Estimate of a heat and freshwater budget for the Arctic Mediterranean and North Atlantic in relation to the main physical processes

Bert Rudels, Bogi Hansen, Johannes Karstensen, Gerald McCarthy, Detlef Quadfasel

Extended Abstract

One aim of the NACLIM programme is to quantify and understand the forcing of the Atlantic Meridional Overtuning Circulation (AMOC), the warm surface water that flows north in the Gulf Stream and then northeast in the North Atlantic Current to lose heat, sink and return southward as cold, dense water in the Deep Western Boundary Current (DWBC) in the deep North Atlantic. The NACLIM observations have focussed on the exchanges across the Greenland-Scotland Ridge and on the processes in the Subpolar North Atlantic, but with extensions southward to the Subtropical North Atlantic and the RAPID array at 26^{o}N and northward into the Arctic Mediterranean, comprising the Nordic Seas and the Arctic Ocean. Results from other programmes and observational efforts in the Subpolar North Atlantic and in the Arctic Mediterranean have been incorporated to better understand the dominant processes and driving mechanisms.

The measured inflows over the Iceland-Scotland Ridge are 3.8Sv west of the Faroes and 3.5Sv along the continental slope through the Faroe-Shetland Channel. However, 0.8Sv Atlantic water flows south east of the Faroes making the total northward flow 6.5Sv. In addition, there is a small, 0.8Sv, Atlantic inflow west of Iceland. Most of the northward flowing water returns as deep overflows, 2Sv through the Faroe Bank Channel, 0.2Sv passing over the Wyville-Thomson Ridge, between 0.5 and 1Sv crosses the ridge between Iceland and the Faroes, and 3.4Sv flow through Denmark Strait west of Iceland. The rest returns to the North Atlantic as low salinity Polar water in the East Greenland Current and through the Canadian Arctic Archipelago and Baffin Bay. The dense overflows entrain intermediate waters south of the ridge, almost doubling their volume as they sink into the deep basins and ultimately forming the densest waters that flow southward in the Deep Western Boundary Current (DWBC). Starting in the east, the dense water circulates along the Reykjanes Ridge, passes through the Charlie Gibbs Fracture Zone and then moves around the Irminger Sea to enter the Labrador Sea at the southern tip of Greenland. South of Greenland the transport has increased to 10Sv. In the Labrador Sea and in the Irminger Sea the waters of the North

Atlantic Current, which have remained in the Subpolar gyre south of the Greenland-Scotland Ridge, and the low salinity water from the Arctic Mediterranean Sea are homogenised by convection, forming deep mode waters, less dense than the overflows, which join the DWBC and add to the AMOC.

The RAPID array at 26°N captures the entire AMOC, the wind driven upper layer circulation in the Subtropical gyre, as well as the AMOC waters, as they move north in the upper layer, and when they return south in the deep. The RAPID array has now been in the water 10 years and the mean total northward transport is estimated to ~35Sv, with 17Sv returning in the upper Subtropical gyre and 18Sv as part of the deep overturning circulation. The transports, however, show large variations, both seasonally and annually. The transports are weakest in winter, and in 2009 and 2010 a strong reduction of the northward transport was observed. During the last 5 years a weakening trend of the AMOC has been observed, and especially the denser, overflow, part of the AMOC has been reduced. This is surprising, considering that the overflows and the exchanges across the Greenland-Scotland Ridge, although variable, do not reveal any, or perhaps rather small increasing trends, while the convection in the Labrador and Irminger seas shows strong annual variability. This difference could be due to the fact that the ocean circulation, also its AMOC part, south of the Greenland-Scotland Ridge is mainly dominated by the winds, and the atmospheric circulation changes on shorter time scales than the thermohaline processes active north of the Greenland-Scotland Ridge.

The water flowing across the Greenland-Scotland Ridge continues northward in the Norwegian Atlantic Current and enters the Arctic Ocean through Fram Strait and over the Barents Sea. It loses heat and becomes denser, especially in the Norwegian Sea and in the Barents Sea. In the Arctic Ocean it eventually becomes covered by low salinity shelf water, mainly originating from interactions between river runoff and the Barents Sea inflow. This low salinity layer separates the Atlantic water from the sea ice and the atmosphere. It becomes isolated, and its heat remains stored in a warm (>0°C) Atlantic layer. Only in the Nansen Basin and in the Barents Sea does the Atlantic water get in direct contact with and melt sea ice. In the interior of the Arctic Ocean the Atlantic layer is cooled by mixing with the now colder Barents Sea inflow and by slope convection. Dense, saline water, created by ice formation and brine rejection, sinks down the slope, either entering and cooling the Atlantic layer, or by-passing the layer, while entraining Atlantic water and redistributing it downwards, increasing the salinity and temperature of the deeper layers.

In a warmer climate the cooling of the entering Atlantic water will be reduced and warmer, and possibly less dense, overflow water will be formed. In addition, a warmer climate is also expected to increase the atmospheric meridional freshwater flux to the Arctic, which would result in higher salinity of the entering Atlantic water, perhaps compensating the density change due to higher temperatures in the overflows. Together with the reduction of the Arctic Ocean ice cover, which is already observed, this will increase the stability of the Arctic Ocean and possibly also prevent, or reduce, dense water formation. However, dense water is not created in the interior of the Arctic Ocean, where the stability increase would be the strongest, and the low salinity water is exported from the Arctic Ocean as buoyant boundary currents through Fram Strait and through the channels in the Canadian Arctic Archipelago, which flow with the coast to the right. In the Nordic Seas the outflowing low salinity water is separated from the entering Atlantic water that moves north, either as a topographically steered current at the European continental slope, or as a baroclinic current along the front between Atlantic and Arctic Intermediate water above the Mohn-Knipovich Ridge. The cooling and the densification of the Atlantic water will therefore not be affected by increased freshwater input, but mainly by a smaller heat loss due to a warmer climate.

The reduction of the sea ice cover in the Arctic Ocean is not caused by warmer Atlantic water entering the Arctic Mediterranean but due to changes in the radiation balance caused by the higher air temperatures in the Arctic. This reduction might lead to, perhaps unexpected, effects. The upper layer in the Nansen Basin is created by sea ice melting by heat from the Atlantic water and the melt water is mixed into the upper part of the Atlantic water. The sea ice is formed elsewhere, and in a warmer climate not enough sea ice might drift to the Nansen Basin to maintain the ice cover throughout the winter. The buoyancy input due to ice melt will then disappear, and the Atlantic water entrained into the upper layer will lose its heat but retain its salinity. By the end of the winter the upper layer might be dense enough to convect back into the Atlantic layer. The Nansen Basin would then not form low salinity Polar water, as it presently does, but dense overflow water and the production of overflow water in the Arctic Mediterranean could increase.

The ice drift is much more affected by the wind than the flow of liquid freshwater, which is mainly controlled by geostrophy. To drastically affect the dense water formation in the Arctic Mediterranean Sea, ice must be present and drift into the Norwegian Sea, allowing for the formation of an upper layer akin to that presently found in the Nansen Basin. This is not expected to happen in the present day, or in a future warmer, climate. It could, however, have been a reality during glacial periods, when spells of more, or less, sea ice available in the Nordic Seas could keep the Norwegian Sea either open or ice covered. An open Norwegian Sea would lose heat, create dense water and likely induce a stronger northward Atlantic flow into the Nordic Seas. The Dansgaard-Oeschger events reported from the last glacial period could be indications of such short periodic changes.