Ocean Circulation and Climate: an Overview

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Ocean circulation plays a central role in regulating climate and supporting marine life by transporting heat, carbon, oxygen, and nutrients throughout the world's ocean. As human-emitted greenhouse gases continue to accumulate in the atmosphere, the Meridional Overturning Circulation (MOC) plays an increasingly important role in sequestering anthropogenic heat and carbon into the deep ocean, thus modulating the course of climate change. Anthropogenic warming, in turn, can influence global ocean circulation through enhancing ocean stratification by warming and freshening the high latitude upper oceans, rendering it an integral part in understanding and predicting climate over the 21st century. The interactions between the MOC and climate are poorly understood and underscore the need for enhanced observations, improved process understanding, and proper model representation of ocean circulation on several spatial and temporal scales.

The ocean is in perpetual motion. Through its transport of heat, carbon, plankton, nutrients, and oxygen around the world, ocean circulation regulates global climate and maintains primary productivity and marine ecosystems, with widespread implications for global fisheries, tourism, and the shipping industry. Surface and subsurface currents, upwelling, downwelling, surface and internal waves, mixing, eddies, convection, and several other forms of motion act jointly to shape the observed circulation of the world's ocean. Several processes contribute differently and concurrently to this circulation, including, but not limited to, solar heating, tides, winds, the Coriolis effect, and density changes due to variations in temperature and salinity. In this article, we describe some of the major mechanisms driving global ocean circulation with a focus on the MOC, and briefly discuss its importance to the climate system, its current observations, and its projected future in a warming world.

DRIVING MECHANISMS

Global ocean circulation can be divided into two major components: *i)* the fast, wind-driven, upper ocean circulation, and *ii)* the slow, deep ocean circulation. These two components act simultaneously to drive the MOC, the movement of seawater across basins and depths.

As the name suggests, the wind-driven circulation is driven by the prevailing winds, primarily the easterlies in the tropics and the westerlies in the mid-latitudes. As the winds blow above the ocean surface, the upper ocean moves in a balance of frictional and Coriolis forces known as Ekman transport. This mechanism drives a net transport of water that is perpendicular to the wind (to the right in the Northern Hemisphere and left in the Southern Hemisphere). This transport results in areas of divergence and convergence that lead, respectively, to upwelling (*i.e.* upward motion of interior waters) and downwelling (*i.e.* sinking of surface waters). In the equatorial Pacific for instance, the easterlies drive poleward divergence of surface waters that are replenished by upwelling of cold interior waters forming the equatorial "cold tongue". In the Southern Hemisphere, the westerlies drive equatorward Ekman transport and upwelling of deep waters that formed centuries ago (Morrison *et al.*, 2015).

General patterns of the wind-driven circulation are shown in Figure 1 as a series of zonal currents (*e.g.* North Equatorial and South Equatorial currents), eastern boundary currents (*e.g.* California and Chile/Peru Currents), and western boundary currents (*e.g.* Kuroshio Current and Gulf Stream) that form the subtropical and subpolar gyres. The subtropical gyres are especially important as they transport heat from the equator towards the poles through western boundary currents and ventilate the O_2-depleted interior waters of the low latitudes through subsurface return flow of these surface waters (Duteil *et al.*, 2014). These waters upwell again along the equator, closing the "shallow" overturning cells of the MOC. Through its tight dependence on the fast and rigorous circulation of the atmosphere, the wind-driven circulation dominates the short-scale variability of the upper ocean and is the most energetic component.

The deep circulation, on the other hand, acts on much longer timescales. This component is sometimes referred to as the "thermohaline" circulation, due to its dependence on changes in temperature ("thermo") and salinity ("haline"), both of which regulate the density of seawater. When seawater cools or gets saltier, its density increases and the parcel sinks to depth. This sinking occurs primarily in the high latitudes, where heat loss to the atmosphere and sea ice formation leads to significant changes in temperature and salinity, linking the surface and deep oceans, and setting interior ocean properties along its path.

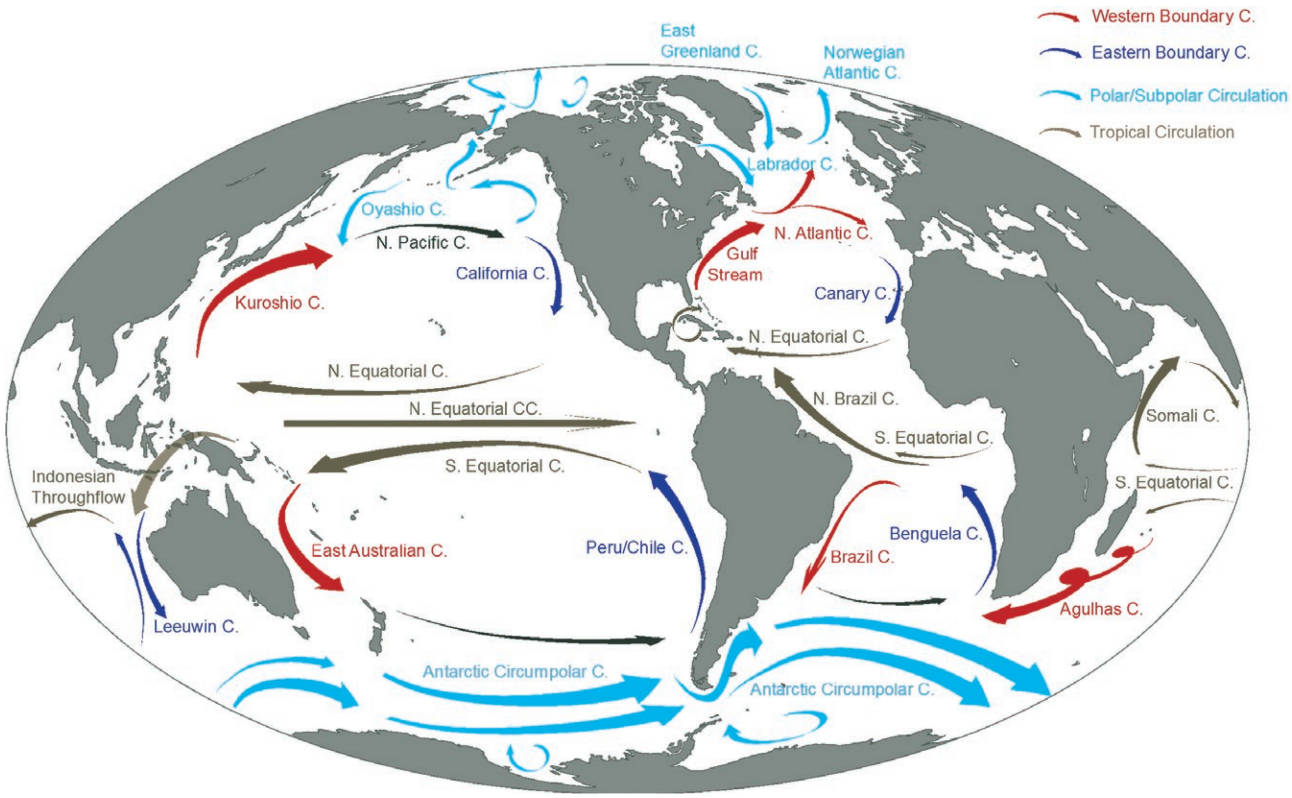

Fig.1 – a) The wind-driven surface ocean circulation. Driven by winds, the surface currents form the main subtropical and subpolar gyres and the tropical/equatorial circulation. Illustration based on wind-driven circulation discussion of Talley *et al.* (2011) and Schmitz (1996). [C. = Current]. © B. Delorme and Y. Eddebbar.

The subpolar North Atlantic is one such important high latitude region, where deep convection and sinking of North Atlantic Deep Water (NADW) occurs as a result of northward transport of heat by the Gulf Stream and subsequent heat loss to the atmosphere (Send and Marshall, 1995). In the Weddell and Ross seas surrounding Antarctica, ice formation over leads (or "Polynyas") and its rejection of brine renders the underlying waters more saline. This process forms a dense water mass known as the Antarctic Bottom Water (AABW), which sinks to the bottom and fills most of the global abyssal ocean (Talley *et al.*, 2011). In contrast, the Indian and Pacific Deep Waters (IDW; PDW) of the Indian and Pacific oceans are formed much more slowly through deep ocean mixing in the low latitudes, and are thus older and richer in carbon and nutrients and depleted in O_2 (Talley, 2013).

The pathway and mechanisms by which this large volume of deep waters returns to the surface, however, have long puzzled oceanographers. Initially, it was thought that dense deep waters upwell back to the upper ocean through widespread vertical mixing, which called for diffusivity on the order of 10^{-4} m^2/s (Munk, 1966). Observations over wide regions however show typically lower values (Lumpkin and Speer, 2007; Ledwell *et al.*, 2011). Thus, recent studies proposed upwelling in the Southern Ocean driven by the westerly winds as the main dynamical return pathway of deep waters to the surface (Toggweiler and Samuels, 1995; Marshall and Speer, 2012). This upwelling links deep waters back to the surface, after which they either sink to the abyss as AABW, or are subducted equatorward through Ekman transport as mode or intermediate waters, to later reach the North Atlantic again, closing the MOC (Marshall and Speer, 2012).

These processes, however, are spatially and mechanistically very complex, and involve both wind-driven and mixing-driven upwelling of NADW, IDW, and PDW across all three basins (Talley, 2013). Deep ocean turbulent mixing is central to these interactions, and is driven by breaking internal waves generated by tidal flow over rough topography as well as winds (Munk and Wunsch, 1998). This mixing

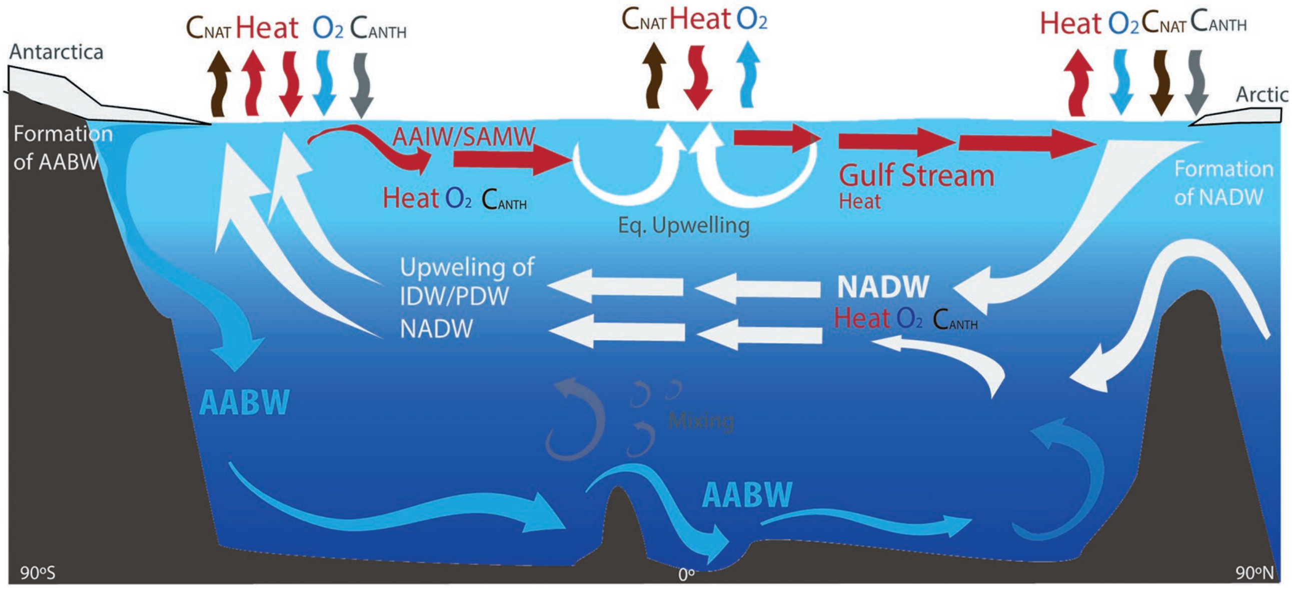

Fig.2 – A simplified 2-d illustration of the Meridional Overturning Circulation and its impact on the mean air-sea flux and transport of heat, oxygen (O_2), anthropogenic (C_{ANTH}) and natural carbon (C_{NAT}). High latitude basins such as the North Atlantic are regions of strong heat loss and uptake of C_{ANTH}, C_{NAT} and O_2. Upwelling in the Southern Ocean leads to simultaneous release of C_{NAT}, uptake of C_{ANTH} and O_2 ventilation as the upwelled deep waters are low in O_2 and rich in Dissolved Inorganic Carbon (DIC). The equatorial zone is a region of intense upwelling of cold, nutrient and DIC-rich waters, driving enhanced uptake of heat, biological production and thermal outgassing of O_2, and strong release of C_{NAT}. [AABW=Antarctic Bottom Water; NADW=North Atlantic Deep Water; IDW=Indian Deep Water; PDW=Pacific Deep Water; AAIW=Antarctic Intermediate Waters; SAMW=Subantarctic Mode Water]. © B. Delorme and Y. Eddebbar.

diffuses surface heat downward to warm and upwell the cold and dense deep waters of the abyss up the water column to reach the Southern Ocean upwelling branch of the MOC. The major role of the Southern Ocean and its complex processes highlight the intertwined nature of the different components of the MOC, which is simplified in an illustration in Figure 2.

OCEAN CIRCULATION: A CLIMATE REGULATOR

Ocean circulation has profound impacts on the mean state and variability of the climate system. Equatorial upwelling and poleward divergence of cold, nutrient and carbon rich waters maintain cool temperatures along the equator, large outgassing of natural carbon and oxygen, biological productivity, and intense heat uptake. The subsequent meridional transport of heat to the poles and its loss to the atmosphere moderates climate in mid-to-high latitude regions (*e.g.* Northwest Europe). Furthermore, changes in equatorial upwelling and currents play central roles in driving *El Niño* and *La Niña* phenomena, thus influencing global climate on interannual to decadal timescales, and modulating the intensity of anthropogenic climate change (Kosaka and Xie, 2016).

Particularly, the MOC alleviates the impacts of climate change by transporting most of the anthropogenic heat to depth (Kostov *et al.*, 2014). Recently, variations in the MOC and its subsequent impacts on ocean heat uptake have been proposed as potential drivers for the "hiatus" in global mean surface warming through the intensification of the shallow overturning cells in the Pacific (Meehl *et al.*, 2011; Balmaseda *et al.*, 2013; England *et al.*, 2014) and through changes in rates of deep water formation in the North Atlantic and upwelling in the Southern Ocean (Chen and Tung, 2014; Drijfhout *et al.*, 2014). Additionally, upwelling of old preindustrial waters that have been isolated from anthropogenic forcing was evoked as a driving mechanism for the surface cooling trends observed over recent decades in the Southern Ocean (Armour *et al.*, 2016).

OCEAN CIRCULATION AND BIOGEOCHEMICAL DYNAMICS

The ocean absorbs over a quarter of anthropogenic CO_2 emissions every year through interactions that involve its complex carbon cycle and circulation (LeQuéré *et al.*, 2013; Stocker *et al.*, 2013). Similarly to heat sequestration, most oceanic carbon uptake occurs at high latitudes. In the North Atlantic, the formation and sinking of NADW act as a gateway for storing anthropogenic carbon at depth. The Southern Ocean is also a major sink of anthropogenic carbon accounting for nearly half the global oceanic uptake (Morrison *et al.*, 2015). Here, upwelling in this region exposes old preindustrial deep waters to high atmospheric CO_2 concentrations. Carbon uptake in this region however reflects a subtle balance between vigorous uptake of anthropogenic carbon and outgassing of natural carbon due to the carbon-rich contents of these upwelled waters. The future of this balance is unclear, requiring deeper understanding of the physical and biogeochemical dynamics that govern the Southern Ocean.

The rate of formation of intermediate and deep water masses in the high latitudes and upwelling in the Southern Ocean also exert major controls on the oceanic O_2 inventory. The poleward transport and subsequent loss of ocean heat to the atmosphere and vertical mixing at high latitudes drives substantial uptake of O_2 (Gruber *et al.*, 2001). The sinking of these waters ventilates the interior ocean where microbial respiration continuously consumes O_2 during the remineralization of sinking organic matter. As the ocean warms, its oxygen content is expected to decline due to reduced gas solubility and weakened ventilation due to surface warming effects on stratification. O_2 decline has been observed in several regions globally, raising serious concerns for marine ecosystems, biogeochemical cycling, and global fisheries (Keeling *et al.*, 2010). The attribution and prediction of ocean oxygen decline however remain challenging due to its tight coupling to ocean circulation and natural variability, which are not well observed or understood.

Changes in ocean circulation are also likely to influence the rate of nutrients supply from depths to the surface.

Again, the Southern Ocean is a major player in this balance, as its upwelling supplies nutrients for 75% of global primary productivity (Morrison *et al.*, 2015). Changes in global ocean circulation thus have major implications for marine primary productivity, the building block of life in the ocean.

OBSERVING OCEAN CIRCULATION: A MAJOR CHALLENGE

Observing ocean circulation is inherently challenging due to its long timescale and large spatial extent (Abraham *et al.*, 2013). Recent observational efforts however have drastically improved our understanding of ocean circulation. Satellite altimetry observations of sea surface height, for instance, have provided powerful insights on surface velocity fields and the spatiotemporal variability of the wind-driven circulation

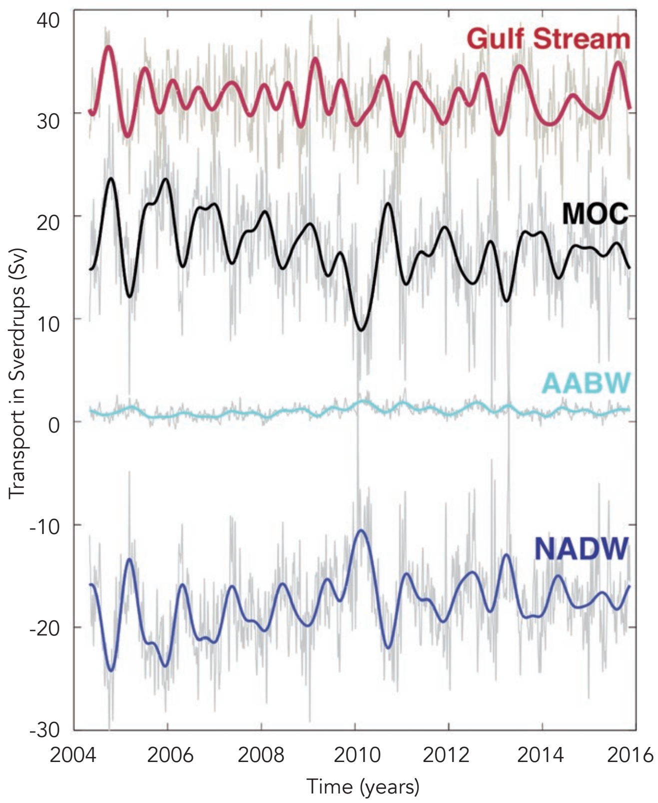

Fig.3 – Timeseries of AMOC and its components at 26.5 °N shown as northward transport in Sverdrups (1 Sverdup=10^6 m^3/s). Bold lines indicate smoothed timeseries using a 6-month low-pass filter. Data obtained from the RAPID/MOCHA array (www.rapid.ac.uk). [AABW=Antarctic Bottom Water (cyan); MOC=net Meridional Overturning Circulation (black); NADW=North Atlantic Deep Water (navy blue); and Gulf Stream (red)]. © B. Delorme and Y. Eddebbar.

(Rhein *et al.*, 2013). The components and structure of the MOC were clearly outlined by hydrographic measurements of temperature, salinity, O_2, nutrients, and other tracers thanks to the World Ocean Circulation Experiment (WOCE) and other hydrographic surveys of the world's ocean. These measurements, though essential for basic understanding of the MOC, provide only a snapshot of the ocean at a specific time and region, and thus significant gaps remain in observing the MOC, including its temporal and spatial variability. Recently, continuous monitoring using 19 moorings located along the 26.5°N latitude of the Atlantic by the RAPID/MOCHA array (Smeed *et al.*, 2016) provided new and unique insights on the Atlantic MOC (AMOC). Figure 3 shows substantial variability in AMOC and its components on monthly to interannual and longer timescales. A markedly steep downward trend from 2006 through 2010, for instance, shows a nearly 50% reduction in amplitude, that was followed by a rapid partial recovery in 2011. Much of this variability arises from changes in the southward transport of NADW at depth, and reflects the influence of high latitude processes where these waters form.

Similarly to other observed regions, no long-term trends have been detected in the MOC intensity so far (Rhein *et al.*, 2013), though observational records are too short to infer long-term changes. The increasing length of continuous timeseries such as the RAPID/MOCHA array are fundamental to assessing secular trends that may be related to anthropogenic warming or natural variability phenomena. Furthermore, the recent advances and expansion of the Argo floats program (Roemmich and Gilson, 2009) is beginning to paint a global 3-dimensional picture of ocean circulation. Together, these observations not only offer a wealth of information for understanding the MOC, but also present a powerful validation test for global climate models (Danabasoglu *et al.*, 2014), an essential task for reliable climate predictions.

THE MOC IN A WARMING WORLD: FUTURE PROJECTIONS

With the accumulation of greenhouse gases in the atmosphere, the MOC is expected to weaken, as warming and ice melt at high latitudes reduces the density of upper ocean waters and thus increases the stratification of the water column. While a collapse of the MOC in the Atlantic is unlikely, climate models predict a 34 % weakening of AMOC by 2100 for a high emission (RCP8.5) scenario (Collins *et al.*, 2013). The magnitude of this weakening is not well constrained, ranging from 12-54 %, and thus the future of the MOC and its role in transporting anthropogenic heat and carbon from the surface to the deep ocean remains highly uncertain (Stocker, 2013).

In the Southern Ocean, the Antarctic Circumpolar Current is expected to move poleward in the future, as a response to the anticipated poleward contraction and intensification of westerly winds around the Antarctic continent. This displacement is expected to cause enhanced warming between 40 °S and 60 °S and increased equatorward Ekman transport, increasing the upwelling of relatively warm deep-water masses (Collins *et al.*, 2013). Due to temperature-driven decreases in density, the formation of Antarctic Bottom Water and its northward sinking towards the global abyss is expected to weaken.

Furthermore, as warming dramatically changes the physical landscape of the high latitudes, interactions between polar ice sheets and ocean circulation become increasingly important. This is due to: *(1)* the potential of freshwater input from ice shelf melt to alter the deep branch of the MOC, and *(2)* the influence of subsurface warming on ice shelf melting which may contribute significantly to global sea-level rise (Shepherd *et al.*, 2012). Warming around Antarctica is expected to have a major influence on ice shelves' mass balance through intrusion of warm currents below ice shelves, accelerating basal melt. In these waters, where salinity dominates density, freshwater input forms a thin lid of cold, low-salinity water, which increases stratification and prevents warmer interior waters from reaching the surface (Hansen *et al.*, 2016). The surplus of subsurface heat is hence made available to melt ice shelves, which in turn leads, through a positive feedback, to further melt and stratification. Crevassing due to warming atmospheric temperatures and subsurface warm currents under ice shelves may also drive non-linear responses of ice melt to anthropogenic warming with potential for significant sea-level rise (DeConto and Pollard, 2016). These processes are currently subject to intensive observational and modeling research, and may provide key insights for global climate models that currently do not simulate ocean-ice sheets interactions due to their relatively large resolutions (Winton *et al.*, 2014).

Understanding the past, present, and future of the MOC is crucial to understanding climate change in the 21st century. This is only possible through continuous and expanded monitoring of the MOC, improved process understanding of mechanisms driving ocean circulation and interactions with the cryosphere, and proper representation of these processes in climate models. The MOC's control over global surface temperatures and carbon uptake has major implications for international climate policy, which often relies on these quantities in setting international policy goals (*e.g.* the 2 °C target), and should thus be taken into account when designing long-term mitigation and adaptation strategies.

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