Introduction: The Ocean's Meridional Overturning Circulation

Andreas Schmittner[1], John C.H. Chiang[2], and Sidney R. Hemming[3]

The meridional overturning circulation is a system of surface and deep currents encompassing all ocean basins. It transports large amounts of water, heat, salt, carbon, nutrients and other substances around the globe, and connects the surface ocean and atmosphere with the huge reservoir of the deep sea. As such, it is of critical importance to the global climate system. This monograph summarizes the current state of knowledge of this current system, how it has changed in the past and how it may change in the future, its driving mechanisms, and the impacts of its variability on climate, ecosystems and biogeochemical cycles.

The surface waters of the Earth's oceans are dense enough to sink down to the abyss at only a few key locations (Plate 1). These sites of deep water formation are located at high latitudes because the density of seawater is strongly temperature dependent, colder ocean water being denser than warmer water. However, the density of seawater also depends on its salt content. This is why deep water is presently formed in the North Atlantic, which is salty, but not in the North Pacific, which is fresher. Subduction in the North Atlantic is fed by northward flow at the surface, transporting tropical and subtropical water masses into the subpolar and polar North Atlantic. The Gulf Stream and North Atlantic Drift are part of these northward flowing warm and salty surface currents. In winter, the warm current prevents excessive sea ice formation in the subpolar North Atlantic, and its heat is released into the atmosphere. The net result is relatively warm conditions over the greater North Atlantic region compared to similar latitudes of the North Pacific; this exemplifies the climatic importance of the Atlantic overturning circulation.

[1]College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, Oregon, USA.
[2]Department of Geography and Center for Atmospheric Sciences, University of California, Berkeley, California, USA.
[3]Department of Earth and Environmental Sciences, Columbia University, New York, New York, USA.

Ocean Circulation: Mechanisms and Impacts
Geophysical Monograph Series 173

10.1029/173GM02

Newly formed deep water in the North Atlantic, called North Atlantic Deep Water, flows southward as deep western boundary currents along the eastern margin of the Americas, crosses the equator, and eventually enters the Antarctic circumpolar current (ACC) of the Southern Ocean. There, it mixes with other deep water masses like Pacific Deep Water to form a new identity, the Circumpolar Deep Water; as such, the circumpolar current is sometime referred to as a "giant mixmaster". Some of this deep water then penetrates northwards, filling the deep waters into the Pacific and Indian oceans.

Ultimately, these deep waters have to return to the surface. However, where and how exactly the ocean upwells is poorly understood. Presently it is believed that most deep water returns to the surface in the high latitude Southern Ocean by mechanical uplift driven by strong westerly winds there (see e.g. chapter by Gnanadesikan et al. in section 2), but it might be possible that some deep water resurfaces at low latitudes, owing to vertical (diapycnal) mixing processes.

The second area of deep and bottom water formation is the Antarctic coast, including the marginal Ross and Weddell Seas (R and W in Plate 1, respectively). There, processes associated with sea ice formation (e.g. brine water rejection) are important in creating the densest waters of the world ocean. This deep water, called Antarctic Bottom Water, is distinctly colder and fresher than North Atlantic Deep Water, and flows northward underneath it in the Atlantic below 4000m in depth.

The current system as sketched above and in Plate 1 is popularly called "the great conveyor belt" and sometimes "thermohaline circulation". The latter term points to density differences, controlled by temperature and salinity changes, in driving the flow. However, the interior density distribution is not determined only through buoyancy (heat and freshwater) fluxes at the surface, but also by internal mixing processes as well as the flow itself, and hence also depends on forcing by winds and tides. In fact, the wind-driven ocean circulation, which is not included in Plate 1, dominates the strong current systems in the upper few hundred meters of the ocean, such as the subtropical and subpolar gyres, and interacts nonlinearly with the buoyancy-driven flow. Moreover, as pointed out in the chapter by Wunsch, the ocean is a turbulent fluid, and mesoscale transient eddies (the ocean weather) lead to complex and chaotic flow trajectories of individual water parcels. The interaction of these eddies with the mean flow is not well understood.

Deep water production, and hence the overturning circulation, is sensitive to perturbations of surface buoyancy fluxes. The modeled Atlantic overturning exhibits nonlinear hysteresis behavior with the possibility of rapid transitions between different states triggered by small freshwater perturbations. This behavior was first shown by Henry Stommel in the 1960's, using a box model analysis, and subsequently was reproduced by more complex two- and three-dimensional ocean and coupled ocean–atmosphere models. The sensitive nature of the Atlantic overturning circulation is supported by the paleoclimate record. Analysis of data from various paleoclimate archives, such as ice cores from Greenland and Antarctica, sea and lake sediments, and speleothems, draws a fascinating picture of substantial and abrupt fluctuations in climate during the last ice age that is consistent with repeated transitions between different states of the overturning circulation, as described in sections 5 and 6. Inferences from the past also raise the possibility that future anthropogenic global warming might seriously weaken the circulation or even lead to an abrupt slowdown (section 7). In fact, model projections of future climate show that buoyancy input through warming and freshening of North Atlantic surface waters will likely lead to a reduction of the circulation. However, how much of a weakening to expect for a particular forcing scenario, or the likelihood of a complete shutdown, are currently not known and a subject of intense research.

This monograph brings together different perspectives on the ocean's overturning circulation and its impacts, with authors ranging from physical oceanographers studying the modern system and the recent past, paleoceanographers with their view of changes in the distant past, and climate modelers trying to understand its global impacts and future evolution. Together the studies form a comprehensive description of the variability of the overturning circulation on all time scales from interannual to millennial. The book is aimed not only at active researchers and experts in the field but is intended also for students and everyone with an interest in climate change and the oceans. It contains significant educational aspects and a well-balanced mix of overview papers and research papers. The authors, acknowledged experts in their areas of research, range from world-renowned senior pioneers to young scientists with fresh ideas.

The book begins with an historic account by Longworth and Bryden on the quantification of the flow in the Atlantic and how our perception of it changed during the last 50 years, influenced by important progress in measurements and theory. Despite significant advances in our theoretical understanding of the overturning circulation, it is still very much an active area of research as demonstrated by the papers in section 2. Gnanadesikan, de Boer, and Mignone review the theoretical concepts relating the ocean's density structure to the flow, and highlight the importance of the Southern Ocean in the return flow of deep water to the surface and its role for the Atlantic overturning. Marchal et al. examine the role of sub-grid scale vertical mixing on the circulation. Numerical models play an important role in this research and their fidelity has improved in recent years. However, despite success in reproducing many features of the large-scale circulation, major issues remain, as pointed out in the perspective by Carl Wunsch, one of the great pioneers in physical oceanography. He also highlights the difficulties in quantitatively estimating the flow field from present-day observations, let alone from the much sparser paleoclimate data set. His critical assessment of the paleoclimate literature reveals many unanswered questions and cautions us not to mistake even well-established hypotheses as facts.

Measurements provide the basis for our understanding of the present-day circulation. The papers in section 3 demonstrate that many elements of the current system in the North Atlantic are now known in unprecedented detail. Quadfasel and Kaese summarize observations from the past decade of the flows of dense water from the Nordic Seas over the ridges between Greenland and Scotland. These overflows link deep water formation in the polar North Atlantic and Arctic oceans with the circulation to the south of the ridges. The observed state and variability during the last decade of the flow in the subpolar North Atlantic, including convection in the Labrador and Irminger Seas, are described in great detail by Schott and Brandt. Smethie and coauthors review the use of anthropogenic tracer (chlorofluorocarbon) measurements in estimating the overturning circulation and its variability.

Section 4 summarizes our knowledge on decadal to centennial variability of the circulation and its climatic impacts. The review by Delworth, Zhang, and Mann suggests that fluctuations of the meridional overturning circulation are involved in multidecadal to centennial variability of North Atlantic climate, and that their impacts are global, including modulations of tropical rainfall and possibly influencing

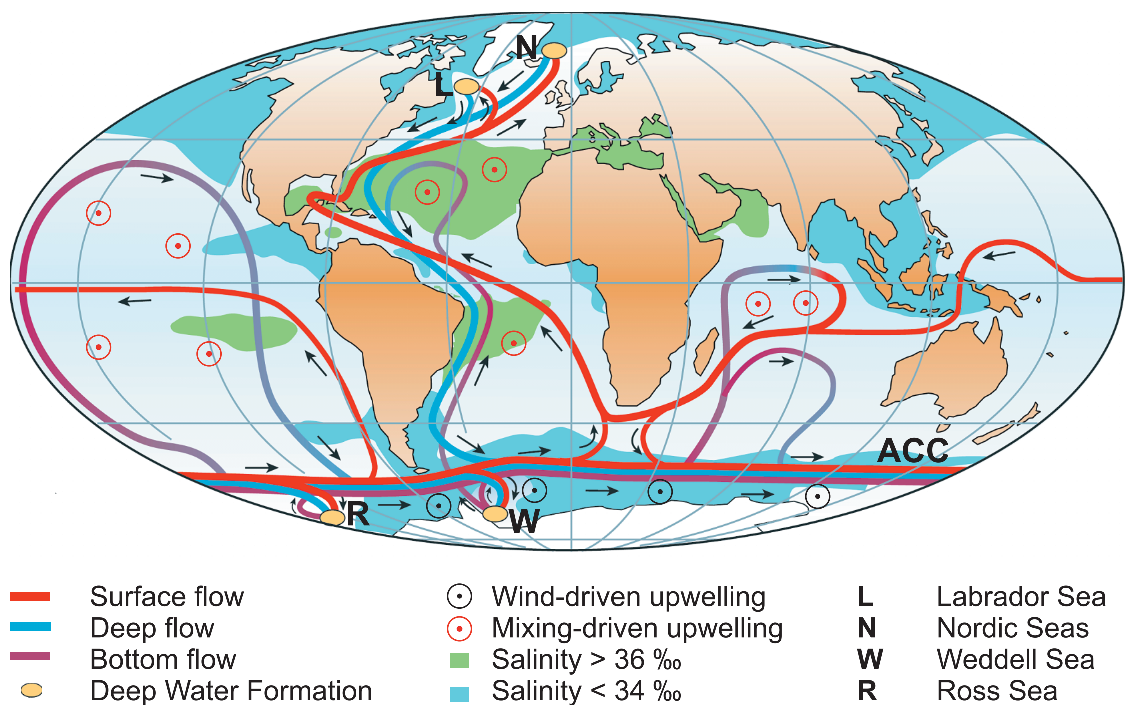

Plate 1. Schematic of the global overturning circulation. See text for explanation. From *Kuhlbrodt et al*. (2007).

Atlantic hurricane activity. Latif and coauthors examine the very different mechanisms responsible for decadal versus multidecadal variability and suggest a high degree of predictability of the Atlantic overturning and hence North Atlantic climate on decadal time scales.

The papers in section 5 demonstrate the abundance of new paleoproxy information on millennial time scale variability during the last glacial and deglacial periods, and the increasing convergence between observed changes and the hypothesis that the Atlantic meridional overturning circulation is central to those changes. Clark and coauthors provide a synthesis of multi-millennial time scale variability during the last glacial period, using empirical orthogonal functions analysis of proxy observations together with model results, and propose a new mechanism of multi-millennial oscillations of ocean circulation and sea level. Came and coauthors demonstrate the consistency of proxy measurements of deglacial temperature and salinity variations at intermediate depths in the western tropical Atlantic, with changes simulated in a coupled model in response to freshening of the high North Atlantic; together, they provide evidence of significant slowdown of the Atlantic meridional overturning during deglaciation. Rial and Yang present intriguing evidence from models exhibiting spontaneous Dansgaard/Oeschger-like climate oscillation to suggest that the timing of abrupt climate changes may be modulated by longer frequency insolation changes. Sarnthein and coauthors develop a novel method that they call "C^{14} plateau-tuning" to determine paleowater mass reservoir ages at four key Pacific and Atlantic locations, and the new information is used to infer changes in ocean circulation and ventilation during deglaciation. Finally, Skinner, Elderfield, and Hall present a synthesis of deep water temperature, oxygen isotope and carbon-13 measurements to shed light on links between overturning circulation perturbations, sea level, and interhemispheric climate changes on millennial timescales.

Section 6 focuses on the impact of changes in the overturning on global climate, ecosystems and biogeochemical cycles. Wallace Broecker, one of the great pioneers of paleoceanography, presents a very personal account on his thinking about the "great conveyor belt" and its impact on climate. Many lines of paleoproxy evidence from the tropics now convincingly show that abrupt climate changes are strongly manifest there, especially in precipitation. Wang and coauthors use a new precipitation proxy record from speleothems to infer how millennial oscillations during the last glacial were associated with north-south shifts in the Intertropical Convergence Zone. This is consistent with the study of Cheng, Bitz, and Chiang, who analyze the short-term climatic response of a coupled climate model to an abrupt reduction in the Atlantic overturning. They show a fast coupling of the high latitudes with the tropics through adjustments of the atmospheric circulation. Schmittner, Brook, and Ahn use a coupled climate carbon cycle model to suggest that changes in Southern Ocean stratification caused by a reduction of North Atlantic Deep Water formation are important in understanding the impact of changes in the overturning on atmospheric CO_2. A similar mechanism is invoked by Sigman, de Boer, and Haug as part of a new hypothesis linking changes in the overturning to the deglaciation.

The final section (section 7) looks to future projections. Bryan and coauthors examine the response of the Atlantic overturning over the next few centuries to CO_2 stabilization scenarios in a coupled climate model. Saenko investigates possible effects of projected changes in Southern Ocean winds on upwelling and the associated conversion of dense deep waters to light surface waters. Lastly, Swingedouw and Braconnot show in their climate model that the melting of the Greenland ice sheet, not incorporated in most other model projections, can push the system over the edge and lead to a collapse of the circulation, even in the moderate $2{\times}CO_2$ stabilization scenario.

The interdisciplinary nature of the problem of the ocean's overturning circulation and its impacts, as evidenced by the range of topics and expertise of contributors, is one of the fascinating aspects of the research. We believe we can learn a lot from each other and hope this book contributes to bringing the different disciplines together.

REFERENCE

Kuhlbrodt, T., A. Griesel, M. Montoya, A. Levermann, M. Hofmann, and S. Rahmstorf, On the driving processes of the Atlantic meridional overturning circulation, *Rev. Geophys.*, 45, RG2001, 2007, doi:10.1029/2004RG000166.

J. C. H. Chiang, Department of Geography and Center for Atmospheric Sciences, 547 McCone Hall, University of California, Berkeley, California 94720, USA.

S. R. Hemming, Lamont-Doherty Earth Observatory, Department of Earth and Environmental Sciences, Columbia University, New York, New York 10025, USA.

A. Schmittner, College of Oceanic and Atmospheric Sciences, 104 Ocean Administration Building, Oregon State University, Corvallis, Oregon 97331, USA. (aschmittner@coas.oregonstate.edu)