

Thermohaline circulation changes: a question of risk assessment

An Editorial Review Essay

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This May, Bjørn Lomborg's "Environmental Assessment Institute" published a report [*Olsen and Buch, 2004*] on the risk of ocean circulation changes in the Atlantic, to coincide with the release of Roland Emmerich's Hollywood blockbuster *The Day after Tomorrow* (a film based on a shut-down of the North Atlantic Current). Given its lack of expertise on ocean circulation and climate, the Environmental Assessment Institute commissioned two scientists from the Danish Meteorological Institute to produce the report. Nevertheless, the report is published and the copyright owned by Lomborg's institute. Admittedly, the somewhat unusual process of gestation and launch for a scientific document made us approach it with some caution.

The report starts by presenting a useful review of what is known about the Atlantic ocean circulation, enhanced by an interesting historical perspective. It then discusses short-term climate variability in the region, focussing on the North Atlantic oscillation (NAO). The next chapter discusses model studies of possible future changes in Atlantic ocean circulation due to greenhouse warming. It is followed by a chapter on historic ocean circulation changes during glacial times and the Holocene, and by some discussion and conclusions.

A number of factual errors cast doubt on the authors' familiarity with the cited literature and basic science; such errors could have been avoided had the report been subject to the usual independent peer review process. To give two examples, the report claims a sensitivity study was performed with the CLIMBER model, even though the study in question was published years before this model existed. And the authors fail to understand the basic oceanographic concept of steric height, claiming it "reflects the sea-surface height at a given location if the ocean were to be motionless" (to the contrary, the steric height field reflects the surface currents of the ocean – this is why oceanographers routinely determine steric height).

The usefulness of the report is hampered by a strangely selective choice of the literature. Many of the key studies that have considered the risk of ocean circulation changes in greenhouse warming scenarios are neither cited nor discussed. Not mentioned are the classic papers by [*Manabe and Stouffer, 1993; Manabe and Stouffer, 1994*], showing that the Atlantic thermohaline circulation breaks down in a scenario of quadrupling CO₂, but weakens and recovers in a scenario of doubling CO₂ in the GFDL climate model. Not mentioned is the paper by [*Stocker and Schmittner, 1997*], showing that the risk of a circulation breakdown increases if CO₂-levels rise more quickly. Not mentioned is Broecker's discussion of the thermohaline circulation as the "Achilles heel" of the climate system [*Broecker, 1997*]. Not mentioned is the paper by [*Wood et al., 1999*], showing a shutdown of Labrador Sea convection early in this century in the Hadley Centre climate model, considered by many the climate model with the most realistic ocean circulation. And not mentioned is the study by [*Schaeffer et al., 2002*] with the

Dutch climate model, showing major changes in Norwegian Sea convection. These omissions are puzzling, since the papers concerned have appeared in high-profile journals (many in *Nature* or *Science*) and are widely cited. The omission of the last study is particularly surprising, as it shows a major cooling occurring over Scandinavia in the middle of this century. It is thus highly relevant to an assessment of the risks of future ocean circulation changes, especially for Scandinavian society. Whether these scenarios are considered realistic or not – they clearly need to be discussed in such a 71-page review. Also, it is strange to find no mention of the recent report of the US National Research Council, “Abrupt Climate Change – Inevitable Surprises” [Alley and *et al.*, 2002].

What else is missing is a discussion of the uncertainties. One major uncertainty lies in the future meltwater runoff from Greenland, which would contribute to diluting the high-latitude Atlantic waters and thus inhibit convection. In the only available study using a climate model coupled to an ice sheet model [Fichefet *et al.*, 2003], Greenland runoff increased by 15,000 m³/s by 2080 – almost doubling the total warming-related increase in freshwater flux into the northern Atlantic. This caused an abrupt weakening of the ocean circulation that did not occur in a comparison experiment without Greenland meltwater. The Lomborg report states that “neither of the projections performed as part of the IPCC 2001 assessment showed an abrupt response to enhanced greenhouse gas concentrations”, but it fails to mention that these simulations did not include Greenland meltwater, let alone an uncertainty assessment of the consequences of different melting rates. Measurements show that the Greenland ice sheet has been rapidly losing mass in recent decades [Schiermeier, 2004].

The report’s discussion of the possible impacts of ocean circulation changes is restricted to the effects on surface temperatures. However, as for most climate changes, the most serious impacts are unlikely to be the changes in mean temperatures [Vellinga and Wood, 2002] – especially in this case, where a regional cooling due to an ocean circulation change would be countered by greenhouse gas warming (except for the Southern Hemisphere, where the reduced ocean heat transport to the north would *enhance* the greenhouse warming – a “climate see-saw” effect familiar to paleo-climatologists).

Ocean circulation changes would also lead to rapid dynamic sea level changes (changes in “dynamic topography” - the steric height mentioned above) that could reach up to a meter on some northern Atlantic coasts, and that come in addition to other sea level rise [Levermann *et al.*, submitted]. They would also lead to further deep ocean warming, causing up to another meter of global sea level increase in the long run [IPCC, 2001]. They would disrupt marine ecosystems and fisheries and likely reduce the CO₂ uptake of the ocean [Sarmiento and Le Quéré, 1996], given that the largest uptake of anthropogenic CO₂ by the ocean has occurred in the North Atlantic associated with deep-water formation [Sabine and *et al.*, 2004]. Paleoclimatic data [Peterson *et al.*, 2000] and models [Claussen *et al.*, 2003] both indicate that a change in ocean circulation would shift the intertropical convergence zone (ITCZ), disrupting tropical precipitation patterns around the globe. None of these impacts are mentioned in the report.

The report also disappoints in a more fundamental way: it fails to understand the issue of future ocean circulation changes as an issue of risk assessment, rather than one of climate prediction. In climate prediction, the question is “What is most likely to happen?” In a risk assessment, the question is “What could go wrong, and what would the consequences be?”

A major ocean circulation change can be viewed as a possible “accident” of climate change – comparable, say, to a nuclear power accident. Climatologists have long discussed it as an event that is unlikely but could have serious consequences – a so-called *low probability – high impact* risk (e.g., [IPCC, 2001]). It is thus not surprising that the authors of the Lomborg-report come to the conclusion that an abrupt ocean circulation change is, well, unlikely. Few experts would disagree. But as a risk assessment, this is of rather limited use. It is as if engineers were asked to prepare a report on the risk of a nuclear accident, and after discussing in detail some examples of nuclear power stations that worked perfectly well, they come to the conclusion that a nuclear accident appears to be quite unlikely.

We have long argued that a risk assessment and a “best guess” climate scenario are two fundamentally different things [Rahmstorf, 1999]. A useful risk assessment would have focused on a discussion of all model studies where major circulation changes did happen, instead of ignoring most of those. It would have focused on the main uncertainties - including the risk of relatively large runoff from Greenland. It would have discussed the few sensitivity studies available so far, looking at the effects of different runoff amounts, different warming rates, etc. It would have discussed whether current climate models might underestimate the risk – e.g., to what extent they are able to reproduce the abrupt ocean current shifts that have occurred in climate history [Rahmstorf, 2002]. It would have discussed all eventualities, e.g., the possibility of more limited shifts in circulation, not just a full shut-down. And it would have discussed all possible impacts of ocean circulation changes.

It is a shame that this opportunity was missed, and one is left asking oneself whether this report was intended to assess the risks, or rather to downplay them.

A proper assessment of these risks is important. Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC) states that “dangerous interference with the climate system” must be avoided. But what is dangerous? An event with only 1% probability is highly unlikely – but most people would consider it far too dangerous to board a plane that has a 1% chance of crashing. In the foreseeable future, we will not be able to make reliable forecasts of when or whether a “climate accident” might be triggered by global warming. As in other human affairs, we will have to act on a judgement of uncertain risks. Hence, we need to discuss what level of risk of triggering major non-linear climate shifts is acceptable, and at what level a “dangerous interference” starts.

A simple example for estimating the risk under uncertainty is illustrated in Fig. 1. The top panel shows the probability of a major change of the North Atlantic

Current, *given* a specified global temperature rise until 2100*. Like the risk of an accident in a particular new class of power station, such a probability for a single future event cannot be calculated objectively; it is an expression of a subjective assessment of the likelihood based on limited available knowledge. (We are currently conducting a systematic expert elicitation, as pioneered by [Morgan and Keith, 1995], to find out the subjective probabilities judged by leading experts in the field.)

The numbers given here are illustrative only, but not unreasonable. In the example shown, the likelihood is very small for a global warming of a degree or two; it increases to 15% for a scenario of 4°C global warming, and then levels out again assuming that even for very strong warming the probability approaches 30% at most (this accounts for the possibility that even for unlimited warming, the ocean circulation might not undergo any major changes since there could be stabilising feedbacks [Latif *et al.*, 2000]). This curve thus corresponds to the more qualitative assessment shown in the IPCC TAR (Vol. 2, Fig. 19-7, known as the “burning embers diagram”).

To determine the risk of a thermohaline circulation change for a given greenhouse gas concentration scenario, we further need to account for the uncertainty in the climate sensitivity. As illustrated in the middle panel, a scenario leading to a predicted median warming of 3°C in fact has some probability that the warming could turn out to be lower or higher, with correspondingly lower or higher risk of a change in North Atlantic ocean currents. To compute the probability of a major circulation change for a given emission scenario, we simply combine the probability distribution for warming under this scenario (as shown in the middle panel) with the probability of the circulation change given a particular warming, as shown in the upper panel. (This is done by integrating the product of the two curves over temperature.) This probability is 2% for a scenario with median warming of 1.9°C, 5% for a median warming of 2.4°C, and 10% for a median warming of 3.2°C.

With this result, we can compute emission corridors, i.e. admissible ranges of CO₂ emissions that limit the risk of a major ocean circulation change to a given percentage (i.e., limit the predicted median warming to a certain value) using the modelling framework of [Zickfeld and Bruckner, 2003]. The result is shown in the lower panel of Fig. 1. A particular corridor contains all possible emission scenarios that limit the probability of a major circulation change to the value shown.

This result shows that the assumptions illustrated in panels (a) and (b) lead to the conclusion that by the year 2030, the SRES scenario A2 leaves the emission corridor that could contain the risk to less than 5%, and even the optimistic B1 scenario touches the upper corridor boundary by mid-century. *If* society thinks like the airplane passenger mentioned above and considers a 5% probability for a major ocean circulation change as “dangerous” in the sense of Art. 2 UNFCCC, then successful mitigation efforts are required well

* Note that conceptually this is a simple probability, not a probability density or a cumulative probability. Even though it is shown here as a continuous line depending on temperature, each temperature value denotes a different warming scenario, not a point in time along a single scenario. The different temperature values, associated with different probabilities of thermohaline circulation changes, thus represent different societal choices of emission scenarios: they represent low temperature (low risk) or high temperature (high risk) futures.

before then. If the risk is to be contained to 2%, the required emission reduction needs to be even more ambitious. Hence, a broad discussion is needed now about what level of risk of triggering “climate accidents” society is willing to take.

References

- Alley, R., et al., *Abrupt Climate Change - Inevitable Surprises*, 230 pp., National Academy Press, Washington, 2002.
- Broecker, W., Thermohaline Circulation, the Achilles Heel of Our Climate System: Will Man-Made CO₂ Upset the Current Balance?, *Science*, 278, 1582-1588, 1997.
- Claussen, M., A. Ganopolski, V. Brovkin, F.-W. Gerstengarbe, and P. Werner, Simulated global-scale response of the climate system to Dansgaard/Oeschger and Heinrich events, *Climate Dynamics*, 21, 361-370, 2003.
- Fichefet, T., C. Poncin, H. Goosse, P. Huybrechts, I. Janssens, and H. Le Treut, Implications of changes in freshwater flux from the Greenland ice sheet for the climate of the 21st century, *Geophysical Research Letters*, 30 (17), doi: 10.1029/2003GL017826, 2003.
- IPCC, *Climate Change 2001*, Cambridge University Press, Cambridge, 2001.
- Latif, M., E. Roeckner, U. Mikolajewicz, and R. Voss, Tropical stabilization of the thermohaline circulation in a greenhouse warming simulation, *Journal of Climate*, 13 (11), 1809-1813, 2000.
- Levermann, A., A. Griesel, M. Hofmann, M. Montoya, and S. Rahmstorf, Dynamic sea level changes following changes in the thermohaline circulation, *Climate Dynamics*, submitted.
- Manabe, S., and R.J. Stouffer, Century-scale effects of increased atmospheric CO₂ on the ocean-atmosphere system, *Nature*, 364, 215-218, 1993.
- Manabe, S., and R.J. Stouffer, Multiple-century response of a coupled ocean-atmosphere model to an increase of atmospheric carbon dioxide, *Journal of Climate*, 7, 5-23, 1994.
- Morgan, M.G., and D.W. Keith, Subjective judgments by climate experts, *Environmental Science and Technology*, 29, 468-476, 1995.
- Olsen, S.M., and E. Buch, A Review of the North Atlantic Circulation, Marine Climate Change and its Impact on North European Climate, pp. 71, Environmental Assessment Institute, Copenhagen, 2004.
- Peterson, L.C., G.H. Haug, K.A. Hughen, and U. Röhl, Rapid changes in the hydrologic cycle of the tropical Atlantic during the last glacial, *Science*, 290, 1947-1951, 2000.
- Rahmstorf, S., Shifting seas in the greenhouse?, *Nature*, 399, 523-524, 1999.
- Rahmstorf, S., Ocean circulation and climate during the past 120,000 years, *Nature*, 419, 207-214, 2002.
- Sabine, C.L., et al., The oceanic sink for anthropogenic CO₂, *Science*, 305, 367-371, 2004.
- Sarmiento, J.L., and C. Le Quéré, Oceanic carbon dioxide uptake in a model of century-scale global warming, *Science*, 274, 1346-1350, 1996.
- Schaeffer, M., F.M. Selten, J.D. Opsteegh, and H. Goosse, Intrinsic limits to predictability of abrupt regional climate change in IPCC SRES scenarios, *Geophysical Research Letters*, 29 (16), art. no.-1767, 2002.
- Schiermeier, Q., Greenland's climate: a rising tide, *Nature*, 428, 114-115, 2004.
- Stocker, T., and A. Schmittner, Influence of CO₂ emission rates on the stability of the thermohaline circulation, *Nature*, 388, 862-865, 1997.
- Vellinga, M., and R.A. Wood, Global climatic impacts of a collapse of the Atlantic thermohaline circulation, *Climatic Change*, 54, 251-267, 2002.
- Wood, R.A., A.B. Keen, J.F.B. Mitchell, and J.M. Gregory, Changing spatial structure of the thermohaline circulation in response to atmospheric CO₂ forcing in a climate model, *Nature*, 399, 572-575, 1999.
- Zickfeld, K., and T. Bruckner, Reducing the risk of abrupt climate change: emissions corridors preserving the Atlantic thermohaline circulation, *Integrated Assessment*, 4 (2), 106-115, 2003.

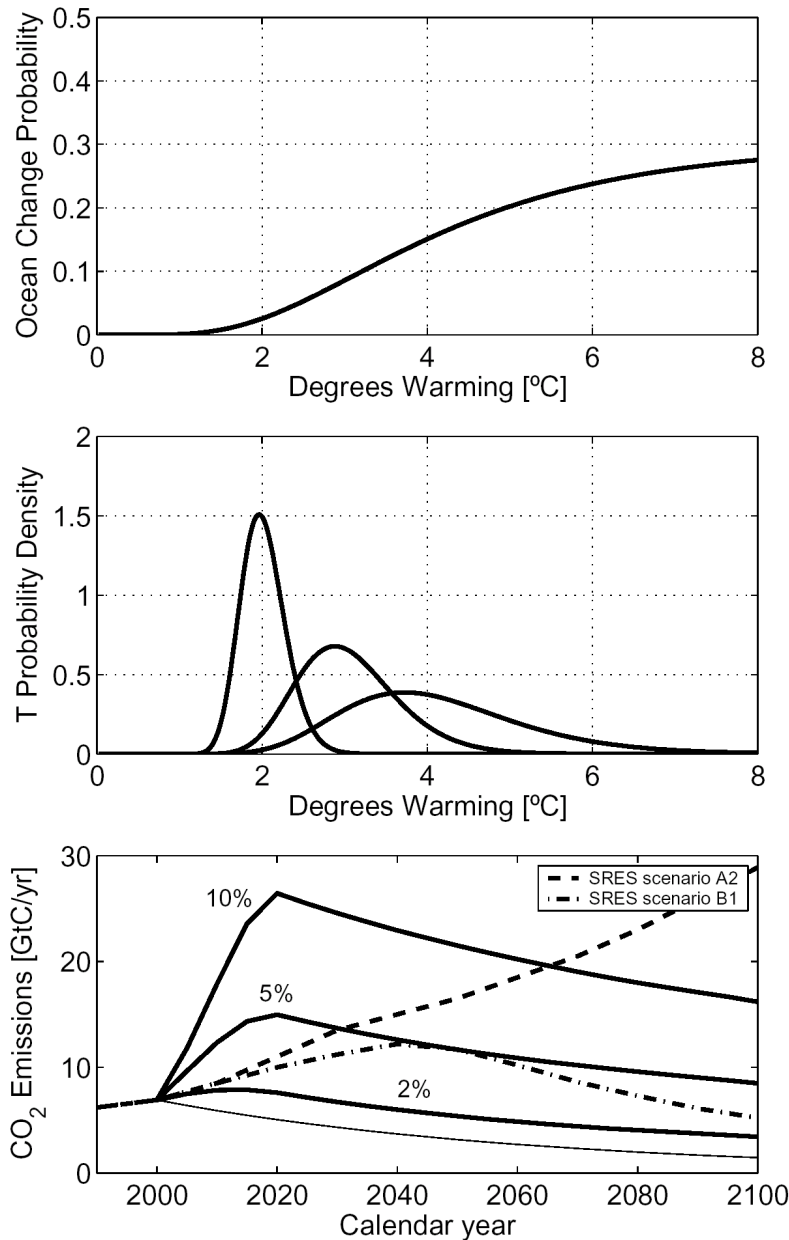


Fig. 1. (a) Schematic representation of the probability for a major change in the North Atlantic circulation as it depends on the actual global warming until the year 2100. For simplicity, the curve chosen is the integral of a lognormal distribution with median value $m=4^{\circ}\text{C}$ and $\sigma=0.5^{\circ}\text{C}$, multiplied by 0.3 to give a maximum probability of 30% for unlimited warming. (b) Probability density for global warming up to the year 2100 for three different greenhouse scenarios, with median warmings m of 2°C , 3°C and 4°C . The spread in these scenarios reflects the uncertainty about climate sensitivity; the given median value is the warming obtained for a particular greenhouse gas scenario assuming a median (or loosely speaking, 'best guess') climate sensitivity. A lognormal distribution was used, with a spread proportional to the median value ($\sigma=0.2^{\circ}\text{C}$ for $m=3^{\circ}\text{C}$; $\sigma=0.133^{\circ}\text{C}$ for $m=2^{\circ}\text{C}$; etc.) Combining the curves shown in (a) and (b) gives a probability for a circulation change under a given greenhouse scenario, accounting for the uncertainty in climate sensitivity. (c) Emission corridors (thick lines denote their upper boundaries) avoiding a breakdown of the North Atlantic Current with a given probability: any emission path leaving the $x\%$ risk corridor would lead to a major change in the North Atlantic Current with a probability greater than $x\%$. The corridors were calculated with the integrated assessment framework presented in [Zickfeld and Bruckner, 2003], using the assumptions shown in panels (a) and (b) about the uncertainty in thermohaline circulation response and climate sensitivity, using a median value of climate sensitivity of 2.7°C . The thin line represents the lower bound of all three corridors, which is determined by economic constraints on how fast emissions can be reduced.