Perspective: The Great AMOC Shutdown

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1 A Perspective

Much discussion of the influence of the changing ocean on climate past and present, invokes the idea of a "shutdown" of the Atlantic meridional overturning circulation (Atlantic MOC, or AMOC. See e.g., Cronin, 2010, Stammer et al., 2019 and numerous references to be found there). The specific definition of the AMOC is often omitted and thus the meaning of a "shutdown" mantra remains obscure. The purpose of this note will be regarded by some as simplistic: to point out that a shutdown-AMOC in most implied usage nonetheless requires: (1) a remaining massive transport of fluid and its properties and (2) curiously, is most simply interpreted as an ocean circulation conforming to the classical laminar gyre circulation picture of a Sverdrup-interior plus western boundary current.

A deprecated device in ancient Greek drama is labelled as a *deus ex machina* or 'god from a box' (Oxford English Dictionary), a theatrical device in which a god emerges from a container at the end of the a play resolving all plot and human difficulties. In climate and paleoclimate, the idea of a shutdown in the so-called Atlantic Meridional Overturning Circulation (AMOC) is meant to explain many observations, past, present, and future, and to describe the impact on the wider observational system. An arbitrary, but recent, example is Stocker (2021).

To a great extent, the emphasis on the AMOC stems from a cartoon picture of the ocean circulation by the late Wallace Broecker—what he called the "Great Ocean Conveyor", and his invocation of a zoomorphic attribute "the climate is an angry beast..."; recently reproduced as part of a New York Times story. Much of the scientific literature purporting to describe the oceanic past, present, and future, simply invokes the idea of "the" AMOC without ever bothering to define it. A useful working definition is essential, even if it need not be a unique one. A general definition, applying to any ocean, zonally bounded or otherwise, is the meridional overturning circulation or the sum of the mass flux from a western to an eastern boundary of the ocean, to some specified depth (usually not the bottom) at some specified latitude of the northward and southward going flows.[1] Thus the meeridional overturning circulation (MOC) is the net flow going north or south above the integration depth (which is potentially a complicated curve). If an ocean is bounded e.g., at the north, the integral (sum) from top to bottom would have to vanish, and thus the MOC is normally defined in terms of some finite depth, not the bottom, perhaps varying with longitude, and definitely varying with latitude. If unbounded zonally, as in some latitudes of the Southern Ocean, the integral can be over 360° zonally, or over any finite longitudinal interval. In a useful definition, a temporal averaging time is specified as well.

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. The major, permanent feature, of the North Atlantic Ocean is the powerful *poleward* flow on the western side, known as the Gulf Stream—a western boundary current (WBC) which is a fundamental phenomenon of all ocean basins bounded on the west. 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., 30°N and definable with different numbers at other latitudes, must return southward in the ocean further east.

To the extent that a meridional mass transport imbalance exists above the integration depth, inference is made of a convective vertical exchange motion at high latitudes, with the balancing fluid returning at great depths. Recall however, that Scott and Marotzke (2002) pointed out that the conversion in ocean circulation models between the nominal upper layer and the oceanic abyss occurred not as a mass advection, but instead as an enhanced vertical mixing rate localized at the horizontal boundary.

A large heat transport can exist by virtue of the balancing return flow having lower temperatures than fluid carried northward by the WBC. The "shutdown" of this system is best understood in terms of the two-different eras of thought concerning the ocean circulation generally.

Classical and Modern Periods

Understanding and study of physical oceanography over the years led to views that are usefully divided into two periods: a classical one prior to about 1975, and a modern one thereafter.[2] In the classical period, driven by the available observational capability, the ocean was widely

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

[2] A "post-modern" period, may some day be defined—but not yet.

perceived as a slow-moving, large-scale, laminar, near-steady state, changing at depth only over thousands of years. The classical period gave rise to a remarkable analytical literature of ocean fluid phenomena including Ekman layers, Sverdrup balance, western intensification, Stommel-Arons flows, abyssal recipes, Rossby waves, and numerous other laminar flow regimes. Wunsch and Ferrari (2018) provided a historical sketch and the overall classical picture can be found in any of several readable textbooks.

In this classical period, a central paradigm explained the existence of the intense time-mean flows on the western sides of oceans as a consequence of the torque of the large-scale windfield acting on the ocean. The textbook result is a picture (1) of the oceanic "gyres" with strong poleward motions in currents such as the Gulf Stream in the North Atlantic, the Kuroshio in the North Pacific, and the Agulhas in the Indian Ocean, and the Brazil Current, and East Australia Current in the Southern hemisphere oceans. Understanding in this classical picture, dating back to about 1950, is that the massive poleward flow is returned further east in an upper ocean layer usually labelled as "Sverdrup balance". Any motions at depth (below, very roughly, 1000m) are regarded as negligible.

Thus for example, in the North Atlantic at about 30°N, the resulting major northward transport in the Gulf Stream is about $35{\times}10^6\mathrm{m}^3/\mathrm{s}$ (35 Sverdrups, Sv) $\approx 35 \times 10^3$kg/s. The Gulf Stream exists (as shown by Stommel, 1948 and numerous later authors) as a consequence of the presence of an oceanic western boundary, and a large-scale wind system consisting of the trade winds (easterlies)—and the westerlies to their north. *Barring a major planetary collision, no circumstances exist, for tens of millions of years in the past or future, in which this feature could or will, have vanished.* A major change in the wind system could strengthen or weaken it, but no known phenomenon is capable of completely eliminating the westerlies and easterlies which are fundamental phenomena of angular momentum conservation in a heated, rotating, atmosphere on a sphere.

In a well-known paper from the end of the classical period, Leetmaa et al. (1977) attempted to show that the North Atlantic Ocean was in Sverdrup balance at 16°N, 24°N, 32°N . They assumed, as was then conventional wisdom, that a level-of-no-(horizontal) motion existed near 1500m, giving rise to a 2-layer ocean in which the lower layer flow was effectively negligible. Their Gulf Stream carried the requisite mass fluxof order 30 Sv northward, but varying considerably with latitude, and with a nearly opposite southward return flow, in the open ocean east of the Gulf Stream, governed by the wind-stress curl, existing in the upper layer.

This picture is one of an ocean in which the AMOC is shutdown: The zonal integral in the upper ocean vanishes—nothing is returned at depth—but a massive oceanic flow exists, nonetheless (uncertainties are large however). The return flow carries (in their picture) the same

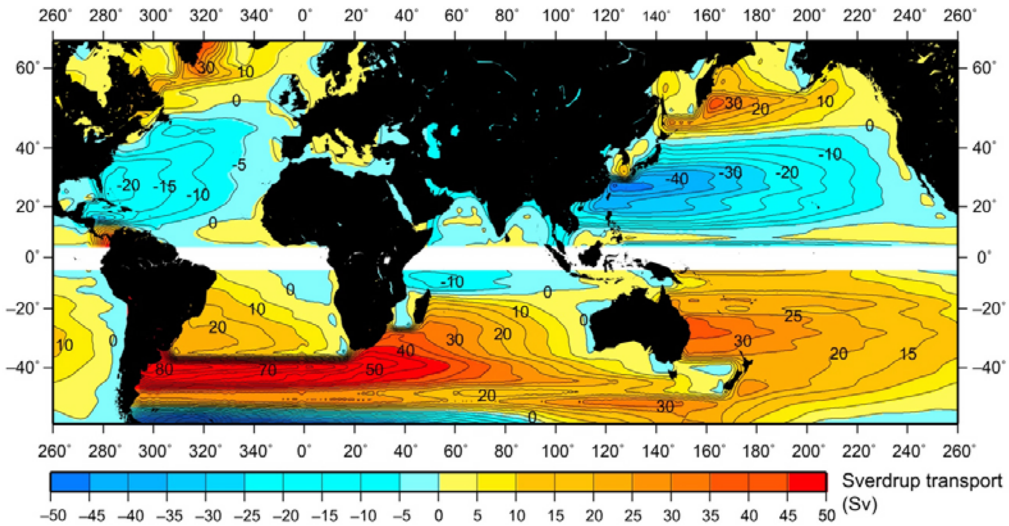

Figure 1: Talley et al. (2011) estimate from a particular estimate of the time-average wind field, of the Sverdrup transport flow. The Gulf Stream and other near-surface western boundary currents (WBCs) are largely fed from the zonal component of the interior Sverdrup flow. But note that sources of fluid in the WBC, can lie also far-distant in the opposite hemisphere. For example, note that the Gulf Stream is fed in part from the South Atlantic (e.g., Schmitz and Richardson, 1991). Equatorial band calculation is omitted for technical reasons.

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volume flux, but a different temperature (enthalpy), salt, carbon, etc. content than does the northward-going Gulf Stream. A net northward North Atlantic flux of heat thus exists—*despite the shutdown*—although it is smaller than existing best estimates (Wunsch and Roemmich, 1985). In a theoretical ocean, the Gulf Stream return flow need not be in Sverdrup balance, but vorticity conservation of the ocean circulation must still exist. No other simple dynamical balance is known. AMOC shutdown does not, and cannot, involve a cessation of the Gulf Stream flow, barring a radical change in the most fundamental Earth physics.

In this period, Stommel's (1961) one-dimensional laminar loop model controlled by thermohaline sources gave rise to the notion of switching between two different states (directions) of flow. Much subsequent investigation showed that including the wind field and more spatial dimensions greatly modified the possible inferences, but the popularity of the simple concept has been little reduced.

The Modern Era and Eddying Models

In the period following the Mid-Ocean Dynamics Experiment-1 (MODE), which took place in 1973, it came to be recognized that the system was turbulent, on all measurable time and space scales from the full size of the ocean (10,000km) to order 1 cm, and on time-scales from seconds

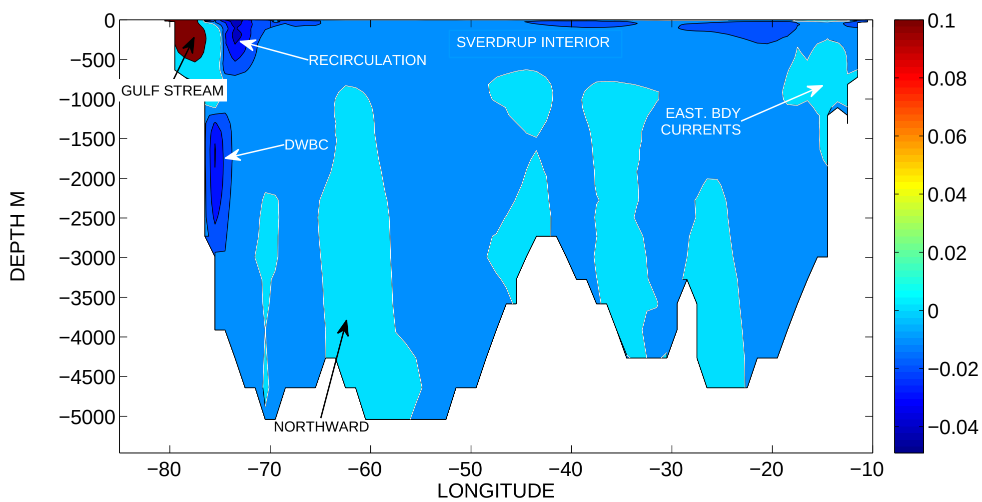

Figure 2: 19-year average meridional flow at 30°N, Wunsch and Heimbach (2013). The flow field was computed using a dynamically consistent, energy, mass, etc. conserving model, driven by known atmospheric forcing, and adjusted to be consistent with the great majority of observed data. Underlying model time step is about 1 hour. The eddy field is parameterized. The result shows the known dominant elements of the North Atlantic Ocean circulation including an intense Gulf Stream, a Deep Western Boundary Current, an interior 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.

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and potentially out to the age of the fluid ocean. The parallel rise of modern computers was an essential element of the modern period. MODE confirmed what many oceanographers had suspected for decades—that the role of eddies and variability was much more fundamental to the ocean circulation than any textbook demonstrated or explained. Accompanying the inference of a fundamentally turbulent system was the recognition of the very strong, rapid, regional variations in the balance of terms. In the classical period, one had subpolar and subtropical gyres, equatorial region physics, eastern and western boundaries, the Southern Ocean, etc. The modern era description contains all of these major regions, but with all intricately further subdivided into a very long list of subregions dependent upon abyssal topographic features, recirculations near eastern and western boundary currents, strongly seasonal flows, etc., rendering difficult the extraction of simple overall descriptors.

An intuition for the complexity can be gained from viewing one of the numerous model animations now available online including e.g., the one employed by the New York Times: *https://www.nytimes.com/interactive/2021/03/02/climate/atlantic-ocean-climate-change.html?-searchResultPosition=6*. Such animations are not correct in details, but do provide some intuition as to the complexity of the real motion. The extent to which classical laminar phenomena survive as major elements of the ocean circulation as it is now perceived in the modern period is the subject of intense ongoing investigations, partly because they can hypothetically provide an elegant description tool. Known physical elements of the variability include the spatial and temporal scales of the balanced 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 (see e.g., Arbic et al., 2014).

A truly realistic climate model must be one of the most complicated of all pieces of non-biological machinery that the human mind can encompass. A great deal has been learned from model sub-components, including those that represent the ocean alone, and that model the AMOC, and we are not deprecating the huge accomplishment in the modern period of global and regional ocean modelling. On the other hand, a basic question that has always been present concerns the realism and temporal stability of the larger laminar scales in such models when the smaller scales are not resolved—and are represented by some form of simplified parameterization.

The ocean is a fluid, and any representation not able to include the full spectrum in space and time of all motions interacting with other space and time scales must be regarded with some skepticism particularly when integrated over long periods of time.. Since the time of O. Reynolds, a very large literature has grown up attempting turbulence closures for very basic fluid systems, often homogeneous, isotropic, unbounded. Homogeneity includes the fluid itself (e.g., no stratification) and no physics changes with position. This subject remains unfinished. The ocean is inhomogeneous, anisotropic, bounded. Its most basic circulation elements include stratification, rotation, complicated three-dimensional topography, complicated mechanical, thermal, and mass forcings. To the extent that any representation of the ocean e.g. at 1 °of latitude and longitude has, through parameterizations, successfully been able to quantitatively compute large-scale quantities such as an MOC, *a quite remarkable turbulence closure* has been accomplished—surely a landmark in the history of fluid dynamics!

2 Discussion

Curiously, invocation of AMOC shutdown, a favorite *deus ex machina* of climate science, implies in the most obvious and simplest physics, an ocean circulation resembling that of the classical period of physical oceanography, but inevitably encountering the complexities now known to exist in the modern period ocean view. In the modern period, ocean flows are known to be fully three-dimensional and turbulent, and the classical quasi-steady, laminar, upper-layer flow controlled by a time-mean wind stress curl has become a will-o'-the-wisp—to be sought, hopefully, in long time-average estimates of the ocean circulation over unknown durations.

An AMOC estimate must integrate across a wide-variety of features (Fig. 2) Determining the amount of heat 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 is likely to vary enormously depending upon the property and the latitude. In the classical view, property transports of mass, heat, etc. can increase or decrease with the wind system, air-sea exchanges of enthalpy, carbon, etc. all in the "shutdown" state.

Time-averaging, as in Fig. 2, greatly simplifies the instantaneous flows, although the averaging process involves an intricate product of terms in the underlying hydrodynamical/-themodynamic equations. An interesting question—one not now answerable—is whether averaging over some long, unknown, time interval produces a classical laminar ocean circulation, one that is describable from the classical time-independent equations (e.g., does Sverdrup balance emerge from a 100-year average?). Representing the flow and its influence by cartoons carries one far from the science of oceanography.

Discussion of the heat carried by the ocean, or a small part of the ocean, makes little sense except in the overall context of the Earth's heat budget. Even when undergoing a global warming or a cooling as into an ice age, the imbalance of incoming and outgoing radiation remains a very small part of the net solar incoming flux. Modern warming rate estimates never exceed a few W/m^2 at most, but the net incoming solar radiation is approximately $1400W/m^2$ (e.g., Saltzman, 2002). Thus, even when entering or leaving an ice age or a tropical period, the imbalance of incoming and outgoing radiation remains very small compared to the overall thermal forcing.

If it is true that a shutdown reduces the poleward high latitude transport of energy by the ocean, one can expect at zero-order that the atmosphere—globally—will tend to compensate it. Bjerknes (1964) dealt specifically with the Atlantic Ocean. But the system has many ways to maintain near-balance globally of incoming and outgoing radiation if the North Atlantic transport of heat should shift. Changes can occur elsewhere in the oceanic poleward transport (in either hemisphere), in the atmospheric transport, in the nature and degree of cloud cover, surface albedo, etc. That a reduction in the AMOC heat transport would cool the northern hemisphere as some like Broecker have insisted, is far from clear—the atmosphere there may well warm so as to increase its radiation back to space.

The AMOC is one element of an immensely complicated system determining climate. Suggesting that the entire climate system can be understood from variations in the AMOC is a bit like doing an intensive study of a carburetor on an internal combustion engine, and then simply assuming that all the behavior of an automobile so-powered can be inferred from its characteristics. A carburetor is, per se, an extremely important part of a car, but hardly obviously the determining factor in all of its complex behavior when driven.

Curiously, the invocation of an AMOC shutdown, as an anomalous climate state, implies that the old classical understanding of the ocean circulation has become applicable. What seems to be ignored, in contrast to the implications of the label, is that massive amounts of fluid are moving north and south, conveying not just mass but also net amounts of heat, freshwater, carbon etc.

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