Evidence for an exceptional 20th-Century slowdown in Atlantic Ocean overturning

Stefan Rahmstorf*, Jason Box, Georg Feulner, Michael E. Mann, Alexander Robinson, Scott Rutherford and Erik Schaffernicht

Possible changes in Atlantic meridional overturning circulation (AMOC) provide a key source of uncertainty regarding future climate change. Maps of temperature trends over the 20th Century show a conspicuous region of cooling in the northern Atlantic. Here we present multiple lines of evidence suggesting that this cooling may be due to a reduction in the AMOC over the 20th Century and particularly after 1970. Since 1990 the AMOC appears to have partly recovered. This time evolution is consistently suggested by an AMOC index based on surface temperatures, by the hemispheric temperature difference, by coral-based proxies and by oceanic measurements. We discuss a possible contribution of the melting of the Greenland Ice Sheet to the slowdown. Using a multi-proxy temperature reconstruction for the AMOC index suggests that the AMOC weakness after 1975 is an unprecedented event in the past millennium ($p > 0.99$). Further melting of Greenland in the coming decades could contribute to further weakening of the AMOC.

Global warming during the 20th Century has not proceeded uniformly over the globe. A small portion of the Earth's surface has even cooled since the start of the 20th Century: a region over the subpolar gyre of the North Atlantic, to the south of Greenland (Fig. 1). Model simulations show the largest cooling response to a weakening of the Atlantic meridional overturning circulation (AMOC) in this same region[1], suggesting this area has so far defied global warming due to a weakening of the AMOC over the past century. The time history of the AMOC over this period is poorly known, however, due to the scarcity of direct measurements. Because of the large heat transport associated with the AMOC, changes in sea surface temperatures (SSTs) can be used as an indirect indicator of the AMOC evolution[2].

Dima and Lohmann[3] identified two distinct modes in global SST evolution, one associated with a gradual decline of the global thermohaline circulation and one due to multidecadal and shorter AMOC variability, and concluded "that the global conveyor has been weakening since the late 1930s and that the North Atlantic overturning cell suffered an abrupt shift around 1970". Thompson et al.[4] found that the SST difference between the Northern and Southern Hemisphere underwent a sudden decline by ~0.5 °C around 1970, with the largest cooling observed over the northern Atlantic. We

interpret this as indicative of a large-scale AMOC reduction, since the most plausible explanation for such a rapid change in the interhemispheric temperature difference is the cross-equatorial heat transport of the AMOC[5]. Drijfhout et al.[6] regressed the AMOC strength and global-mean temperature on surface temperature fields in models and concluded that the conspicuous "warming hole" south of Greenland is related to a weakening of the AMOC. They further found that a possible contribution of aerosol forcing to the cool patch as proposed by Booth et al.[7] cannot be excluded.

Zhang et al. [8], however, argue that the model simulation by Booth et al. overestimates the effect of aerosol forcing, by not accounting for any increase in ocean heat content in the North Atlantic over the second half of the 20th Century, in contrast to what is suggested by the observations. The observational data show a clear dipole response in the Atlantic, with the North Atlantic cooling and the South Atlantic warming when comparing 1961-1980 with 1941-1960. The maximum of South Atlantic warming is within the Benguela Current off southern Africa and the maximum of North Atlantic cooling is found within the Gulf Stream. These patterns are highly characteristic of AMOC changes and are found in many model simulations wherein the AMOC is weakened by freshwater hosing experiments. The Atlantic see-saw pattern can also be seen in Fig. 1, where out of all Southern Hemisphere ocean regions the South Atlantic has warmed the most.

Terray[9] has analysed the current CMIP5 ensemble of model simulations together with observed SST data in order to quantify the relative contributions of radiatively forced changes to the total decadal SST variability. While in most models forced changes explain more than half of the variance in low latitudes, they explain less than 10% in the subpolar North Atlantic, where in most cases their contribution is not significantly different from zero (the notable exception is the model used by Booth et al. as mentioned above).

In order to put the 20th Century AMOC evolution into a longer-term context, in the following we develop an AMOC index based on surface temperatures from instrumental and proxy data.

An AMOC index based on surface temperatures

We take the results of a climate model intercomparison[1] to identify the geographic region that is most sensitive to a reduction in the AMOC (Fig. 1), which for simplicity we henceforth refer to as 'subpolar gyre', although we use the term here merely to describe a geographic region and not an ocean circulation feature. To isolate the effect of AMOC changes from other climate change, we define an AMOC index by subtracting the Northern Hemisphere mean surface temperature from that of the subpolar gyre (see *Supplementary Information* for an alternative index obtained by subtracting Northern Hemisphere SST). We thus assume that differences in surface temperature

evolution between the subpolar gyre and the whole Northern Hemisphere are largely due to changes in the AMOC. This appears to be a reasonable approximation in view of the evidence on North Atlantic SST variability discussed in the introduction. We decided against using an index based on a dipole between North and South Atlantic temperatures[2, 10], as this might be affected by the large gradient in aerosol forcing between both hemispheres.

We test the performance of the index in a global warming scenario experiment for 1850-2100 with a state-of-the-art global climate model, the MPI-ESM-MR. This model has a realistic representation of the AMOC[10, 11] based on criteria that include the magnitude and shape of the AMOC stream function and the realism of sites of deep-water formation. Without satisfying those criteria, we cannot expect realistic spatial patterns of SST response to AMOC variations and hence a good correlation of our temperature-based AMOC index with the actual AMOC. An analysis of 10 global climate models found that a surface temperature response in the North Atlantic subpolar gyre is a robust feature of AMOC variability, while the details of this response depend on the quality of representation of the AMOC[10].

Fig. 2 shows a high correlation of the AMOC index with the actual AMOC in the model, particularly on time scales of a decade and longer (smoothed curves). The correlation coefficient of the two smoothed curves after linear detrending is R=0.90 and our temperature-based AMOC index predicts the actual AMOC changes in the model with an RMS error of 0.6 Sv (1.1 Sv for the annual data), where the conversion factor of 2.3 Sv/K has been fitted. Note that both individual components of the index – the subpolar gyre and the Northern Hemisphere temperature – increase during the 21st Century in the simulation; it is the difference between the two which tracks the AMOC decline, as expected by our physical understanding of the effect of AMOC heat transport.

The lower panel of Fig. 2 shows the correlation pattern of the AMOC stream function in the model with our AMOC index, which displays coherent large-scale structure that resembles the actual stream function (contoured). The circulation changes captured by the AMOC index are thus not local to the subpolar gyre region but rather represent a large scale response of the Atlantic meridional overturning circulation. Despite the good correlation with the AMOC in the model, our SST-based index only provides indirect evidence for possible AMOC changes.

Reconstructing the AMOC index over the past millennium

To obtain a long-term reconstruction of the AMOC index requires long-term reconstructions of both the Northern Hemisphere mean temperature and sea surface temperature (SST) of the subpolar gyre. For the Northern Hemisphere mean, Mann et al.[9] produced reconstructions using two different

methods, Composite-Plus-Scale (CPS) and Errors in Variables (EIV). Here we use the land-and-ocean reconstruction with the EIV method using all the available proxies, which is the reconstruction for which the best validation results were achieved (see Supporting Online Material of Mann et al.[9]). Based on standard validation scores (Reduction of Error and Coefficient of Efficiency), this series provides a skilful reconstruction back to 900 AD and beyond (95% significance compared to a red-noise null).

The subpolar gyre series is derived from the spatial temperature reconstruction of Mann et al.[10], which reconstructs land and ocean surface temperatures in every 5° latitude by 5° longitude grid box with sufficient instrumental data to perform calibration and validation. The subpolar gyre falls within the region where the individual grid-box reconstructions are assessed to be skilful compared to a red noise null[10]. In addition, we performed validation testing of the subpolar gyre mean series, which indicates a skilful reconstruction back to 900 AD (95% significance compared to a red-noise null; see *Supplementary Information* for details).

Both time series as well as the resulting AMOC index are shown in Fig. 3. Remarkably, the subpolar gyre reaches nearly its coldest temperatures of the last millennium in the late 20th Century (orange curve), despite global warming. Mann et al. [12] already noted that this region near Greenland is anomalous in being colder during the modern reference period (1961-1990) than even in the Little Ice Age. The index (blue curve) shows a rather steady AMOC, with modest changes until the beginning of the 20th Century. There is indication of a maximum in the 15th Century and a minimum around 1600 AD. There is no sign in our index that a weak AMOC caused the 'Little Ice Age' in the Northern Hemisphere[13]; rather the data are consistent with previous findings that the Little Ice Age reflects a response to natural volcanic and solar forcing[14, 15, 16], and if anything this surface cooling strengthened the AMOC at least during the first part of the Little Ice Age. The fact that LIA coldness appears to have been even more pronounced in South America than in Europe[17] further argues against a weak AMOC, as the latter would have warmed the Southern Hemisphere. The 20th Century shows a gradual decline in the AMOC index, followed by a sharp drop starting around 1970 with a partial recovery after 1990 (discussed further below). This recovery is consistent with the finding of an AMOC increase since 1993 based on floats and satellite altimeter data[18].

Our temperature reconstruction for the subpolar gyre differs from three estimates based on sediment cores from the region[19,20]. However, reconciling these cores with each other and with the instrumental SST record proves problematic (see *Supplementary Information*), whereas our reconstruction compares well with the instrumental data during the period of overlap.

Spectral analysis of the AMOC index shows a few marginally significant peaks with periods around 22, 27 and 37 years, but these features are not clearly discernible from the expectations of simple red noise (Fig. 4). We find no significant peak in the 50-70 year period range although our index should pick this up[10], suggesting that the "Atlantic Multidecadal Oscillation" (AMO) described by Delworth and Mann and others[21, 22, 23] is not a prominent feature of our AMOC index time series.

The 20th Century AMOC weakening

The most striking feature of the AMOC index is the extremely low index values reached from 1975 to 1995. It is primarily this negative anomaly that yields the cooling patch in the trend maps shown in Fig. 1. In the following we discuss this downward spike in more detail.

The significance of the 1975-1995 AMOC index reduction was estimated using a Monte Carlo method (see *Supplementary Information*). The annually resolved AMOC reconstruction from 900 to 1850 formed the basis for an ARMA(1,1) model which closely resembles the statistical properties of the data. 10,000 simulated time series of the same length as the AMOC index were constructed. The probability of reaching a similarly weak AMOC index as during 1975-1995 just by natural variability was found to be <0.005, based on the uncertainty of the proxy data and ignoring that this weakening is independently supported by instrumental data.

Fig. 5 shows corroborating evidence in support of a 20th Century AMOC weakening. The blue curve depicts the AMOC–index shown in Fig. 3. The dark red curve shows the corresponding index based on the instrumental GISS global temperature analysis. The green curve denotes oceanic nitrogen-15 proxy data from corals off the US north-east coast from Sherwood et al.[24]. These annually-resolved $\delta^{15}N$ data represent a tracer for water mass changes in the region, where high values are characteristic of the presence of Labrador Slope Water. The time evolution of the $\delta^{15}N$ tracer agrees well with that of our AMOC index (Fig. 5). Sherwood et al. report four more data points from ancient corals preceding the 20th Century, the oldest one from ~500 AD. These lie all above 10.5‰, providing (albeit limited) evidence that the downward excursion to values below 10‰ between 1975 and 1995 and the corresponding water mass change may be unprecedented in several centuries.

Finally Fig. 5 shows data points from repeat hydrographic sections across the Atlantic at 25° North, from which Bryden et al.[25] originally concluded that the AMOC had slowed by 30% since the 1950s. These measurements were later adjusted for seasonal variations[26] and are shown in this form here; recent observations over 2004-2012 show inter-annual variability[27] with a standard deviation of 1.7 Sv which needs to be kept in mind.

Causes of the weakening and implications for the future

Since the AMOC is driven by density gradients related to deep-water formation in the high-latitude North Atlantic, a weakening of the AMOC could be caused by a regional reduction in surface ocean density. Curry and Mauritzen[28] describe an ongoing freshening trend in the northern Atlantic in which the net freshwater storage has increased by 19,000 km^3 between 1961 and 1995, and the rapid AMOC drop in 1970 was preceded by a large-scale freshening known as the Great Salinity Anomaly[29, 30]. This freshwater anomaly was described in 1988 as "one of the most persistent and extreme variations in global ocean climate yet observed in this century"[30], the source of which has been linked to a large sea-ice export from the Arctic Ocean[29, 30]. Dickson et al.[30] and Belkin et al.[29] estimate the freshwater volume anomaly of the Great Salinity Anomaly as 2,000 km^3 along the Labrador coast.

Other possible sources of freshwater addition are increasing river discharge into the Arctic Ocean[31] and meltwater coming off the Greenland Ice Sheet (GIS). Since surface flow is directed northward and freshwater tends to remain near the surface due to its low density, it is difficult to remove freshwater from the northern Atlantic so an accumulation over longer time scales is plausible. According to a recent reconstruction of the total GIS mass balance from 1840 AD[32], the GIS was close to balance in the 19th Century, but a major mass loss from Greenland occurred from 1900 AD to 1970 AD. The cumulative runoff and ice discharge anomaly (relative to the mean over 1840-1900) during this period is estimated as 8,000 km^3, of which 1,800 km^3 was released after 1955 (Fig. 6). It is thus possible that the accumulated freshwater input from Greenland may have made a significant contribution to the observed freshening trend. A comparable freshening around Antarctica has recently likewise been linked to ice sheet mass loss[33].

This dilution of the surface ocean could have weakened deep-water formation, slowing the AMOC. A shutdown of deep convection in the Labrador Sea from 1969 to 1971 is well documented[34] and the stability of Labrador Sea convection has been subject of a number of studies[35, 36]. Perhaps as a consequence of the cooling in the Greenland region starting in 1970, the GIS subsequently was closer to mass balance for three decades until ~2000 AD[32]. Since then the GIS has started to lose mass again at a rapidly increasing rate, consistent with the surface warming of the region which has been attributed to a recovery of the AMOC by Robson et al.[37] based on model simulations initialised with observations. This recovery is also seen in the AMOC index proposed in this paper.

Recent oceanographic measurements from the RAPID array at 26 °N in the Atlantic suggest that the AMOC has been weakening again since these measurements started in 2004[38], although we cannot conclude to what extent this temporary decrease signals an ongoing trend, and the connection between subtropical and subpolar overturning especially on shorter time scales is not clear[39].

Climate models from the CMIP5 ensemble forced by natural and anthropogenic forcings generally show a much weaker subpolar cooling than the observations[6] and do not capture the observed Atlantic subpolar cooling during 1970-1990, even though they show a much smaller and more short-lived cooling following the Agung eruption in 1963/64[9]. The failure of the models to capture the cooling is probably not due to an underestimation of the response to the Agung eruption, since volcanic cooling would if anything strengthen the AMOC while the data indicate an AMOC weakening[40]. Rather, this failure suggests that these models either have an AMOC that is too stable with respect to buoyancy forcing[41, 42], or are missing an important forcing (and indeed the time history of Greenland meltwater runoff is not included as a forcing in the CMIP5 ensemble).

While major uncertainties remain about the past evolution of the AMOC for lack of direct measurements, indirect evidence from various sources provides a consistent picture, linking together the time evolution of temperature, ocean circulation and possibly Greenland mass balance. If the interconnections between these three components continue as we have conjectured, the ongoing melting of the Greenland Ice Sheet, which reached an extreme level in 2012[43], may lead to further freshening of the subpolar Atlantic in the next few decades. Bamber et al.[44] estimate that if current trends continue, the Greenland meltwater input from 1995 to 2025 AD may exceed 10,000 km^3. This might lead to another weakening of the Atlantic overturning circulation within a decade or two, and possibly even a permanent shutdown of Labrador Sea convection as a result of global warming, as has been predicted by some climate model simulations[45, 46].

Acknowledgements

We thank O. Sherwood for providing coral data. MEM acknowledges support for this work from the ATM program of the National Science Foundation (grant ATM-0902133). Three anonymous reviewers made many suggestions that helped to improve this paper.

Author contributions

SRa conceived and designed the research and wrote the paper, ES, SRu, AR and GF performed the research, MEM and JB contributed materials/analysis tools and co-wrote the paper.

References

1. Stouffer R, et al. Investigating the Causes of the Response of the Thermohaline Circulation to Past and Future Climate Changes. *J Clim* 2006, **19:** 1365-1387.

2. Latif M, Roeckner E, Botzet M, Esch M, Haak H, Hagemann S*, et al.* Reconstructing, monitoring, and predicting multidecadal-scale changes in the North Atlantic thermohaline circulation with sea surface temperature. *J Clim* 2004, **17**(7)**:** 1605-1614.

3. Dima M, Lohmann G. Evidence for Two Distinct Modes of Large-Scale Ocean Circulation Changes over the Last Century. *J Clim* 2010, **23**(1)**:** 5-16.

4. Thompson DWJ, Wallace JM, Kennedy JJ, Jones PD. An abrupt drop in Northern Hemisphere sea surface temperature around 1970. *Nature* 2010, **467**(7314)**:** 444-447.

5. Feulner G, Rahmstorf S, Levermann A, Volkwardt S. On the origin of the surface air temperature difference between the hemispheres in Earth's present-day climate. *J Clim* 2013, **26**(18)**:** 7136-7150.

6. Drijfhout S, van Oldenborgh GJ, Cimatoribus A. Is a Decline of AMOC Causing the Warming Hole above the North Atlantic in Observed and Modeled Warming Patterns? *J Clim* 2012, **25**(24)**:** 8373-8379.

7. Booth BBB, Dunstone NJ, Halloran PR, Andrews T, Bellouin N. Aerosols implicated as a prime driver of twentieth-century North Atlantic climate variability. *Nature* 2012, **484**(7393)**:** 228–232.

8. Zhang R, Delworth TL, Sutton R, Hodson DLR, Dixon KW, Held IM*, et al.* Have Aerosols Caused the Observed Atlantic Multidecadal Variability? *J Atmos Sci* 2013, **70**(4)**:** 1135-1144.

9. Terray L. Evidence for multiple drivers of North Atlantic multi-decadal climate variability. *Geophys Res Let* 2012, **39**.

10. Roberts CD, Garry FK, Jackson LC. A Multimodel Study of Sea Surface Temperature and Subsurface Density Fingerprints of the Atlantic Meridional Overturning Circulation. *J Clim* 2013, **26**(22)**:** 9155-9174.

11. Jungclaus JH, Fischer N, Haak H, Lohmann K, Marotzke J, Matei D*, et al.* Characteristics of the ocean simulations in the Max Planck Institute Ocean Model (MPIOM) the ocean component of the MPI-Earth system model. *Journal of Advances in Modeling Earth Systems* 2013, **5**(2)**:** 422-446.

12. Mann ME, Zhang Z, Rutherford S, Bradley RS, Hughes M, Shindell D*, et al.* Global Signatures and Dynamical Origins of the Little Ice Age and Medieval Climate Anomaly. *Science* 2009, **326:** 1256-1260.

13. Wanamaker A, Bulter P, Scourse J, Heinemeier J, Eiríksson J, Knudsen K*, et al.* Surface changes in the North Atlantic meridional overturning circulation during the last millennium. *Nature Communications* 2012.

14. Crowley TJ. Causes of climate change over the past 1000 years. *Science* 2000, **289:** 270-277.

15. Shindell DT, Schmidt GA, Miller RL, Mann ME. Volcanic and solar forcing of climate change during the preindustrial era. *J Clim* 2003, **16**(24)**:** 4094-4107.

16. Feulner G. Are the most recent estimates for Maunder Minimum solar irradiance in agreement with temperature reconstructions? *Geophys Res Let* 2011, **38**.

17. PAGES 2k Network. Continental-scale temperature variability during the past two millennia. *Nature Geoscience* 2013.

18. Willis J. Can in situ floats and satellite altimeters detect long-term changes in Atlantic Ocean overturning? *Geophys Res Lett* 2010, **37:** L06602.

19. Moffa-Sanchez P, Born A, Hall IR, Thornalley DJR, Barker S. Solar forcing of North Atlantic surface temperature and salinity over the past millennium. *Nature Geoscience* 2014, **7**(4)**:** 275-278.

20. Miettinen A, Divine D, Koc N, Godtliebsen F, Hall IR. Multicentennial Variability of the Sea Surface Temperature Gradient across the Subpolar North Atlantic over the Last 2.8 kyr. *J Clim* 2012, **25**(12)**:** 4205-4219.

21. Delworth TL, Mann ME. Observed and simulated multidecadal variability in the Northern Hemisphere. *Clim Dyn* 2000, **16**(9)**:** 661-676.

22. Chambers DP, Merrifield MA, Nerem RS. Is there a 60-year oscillation in global mean sea level? *Geophys Res Let* 2012, **39**.

23. Tung K, Zhou J. Using data to attribute episodes of warming and cooling in instrumental records. *Proc Natl Acad Sci USA* 2013, **110:** 2058–2063.

24. Sherwood OA, Lehmann MF, Schubert CJ, Scott DB, McCarthy MD. Nutrient regime shift in the western North Atlantic indicated by compound-specific delta N-15 of deep-sea gorgonian corals. *Proceedings of the National Academy of Sciences of the United States of America* 2011, **108**(3)**:** 1011-1015.

25. Bryden HL, Longworth HR, Cunningham SA. Slowing of the Atlantic meridional overturning circulation at 25º N. *Nature* 2005, **438:** 655-657.

26. Kanzow T, Cunningham SA, Johns WE, Hirschi JJM, Marotzke J, Baringer MO*, et al.* Seasonal Variability of the Atlantic Meridional Overturning Circulation at 26.5 degrees N. *J Clim* 2010, **23**(21)**:** 5678-5698.

27. Smeed DA, McCarthy GD, Cunningham SA, et al. Observed decline of the Atlantic meridional overturning circulation 2004-2012. *Ocean Science* 2014, **10:** 29-38.

28. Curry R, Mauritzen C. Dilution of the northern North Atlantic Ocean in recent decades. *Science* 2005, **308**(5729)**:** 1772-1774.

29. Belkin IM, Levitus S, Antonov J, Malmberg S-A. "Great Salinity Anomalies" in the North Atlantic. *Progr Oceanogr* 1998, **41:** 1-68.

30. Dickson RR, Meincke J, Malmberg SA, Lee AJ. The "Great Salinity Anomaly" in the northern North Atlantic, 1968-82. *Progr Oceanogr* 1988, **20:** 103-151.

31. Peterson BJ, Holmes RM, McClelland JW, Vörösmarty CJ, Lammers RB, Shiklomanov AI*, et al.* Increasing river discharge to the Arctic Ocean. *Science* 2002, **298:** 2171-2173.

32. Box J, Colgan W. Greenland ice sheet mass balance reconstruction. Part III: marine ice loss and total mass balance (1840-2010). *J Clim* 2013, **26:** 6990–7002.

33. Rye C, Naveira Garabato AC, Holland P, Meredith MP, George Nurser A, Hughes CW*, et al.* Rapid sea-level rise along the Antarctic margins in response to increased glacial discharge. *Nature Geoscience* 2014, **7:** 732–735.

34. Lazier JRN. Oceanographic conditions at Ocean Weather Ship *Bravo*, 1964-74. *Atmos-Ocean* 1980, **18:** 227-238.

35. Kuhlbrodt T, Titz S, Feudel U, Rahmstorf S. A simple model of seasonal open ocean convection. Part II: Labrador Sea stability and stochastic forcing. *Ocean Dyn* 2001, **52:** 36-49.

36. Gelderloos R, Straneo F, Katsman CA. Mechanisms behind the Temporary Shutdown of Deep Convection in the Labrador Sea: Lessons from the Great Salinity Anomaly Years 1968-71. *J Clim* 2012, **25**(19)**:** 6743-6755.

37. Robson JI, Sutton RT, Smith DM. Initialized decadal predictions of the rapid warming of the North Atlantic Ocean in the mid 1990s. *Geophys Res Let* 2012, **39**.

38. Robson J, Hodson D, Hawkins E, Sutton R. Atlantic overturning in decline? *Nature Geoscience* 2014, **7**(1)**:** 2-3.

39. Lozier MS, Roussenov V, Reed MSC, Williams RG. Opposing decadal changes for the North Atlantic meridional overturning circulation. *Nature Geoscience* 2010, **3**(10)**:** 728-734.

40. Zhang R. Coherent surface-subsurface fingerprint of the Atlantic meridional overturning circulation. *Geophys Res Lett* 2008, **35:** L20705.

41. Hofmann M, Rahmstorf S. On the stability of the Atlantic meridional overturning circulation. *Proc Natl Acad Sci USA* 2009, **106**(49)**:** 20584-20589.

42. Weaver AJ, Sedlacek J, Eby M, Alexander K, Crespin E, Fichefet T*, et al.* Stability of the Atlantic meridional overturning circulation: A model intercomparison. *Geophys Res Let* 2012, **39**.

43. Nghiem SV, Hall DK, Mote TL, Tedesco M, Albert MR, Keegan K*, et al.* The extreme melt across the Greenland ice sheet in 2012. *Geophys Res Let* 2012, **39**.

44. Bamber J, van den Broeke M, Ettema J, Lenaerts J, Rignot E. Recent large increases in freshwater fluxes from Greenland into the North Atlantic. *Geophys Res Let* 2012, **39**.

45. Rahmstorf S. Shifting seas in the greenhouse? *Nature* 1999, **399:** 523-524.

46. Wood RA, Keen AB, Mitchell JFB, Gregory JM. Changing spatial structure of the thermohaline circulation in response to atmospheric CO2 forcing in a climate model. *Nature* 1999, **399:** 572-575.

47. Hansen J, Ruedy R, Glascoe J, Sato M. GISS analysis of surface temperature change. *Journal of Geophysical Research-Atmospheres* 1999, **104:** 30997-31022.

48. Morice CP, Kennedy JJ, Rayner NA, Jones PD. Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 data set. *Journal of Geophysical Research-Atmospheres* 2012, **117**.

49. Mann ME, Lees JM. Robust estimation of background noise and signal detection in climatic time series. *Clim Change* 1996, **33**(3)**:** 409-445.

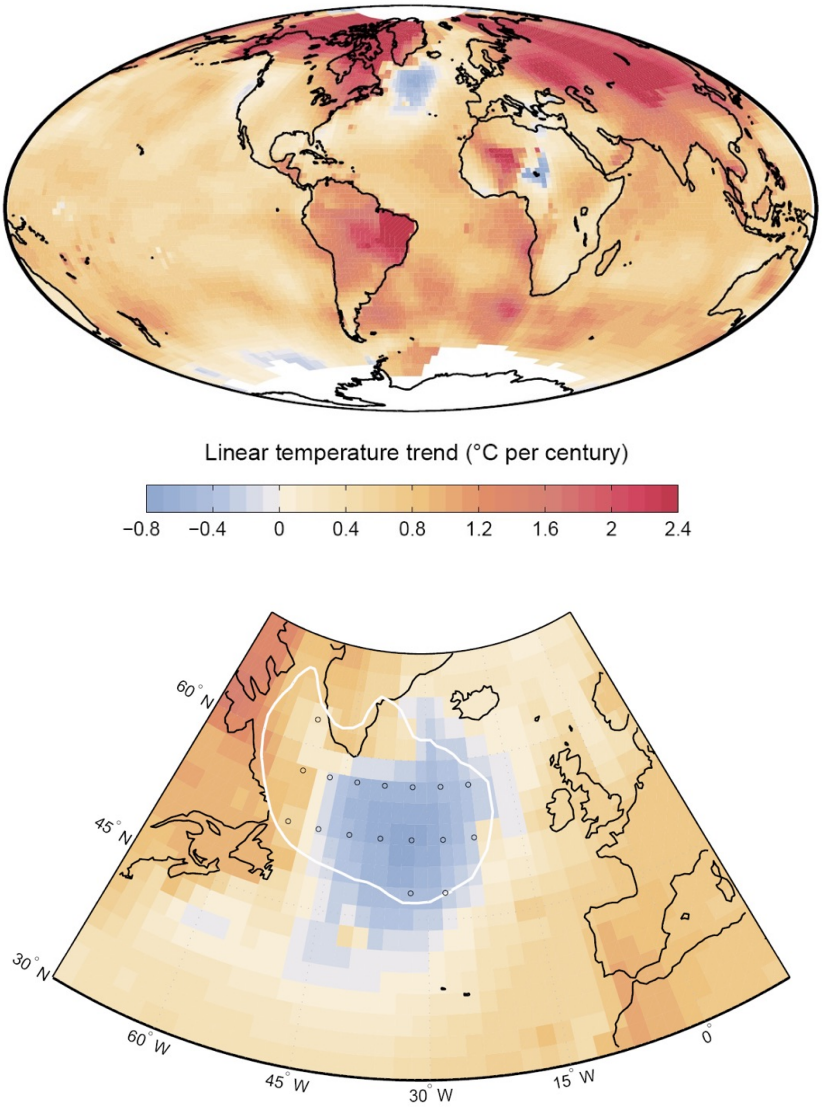
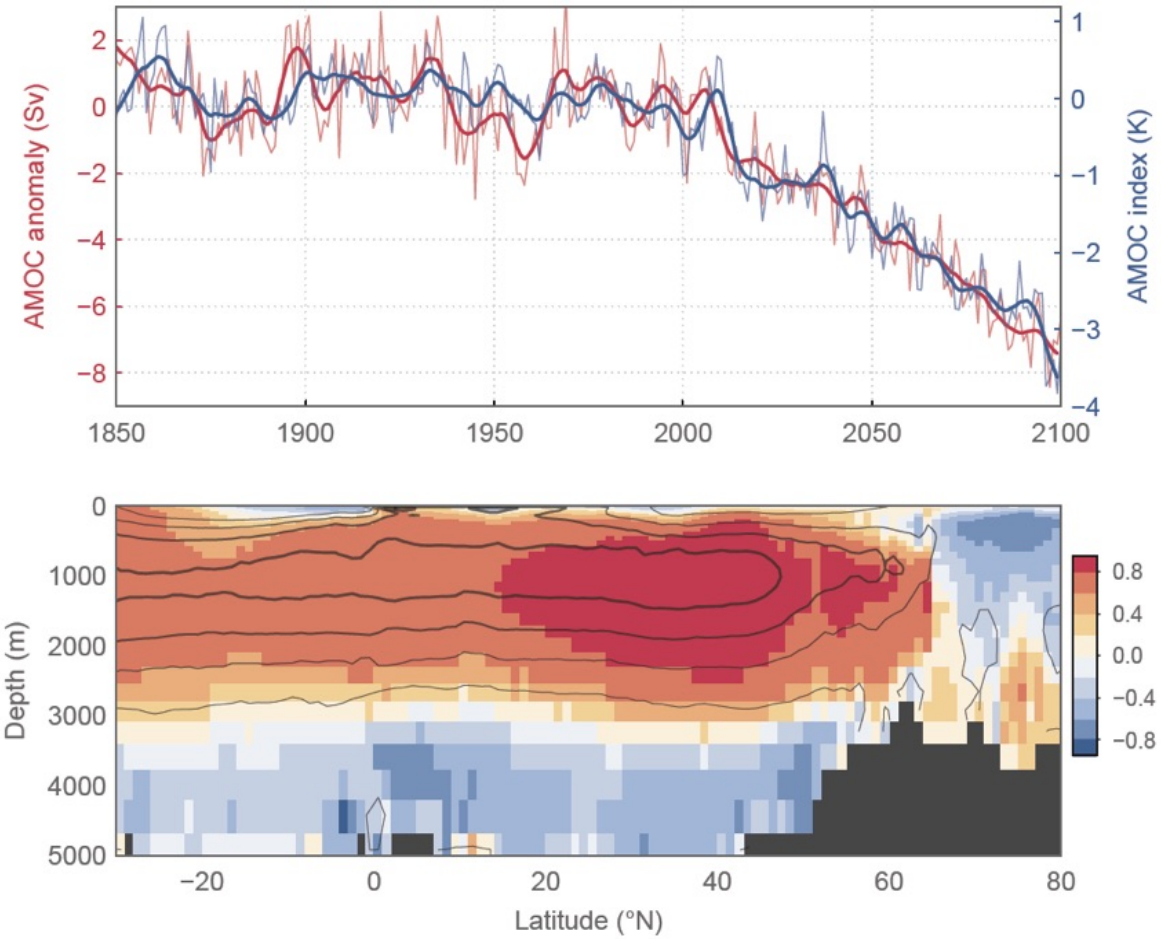
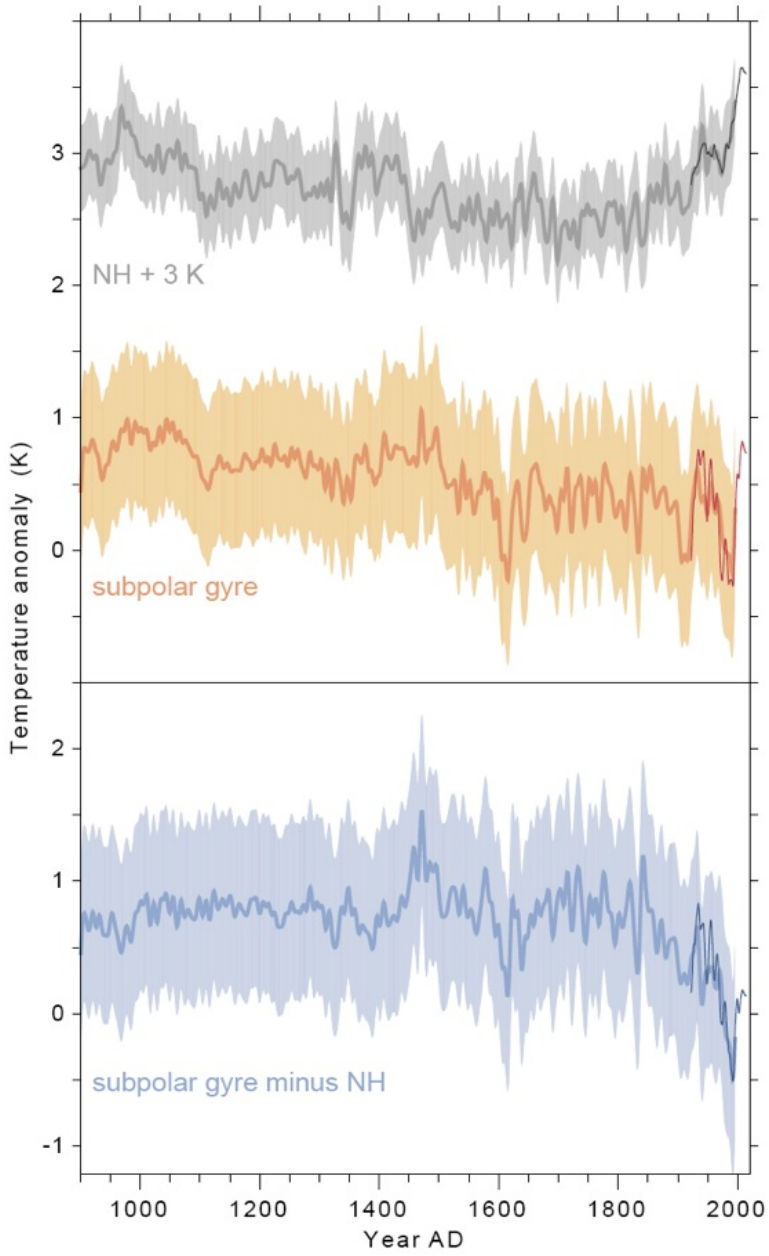


Figure 1 Linear trends of surface temperature since 1901 AD based on the temperature data of NASA GISS [47], in °C per century. The upper panel is a global equal area map (Hammer projection) for 1901-2013; white indicates insufficient data. In the lower panel we show the same analysis for the North Atlantic sector for 1901-2000. In addition to the observed temperature trends the lower panel also shows the grid points (black circles) of the subpolar gyre region for which time series are shown in Figs. 3 and 5, as well as the model-average 2°C cooling contour (white) from a climate model intercomparison[1] in which the models were subject to a strong AMOC reduction induced by adding a freshwater anomaly to the northern Atlantic. The geographic extent of the model-predicted temperature response to an AMOC reduction coincides well with the region of observed 20th-Century cooling. The models are forced more strongly and cooling extends further west due to shutting down Labrador Sea convection, which has only briefly happened in the real world so far. (Note that the second cooling patch in central Africa is in a region of poor data coverage and may be an artefact of data inhomogeneities.)



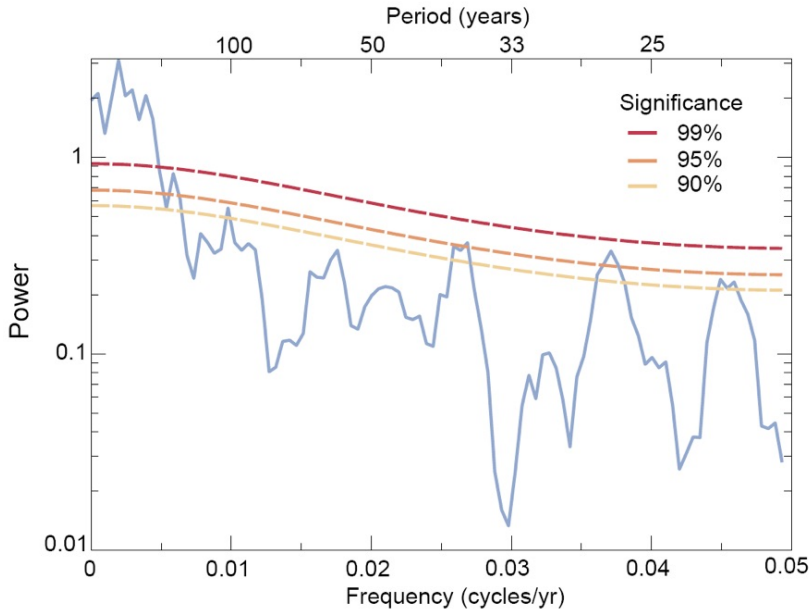
397

398 **Figure 2** Connection between the AMOC stream function and the temperature-based AMOC index in
399 a global warming scenario (RCP8.5) simulated with the MPI-ESM-MR global climate model of the
400 Max Planck Institute in Hamburg[11]. **Top panel:** Time series of the maximum overturning stream
401 function (red) and the AMOC index (blue). Thin lines show annual values, thick lines smoothed
402 curves over 11 years. **Bottom panel:** The correlation coefficient *r* of the overturning stream function
403 in the model with the AMOC index (shading), shown together with the mean stream function (black
404 contours in 5 Sv intervals).



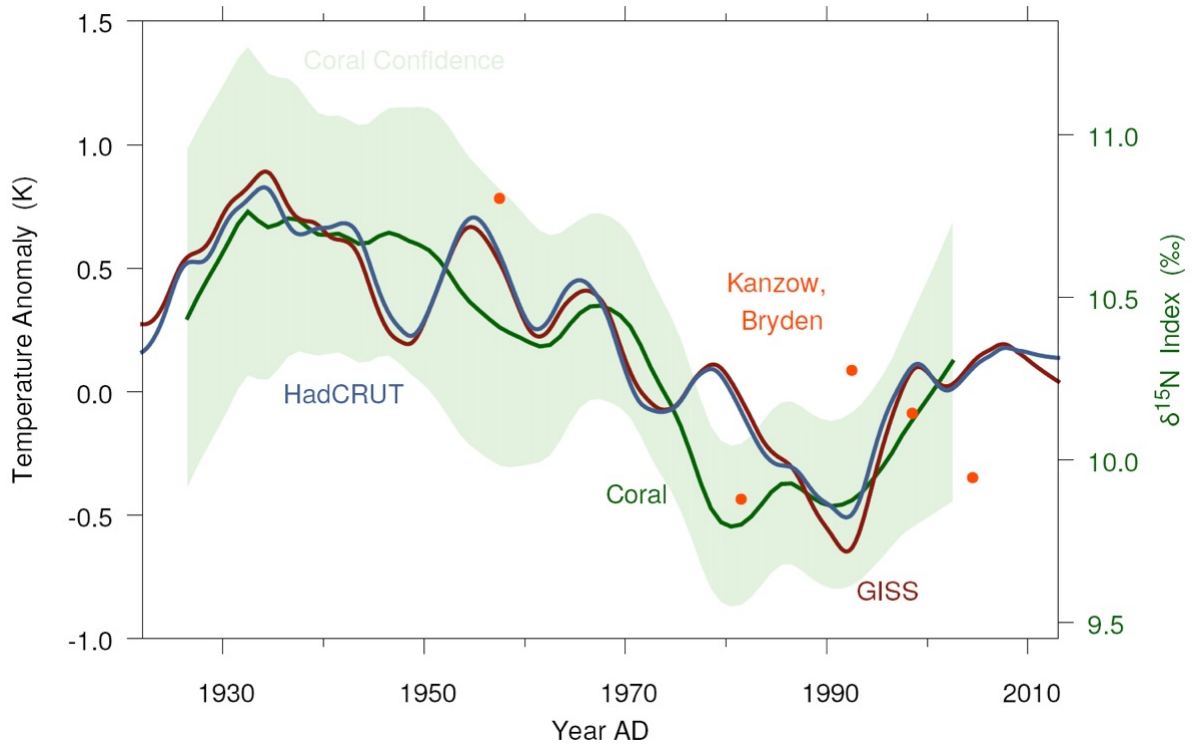
405

406 **Figure 3** Surface temperature time series for different regions from the proxy reconstruction of
407 Mann et al.[12], including estimated 2-sigma uncertainty bands, and from the HadCRUT4 instrumental
408 data[48]. The latter are shown in darker colours and from 1922 onwards, as from this time on data
409 from more than half of all subpolar-gyre grid cells exist in every month (except for a few months
410 during World War II). The orange/red curves are averaged over the subpolar gyre as indicated on Fig.
411 1. The grey/black curves are averaged over the Northern Hemisphere, offset by 3K to avoid overlap.
412 The blue curves in the bottom panel show our AMOC index, namely the difference between subpolar
413 gyre and Northern Hemisphere temperature anomalies (i.e. orange/red curves minus grey/black
414 curves). Proxy and instrumental data are decadally smoothed.



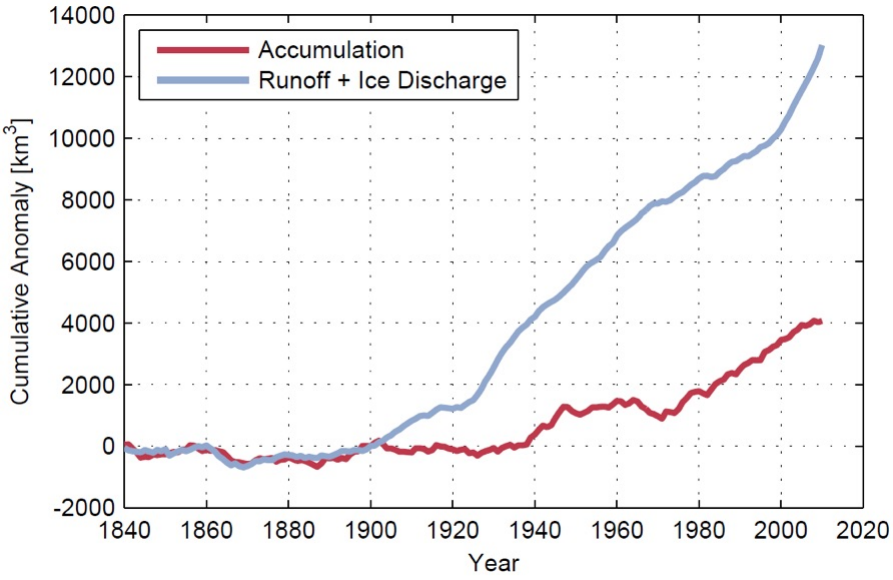
415 **Figure 4** Spectral analysis[49] of the proxy-based AMOC index shown in the bottom panel of Fig. 3.

416



417 **Figure 5** A compilation of different indicators for Atlantic ocean circulation. The blue curve shows
418 our temperature-based AMOC index as shown in Fig. 3 (bottom panel), while the dark red curve
419 shows the same index based on NASA GISS temperature data[47] (scale on left). The green curve with
420 uncertainty range shows coral proxy data [24] (scale on right). The data are decadally smoothed.
421 Orange dots show the analyses of data from hydrographic sections across the Atlantic at 25°N from
422 Kanzow et al. [26], where a 1 K change in the AMOC index corresponds to a 2.3 Sv change in AMOC
423 transport, as in Fig. 2 based on the model simulation.

424



425

426 **Figure 6** Mass balance terms of the Greenland Ice Sheet from Box and Colgan[32]. Shown is the
427 cumulative anomaly relative to the mean over 1840-1900, a preindustrial period during which the
428 Greenland Ice Sheet was approximately in balance.