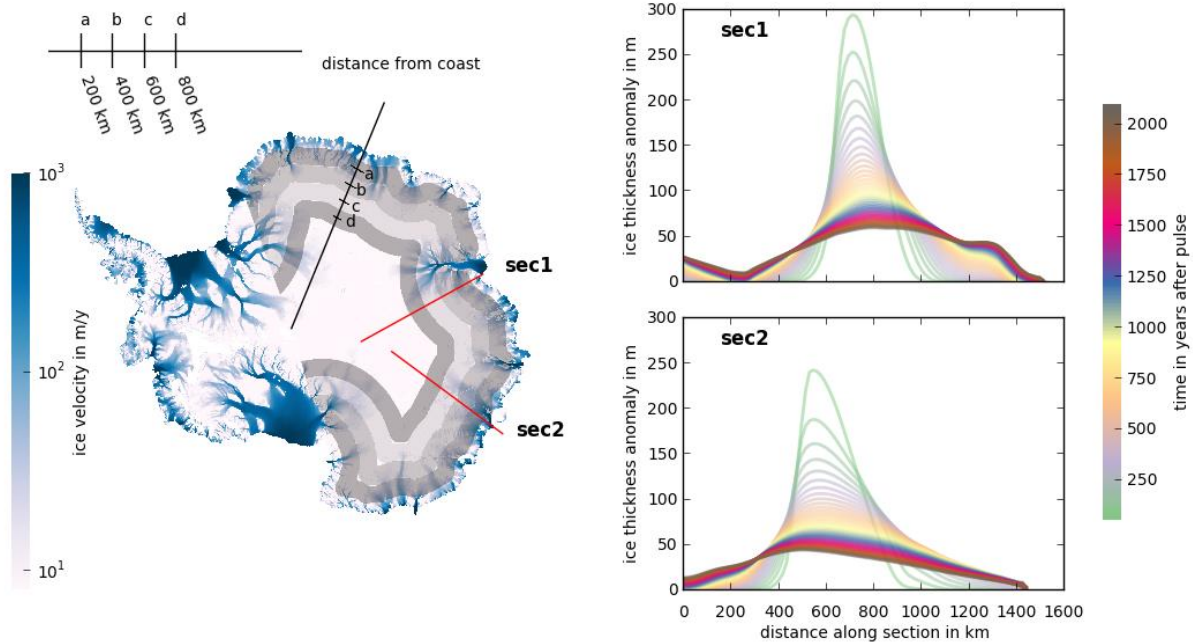
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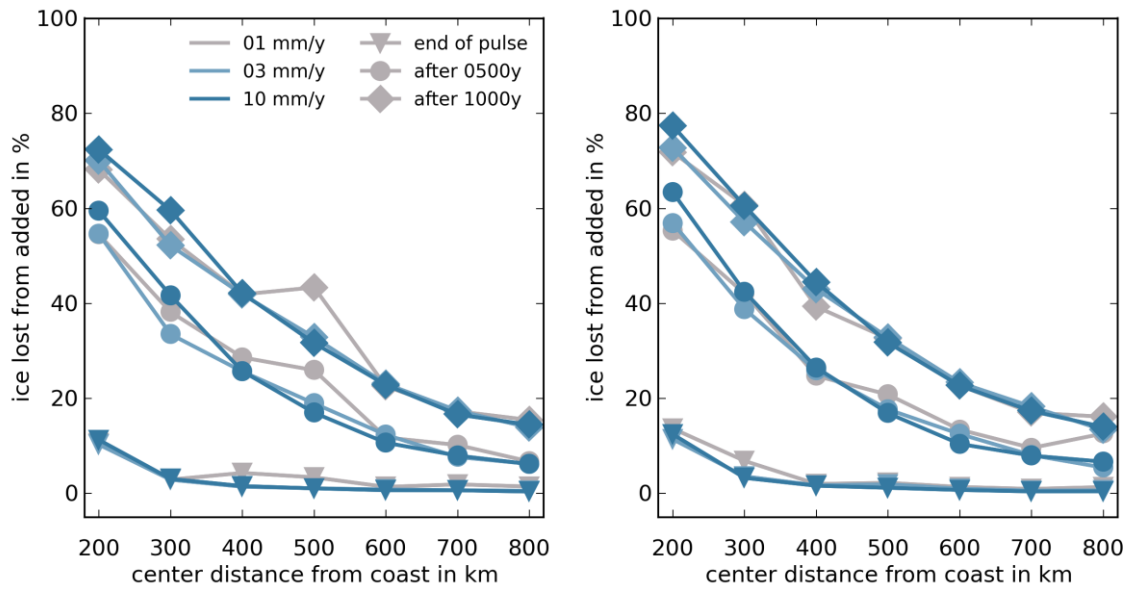
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 2 **Fig. 1 Bands of ice mass addition on East Antarctica and ice thickness relaxation for the**
 3 **800 km band.** Left panel: Surface velocities of the ice flow of the Antarctic ice sheet (blue
 4 shading). Grey strips indicate where ice mass was added to East Antarctica in order to delay
 5 future sea-level rise in the different simulations. The ice was added in strips of 200-km width
 6 for 100 yrs. The right panels show the ice thickness relaxation after the end of the mass
 7 addition to the 800-km band in time steps of 50 yrs for two representative sections (left panel,
 8 red lines) as anomaly to the equilibrium simulation.

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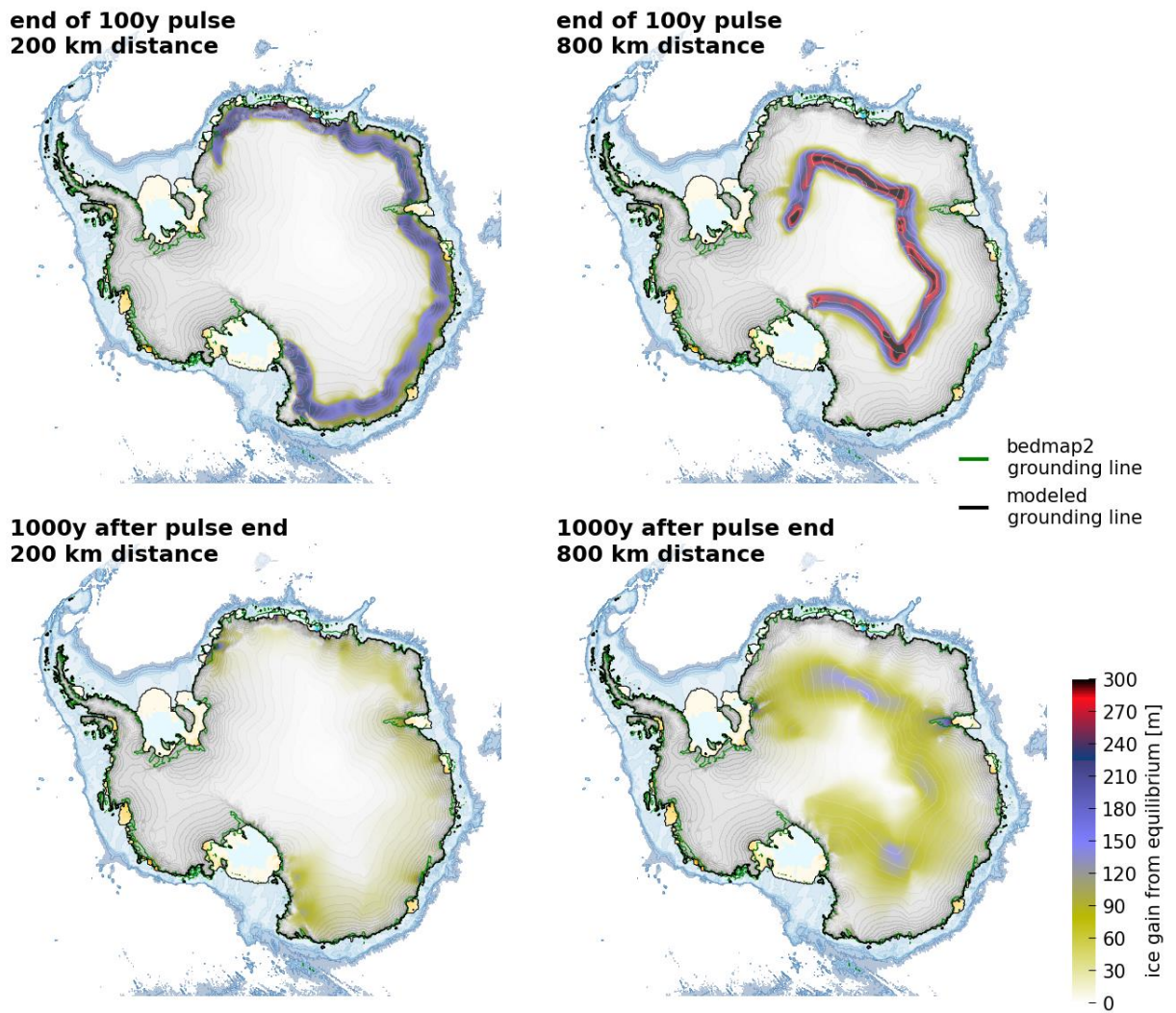


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2 **Fig. 2 Additional ice discharge compared to mass addition for different distances from**
 3 **the coast.** The fraction of the added ice that is lost again to the ocean as a function of distance
 4 from the coast at which the additional ice was placed for the simulations without (left panel)
 5 and with (right panel) surface warming. Colours indicate the magnitude of the mass addition
 6 equivalent to 1, 3 and 10 mm yr⁻¹ sea level rise mitigation. Markers correspond to the
 7 different relaxation times: end of pulse, 500 and 1000 yrs after the pulse of mass addition
 8 ended.

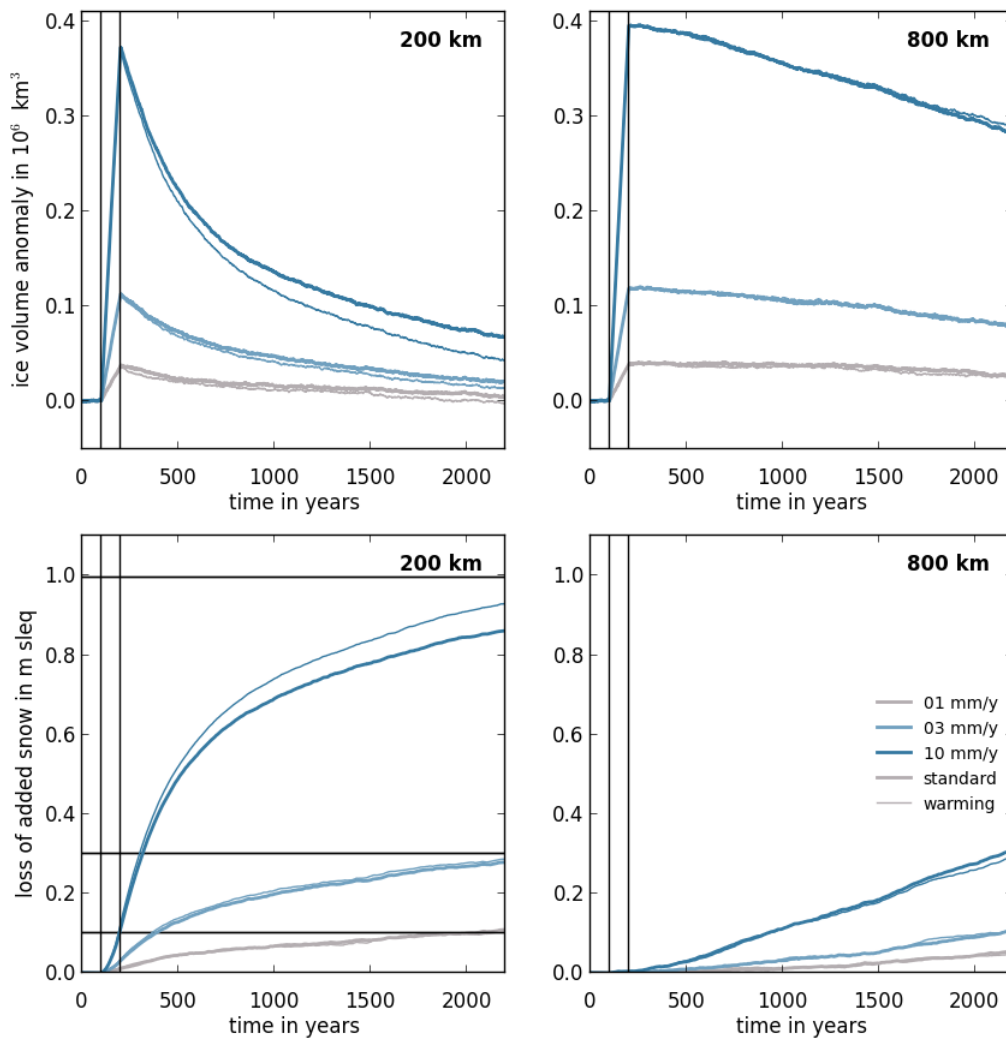
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2 **Fig. 3: Difference in ice thickness compared to the initial state.** Ice thickness gain at the
 3 end of the 100-yr-long mass addition (upper panels) and 1000 yrs after the forcing ended
 4 (lower panels). The close-to-coast simulation (left panels) has lost most of the added ice to the
 5 ocean after 1000 yrs while there is a broad ice gain in the 800-km simulation (right panels).
 6 Figures are shown for the strongest scenario of 10mm yr^{-1} of sea-level mitigation and without
 7 accounting for latent-heat release.



1

2 **Fig. 4: Response of the Antarctic Ice Sheet to a 100-yr-surface-mass addition.** Ice volume
 3 gain and relaxation (upper panels) and equivalent loss of the added snow (lower panels) for
 4 the close-to-coast (200 km, left panels) and farthest-inland (800 km, right panels) simulations
 5 for the 1, 3 and 10 mm yr⁻¹ mitigation cases (grey, light blue and dark blue colours). Thick
 6 lines indicate simulations without surface warming, thin lines with surface temperature held at
 7 sea water freezing point during the forcing (upper bound). Vertical lines indicate the pulse
 8 interval, horizontal lines in lower left panel indicate the total ice volume added.