

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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Received and published: 8 September 2015

Title: The rapid sea level rise and climate change in the late Eemian could happen again as a result of accelerated Arctic warming; but catastrophe can be prevented by international collaboration to cool the Arctic

Caveat

Compelling evidence, comparing past with present, leads us to an extremely disturbing

C6684

view of the Earth System tipping ever faster from the Holocene norm to a new inhospitable state, with rapidly rising sea levels and a destabilised climate system, even without further global warming.

Fortunately, with advanced technology and our improved understanding of Earth System thermodynamic mechanisms, it should be possible to halt this tipping and subsequently reverse it.

But the situation demands rapid intervention specifically to counter the tipping forces, and there is much antipathy to the kind of large-scale intervention required. This antipathy has to be overcome.

However, the requirement for such intervention creates an unprecedented opportunity for international collaboration in mutual self-interest with potential benefits for all humanity, including peace, security and well-being.

Summary of the situation

The Eemian analogue has proved beyond reasonable doubt that our current situation is extremely dangerous, as the Earth System lurches away from the norm of the Holocene towards a new state. Several tipping points have been passed and positive feedbacks are growing. But in their paper, Hansen and colleagues argue that the most immediate danger comes from the Antarctic; whereas the conventional view (and I suspect that of most reviewers of this paper) is that it comes from the Arctic. Either way, drastic actions are required, above and beyond emissions reduction, to prevent further decline in the situation towards a state with massive sea level rise accompanied by abrupt climate change, possibly within a few decades.

The paper also raises the issue of climate change direction. The authors consider that events could lead to a colder Arctic, with great storms as the temperature gradient from tropics to pole increases. A contrary and more conventional view is that Arctic warming is now strong enough to resist cooling from Greenland's meltwater, so the

C6685

temperature gradient will continue decreasing, with a more meandering jet stream and ever longer spells of stuck weather. Such jet stream behaviour will be compounded by global warming to produce acute climate change, at least in the Northern Hemisphere, with potentially catastrophic consequences.

Current efforts by world leaders to significantly reduce CO₂ emissions, even accompanied by CO₂ removal, cannot rescue the situation because of the short timescale required: every year that we delay intervention to cool the Arctic and save the sea ice, the more drastic, expensive and risky the intervention will have to be.

The Arctic situation is even more menacing than suggested by the sea level rise and climate change that are discussed in the paper. Even as the Greenland Ice Sheet continues to lose integrity, huge icebergs could be released creating mega-tsunamis in the North Atlantic; hence precautions against tsunami are necessary while efforts are made to stabilise the ice sheet. And escalating emissions of methane from a 1.5 teraton store under the Arctic Ocean's continental shelf could lead to gigatons being released, sufficient to overwhelm efforts to curb global warming; hence some means of methane capture and/or suppression has to be considered.

The case for urgent action

The paper, "Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2C global warming is highly dangerous", by Hansen et al. explores the possibility that Antarctic ice sheets could disintegrate before the Greenland Ice Sheet (GIS), based on analogy with what might have happened in the Eemian; but it is far more likely that GIS will go first.

It is generally acknowledged that what happens in the Arctic does not stay in the Arctic. Over thousands of years, the Arctic has been providing services for our mid-latitudes: firstly by keeping the Greenland Ice Sheet frozen so that the sea level hasn't significantly changed allowing coastal communities to flourish; and secondly by keeping a temperature differential from lower latitudes so that the jet stream behaviour has

C6686

been steady and Northern Hemisphere (NH) climate has been conducive to agriculture. These benefits to our modern civilisation are about to disappear unless appropriate interventions are taken to prevent the ice sheet and sea ice from further decline, especially urgently for the latter.

This changes the direction and urgency of the required climate change response. And it underlines the need for a proper understanding of the Earth System processes which led to the current situation, so that we can see our way out of our current predicament.

Note that there is not only the challenge of halting the processes working against us, but also the opportunity for reversing them. For example, by restoring sea ice, one might reduce the number of extreme weather events, which have been growing over the past 20 years (Munich Re, 2014).

The Arctic sea ice is retreating rapidly and there is high risk that the Arctic Ocean could become seasonally ice-free within a few years, as the state of the ice at the end of summer is now so precarious. The loss of albedo by this occurrence will be immense and the associated rapid warming of the Arctic (absent of intervention) will have a number of inevitable repercussions: (i) increasingly rapid melting of the Greenland Ice Sheet, (ii) increasingly rapid loss of terrestrial Arctic snow cover, (iii) further disruption of the jet stream to produce global abrupt climate change in the Northern Hemisphere and (iv) further escalation of methane emissions from land permafrost and from marine hydrates, jeopardising attempts to keep global warming within safe limits.

There is evidence of these four processes already proceeding on exponential trends. It is difficult to credit that such disasters could happen without there being a precedent in the history of the planet.

The paper by Hansen and colleagues is vitally important because it provides strong evidence that the current trajectory of the Earth System has extraordinary similarities to what must have happened at the end of the Eemian. The mid-Eemian period would have been very similar to the pre-industrial Holocene in terms of temperature,

C6687

ice sheets and sea level with relatively small changes. But changes in the late Eemian were due to the forcing of the Milankovitch cycles over a timescale of thousands of years, whereas post-industrial changes have been initiated by forcing from greenhouse gases over a timescale of decades. So we can expect events to unfold much more rapidly and somewhat differently. In particular, because of the build-up of greenhouse gases, we are unlikely to experience a global cooling as a result of meltwater pulses, either from the Greenland Ice Sheet (GIS) or the West Antarctic Ice Sheet (WAIS), even if the Atlantic Meridional Overturning Circulation (AMOC) is disrupted.

Looking back at the Eemian we can see that our current situation is far more dangerous than anyone had previously thought. Preventative action is required and required far more urgently than anyone had previously considered, otherwise we could face unstoppable and intolerable sea level rise (SLR) as well as abrupt climate change and escalating emissions of methane from huge sources in permafrost and subsea hydrate deposits.

These conclusions are based on evidence from the Eemian which give an improved understanding of the Earth System, confirming that it is far less stable than we used to think. The paper may have produced the crucial piece in the puzzle of how the Earth System operates to control temperature, sea level and climate. This could be in the nick of time before the point of no return is passed when meltdown of sea ice and ice sheets becomes unstoppable. Prevention of rapid and potentially catastrophic changes in climate and sea level is still possible; governments must be advised to deal with these security threats at top priority. This is no time for reticence from the scientific community.

The final piece in the puzzle concerns the negative forcing to end periods of rapid warming. A mechanism is required which can halt rapid warming from albedo feedback in the Arctic and switch the Northern Hemisphere from rapid warming into slow cooling. This is where giant iceberg calving, as possibly evidenced by tsunami generation, come into play.

C6688

In his short paper (Hansen, 2015, "Boulders in the Bahamas") Hansen admits multiple tsunamis as a possible cause of the boulders and chevron structures dated to the Eemian. Support for the tsunami origin of the boulders is given in a book by Edward Bryant (Bryant, "Tsunami: The Underrated Hazard"). But Hansen points to smaller boulders and chevron structures at a lower height dated to the Holocene. Could these also be of multiple tsunami origin? Multiple tsunamis would come from the collapse of ice sheets; and collapse of the Hudson Bay Ice Dome about 8.2 thousand years ago turns out to be a prime candidate (Wagner, 2013, "Model support for forcing of the 8.2 ka event by meltwater from the Hudson Bay ice dome")

If one interprets the boulders at various heights and sizes on the Bahamas as the product of multiple tsunamis resulting from the collapse of the GIS in the late Eemian and the collapse of the Hudson Bay ice dome during the early Holocene (most likely at the time of the 8.2 thousand year b2k event), then one has confirmatory evidence of giant icebergs which could provide powerful negative forcing in the Earth System, able to switch the Northern Hemisphere from rapid warming into slow cooling. This mechanism involves restoration of sea ice in the Arctic Ocean.

It has been known for some time that the Arctic has been seasonally free of sea ice, from the evidence of iceberg debris deposits on the Arctic Ocean floor (Darby et al, 2006 "History of the Arctic").

The albedo loss (1979 to 2008) has been estimated as equivalent to a global forcing of 0.22 W/m^2 . Together with snow albedo loss, the global forcing is approximately double this figure at 0.45 W/m^2 (Flanner, 2011, "Radiative forcing and albedo feedback from the Northern Hemisphere cryosphere between 1979 and 2008"). If the sea ice is allowed to disappear at the end of summer, and the terrestrial snow cover continues its sharp decline, the forcing could rise to a level of $1-2 \text{ W/m}^2$.

It was remarked at the Royal Society event on "Arctic Sea Ice" (September, 2014) that the warming of the Arctic and retreat of snow and ice has actually been slower than

C6689

one would expect from such a strong albedo positive feedback. Thus there must be significant negative feedback from the extra thermal radiation as land and open sea is exposed by the retreating snow and ice. In fact certain models suggest that this negative feedback from sea ice retreat should be greater than the positive feedback (Notz, 2014, "Processes controlling the Arctic sea ice mass balance"). But this negative feedback has been diminished by greenhouse gases, allowing the positive to dominate for the past thirty years, as witness accelerated Arctic warming and an exponential decline in sea ice thickness, extent and hence volume (Wadhams, 2014, "Sea ice thickness from submarines"), particularly noticeable for August, September and October.

Current climate models predict that the Arctic Ocean will become seasonally free of sea ice sooner or later. The soonest is September 2016 (Maslowski, 2014, "Processes and interactions involved in Arctic sea ice change") whereas IPCC has a time-scale of decades with the earliest date as 2050 for the worst-case emissions scenario (AR5 WG1, 2013, "The Physical Science Basis"). Actual observations of the sea ice and its accelerated decline trend in a "death spiral" suggest that an end-summer disappearance of sea ice could happen any year now – even this year (Wadhams, 2014, as above).

Whenever this arrival of a seasonally ice-free ocean actually happens, the huge climate forcing from albedo loss could provide enough extra heat energy to melt GIS at the rate of 5-6 cm SLR per year: the maximum rate observed over periods of a few hundred years for the huge meltwater pulses which have occurred since the last glacial maximum, twenty thousand years ago.

This leads us to a reasonable hypothesis of how the Earth System may have operated in the past to produce massive changes in temperature, sea level and climate over the past 2.8 million years of the current Ice Age. Milankovitch cycles cause periodic summer warming in the Northern Hemisphere, but this is not sufficient to explain the huge swings in temperature, sea level and climate. The hypothesis assumes that the Milankovitch warming signal is amplified by positive albedo feedback in the Arctic,

C6690

but that this amplification can be switched off according to the melting of ice sheets. When the amplification is switched on and the Arctic has warmed, the temperature gradient from tropics to pole is reduced, affecting the stability of atmospheric circulation in the hemisphere and allowing the jet stream to meander and get stuck in patterns, giving rise to extreme weather (Francis and Skific, 2015 "Evidence linking rapid Arctic warming to mid-latitude weather patterns"). Within a decade or two, a completely new pattern of atmospheric circulation could establish itself, abruptly changing the climate across the whole Northern Hemisphere.

Consider now what happened in the Eemian under this hypothesis. Towards the end of the Eemian, when the Milankovitch cycles produced a strong summer warming in Northern Hemisphere mid-latitudes, the surface water flowing into the Arctic from the Atlantic and Pacific was warmed several degrees and the Arctic Ocean became seasonally ice-free. The albedo feedback would have led to rapid warming of the whole Arctic region, spreading to the whole Northern Hemisphere. The remaining ice sheet, GIS, would have been the source of the two metres of SLR over a few decades. The rate of discharge might have risen steadily at first, but eventually there must have been some kind of collapse. This would have produced giant icebergs off the west coast of Greenland, scouring the seabed at a depth of up to 1000 metres and causing a succession of pressure waves into the North Atlantic. The pressure waves would be partially reflected off the mid-Atlantic Ridges, producing a succession of tsunamis striking the island of Eleuthera in the Bahamas, leaving huge boulders many metres above sea level and a succession of chevron structures.

The melting of the icebergs calving from the west side of GIS would have cooled the North Atlantic and suppressed the warm saline water from the Gulf Stream flowing into the Arctic; and the melting of icebergs from east side GIS would have resurfaced the Arctic Ocean with cold fresh water. This combination would have ensured the recovery of sea ice. The rapid warming would have been switched off. The Northern Hemisphere would have started gradually cooling again.

C6691

Meanwhile in the Southern Hemisphere, the SLR from GIS would have helped towards unseating the terminations of WAIS glaciers, making them susceptible to accelerated discharge, as discussed in the paper. This effect would have been greatly aggravated by the arrival of Milankovitch warming in the Southern Hemisphere. This would have produced the observed contribution of SLR from Antarctica in the Eemian record. The paper indicates that, in the Eemian, the total SLR from Arctic and Antarctica reached up to 9 metres above the present-day level.

Based on the above hypothesis of Earth System operation, one can ascertain that current conditions in the Arctic are extremely dangerous. Over the next decade or few decades, the Arctic Ocean is liable to become seasonally free of sea ice. The Arctic will continue its rapid warming, and melt of GIS could produce as much as half a metre SLR per decade and thus several metres by 2050, with the possibility of the calving of huge icebergs producing devastating tsunamis. This rate of SLR would be intolerable and unstoppable but might be preventable.

The paper suggests that a rapid reduction of atmospheric CO₂ to around 350 ppm would keep global warming below 1.5°C, and this could prevent such SLR. But the paper only considers SLR from the Antarctic. If one considers a large SLR from the Arctic, it is difficult to imagine how it could be prevented other than by cooling the Arctic and saving the sea ice.

Required actions

Governments must take Arctic sea ice collapse and associated SLR, climate change and escalation of methane emissions as a major security threat.

Prevention is better than adaptation, especially to prevent a non-linear situation getting out of hand, as could happen with Arctic meltdown.

Therefore the first priority of governments must be to collaborate in the evaluation of, and preparation for, emergency interventions and other measures which can collec-

C6692

tively cool the Arctic and save the sea ice.

Note that even a dramatic reduction in short-lived forcing agents, such as methane and black carbon, is unlikely to be sufficient to cool the Arctic and save the sea ice. Interventions to directly cool the Arctic and save the sea ice will almost certainly be needed; and preparation for such interventions needs to be started as soon as possible.

In addition governments should take precautionary measures: 1. build sea defences against multi-metre SLR, e.g. for London and Manhattan; 2. develop techniques to reduce surface melt on GIS; 3. issue a moratorium on drilling in the Arctic until the sea ice retreat has been halted; 4. build a North Atlantic tsunami early warning system with sensors off Greenland; 5. develop emergency procedures in case of tsunamis; 6. re-appraise nuclear safety in case of mega-tsunami, e.g. in England for the half dozen nuclear power stations sited along the Bristol Channel and the new one about to be approved for Hinkley Point; and 7. further assess the Antarctic as a source of SLR.

Note that, although reducing carbon emissions is essential, it will not stop the sea ice or GIS from continued or accelerated melting over the coming years.

Rather than fighting a cold war over the spoils from sea ice retreat, as it opens access to vast deposits of fossil fuels (New York Times, "Mr. Obama's urgent Arctic message", 1 September 2015), countries bordering the Arctic should be fighting to save the Arctic sea ice, using every means at their disposal including geoengineering techniques as necessary.

The urgency of action to try to prevent Arctic meltdown, argued above, should in no way detract from the urgency of action to reduce carbon emissions, bring the CO₂ level down to 350 ppm, keep global warming below 1.5°C and avoid excessive ocean acidification, argued in the paper.

Scientists must speak out

Four luminaries have guided my research. Peter Wadhams drew my attention to the

C6693

danger from sea ice decline in a vicious cycle of warming and melting from albedo loss; James Hansen drew my attention to the danger from sea level rise with exponential melt of the Greenland Ice Sheet; Natalia Shakhova told me about the dramatic escalation of methane gas bubbling up from the East Siberian Arctic Shelf; and Jennifer Francis showed how sea ice retreat was leading to dangerous climate change in the Northern Hemisphere. These dangers could all be reduced by cooling the Arctic. For example one can observe that sea and land ice melt will slow if there is unusually cold weather in the Arctic during the summer months.

Two interventions seem practical, either of which could provide the necessary cooling power. Cloud brightening is extraordinary benign; and stratospheric aerosols injected at appropriate season, latitude and altitude could be equally benign. Yet scientists seem strangely reluctant to advocate the use of such techniques, even with conspicuous evidence of the requirement to cool the Arctic quickly before it is too late. Surely the risks of inadvertent side-effects from using such techniques are trivial compared to the risk of catastrophe from continued rapid warming of the Arctic.

Several positive feedbacks are at play in the Arctic, but the strongest is the albedo feedback, whose strength grows as snow and sea ice retreat. This is a highly non-linear process, and one would expect to see an exponential trend in retreat as actually observed; so it alarming to find a clear exponential trend being ignored in the models used by IPCC and by most leading sea ice experts. We can no longer rely on such models for forecasting the future of the Arctic sea ice, Arctic warming or repercussions of sea ice retreat and Arctic warming.

Furthermore, IPCC has not taken methane into account. If methane seabed emissions grow exponentially to reach the gigaton per annum level, there will be no chance to keep global warming below 2 degrees. (There are estimated to be about 1.5 terratonnes of carbon stored below the seabed – a similar quantity to the carbon stored in land permafrost and about double the amount of carbon in the atmosphere. But whereas land permafrost can break down aerobically to produce CO₂, the subsea

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carbon will almost entirely be emitted from the seabed as methane, which is 86 more potent than CO₂ as a greenhouse gas over 20 years, weight for weight.)

Governments need to be warned of the severe limitations of the IPCC process which has essentially ignored what is happening in the Arctic and the extreme danger that this represents. Yet they also need to be told about the possible interventions to cool the Arctic which appear extraordinarily benign, and might cost only a few billion dollars a year to implement. The scientific community must accept that the situation is such as to demand such interventions, before it gets out of hand.

In his paper “Boulders and Storms Redux”, 14 August 2015, Hansen writes:

“Governments, especially the legislative and executive branches, were and are largely under the heavy largesse-laden thumb of the fossil fuel industry.”

So, why are scientists keeping quiet about what is happening in the Arctic? Is it because they are so fearful of the situation? Or are they under pressure from the fossil fuel industry to keep quiet? The fossil fuel industry is certainly looking forward to a bonanza when the sea ice disappears. But the industry may be genuinely ignorant of the imminence and consequences of a seasonally ice-free Arctic Ocean. This makes it all the more important for the scientific community to speak out. Governments must collaborate to solve the problem of restoring sea ice, slowing GIS melt and suppressing methane. If this involves the use of geoengineering techniques, so be it. There will always be a temptation for those in authority to wait and see what happens. Our message to them must be “Don’t funk it and try to make the best of a bad job with sea ice gone – do what it takes to save the sea ice while there’s time. It can be done, it must be done”.

The fossil fuel industry must collaborate also. It has the expertise and the resources for working in the Arctic. The sea ice retreat was started as a result of fossil fuel emissions during the last century. It seems only fair that the industry should help in dealing with rapid Arctic warming and sea ice decline, which, left unchecked, will have devastating

C6695

consequences for everyone, including the companies and their stakeholders.

Hansen warns about a devastating sea level rise if emissions from fossil fuels continue; but we, as climate scientists, should be warning even more urgently about the dire consequences of continued Arctic warming and precipitous sea ice decline, not only on sea level rise but also climate change and methane.

And we should be arguing passionately for rapid intervention to break this vicious cycle of albedo feedback before it is too late. Otherwise the history of the Eemian is likely to repeat itself.

Interactive comment on Atmos. Chem. Phys. Discuss., 15, 20059, 2015.

C6696