The Atlantic Meridional Overturning Circulation (AMOC) and its Hypothetical Collapse

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ABSTRACT

Collapse of the Atlantic Meridional Overturning Circulation is often invoked as an explanation of major past climate changes and as a major risk for future climate. Many of these arguments appear, from an observers' point of view, as far-more definitive than is warranted. In the hypothetical event of a future collapse, the implications may be much less severe than those from many other elements of global change already underway. The Gulf Stream system, and its required return flow of mass, implies that changed circulations will nonetheless continue to carry significant amounts of heat, carbon etc., poleward even without any AMOC.

Keywords: AMOC, Gulf Stream, Thermohaline circulation, collapse

The AMOC in the climate system

The Atlantic Meridional Overturning Circulation (AMOC) is a complex system of oceanic currents carrying surface waters northward across the Atlantic basins—plunging in high latitudes and forming the North Atlantic Deep Water which flows back southward (Buckley and Marshall, 2016). As a major component of the global ocean circulation, acting as a conduit for the movement of climatological heat, carbon, and other important properties, it is widely believed that any changing AMOC would have profound climatic impacts. As such, the AMOC is an important focus of research on both the modern climate system (Frajka-Williams et al., 2019) and as a nearly all-purpose explanation for inferred paleo-climate states (Cronin, 2009), (Lynch-Stieglitz, 2021). Its collapse could, in the literature, arise from a number of possible causes, generally connected with suppression of high latitude convective exchange between upper and lower oceans.

Although understanding the science of the AMOC is undeniably important, what is perhaps surprising is the way in which its existence and possible change have captured the imagination not only of the fluid dynamics community, but also scientists working on the edges of fluid oceanography, and, somewhat disturbingly, the popular media, including a widely seen 2004 movie, "The Day After Tomorrow". More recently, a New York Times article (https://www.nytimes.com/2021/08/05/us/gulf-stream-collapse.html) made prominent a recent paper (Boers, 2021) suggesting that the AMOC was nearing a point of collapse, with perhaps dire consequences. To a great extent, the emphasis on the AMOC stems from a cartoon picture of the ocean circulation of the "Great Ocean Conveyor" and the invocation of a zoomorphic attribute "the climate is an angry beast..."; (Broecker, 1987), recently reproduced as part of the New York Times story. Intense research in the past 30 years demonstrates however that such a sweeping sketch of the AMOC fails to capture the complex, intrinsically fully turbulent, three-dimensional nature of the real flow field as portrayed in observational studies (Ferrari and Wunsch, 2009).

Here we seek to provide some perspective on the AMOC and its role in climate. Much discussion of the influence of the changing ocean on past climate states, has invoked the idea of a collapse of the AMOC (Cronin, 2009), brought on by suppression of the vertical convection—by differing mechanisms. This idea has been translated to the study of present and future climates, motivating research on the potential occurrence of an AMOC collapse in a more or less distant future (Rahmstorf, 2000), triggered by anthropogenic climate change. The literature on this topic is abundant, and it is not the goal of this perspective to provide a comprehensive review, but see for example (Weijer et al., 2019). Representations of the AMOC in numerical ocean simulations suffer from important biases (Lee

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et al., 2019) and they have often shown a stable response incompatible with the idea of a collapse (Stouffer et al., 2006). Recent studies may however give the impression that new observations are now confirming unequivocally the decline of the AMOC (Caesar et al., 2021) and a large potential for collapse (Boers, 2021).

Defining the AMOC

A general definition, applying to any ocean, zonally bounded or otherwise, is the meridional overturning circulation (MOC) or the sum of the mass flux from a western to an eastern longitude of the ocean, to some specified depth (not the bottom) at some specified latitude of the northward and southward going flows[1]. Thus the MOC is the net flow going north or south above the integration depth (often taken as a fixed depth or bounded by a surface of constant potential density). If an ocean is closed e.g., at the north, the integral (sum) from top to bottom has to vanish, and thus the MOC is normally defined in terms of some finite depth (or density), perhaps varying with longitude, and definitely varying with latitude. Gross spatial averages, such as long zonal means, often do display many of the elements of classical physical oceanography, including boundary currents, gyres, equatorial flows etc., but masking the observed three-dimensional, intensely time-varying flow that comprises the apparent average.

In the Atlantic Ocean, various definitions of the AMOC exist, generally all referring to the net northward movement of mass above depths of order 1000m from the western to the eastern boundary, over greatly varying time-averages. The major, permanent, feature of the North Atlantic Ocean is the powerful, warm, largely wind-driven, *poleward* flow on the western side, known as the Gulf Stream—a western boundary current (WBC) that is a fundamental phenomenon of all ocean basins bounded on the west. The Gulf Stream is a dominating part of the AMOC, but should not be confused with the AMOC itself[2]. The North Atlantic is nearly closed at its northernmost reaches (a weak mass *input* exists there from the Arctic Sea) and the far larger amount of water headed northwards in the Gulf Stream at e.g., about $35 \times 10^6 \text{m}^3\ s^{-1}$ at 30°N, and definable with different numbers and different averaging times at other latitudes (Richardson, 1985), must return southward in the ocean further east or at depth.

Historically, the conventional view was that the dominant northward WBC mass transport would be compensated largely by a southward return flow over the entire ocean to the east, in what is known as Sverdrup balance, one confined primarily to the upper layers of the ocean and driven by the large-scale distribution of winds. Superimposed upon this circulation would be an additional, meridional overturning, directly involving the deep ocean, also returning strongly cooled water at high latitudes through a convectively driven very cold deep western boundary current (Gordon, 1986). Transports of heat, carbon, oxygen, and other tracers result from the differing properties of the massive northward and southward-going flows. In the last three decades however, this laminar and nearly-steady picture has been replaced in observations by one of an ocean effectively turbulent on all measurable time and space scales (although envisioned much earlier(Stommel, 1948)). Ranges are from the full size of the ocean (10,000km) to order 1 cm, and on time-scales from seconds and potentially out to the age of the fluid ocean. Eddies and their variability are fundamental to the ocean circulation in a way the classical theories could not describe. Thus the AMOC is in practice the superposition of a myriad of complex circulations more or less interconnected and varying—at vastly different time and spatial scales (see e.g. Bower et al. (2009) or Kostov et al. (2021)). It can be regarded as a mass residual of the upper ocean gyre with its return flow. Known physical elements of the variability at all depths include the spatial and temporal scales of the boundary currents, bal-

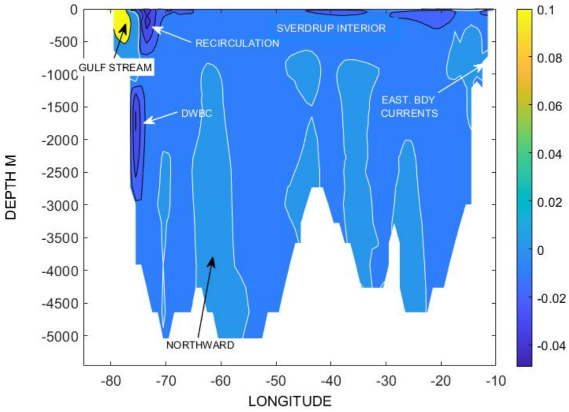

Fig. 1. 19-year average meridional flow at 30°N (Wunsch and Heimbach, 2013) in the Atlantic. The flow field was computed using a dynamically consistent, energy, mass, etc. conserving model, driven by known atmospheric forcing, and adjusted to be consistent with the great majority of observed data. Model time-step is about 1 hour. The eddy field was parameterized and thus is not visually apparent. As expected, the averaged result shows the known dominant elements of the North Atlantic Ocean circulation including an intense Gulf Stream, a Deep Western Boundary Current, an interior Sverdrup-like return flow, eastern boundary currents and less well-documented interior flows over the entire water column associated in large part with the topography. Structures and volume transports vary considerably with latitude, and also temporally—as suppressed by averaging. Reproduced from Wunsch and Heimbach, 2013.

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[1] The equivalent volume flux in the Boussinesq approximation.

[2] Sadly, this confusion is frequent in much media coverage, partly because of scientific miscommunication (e.g. Potsdam Institute for Climate Impact, 2021). Short of a planetary-scale collision, no known physics permits the stopping of the Gulf Stream and other WBCs for hundreds of millions of years into the future.

anced and sub-mesoscale eddies, internal waves, and likely inertial and viscous sub-ranges. Energy is believed to move both towards larger and smaller scales relative to the spatial scale of input (Arbic et al., 2014).

Observing the AMOC

To observe this complex system is challenging. A useful AMOC estimate at any latitude must integrate across a wide-variety of features (Fig. 1). Some useful estimates of the AMOC transport have become available only for the last 25 years, none of them showing any indication of significant long-term trends (Frajka-Williams et al., 2019). Localized estimates of the MOC in Nordic Seas are available for longer time periods, but again with no sign of any long-term trend (Hansen et al., 2016; Rossby et al., 2020) within the intense spatial and temporal variability. Determining the amount of heat or other property transported poleward by the circulation (the major focus of most AMOC discussions, albeit usually only implicit) is a complicated matter, one in which the time required to obtain a stable average of a quadratic quantity (velocity times property) is likely to vary greatly depending upon the property and the latitude. Such accurate calculations lie beyond any observing system in place before the very recent past–and one with still remaining issues.

If it is true that a collapse or other physics reduces the poleward high latitude transport of heat by the Atlantic Ocean, one can expect, at zero-order, that the atmosphere—globally—will tend to compensate it (Bjerknes, 1964) along with corresponding shifts in the rest of the world ocean. Changes can occur elsewhere in the oceanic poleward transport, in the atmospheric transport, in the nature and degree of cloud cover, surface albedo, and the near-surface return flow, etc (e.g. Nummelin et al., 2017), (Chen and Tung, 2018). Climate change is a fully global process involving ocean, atmosphere, ice, chemical, and biological processes.

On the risks of a collapsing AMOC

Recent claims of "observation-based" signals for an ongoing collapse of the AMOC (Boers, 2021) or that the AMOC is at its weakest point in the last thousand years (Caesar et al., 2021) were obtained by making some extreme assumptions about the implications of existing fragmentary, short-duration, observations of the modern intensely variable system. Both analyses assumed a strong correlation between subpolar Atlantic sea surface temperature and the AMOC, and which is only weakly supported by observations (Keil et al., 2020; Li et al., 2021). The proxy-based inferences in (Caesar et al., 2021) have also been criticized for methodological reasons (Kilbourne et al., 2022) and they appear to be in contradiction with evidence for a stable AMOC during the last century (Fraser and Cunningham, 2021; Latif et al., 2022). Recognition is needed of the turbulent, complex, nature of the ocean circulation and of the difficulty in observing its variability (Wunsch et al., 2013). Apart from a few local exceptions (Hansen et al., 2016; Rossby et al., 2020), too few direct observations of the AMOC exist to warrant definite conclusions about the distant past or future of the circulation.

Most modern-climate models show that the consequences of AMOC collapse, although non-negligible, would remain limited compared to the global effects that anthropogenic greenhouse gases already have on the climate system. Even in the most extreme scenarios for the AMOC, the global mean temperature would continue to increase (Sgubin et al., 2017). A variety of regional impacts are expected, some through cooling of the North Atlantic region and a shift in the mean latitude of the Inter-tropical Convergence Zone (Bellomo et al., 2021). Curiously, the invocation of an AMOC collapse, as a general explanation for anomalous climate states, implies that the old, classical, understanding built upon gyres and Sverdrup balance, again becomes directly applicable (Pedlosky, 1996)—but one with all of its own variability and complexities. Even in a state with no AMOC, massive amounts of fluid would still be moving north and south, conveying not just mass, but also net amounts of heat, freshwater, carbon etc.

Dramatic proclamations of major shifts to take place in the ongoing ocean circulation may serve the useful purpose of alerting the public to the dangers of climate change; nonetheless, they should be as scientifically defensible as possible and should not divert attention from the immediate dangers posed by increasing greenhouse gas emissions—global warming, sea-level rise, loss of biodiversity etc. Continued monitoring in the decades to come of the entire ocean-atmosphere coupled system, will be required to assess the true risks of a collapsing AMOC, yet no evidence of the imminence or predominance of such danger exists to date.

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