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Shutting Down the Thermohaline Circulation

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Abstract: Past climatic changes were caused by a slowdown of the thermohaline circulation. We use results from experiments with three climate models to show that the expected cooling due to a slowdown of the thermohaline circulation is less in magnitude than the expected warming due to increasing greenhouse gas concentrations. The integrated assessment model FUND and a meta-analysis of climate impacts are used to evaluate the change in human welfare. We find modest but by and large positive effects on human welfare since a slowdown of the thermohaline circulation implies decelerated warming.

Key words: Climate change; thermohaline circulation; integrated assessment; climate impacts

JEL classification: Q54

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Past climatic changes in the Earth's history have been associated with a shut- or slowdown of the thermohaline circulation as vast amounts of freshwater were introduced into the Atlantic Ocean (Gerard C. Bond et al., 1997). We use data on future climate from hosing experiments with three climate models with and without a slowdown of the thermohaline circulation. These experiments show that the expected cooling in Western Europe due to a slowdown of the thermohaline circulation is less in magnitude to the expected warming due to increasing greenhouse gas concentrations. As ocean currents redistribute rather than create heat, a slowdown of the thermohaline circulation would also lead to a slightly accelerated warming elsewhere. The integrated assessment model FUND and a meta-analysis of climate impacts are used to evaluate the change in human welfare associated with a slowdown of the thermohaline circulation. We find modest but by and large positive effects on human welfare. Compared to earlier papers (P. Michael Link and Richard S. J. Tol, 2011, 2004), we use more realistic climate scenarios and more detailed and up to date impact estimates.

I. The Thermohaline Circulation

The Thermohaline Circulation (THC) is a vast system of currents across all four oceans, with deep water formation off the Antarctic Peninsula and Greenland and upwelling in the northern parts of the Pacific and Indian Ocean. The Gulf Stream and North Atlantic Current, part of the THC, transport water from the tropics north and east – keeping Europe warm – where evaporation increase salinity and density so that the water sinks. This mechanism can be disrupted and it has been in the past, most recently by meltwater of the Laurentide Ice Sheet (Donald C. Barber et al., 1999). Melting of the Greenland Ice Sheet and an increase in rainfall over the North Atlantic due to the increase in the atmospheric concentrations of greenhouse gases could have a similar effect (Wallace S. Broecker, 1997).

Early papers suggested that the THC was rather fragile to anthropogenic climate change (Stefan Rahmstorf, 1995), but later research find a more robust THC. For instance, a model intercomparison finds a reduction in THC strength of 18-25% for moderate climate change, and 36-44% for more pronounced warming (Andrew J. Weaver et al., 2012). One expert elicitation finds that the chance that the THC weakens by 50% or more by 2100 is 0 to 40%, with an average across experts of 22% (Kirsten Zickfeld et al., 2007). Another expert elicitation puts the probability of a halving of the THC by 2100 at 4 to 74%, with an average of 24% (Nigel W. Arnell et al., 2005). In a

Bayesian study, the THC is expected to weaken by 17% between 2000 and 2100, with a 10% probability of a total collapse (Nathan M. Urban and Klaus Keller, 2010). We do not contribute to that debate. Indeed, we do not even assign a probability to a THC shutdown or explore the implications for climate policy. Instead, we focus on the impacts of a THC shutdown. In order to do so, we use the results of so-called hosing experiments with three General Circulation Models. In this set-up, the THC shutdown is not caused by internally consistent physical processes in the model. Instead, additional fresh water is added to the North Atlantic, like a Death Star suddenly appearing in the sky and hosing down water.

Figure 1 shows the effect on temperature at the country level. As is common, we use the change in the average annual temperature as an indicator of the severity of climate change. Three of the models consider a freshwater input of 0.1 Sv[1] near Greenland, not inconsistent with the amount of meltwater that could be expected from that ice-sheet (Miren Vizcaíno et al., 2010). This implies a slowdown of the THC of 27 ± 14% (Didier Swingedouw et al., 2013), and a cooling of less than 1°C for most countries. The impacts are more pronounced if the THC slows down by two-thirds, as it is in the fourth scenario (Michael Vellinga and Richard A. Wood, 2008), but cooling is still less than 2°C in most countries; some countries see a small warming. Note that the models agree on the sign of the temperature change for only 70 out of 155 countries.

[Insert Figure 1 Here]

II. Impacts of climate change

A. Meta-analysis

Richard S. J. Tol (2015) surveys the literature on the total welfare impacts of climate change. He finds that a piecewise linear function best describes the relationship between global impacts and climate change. The impacts are static, that is, the change in equilibrium welfare due to a change in the equilibrium climate. We here use the same function for national impacts imputed from regional and global impact estimates reported in the literature. See Appendix A.

[1] A Sverdrup (Sv) is a million cubic metres per second.

B. FUND

The Climate Framework for Uncertainty, Negotiation and Distribution (FUND) is an integrated assessment model. We here only use it to estimate the impacts of climate change. FUND's impact module differs in three ways from other integrated assessment models and indeed the meta-analysis above. First, FUND has separate representations of all major impacts. This allows for richer dynamics and more realistic non-linearities. Second, impacts do not just depend on climate change, but also on sea level rise and the atmospheric concentration of carbon dioxide. This mutes the effect of a THC slowdown. Third, in FUND, vulnerability to climate change changes with development. We use the impact module of FUND version 4.0; see Appendix B. The impacts in FUND, and indeed other integrated assessment models, are level effects on welfare, assuming both smooth economic development and climate change (Richard S. J. Tol, 2009).

Melissa Dell et al. (2014) discuss the effects of weather on economic activity. Samuel Fankhauser and Richard S. J. Tol (2005) study the effects of climate change on economic growth. Francisco Estrada and Richard S. J. Tol (2015) model the economic effects of climate change and year-to-year weather variability.

III. Results

A. Meta-analysis

The meta-analysis assumes a piecewise linear impact function, by far the best fit for the global data (Richard S. J. Tol, 2015). The impact of warming (or cooling) depends on whether it pushes a country towards or away from its climate optimum. The combined effect of greenhouse warming and THC cooling further depends on the relative size of the two effects.

[Insert Figure 2 Here]

Figure 2 shows the effects on all countries. Global warming is assumed to be 3.2°C, with greater warming closer to the poles and further inland. The THC slowdown in Figure 1 is for the year 2085. As the cooling is small relative to the assumed warming, and as 3.2°C of global warming would push most countries beyond their climate optimum, THC cooling is best seen as reduced warming. The effects on welfare are therefore by and large positive.

This is confirmed by Table 1, which shows the global aggregate impacts. If the THC slows down a little, the global impact is a positive 0.2-0.3% of income. This goes up to 1.3% for a more pronounced slowdown.

[Insert Table 1 Here]

B. *FUND*

Figure 3 shows the results according to FUND. The THC slowdown scenario is phased in linearly between 2050 and 2085; see Figure 1. The results in Figure 3 are averages for 2085-90. Although FUND is far more complicated than the meta-analytic function, the mechanisms are the same. The impact depends on whether a THC slowdown leads to reduced warming or absolute cooling, on the shape of the impact function, and on the position on that function when the THC slows down.

The FUND results in Figure 3 are qualitatively similar to the meta-analytic results in Figure 2. The background warming is 3.2°C. A THC slowdown decelerates warming at a point in time when additional warming is mostly harmful. A THC slowdown thus brings welfare gains. The FUND results tend to be smaller. This is, first, because the impacts in FUND are driven not just by climate change but also by the atmospheric concentration of carbon dioxide and the level of the sea, which are hardly affected by a THC slowdown. Furthermore, in FUND, people are assumed to be richer in 2085 than they are now and therefore, by and large, less vulnerable to climate change.

Table 1 shows the global impacts, which range between 0.1 and 0.2% of income for a modest THC slowdown but may go up to 0.8% for a more pronounced slowdown.

IV. Discussion and Conclusion

We show four scenarios of a slowdown of the thermohaline circulation, and find that it modestly decelerates warming. We estimate the impact using two alternative models, and find that reduced warming means a small gain in welfare.

The qualitative results are intuitive and probably robust. The quantitative results are of course no stronger than the underlying models. Other models should run the same scenarios, but as they have a similar structure, we would expect similar results. Only very non-linear impact functions would drastically change our findings. More importantly, the models should be improved. Impacts as modelled are largely driven by the level of climate change rather than by its rate. Ocean acidification, for instance, would continue apace if the thermohaline circulation slows down. A change in ocean currents may well affect the upwelling of nutrients from the bottom of the ocean. It would bring about a shift in the patterns of wind and rain. Integrated assessment models often assume that other climate variables scale with temperature, but the relationship may be different for greenhouse warming and THC cooling. There may be enhanced drought in Europe, Central America and Southeast Asia (Ronald J. Stouffer et al., 2006), and more frequent and intense winter storms in Europe (Laura C. Jackson et al., 2015). The pattern of sea-level rise may also be affected by changes in the thermohaline circulation. Adaptation to climate change, as modelled, ignores the heightened uncertainty that a thermohaline circulation slowdown would bring. Therefore, although the results presented here are small but benign, these findings may be overturned by future research.

REFERENCES

Arnell, Nigel W.; E. L. Tompkins and W. Neil Adger. 2005. "Eliciting Information from Experts on the Likelihood of Rapid Climate Change." *Risk Analysis*, 25 (6), 1419-31.

Barber, Donald C.; A. Dyke; C. Hillaire-Marcel; A. E. Jennings; J. T. Andrews; M. W. Kerwin; G. Bilodeau; R. McNeely; J. Southon; M. D. Morehead, et al. 1999. "Forcing of the Cold Event of 8,200 Years Ago by Catastrophic Drainage of Laurentide Lakes." *Nature*, 400(6742), 344-48.

Bond, Gerard C.; W. Showers; M. Cheseby; R. Lotti; P. Almasi; P. DeMenocal; P. Priore; H. Cullen; I. Hajdas and G. Bonani. 1997. "A Pervasive Millennial-Scale Cycle in North Atlantic Holocene and Glacial Climates." *Science*, 278(5341), 1257-66.

Broecker, Wallace S. 1997. "Thermohaline Circulation, the Achilles Heel of Our Climate System: Will Man-Made Co2 Upset the Current Balance?" *Science*, 278(5343), 1582-88.

Dell, Melissa; B. F. Jones and B. A. Olken. 2014. "What Do We Learn from the Weather? The New Climate-Economy Literature." *Journal of Economic Literature*, 52(3), 740-98.

Estrada, Francisco and Richard S. J. Tol. 2015. "Towards Impact Functions for Stochastic Climate Change." *Climate Change Economics*, 6(4), 1550015.1-15.13.

Fankhauser, Samuel and Richard S. J. Tol. 2005. "On Climate Change and Economic Growth." *Resource and Energy Economics*, 27(1), 1-17.

Jackson, Laura C.; R. Kahana; T. Graham; M. A. Ringer; T. Woollings; J. V. Mecking and R. A. Wood. 2015. "Global and European Climate Impacts of a Slowdown of the Amoc in a High Resolution Gcm." *Climate Dynamics*, 45(11-12), 3299-316.

Link, P. Michael and Richard S. J. Tol. 2011. "The Economic Impact of a Shutdown of the Thermohaline Circulation: An Application of Fund." *Climatic Change*, 104(2), 287-304.

____. 2004. "Possible Economic Impacts of a Shutdown of the Thermohaline Circulation: An Application of Fund." *Portuguese Economic Journal*, 3(2), 99-114.

Rahmstorf, Stefan. 1995. "Bifurcations of the Atlantic Thermohaline Circulation in Response to Changes in the Hydrological Cycle." *Nature*, 378(6554), 145-49.

Stouffer, Ronald J.; J. Yin; J. M. Gregory; K. W. Dixon; M. J. Spelman; W. Hurlin; A. J. Weaver; M. Eby; G. M. Flato; H. Hasumi, et al. 2006. "Investigating the Causes of the Response of the Thermohaline Circulation to Past and Future Climate Changes," *86th AMS Annual Meeting.*

Swingedouw, Didier; C. B. Rodehacke; E. Behrens; M. Menary; S. M. Olsen; Y. Gao; U. Mikolajewicz; J. Mignot and A. Biastoch. 2013. "Decadal Fingerprints of Freshwater Discharge around Greenland in a Multi-Model Ensemble." *Climate Dynamics*, 41(3-4), 695-720.

Tol, Richard S. J. 2009. "The Economic Effects of Climate Change." *Journal of Economic Perspectives*, 23(2), 29-51.

____. 2015. "Economic Impacts of Climate Change," *Working Paper*. Falmer: University of Sussex,

Urban, Nathan M. and Klaus Keller. 2010. "Probabilistic Hindcasts and Projections of the Coupled Climate, Carbon Cycle and Atlantic Meridional Overturning Circulation System: A Bayesian Fusion of Century-Scale Observations with a Simple Model." *Tellus, Series A: Dynamic Meteorology and Oceanography*, 62(5), 737-50.

Vellinga, Michael and Richard A. Wood. 2008. "Impacts of Thermohaline Circulation Shutdown in the Twenty-First Century." *Climatic Change*, 91(1-2), 43-63.

Vizcaíno, Miren; U. Mikolajewicz; J. Jungclaus and G. Schurgers. 2010. "Climate Modification by Future Ice Sheet Changes and Consequences for Ice Sheet Mass Balance." *Climate Dynamics*, 34(2), 301-24.

Weaver, Andrew J.; J. Sedláček; M. Eby; K. Alexander; E. Crespin; T. Fichefet; G. Philippon-Berthier; F. Joos; M. Kawamiy; K. Matsumoto, et al. 2012. "Stability of the Atlantic Meridional Overturning Circulation: A Model Intercomparison." *Geophysical Research Letters*, 39(20).

Zickfeld, Kirsten; A. Levermann; M. G. Morgan; T. Kuhlbrodt; S. Rahmstorf and D. W. Keith. 2007. "Expert Judgements on the Response of the Atlantic Meridional Overturning Circulation to Climate Change." *Climatic Change*, 82, 235-65.

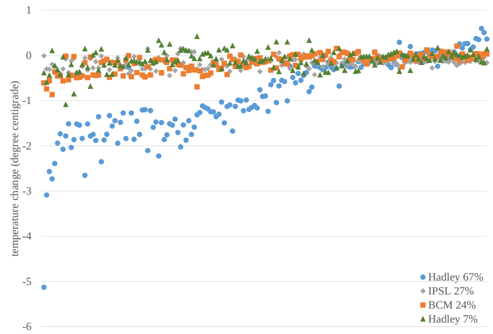

FIGURE 1. TEMPERATURE CHANGE BY COUNTRY IF THE THERMOHALINE CIRCULATION SHUTS DOWN

Note: Results are for hosing experiments from three climate models. Temperature anomalies represent the difference between a scenario with greenhouse warming and a scenario with greenhouse warming and the effects of changes in the thermohaline circulation. Results were aggregated from the grid to the country using area-weights by the current authors. The temperature change is the difference in the annual mean surface air temperature, averaged over the last 30 years of the model run. The percentages in the legend refer to the extent of the slowdown of the thermohaline circulation.

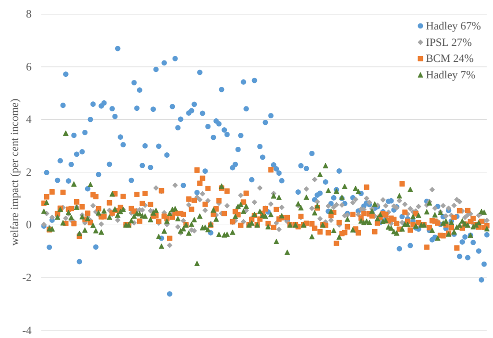

FIGURE 2. THE IMPACT OF A THERMOHALINE CIRCULATION SHUTDOWN BY COUNTRY ACCORDING TO THE META-ANALYTIC FUNCTION.

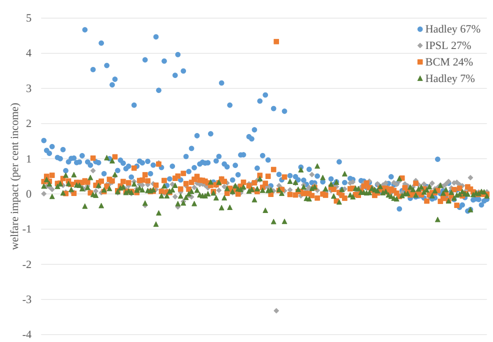

FIGURE 3. THE IMPACT OF A THERMOHALINE CIRCULATION SHUTDOWN BY COUNTRY ACCORDING TO FUND.

TABLE 1— GLOBAL IMPACT OF A THERMOHALINE CIRCULATION SHUTDOWN

	Hadley 67%	IPSL 27%	BCM 24%	Hadley 7%
Meta-analysis	1.29	0.32	0.20	0.16
FUND	0.84	0.19	0.17	0.05

Notes: Impacts are welfare-equivalent income gains, measured as a percentage of global income in 2085.

Source: Author calculations.

Online Appendix A. Meta-analysis

The meta-analysis is detailed in Tol (2015). Twenty-seven estimates of the total welfare impact of climate change were taken from twenty-two studies. Various impact functions were fitted to the data. A piecewise linear function is, by far, the best fit. This function defines an optimal temperature. Welfare falls linearly if the temperature is above or below the optimum.

Thirteen estimates report at least some regional detail; the remaining fourteen only show a global total. Regressing the regional estimates on the natural logarithm of per capita income and annual mean temperature, both regionally averaged, suggests that the welfare loss due to a 2.5°C warming is 1.2% of income less, with a standard deviation of 0.6%, for a country that is twice as rich and 0.4% less, with a standard deviation of 0.1%, for a country that is 1°C colder.

The function estimated using the regional results is used to impute national impact estimates. We ensure that the national estimates add up to the estimated regional and global totals by shifting the imputed values, that is, by changing the intercept.

Having thus obtained twenty-seven estimates of the national welfare impact of climate change, we fit a piecewise linear impact function for each country. Table A1 shows the parameters. All data and computations are shown in http://users.sussex.ac.uk/~rt220/totalimpactaer.xlsx. The full set of results for this paper is at http://users.sussex.ac.uk/~rt220/hosingaer.xlsx.

TABLE A1— PARAMETERS OF THE PIECEWISE LINEAR IMPACT FUNCTION

	Cold Slope	Optimum temperature	Hot Slope
Global impacts	-0.7	1.0	-1.4
Average of country results			
No weights	-7.1 (5.4)	0.3 (1.3)	-3.3 (1.4)
Population weights	-6.1 (5.2)	0.4 (1.2)	-3.3 (1.8)
GDP weights	-2.2 (3.3)	1.7 (1.5)	-1.7 (1.8)

Notes: "Global impacts" shows the parameters, fitted by least squares, to the globally aggregated impacts. "Average of country results" shows the average and standard deviation of the parameters fitted to the national impacts. "No weights" shows the unweighted average and standard deviation of the country results, "population weights" weights the results by the population size in 2005, and "GDP weights" uses 2005 GDP as weights. The optimum temperature is measured in degrees Celsius. The slopes are measured in welfare loss (in percent equivalent income change) per degree Celsius. The cold slope applies to temperatures below the optimum, the hot slope to temperatures above.

Source: Author calculations.

Online Appendix B. FUND, version 4.0

We use version 4.0 of the Climate Framework for Uncertainty, Negotiation and Distribution for this paper. The major innovation in FUND 4.0 is that the model can be run with a country level resolution in addition to the regional level resolution of previous FUND releases. The world is divided into 198 countries or 16 regions. Both resolution modes use the same equations, but a different set of parameter values that are matched to the respective resolution. The regional resolution version of FUND 4.0 is almost identical to the previous FUND 3.10 version, except for a few minor updates that are described in the full model documentation. FUND 3.10 is equivalent to FUND 3.9, but was rewritten in the julia programming language.

The parameters for the national version of FUND were obtained as follows. For many parameters the regional value was used for all countries in that region, if the definition of the parameter made such an approach feasible (e.g. if a benchmark impact parameter was expressed as a share of GDP, it was reused as the benchmark impact for all countries in that region). The sea-level rise impact component was recalibrated from World Bank Data; see http://data.worldbank.org/. The scenarios of population and economic growth were initialized with World Bank country level data, and then follow the same trajectory as the regional resolution scenarios of FUND. Details of the national resolution calibration can be found in the calibration code that is part of the standard FUND 4.0 source code.

The FUND source code is open source under the MIT license and available at http://www.fund-model.org. The FUND homepage also has the full model documentation. FUND 4.0 is programmed in the open source julia programming language (http://www.julialang.org), and uses the open source Mimi component framework for integrated assessment models (https://github.com/davidanthoff/Mimi.jl). The full set of results for this paper is at http://users.sussex.ac.uk/~rt220/FUNDresultsaer.xlsx.