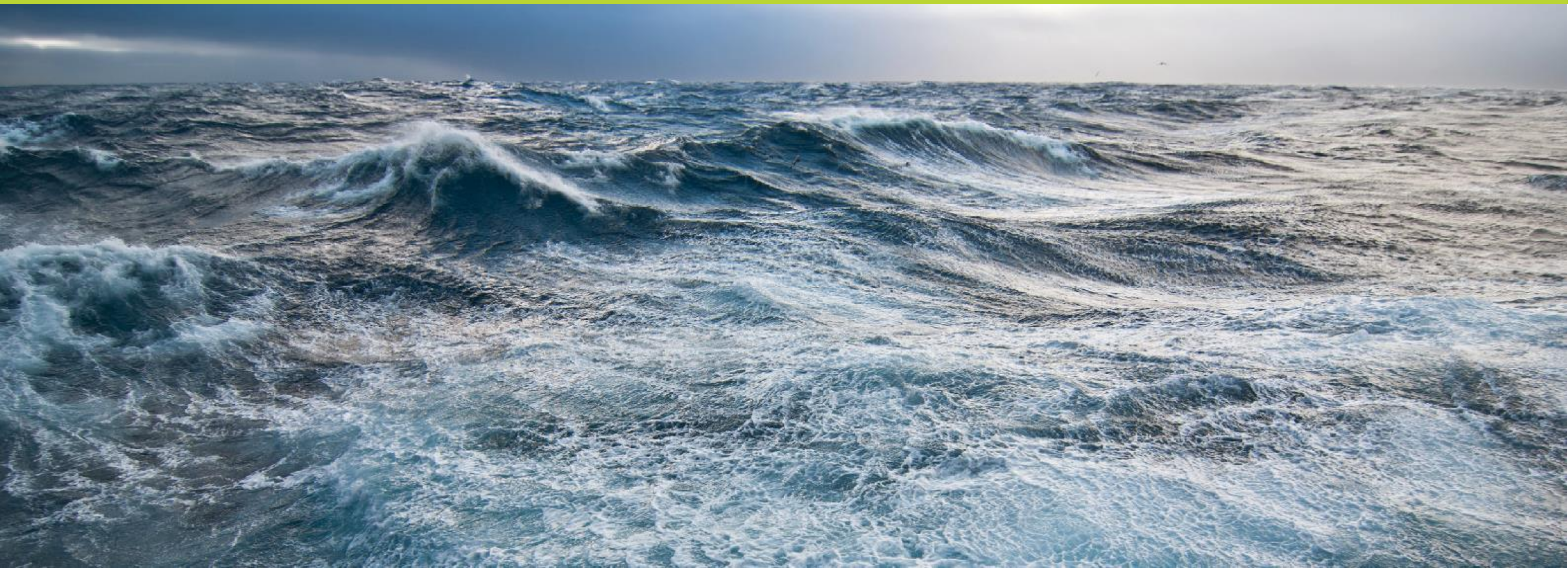
Factsheet 2 of 6
Version date: Dec 2019

Risk management of climate thresholds and irreversible change: Atlantic Meridional Overturning Circulation (AMOC)



What is the nature of the threshold?

The AMOC is a system of ocean currents (Fig. 1) which plays an important role in the climate system by transporting warm water northwards in the Atlantic[1, 2]. The AMOC is maintained by cold, salty water sinking in the North Atlantic, so as the ocean warms from increasing greenhouse gases, and freshwater from melting glaciers enters the ocean, the AMOC may be weakened due to the change in temperature and salinity[3, 4, 5]. Weakening of the AMOC reduces the northward supply of salty water, which may weaken the AMOC further in a positive feedback loop. There is evidence from theory[6], simplified models[7], and palaeo-observations[8] of abrupt changes in the AMOC, indicating the presence of an AMOC threshold. This threshold suggests that if freshwater input exceeds a certain volume, the AMOC could weaken and collapse into a state of reduced flow[9].

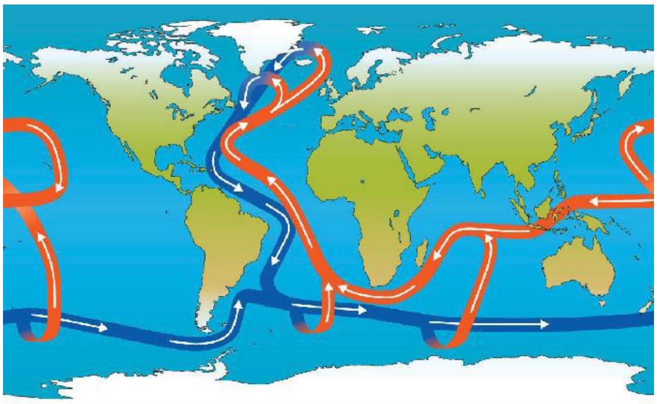


Figure 1. Schematic of the AMOC. Red shows near-surface transport and blue shows return flow at depth.

What impacts might be expected if the threshold were crossed?

An AMOC shutdown would cause cooling of the northern hemisphere (Fig. 2), sea level rise in the Atlantic, an overall decrease in precipitation over Europe and North America, and a southwards shift in monsoons in South America and Africa[10, 11]. These impacts are robust and seen in many models, but their magnitude remains uncertain. Atmospheric circulation over Europe may also change, possibly causing more winter storms in Northern Europe and increasing summer rain around the Mediterranean[11]. Impacts outside of the Atlantic region are less certain but could affect Asian monsoons and El Nino[10, 12].

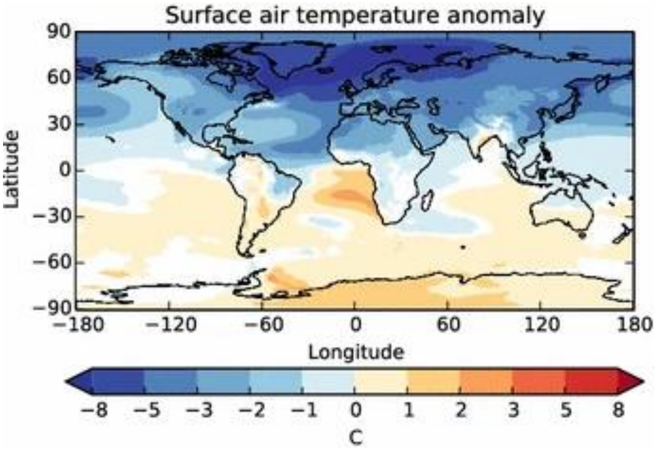


Figure 2. Predicted impact of an AMOC shutdown on global temperature.[11]

If a threshold is crossed, are the changes irreversible?

If the AMOC has a threshold, then increasing the freshwater input could cause the AMOC to collapse into a state of reduced flow. From this collapsed state, even if freshwater input into the oceans decreases to current levels, the AMOC may remain in a collapsed state. The ability of the system to not return to the initial state once the forcing is reversed is referred to as hysteresis (Fig. 3)[13, 14].

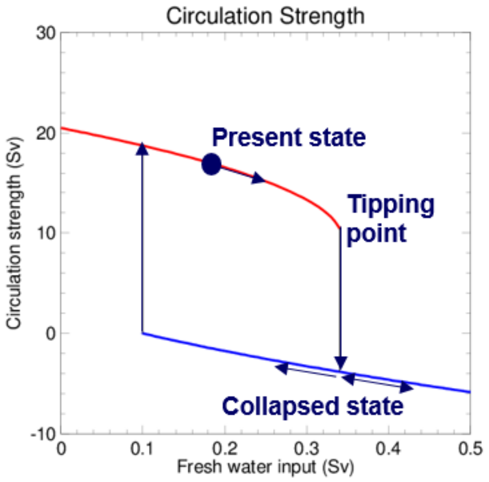


Figure 3. Hysteresis and tipping points in the AMOC. Red shows the present state of the AMOC. After passing the tipping point, the AMOC collapses into the blue state.

Models show that there may be a temporary resilience period in the AMOC after a threshold has been crossed, during which the AMOC could still recover if the freshwater input is reversed rapidly. Irreversible change of the AMOC is not seen in most complex climate models but is present in one high-resolution Met Office Climate Model if high volumes of fresh water are input for long enough[13, 15].

In this experiment, the AMOC recovers if freshwater inflow ceases after 20 years (green line), but not if it ceases after 50 years (red line). This gives a 20-50 year temporary resilience (Fig. 4)[13]. The temporary resilience period would be lower if freshwater was added at a higher rate.

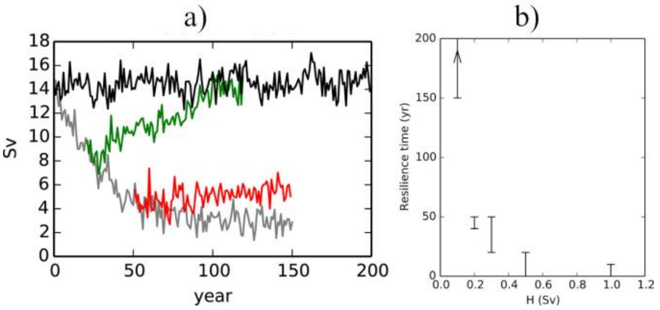


Figure 4. a) The AMOC strength in Sv when adding freshwater of 0.3 Sv (1 Sv=$10^6 m^3/s$) to the North Atlantic (grey), and when freshwater ceases to be added after 20 (green) or 50 (red) years, showing two different final states. b) Temporary resilience as a function of the amount of additional freshwater.[13]

How likely is such a threshold to be crossed?

It is likely, based on current climate models, that the AMOC will weaken over the coming century, but a collapse of the AMOC before 2100 is thought to be very unlikely[16]. However, it is possible that many climate models have biases that prevent them showing irreversible change[15, 17].

What are the prospects for early warning and what long-term observing systems need to be maintained?

The AMOC is currently being monitored by the RAPID[18] array, and the recent OSNAP[19] observing system will extend this capability, potentially providing earlier warning of AMOC changes. Monitoring of the AMOC together with an understanding of the impacts of an AMOC change and predictions from seasonal-decadal prediction systems could give warning of impacts. There is the potential to monitor the ocean state through systems such as ARGO[20] that allow us to detect changes preceding an AMOC reduction[21], and potentially to predict the AMOC using seasonal-decadal systems[22]. However, these would only give a lead time of a few years and cannot indicate whether the weakening would continue after that period. Metrics of Atlantic freshwater transport may be useful indicators of thresholds, and further development is planned.

What future research is planned at the Met Office Hadley Centre?

Work is planned to understand further what controls the presence and location of an AMOC threshold, and what controls temporary resilience. Understanding these drivers may help with identifying which model biases to concentrate on improving. We also plan to assess the potential for crossing a threshold in future projections, and to explore, in more depth, potential early warning indicators, and likely impacts of an AMOC shutdown.

References – Met Office papers in **bold**
[1]**Good et al., (2018) Recent progress in understanding climate thresholds**; [2]Srokosz et al., (2012) Past, present, and future changes in the AMOC; [3]**Haskins et al., (2019) Temperature domination of AMOC weakening due to freshwater hosing in two GCMs; [4]Haskins et al., (2018) Explaining asymmetry between weakening and recovery of the AMOC in a coupled climate model; [5]Jackson and Wood, (2018) Timescales of AMOC decline in response to freshwater forcing;** [6]Rahmstorf, (1996) On the freshwater forcing and transport of the Atlantic Thermohaline Circulation; [7]Rahmstorf et al., (2005) Thermohaline circulation hysteresis; [8]McManus et al., (2004) Collapse and rapid resumption of AMOC; [9]**Wood et al., (2019) Observable, low-order dynamical controls on thresholds of the Atlantic meridional overturning circulation**; [10]Stouffer et al., (2006) Investigating the causes of the response of the thermohaline circulation to past and future climate changes; [11]**Jackson et al., (2015) Global and European climate impacts of a slowdown of the AMOC in a high resolution GCM; [12]Williamson et al., (2017) Effect of AMOC collapse on ENSO in a high resolution GCM; [13]Jackson and Wood, (2018) Hysteresis and resilience of the AMOC in an eddy-permitting GCM; [14]Jackson et al., (2017) Ocean and atmosphere feedbacks affecting AMOC hysteresis in a GCM; [15]Mecking et al., (2016) Stable AMOC off state in an eddy-permitting coupled climate model;** [16]Collins et al., (2013) Long-term Climate Change; Projections, Commitments and Irreversibility (IPCC AR5); [17]**Mecking et al., (2017) The effect of model bias on Atlantic freshwater transport;** [18]https://www.rapid.ac.uk/; [19]https://www.o-snap.org/; [20]http://www.argo.ucsd.edu/; [21]**Jackson and Wood, (2020) Fingerprints for early detection of changes in the AMOC**; [22]Pohlmann et al., (2013)Predictability of the mid-latitude AMOC.