Changes in the Atlantic Meridional Overturning Circulation

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Introduction: the concept of the MOC

Climate models project a slow down of the Atlantic Meridional Overturning Circulation (MOC) in the twenty-first century. This slow down is expected to affect climate over Europe. In particular, it damps the temperature rise due to the emission of greenhouse gases. The MOC is associated with the thermohaline circulation (THC), which is the large-scale ocean circulation driven by fluxes of heat and freshwater at the surface. It is difficult to define the THC exactly. In the real world we cannot disentangle the various driving forces of the ocean circulation, and exclude, for instance, the wind forcing. Even in idealized models in which the wind stress is neglected, a THC which only responds to the 'push' of surface waters, becoming convectively unstable and sinking, cannot be sustained. Also the 'pull' by small-scale mixing, that gradually lightens the deep waters, is necessary. And the main energy source for the small-scale mixing is mechanical (winds and tides). Clearly, the THC is only a theoretical concept. For practical purposes, oceanographers prefer to speak of the MOC: The zonally-integrated mass transport in the ocean. In the Atlantic Ocean it consists of northward flowing water above and southward flowing water below (Figure 1). This typical 'estuarine circulation' captures the essential part of the THC. In the North Atlantic, surface water cools and sinks, forming North Atlantic Deep Water which spreads southward into the deep ocean. As a result, the MOC is associated with a large northward heat flux: North of 30°N, the MOC dominates global ocean heat transport[1]. The loss of heat from the ocean to the atmosphere in the North Atlantic keeps North-Western Europe relatively mild.

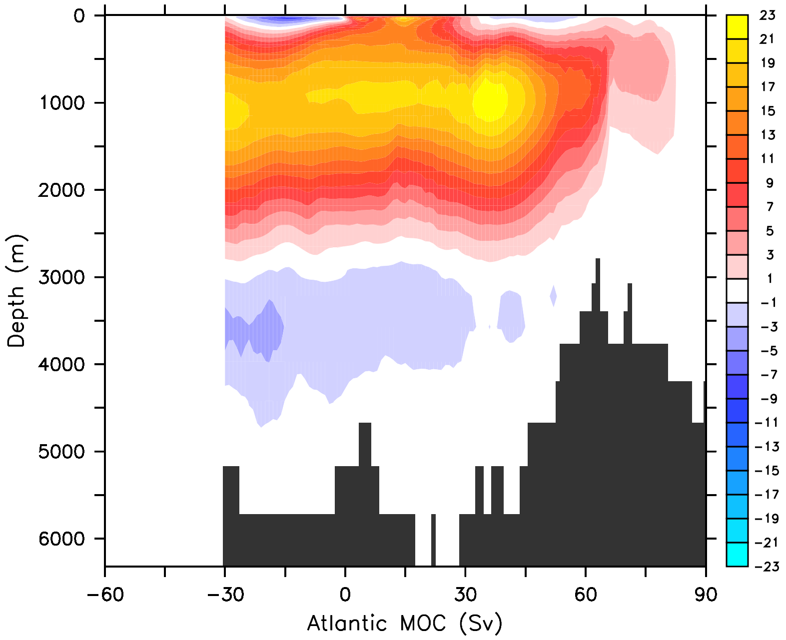

Figure 1. The present day ensemble mean MOC estimated from an ensemble of coupled model integrations carried out with the Max Planck Institute climate model within the ESSENCE project run at KNMI (in Sv = 10^6 m^3 s^{-1}).

The thermal and salt-driven part of the MOC is essentially nonlinear: Small changes in the thermohaline forcing (temperature and salt) can have large effects. As a result, the THC can be subject to sudden transitions. In the popular literature this is often phrased in terms of whether the 'Gulf Stream' will halt or not. In reality, the Gulf Stream is the western boundary current of a large wind-driven subtropical gyre, that will continue to flow as long as the earth rotates and the winds keep blowing. But the wind-driven gyre is not part of the MOC. The part that branches off between 30°N and 40°N and flows further northward along the West European and Scandinavian coastline constitutes the MOC, and this branch is vulnerable to anthropogenic climate change. In the media this branch is often identified with the Gulf Stream; in reality it is one of its many extensions. Here, we report on a number of studies performed at KNMI on the driving mechanisms of the MOC, its potential change and climate impact, and the detection of a slow down induced by anthropogenic climate change.

Forcing of the MOC and abrupt transitions

The Atlantic MOC is dominated by one large, basin-wide circulation of northward flowing waters between 0 and 1500 m depth, and southward flowing waters between 1500 and 3000 m depth. The strength of the MOC is surprisingly well related to the thermohaline forcing, although the MOC itself is partly wind-driven. The sinking branch occurs where water at the surface becomes sufficiently dense. In the present climate this happens in the Labrador Sea and Greenland-Iceland-Norwegian basin, because of cooling. The circulation intensifies when the cooling becomes stronger. It turns out that the circulation depends on the (air) temperature-difference between the tropics and the subpolar regions, just south of the sea-ice margin. However, not only the temperature, but also the salinity affects the density of water. At the surface, the salinity is changed by evaporation, precipitation, and the growth or melt of sea ice. In the tropics evaporation makes the water dense, in the subpolar regions precipitation lightens water. The combination of these salinity-related forcings tends to drive an opposite circulation. Without temperature-effects the MOC would reverse, with sinking in the tropics and rising in the subpolar regions.

So, when the thermal forcing dominates, the result is a strong MOC characterized by northern sinking. When the haline forcing dominates, a much weaker MOC with sinking in the tropics occurs. Most interesting is the regime where both forcings are of comparable strength. In this regime both states are possible, that is, the MOC is bi-stable. The actual state depends on the history of the MOC. When it was already dominated by thermal forcing, it prefers to stay so; the same holds for the haline state. Such behaviour is called hysteresis[2)]. Then, a thermohaline perturbation can induce an abrupt transition from one state to the other within a few decades. The most conceivable perturbation is a freshwater pulse in the North Atlantic (e.g., by glacier or ice-cap melting), which will always tend to bring the MOC from the thermally forced state to the haline state at which the MOC is strongly reduced in strength or even reversed.

Abrupt MOC reduction in future climate

Anthropogenic forcing due to rising emissions of greenhouse gases tends to weaken the thermal forcing: Polar and subpolar temperatures will rise much faster than tropical temperatures in the twenty-first century[3)]. At the same time the haline forcing counteracting the MOC is expected to increase. In a warmer world the hydrological cycle is intensified and sea and land-ice will melt. As a result, most climate models project a decrease of the MOC between 0 and 50% for the next century, although none of them simulates a collapse[3)]. But the concern remains that the MOC not only weakens; also its stability could decrease in the future because it approaches, or further penetrates into the bi-stable regime.

The transition point where the mono-stable, thermally forced state changes to the bi-stable state, at which an abrupt transition can take place, is marked by the sign of the net freshwater transport into the Atlantic basin by the MOC[4)]. The Atlantic is a net evaporative basin; easterly trade winds carry water vapour from the Atlantic to the Pacific across the narrow isthmus of Panama. This water vapour loss is compensated for by the ocean circulation. We discriminate two mechanisms by which the ocean circulation can import freshwater into the Atlantic. When at the southern boundary the upper layers are fresher than the lower layers, the MOC imports freshwater. When at 30°S the water at the eastern boundary has lower salinity than the water at the western boundary, the wind-driven, azonal circulation imports freshwater into the Atlantic. When the MOC imports freshwater into the Atlantic it is mono-stable. This can be understood as follows: Let us assume a positive freshwater anomaly in the north, for instance as a result of increased sea-ice melt. This anomaly decreases the surface density. As a result, the sinking of deep water reduces and the MOC is weakened. If the MOC *imports* freshwater, a weaker MOC will make the Atlantic more saline; the (positive) freshwater anomaly is damped. Also a negative freshwater anomaly will be damped. But if the MOC *exports* freshwater, the opposite occurs and freshwater anomalies in the north are amplified by the response of the MOC. In this case the MOC is bi-stable. It is possible that a positive freshwater anomaly induces a collapse of the MOC. A freshwater export by the MOC is possible when the wind-driven circulation imports enough freshwater to allow for freshwater loss by both the MOC and through net evaporation. Although the error bars are large, a best estimate from the observations indicates that the latter is the case in present climate.

A recent analysis of a suite of coupled models used for paleoclimate research has revealed that nearly all models are biased towards the mono-stable regime[4)]. In these models the evaporation over the Atlantic is too large, and freshwater import by the azonal circulation is too small. In a follow-up study we have repeated this analysis for a series of IPCC-class climate models that simulate both the present as well future climate. The same bias appears again, but more interesting, the MOC tends to shift in the future towards the bi-stable regime in (nearly) all models, despite the future increase of net evaporation over the Atlantic basin which all models predict (Figure 2). This result suggests two important facts: In present-day climate models the Meridional Overturning Circulation is too stable; The risk of abrupt climate change induced by a sudden strong reduction of the MOC due to the enhanced greenhouse effect, is increasing.

KNMI and the University of Utrecht, in collaboration with SARA, have performed a series of climate change

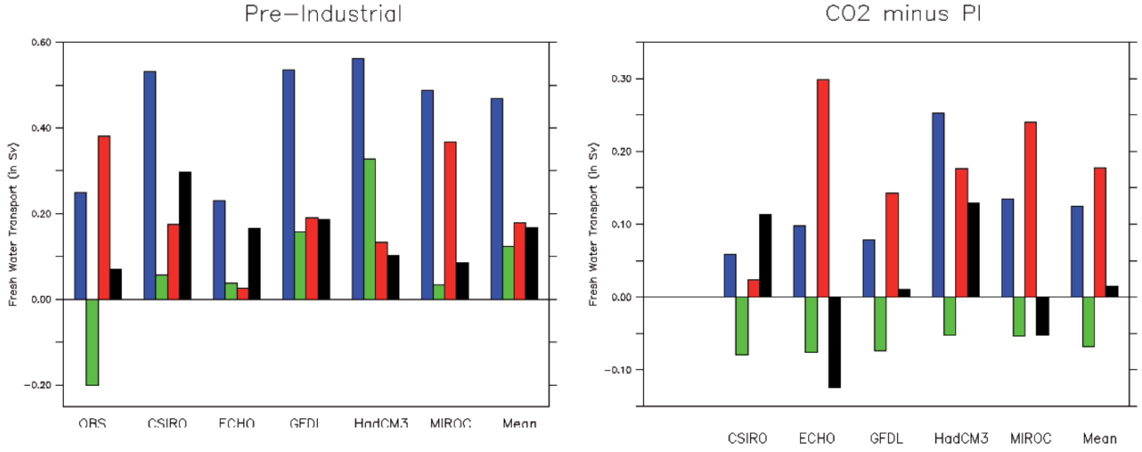

Figure 2. The terms of the Atlantic freshwater budget for the pre-industrial control state (left panel) and the difference between the quadrupled CO_2 state and the control state (right panel) for the simulations indicated on the horizontal axis. The terms (in Sv) are net evaporation (blue), freshwater transport by the MOC (green), transport by the azonal circulation (orange) and drift (black). Open bars denote 'observed' values. From de Swaluw et al., manuscript in preparation.

In present-day climate models the MOC is too stable for perturbations; the risk of abrupt climate change induced by a strong reduction of the moc increases due to the enhanced greenhouse effect is underestimated

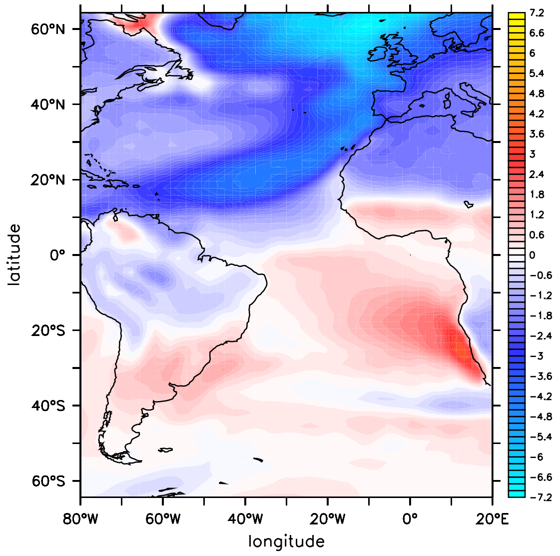

Figure 3. The ensemble mean temperature difference in degrees Celsius between a series of runs with and without imposing a MOC collapse, 90 years after the collapse has been induced by a freshwater pulse (difference between 2100 and 2010 after collapse between 2010 and 2040). The coupled model integrations have been carried out with the Max Planck Institute climate model within the ESSENCE project run at KNMI.

scenario runs with an IPCC-class model in which a MOC collapse was artificially forced, to study its impact on climate (Figure 3). We recover a 3°C cooling over Western Europe which is a well known result. Together with anthropogenic warming this would result in a cooling of only 0.5°C in 2050. Of specific interest is the pattern of the temperature change: Cooling over the North Atlantic, heating over the South Atlantic. The associated Sea Surface Temperature (SST)-anomaly induces a shift in the Inter Tropical Convergence Zone, the net precipitation, and the Hadley circulation. Climate models tend to underestimate the atmospheric response (and possible feedbacks) to such a collapse, as simulated oceanic mixed layers in the tropical Atlantic are too deep and the SST changes are too weak there. Also, such heating patterns might induce a shift in the Atlantic storm tracks inducing additional cooling of North-Western Europe5), but this response is very sensitive to the amplitude and pattern of the SST-anomaly

Detecting changes in the MOC

Recently a slowing of the MOC over the past fifty years was reported6) that was much stronger than simulated by any climate model. The reported decrease, however, may have been severely biased by under-sampling of the natural variability of the MOC. The analysis was based on five ‘snapshot’ measurements over a period from 1950 to 2005 (in situ hydrographic sections across the Atlantic by research vessels). In general, before a long-term change can be detected, one must be able to estimate whether the change is associated with a real trend, or whether it represents a fluctuation that results from the high-frequency internal variability. For a more complete continuous observational assessment of the MOC, a mooring-array was deployed by the UK and USA in 2004.

We simulated the detection problem by analyzing the anthropogenic signal and noise associated with the natural variability of the MOC in a large, 62-member ensemble of climate model simulations, all forced with increasing levels of greenhouse gas concentrations in the atmosphere. We also estimated the noise associated with the measurement error[7]. The signal-to-noise ratio was separately estimated for snapshot measurements and continuous monitoring. The signal-to-noise ratio peaks near 30°N and 30°S at 2000 m depth, confirming the rationale for the mooring-array at 26°N. Also, detection occurs much faster when the MOC is continuously monitored, due to the decrease in noise (Figure 4). The apparent slow-down of the MOC that was recently suggested[6] must have been due to unresolved internal variability.

Conclusions

Based on observations the present-day MOC seems to reside in the bi-stable regime. Nearly all IPCC-class climate models appear to be biased towards a too stable MOC. The apparent stability of the MOC over the last 8000 years, however, suggests that the risk of a collapse in this century is not large. The impact of a of the Meridional Overturning Circulation on European climate would be significant but not dramatic; together with the present anthropogenic warming both effects will neutralize each other in Europe between 2050 and 2100. Detection of the anthropogenic MOC-trend on the basis of episodic measurements appears impossible before 2055. With continuous monitoring, detection becomes possible after 30-35 years of observation. Detection times are shortest near 25°N and 30°S.

The impact of a MOC collapse on European climate would be significant but not dramatic; together with the present anthropogenic warming both effects will neutralize each other in Europe between 2050 and 2100

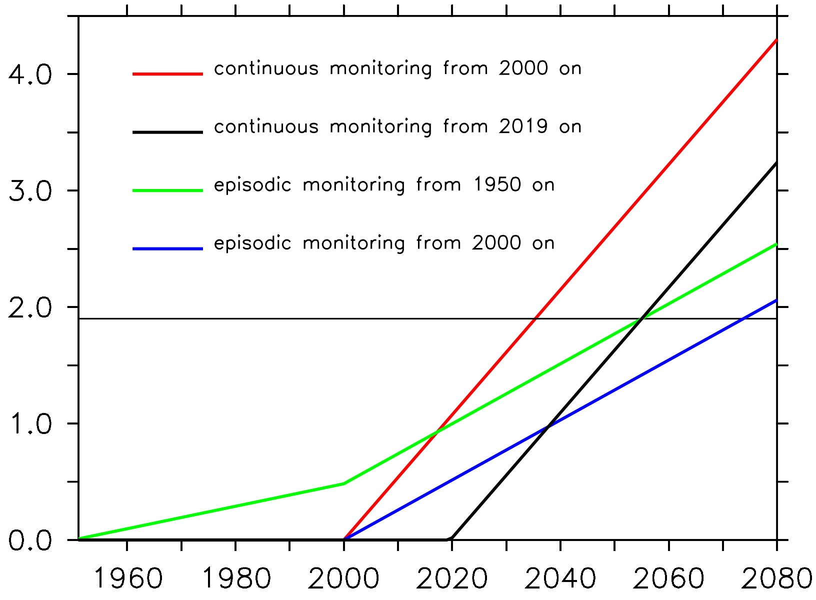

Figure 4. The signal-to-noise ratio of the anthropogenically forced decline of the MOC at 26°N, as a function of time. Estimates are based on sustained measurements starting in 2000 (red) and 2019 (black), and based on snapshot measurements starting in 1950 (green) and 2000 (blue), respectively. The horizontal line marks the signal-to-noise ratio of 1.96, where detection becomes possible.

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