Ocean Circulation

Mechanisms and Impacts

Andreas Schmittner, John C. H. Chiang,
and Sidney R. Hemming
Editors

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Ocean Circulation: Mechanisms and Impacts— Past and Future Changes of Meridional Overturning

Andreas Schmittner
John C. H. Chiang
Sidney R. Hemming
Editors

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Cover Photo: Near the head of Scoresby Sund, east Greenland, looking into Nordvestfjord. Icebergs floating on the ocean symbolize the interactions between the ocean, air, land and ice. Originating from glaciers, such as the one visible on the left, icebergs flow into the ocean and are moved by ocean currents. As the ice melts, it provides fresh-water input, thereby decreasing the density of sea surface waters and affecting the ocean circulation. Heat supplied by ocean currents in turn can lead to melting of the glaciers. Photograph courtesy of Richard B. Alley (The Pennsylvania State University).

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CONTENTS

PREFACE

It has been called the “Achilles heel” of our climate system: oceanographers revel in its complexity, and climatologists are impressed by its variability. Hollywood has even made a movie of it—”The Day After Tomorrow” (2004; 20th Century Fox). Hyperbole aside, no one denies the crucial importance of the ocean’s meridional overturning circulation. In the mean, it transports and redistributes vast quantities of mass, heat, salt, carbon, nutrients and other substances around the globe. However, it is the variations to this circulation and their impact on the global climate that generate awe and instill worry. We know it can change rapidly (in as fast as a few years) with drastic consequences to climate: it did so many times in the past. Paleoproxy studies document abrupt changes of this circulation, affecting climate and biogeochemical systems particularly in the North Atlantic but also globally through communication via the atmosphere and ocean. This raises the question of whether future climatic changes associated with anthropogenic greenhouse gas emissions can trigger such a change, with damaging consequences to society and ecosystems.

This monograph presents an overview of the current knowledge of the ocean’s overturning circulation system, its changes and their global impacts. It combines studies of observations, theory and models and includes variability on all time scales, from sub-decadal to centennial variations in the recent past, to inferred variability on millennial and longer time scales during the last ice age, as well as projected changes under future climate warming scenarios. Also central to the theme of this monograph are the impacts of overturning circulation changes on climate and biogeochemical cycles.

The idea for this monograph originated from two complementary special sessions organized by the editors and their collaborators in the Fall 2005 meeting of the American Geophysical Union in San Francisco: “OS33D: Past and Future Changes of Thermohaline Circulation” focused on changes and causal mechanisms, whereas “PP21E: Climate Impacts of Changes to Thermohaline Circulation” focused on impacts and the global climate adjustment. The sessions brought together an interdisciplinary group comprising paleoceanographers and paleoclimatologists, physical oceanographers, geochemists, modern-day observationalists, and paleo- and modern-day climate modelers. The presentations given ranged from the effects of ocean topography on mixing and global ocean circulation, through to detection of Younger Dryas impacts in the vegetation of the deep tropics. The participants clearly benefited from the broader exposure, and we recognized a need for a synthesis.

The topic is timely from several perspectives. From a paleoclimate point of view, new paleoproxy techniques are providing an unprecedented view of the changes to the circulation and its global impacts during the last glacial and deglaciation. From a modern climate variability perspective, we have increasing appreciation and understanding of the important role variations in the overturning circulation play on decadal and centennial time scales. From a modeling viewpoint, coupled models are just now at a point where they are able to simulate with some fidelity the circulation, its variability and change and its impacts on ecosystems and biogeochemical cycles. The monograph highlights the larger scientific questions surrounding these topics, such as the recent discussion on the present state and trend of the Atlantic circulation, questions on its natural variability, the debate on the climatic importance of the circulation and its role in past climate variations.

We extend our grateful thanks to all our contributors for their time and efforts towards the chapters, and to the reviewers (listed below) for their careful consideration and helpful suggestions. A special thanks to the staff of AGU publishing, in particular Allan Graubard and Dawn Seigler, for their encouragement and tremendous help to bring this project to fruition.

We hope this monograph serves as a comprehensive and up-to-date baseline of our knowledge of all aspects of the ocean’s overturning circulation, for graduate students and experienced researchers alike.

Our helpful reviewers: Jess Adkins, Richard Alley, Helge Arz, Bruce Bills, Roark Brendan, Anthony J. Broccoli, Wallace Broecker, Christopher Charles, Kristina Dahl, Buwen Dong, Mick Follows, Andrey Ganopolski, James Girton, Anand Gnanadesikan, Alexa Griesel, Karl Helfrich, Gideon Henderson, Johann H. Jungclaus, Barry Klinger, Jeff Knight, Reto Knutti, Peter Koehler, Zhengyu Liu, Rick Lumpkin, Jerry McManus, Vikram Mehta, Delia Oppo, Christian Rodehacke, Keith Rodgers, Joellen Russell, Oleg Saenko, William Schmitz, Jr., John Shepherd, Ronald Stouffer, Rowan Sutton, Remi Tailleux, J. Toggweiler, John Tooe, Geoff Vallis, Gerard van der Schrier, Jack Whitehead, Carl Wunsch, and Rong Zhang.

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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.

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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

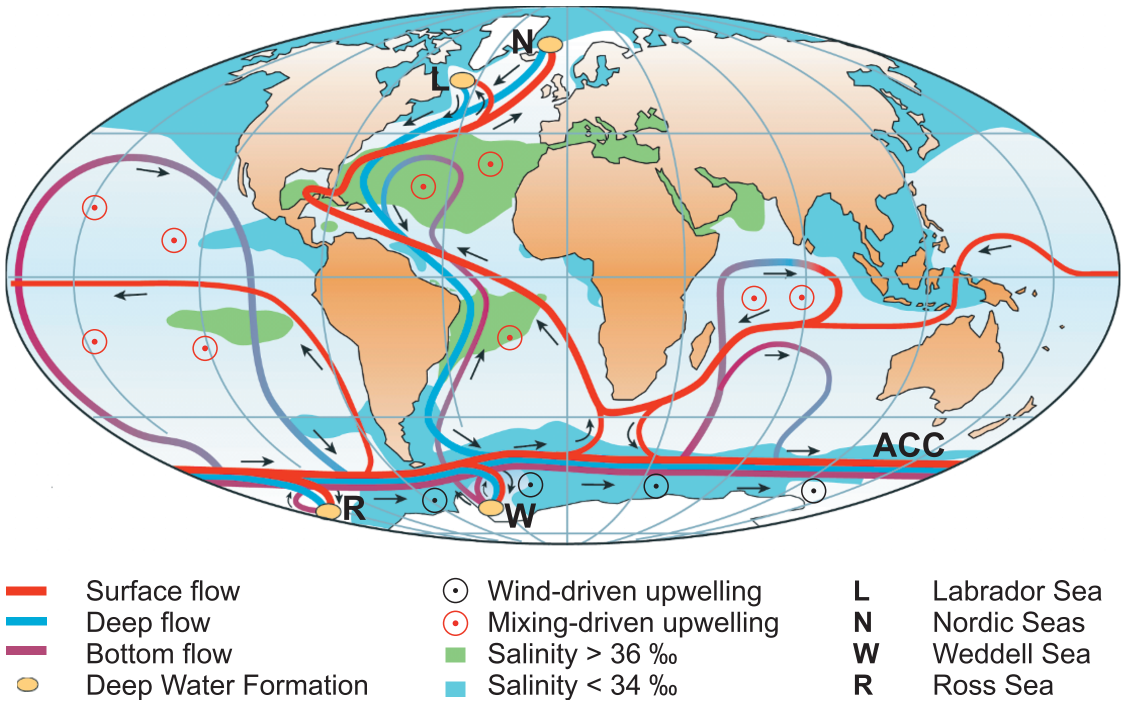

Plate 1. Schematic of the global overturning circulation. See text for explanation. From *Kuhlbrodt et al*. (2007).

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.

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Discovery and Quantification of the Atlantic Meridional Overturning Circulation: The Importance of 25°N

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Here we present a review of the history of modern understanding of the strength of the Atlantic Meridional Overturning Circulation (MOC), which arguably originates in 1957. This was the year that the *Discovery* cruises not only observed the Atlantic deep western boundary current for the first time, but also completed a transatlantic section along 24°N, from which reliable estimates of the size and structure of the MOC were later obtained. It was also the year Stommel began to publish his estimates of the size of the Atlantic overturning. These key developments are put into the context of early qualitative pictures of the Atlantic MOC which can be traced back to 1798. The early proposals differed significantly from Wüst's qualitative picture of layered interhemispheric exchange, published in 1935 but still broadly accepted today, and on which subsequent quantification relied. Early estimates of the Atlantic MOC strength, as by-products of regional circulation schemes, were by today's standard weak at 6-8 Sv. Stommel's work from 1957 and later developments in the 1980's produced much stronger overturning. Recognition of the importance of the MOC's role in meridional heat transport, necessitating studies dedicated to its quantification, led to a consensus regarding its strength in the early 1980's. The accepted 16-18 Sv MOC resulting from the 1957 *Discovery* section analysis supported Stommel's 1957 work and has since been verified by independent observations. We examine only the steady state MOC here; understanding and quantification of its variability are still very much evolving.

1. INTRODUCTION

Fifty years ago a remarkable set of cruises aboard *RRS Discovery II* enabled the first observation of the deep western boundary current in the North Atlantic Ocean to be made and the following transatlantic hydrographic section along 25°N provided data for the first rigorous calculations of the strength and structure of the Atlantic Meridional Overturning Circulation (MOC). Such calculations notably supported *Stommel's* [1957] original proposition of a 15-25 Sv MOC, the significance of which appeared to have gone unrecognised by the community until the supporting 1957 section analyses. 1957 therefore marks the beginning of modern understanding of the strength of the Atlantic MOC.

In March 1957, *Swallow and Worthington* [1957, 1961] tracked neutrally buoyant floats deployed between 2000 and 3000m depths over the Blake Plateau southeast of South Carolina on board *Discovery II* and made hydrographic stations on board *Atlantis* to observe the deep western boundary current (DWBC) recently predicted theoretically by

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Stommel [1957]. The floats moved southward at speeds of 9 to 18 cm s^{-1} and these velocities were used to establish a reference level for geostrophic transport estimates that allowed the transport of a deep southward flow of North Atlantic Deep water (NADW) formed in the Labrador and Nordic Seas to be estimated. These were the first direct measurements of the deep western boundary current in the North Atlantic Ocean. After a brief stop in Woods Hole (Plate 1), *Discovery II* headed back towards the English Channel making the first 48°N hydrographic section.

In October 1957 *Discovery II* again crossed the Atlantic, making the first transatlantic 25°N hydrographic section [*Worthington*, 1958]. This section with later measurements of the Gulf Stream flow through Florida Straits [*Niiler and Richardson*, 1973] enabled reliable estimates to be made of the size and structure of the Atlantic MOC. In contrast to classic ideas of a small overturning circulation of 7 Sv [*Sverdrup et al*., 1942], these estimates suggested a substantially larger overturning of 15 to 18 Sv, with a net northward flow of warm, upper waters above 1200 m depth and a compensating southward flow of cold deep waters below 1200m depth [*Roemmich*, 1980; *Wunsch*, 1980; *Hall and Bryden*, 1982]. Given the estimated error of ± 6 Sv associated with hydrographic section layer transports [*Ganachaud*, 2003] it is perhaps surprising that such consistent MOC strengths of 15-18 Sv have been obtained. Nonetheless, the 1957 *Discovery II* hydrographic section along 25°N led directly to the first modern estimates of the Atlantic MOC strength. *Discovery II* finished 1957 with a hydrographic section from Bermuda to Africa along 32°N.

Thus, modern understanding of the strength of the Atlantic MOC became widespread after the two *Discovery II* expeditions in 1957. Here we review the development of this understanding, starting before the first direct observations in 1957 but concentrating on the last 50 years.

2. DEVELOPMENT OF A QUALITATIVE PICTURE OF THE ATLANTIC MOC

The first modern qualitative picture of the Atlantic MOC, arguably *Wüst's* [1935] scheme, is the culmination of more than a century of deep ocean temperature observations and their interpretation. Here we briefly summarise the key developments that set the scene for the 1957 work aboard *Discovery*, based on the detailed reviews of *Deacon* [1971], *Mills* [2005] and *Warren* [1981]. We have not returned to the original source material, and instead refer the interested reader to these key overviews and references therein.

A meridional overturning in the Atlantic reconcilable with today's understanding was first proposed in 1798, by Count Rumford in his essay on the experimental discovery of convection currents in liquids [*Deacon*, 1971]. He cited the cold isothermal layer below 3900 feet observed by Ellis in 1751 at 25°N, 25°W (above which the temperature increased toward the surface) as evidence of cooling-induced deep water formation near the poles and its subsequent equatorward spreading. Continuity required a poleward surface current and thus the concept of a meridional overturning was established [*Deacon*, 1971; *Warren*, 1981]. Rumford's was not however the first recognition of density driven circulation. Notably, von Waitz published an explanation for the deep Mediterranean Outflow counter current in 1755 [*Deacon*, 1985] based on the salinity gradient between the Atlantic and Mediterranean. This was extrapolated to suggest an Atlantic overturning in which salinity dominated the meridional density gradient, causing equatorial sinking, poleward transport at depth and equatorial flow of cold water at the surface. This was in the opposite sense to Rumford's scheme, since von Waitz was seemingly unaware of observations of cold waters at depth despite their documentation as early as 1665 by Boyle [*Deacon*, 1971].

It was Rumford's scheme which gained acceptance at the time. Detail in the form of two symmetric back to back convection cells was provided by von Lenz in 1845 (Figure 1) following his participation in the Russian circumnavigation of the world (1823-1826]. Equatorial upwelling of the two cells was invoked to explain observed shoaling of the Atlantic equatorial thermocline. Up until the 1920's the circulation schemes that followed von Lenz's (e.g. those of Schott in 1902 and Brennecke in 1909] retained the two-cell and equatorial upwelling structure. Widespread awareness of von Lenz's work only followed Prestwich's supporting paper in 1875, which incorporated all available deep ocean temperature measurements at the time. Meanwhile however, evidence for cross equatorial flows was accumulating from the *Challenger* expeditions [1872-1876]. In 1884 and 1895 Buchanan and Buchan each showed both Antarctic Intermediate Water (AAIW) and North Atlantic Deep Water (NADW) north and south of the

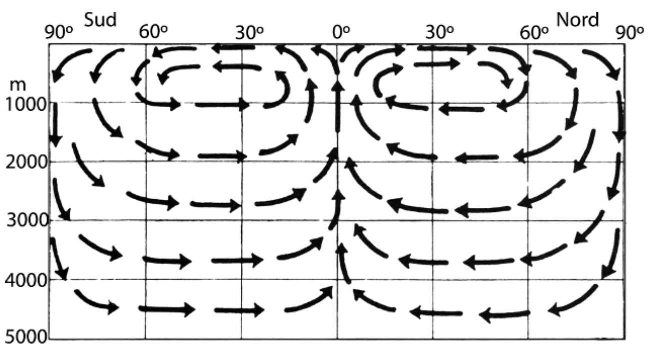

Figure 1. von Lenz's two-cell circulation scheme proposed in the 1830's and 1840's, reproduced from *Mills* (2005).

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Plate 1. *Discovery* leaving Woods Hole, Massachusetts, in 1957.

equator respectively in the hemisphere opposite to that in which they form. Despite this, such findings were not used explicitly to contest the two-cell circulation scheme. In 1911 Brennecke proposed the first cross-equatorial layered circulation scheme comprising southward transport of NADW between the northward moving layers of AAIW and Antarctic Bottom Water (AABW) after the additional observations from *Deutschland*.

The 1920's saw a co-ordinated effort by the Germans to resolve questions about the deep ocean circulation starting with systematic re-examination of all deep temperature and salinity observations by Merz. Explicit rejection of von Lenz's two-cell scheme resulted from Merz and Wüst's basinwide layered picture of inter-hemispheric exchange, published in 1922. From the *Meteor* cruise [1925-1927] Wüst published a modified circulation scheme that was to form the classical picture of Atlantic meridional overturning circulation, reproduced in Figure 2 [*Wüst*, 1935]. The schematic of hemispheric exchange incorporates spreading layers originating at high latitudes bounded by oxygen minima and temperature inversions. Upper NADW is characterised by a deep salinity maximum while Middle and Lower NADW are identified by oxygen maxima and originate from the Labrador and Greenland seas respectively. The 1922 version's subtropical contribution to deep water formation was rejected following Helland-Hansen and Nansen demonstrating the influence of Mediterranean Water on high salinity, and Wattenberg in 1929 tracing a deep oxygen maximum below the Mediterranean outflow to high latitudes [*Warren*, 1981].

It is important to note that even at this time, Wüst recognised that uniform basinwide flows were unrepresentative [*Warren*, 1981]. The 1935 meridional circulation scheme revised the picture of deep circulation filling layers of the ocean as water masses to one of organised currents (albeit confined to the west). Previously "spreading layers" had been utilised: meridional current components were deduced from isohalines constructed from arbitrary longitudinal sections of temperature and salinity [*Reid*, 1981]. This approach restricts interpretation to illustration of the consequences of circulation patterns rather than the flow pathway or strength. Wüst examined maxima and minima of salinity and oxygen to identify "core layers" interpreted as primary spreading paths of water from the formation site, under the assumption that beneath a shallow wind-driven layer, the circulation was almost entirely meridional [*Reid*, 1981]. Vigorous interhemispheric exchange was confined to the western Atlantic, flows in the east comprised zonal spreading or sporadic eddying [*Wüst*, 1935].

Wüst proposed three sites of deep water formation in the Atlantic, the Antarctic, the Mediterranean outflow and the high northern latitudes. Deep water originating from the latter comprised three layers; upper, middle and lower deep water (collectively known as NADW) that spread southwards above and below the layers of bottom water from the Antarctic (or AABW) and Subantarctic Intermediate water (or AAIW) both moving northwards (Figure 2). Bottom water from the Arctic is of secondary importance. Qualitatively at least, the basis of the modern picture of the Atlantic MOC was established with Wüst's 1935 scheme (Figure 2), although formation rates and transports had yet to be determined, and the overflow component of the MOC was not adequately emphasised [*Warren*, 1981].

3. EARLY ESTIMATES OF A WEAK ATLANTIC MOC

The need to determine transports of Wüst's 1935 circulation scheme did not attract immediate attention from observational oceanographers. Most of the progress of the early to

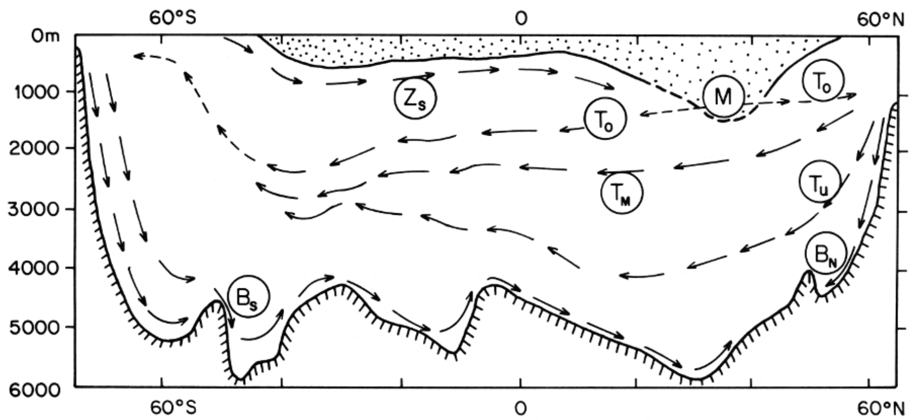

Figure 2. Meridional spreading of water masses in the Atlantic, from *Schmitz* (1995), originally from *Wüst* (1935). Z_S—Subantarctic Intermediate Water; $B_{S(N)}$—bottom water from south (north); T_O—Upper NADW; T_M—Middle NADW; T_U—Lower NADW; M is the Mediterranean influence. The stippled area is Wüst's warm water sphere.

mid 1900's was in application of the dynamic method to regional studies and later their synthesis into basin circulation schemes concentrating on the upper and intermediate waters. A common feature of these studies is that the MOC deduced is weak, with 6-8 Sv cross equatorial exchange.

The dynamic method for computing ocean circulation, developed from Bjerknes circulation theorem by Sändstrom and Helland-Hansen in 1903, provided methods for calculating vertical shear from a density field by use of the geostrophic approximation. In the early 1900's the direction and relative strength of regional circulation were deduced from studies of the upper ocean. *Defant* [1941] was the first to apply the geostrophic method to the large scale density field from the *Meteor* expeditions. In his second paper he addressed the problem of computing absolute current magnitude through employment of a reference level determined by continuity over the Atlantic from 50°N to 50°S [reviewed by *Reid*, 1981]. Defant's flow field at 2000m shows a continuous current from the Labrador Sea to 35°S along the western boundary of the Atlantic, with speeds less than 10 cm s^{-1} in the northern hemisphere. Such maps only covered the upper 3500 dbar at most; determination of interbasin exchange is therefore ambiguous and we turn to *Sverdrup et al.* [1942]'s oceanographic reference text *"The Oceans"* to gain insight into this period's understanding of the MOC (noting that this book itself references Defant's work). Qualitatively *The Oceans* representation of deep flows is largely based on *Wüst's* [1935] schematic with three sources for deep water in the North Atlantic; 2 Sv are formed in each of the Labrador Sea, the Greenland-Iceland-Norwegian Sea and at the Mediterranean outflow. The resulting NADW export to the South Atlantic is 9 Sv, supplemented by the assumed water mass conversion of their prescribed northward transports of 2 and 1 Sv of AAIW and AABW respectively, amounting to a 6 Sv MOC.

Support for this weak MOC was provided by the independent study of *Riley* [1951]. *Sverdrup et al.'s* [1942] 6 Sv NADW formation rate was deduced from comparison of water mass properties between the Sargasso and Caribbean Seas. In their scheme NADW was formed from water sinking in the Labrador Sea (Labrador Sea Water, LSW), in the Nordic seas and from the Mediterranean outflow. The strength of the latter and LSW components were calculated from limited observations of each basin's exchange with the North Atlantic and continuity, but the Nordic sea contribution was merely a residual [*Sverdrup et al.*, 1942]. Riley was motivated to understand not the physical circulation but biological productivity and as such his methods, while again based on the geostrophic method, had a number of differences that resulted in an almost independent Atlantic circulation scheme. The assumed level of no motion was selected to conserve mass in a grid of 10° × 10° boxes covering the Atlantic from 60°N to 60°S using data from *Dana, Atlantis* and *Discovery* expeditions with additional consideration given to the conservative properties of oxygen and nutrients in the deep ocean. A circulation scheme in remarkably good agreement with *Sverdrup et al.* [1942] resulted, with 5 Sv of NADW formed and 8.3 Sv of cross equatorial exchange.

Supporting evidence for an Atlantic MOC weaker than 10 Sv was presented as late as 1976 by *Worthington* [1976]. He attempted to synthesise a self-consistent circulation scheme for the North Atlantic from numerous studies of regional features made during the mid 1900's, concentrating on deep water formation at high latitudes and the Gulf Stream system. A 7 Sv MOC resulted (Figures 3a and b): 10 Sv of NADW formation but with 4 Sv recirculating north of 40°N, and 1 Sv

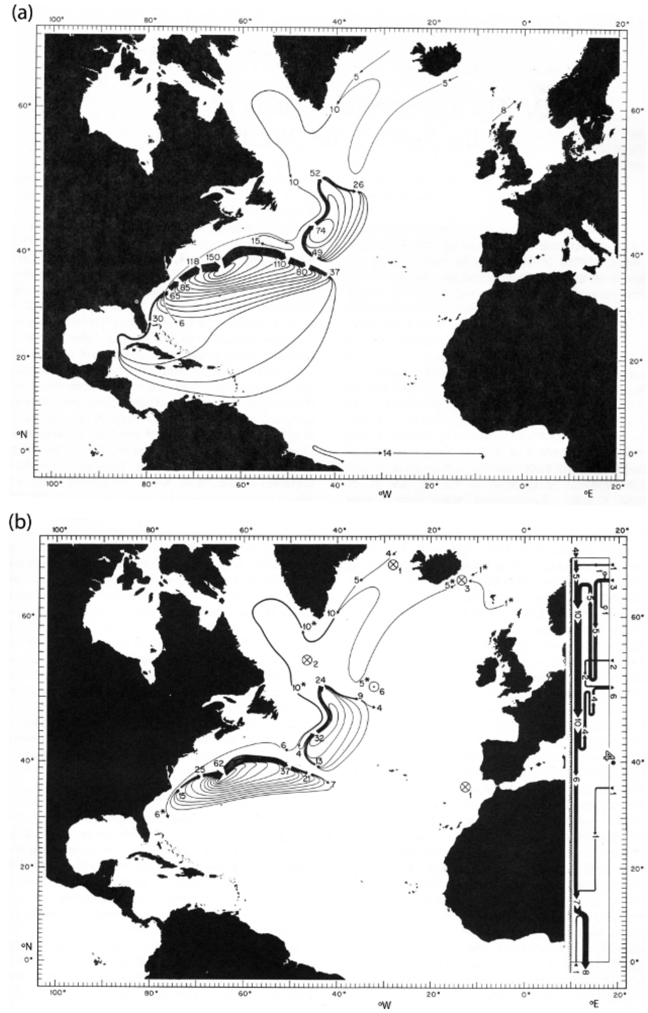

Figure 3. The North Atlantic circulation according to *Worthington* (1976) of the total water column (a) and the deep waters (colder than 4°C) only (b). Panel (a) does not show the 1 Sv of Mediterranean Water formation. The side insert of (b) is a meridional box model showing exchanges with layers above and across the equator, with 7 Sv net export to the southern Atlantic in this layer.

of Mediterranean Water southward flow. The NADW involved in interhemispheric exchange originated entirely from the Nordic seas and was partitioned equally between overflows from the Denmark Straits and the Iceland-Scotland Ridge (Denmark Straits Overflow water, DSOW, and Iceland-Scotland Ridge Overflow Water, ISOW respectively). LSW is formed in the scheme (2 Sv) but circulates only locally.

Despite discrepancies between the different source water contributions of deep cross equatorial flow suggested by different authors, the above studies present a consistent picture of an Atlantic MOC with a strength of 6-8 Sv. *Wüst's* [1935] schematic was retained in structure, and a quantitative element introduced.

4. THE DEEP WESTERN BOUNDARY CURRENT, STOMMEL AND EARLY INDICATIONS OF A STRONGER MOC

Although *Worthington's* [1976] calculations of the North Atlantic ocean circulation showed an MOC consistent in size with those of 20 and 30 years previously, contrasting work had been produced in the intervening period, notably that reported in Stommel's book "*The Gulf Stream*" [1958]. *Stommel's* [1957] prediction of a DWBC was expanded through theoretical and laboratory studies of stationary planetary flow driven by source-sink distribution patterns in a cylindrical tank [*Stommel et al.*, 1958], under similar circumstances on a rotating sphere [*Stommel and Arons*, 1960a], and then extended to a highly idealised model of the world's abyssal ocean circulation [*Stommel and Arons*, 1960b]. Versions of our Figure 4 are present in *Stommel's* 1957 and 1960b papers, showing a cross equatorial exchange of deep waters between 15 and 25 Sv (each line represents approximately 10 Sv). Even the lower limit of this, 15 Sv, would indicate an Atlantic MOC twice as strong as those discussed in the preceding section.

Stommel [1958] presents and explains the observational data behind Figure 4 in *"The Gulf Stream",* although the manuscript was completed in 1955. Zonally integrated meridional transport across hydrographic sections of the Atlantic mid ocean and western boundary regions from 30°S to 50°N, was computed to identify different flow regimes (Figure 5). Transports were referenced to a level between 1200 and 2600m to satisfy mass conservation using the known 26 Sv northward transport through the Florida Straits from cable measurements (discussed in further detail in Section 6) as a starting point. A deep southward flowing western boundary current below approximately 1500m can be traced into the southern hemisphere from 40°N (Figure 5),

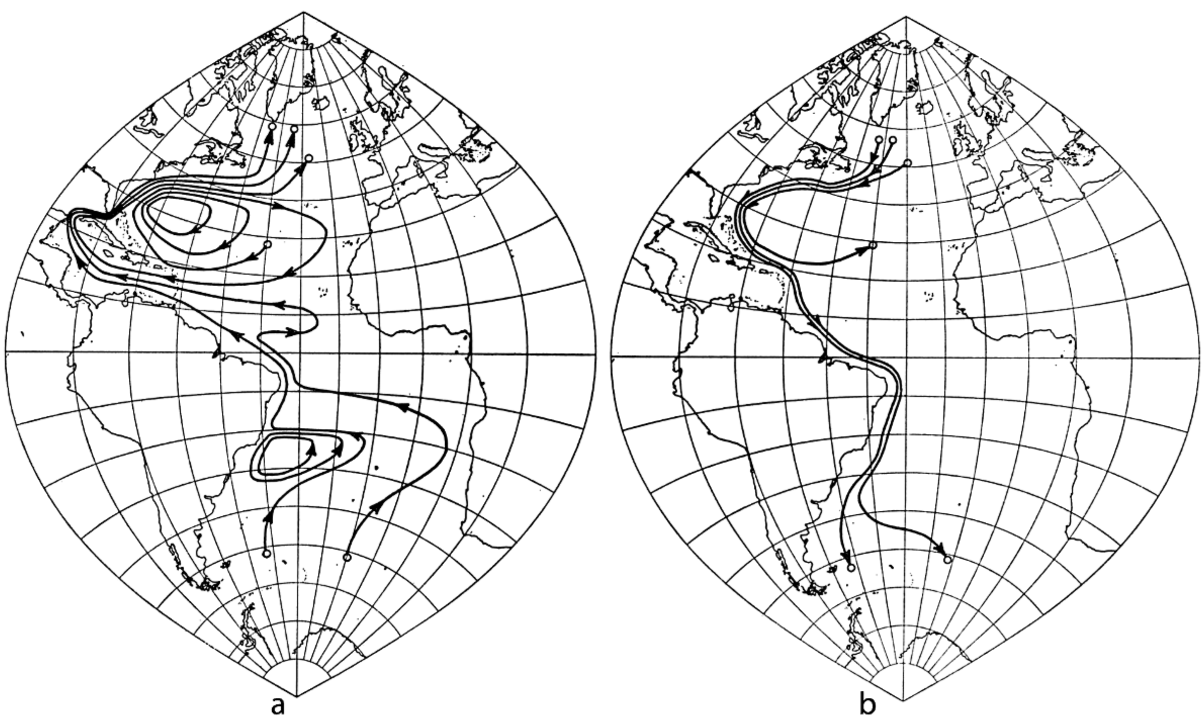

Figure 4. *Stommel's* (1958) schematic of transport in the upper layers (a) and lower layers (b) of the Atlantic, inferred from data in Figure 5. Each transport line represents 10 Sv. Reproduced from *Stommel* (1958).

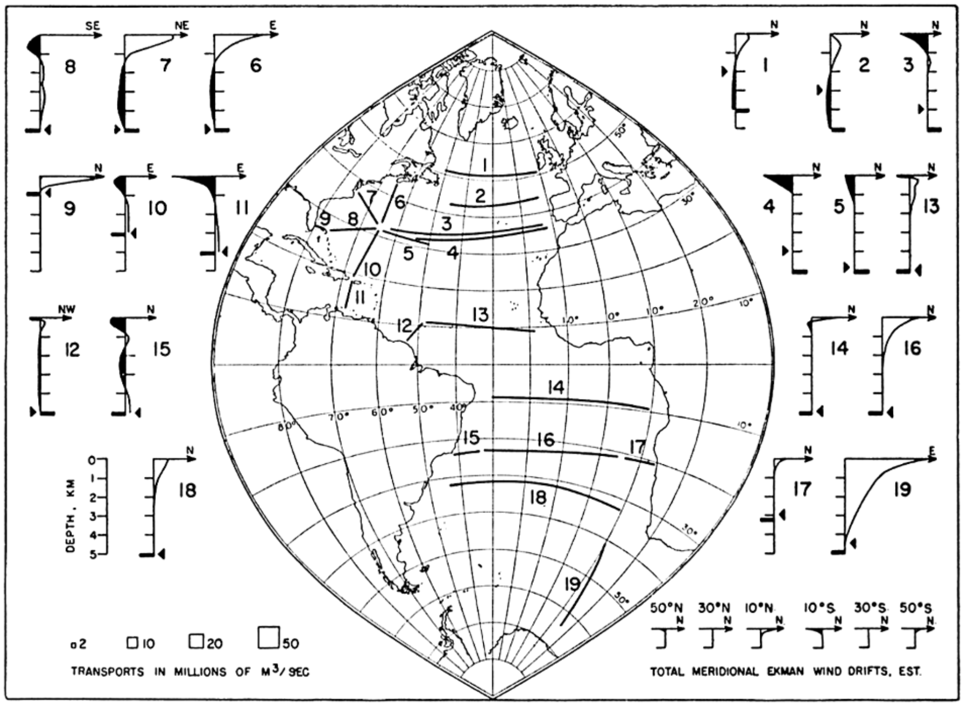

Figure 5. Geostrophic transport per unit depth across sections of the Atlantic Ocean, reproduced from *Stommel* (1958). The Ekman transports are shown in the lower right corner. For each section, the arrow points to the maximum depth of the data and the solid bar the bottom of the ocean.

while deep transports in the interior are negligible (further north, deep transport is spread across the basin). In the upper waters of the western boundary sections, *Stommel* [1958] demonstrated how flow was northward in the northern hemisphere and southward in the southern hemisphere due to the combination of anticyclonic subtropical gyre transport with the thermohaline return flow that is northward in both hemispheres. In the mid-ocean sections, transport computed is that of the subtropical gyre return flow. Figure 4 is the two-layer summary of these section transports [*Stommel*, 1958].

The differences between *Stommel's* [1958] Atlantic circulation scheme (Figure 4) and that of *Worthington* [1976] (Figure 3) are striking, particularly in the overturning circulation strength (15-25 Sv and 7 Sv respectively). Worthington was aware of *Stommel's* [1958] work but did not favour its implied heat loss to the atmosphere related to the strong formation of deep water associated with the northward transport above the mid depth reference level, which itself Worthington also judged unsuitable for Gulf Stream geostrophic transports following float observations [*Worthington*, 1976, and references therein]. It is interesting that the mid-depth reference level used by *Stommel* [1958] was later judged preferable to that of *Worthington* [1976] for representation of the DWBC transports by *Wunsch* [1978], work that had itself been motivated by *Worthington's* [1976] study. In attempting to produce an overall circulation scheme for the North Atlantic through application of the dynamic method with flows satisfying layer conservation of mass and salt, *Worthington* [1976] found that he had to invoke non-geostrophic flows. Following this, *Wunsch* [1977] developed a method of determining the level of no motion as a classical geophysical inverse problem. The inverse method of computing geostrophic circulation from hydrographic sections has gone on to yield many estimates of the Atlantic MOC strength (see Sections 5 and 7), but in the late 1970's the interesting study was application of the inverse method to determine transports across two sections crossing the Gulf Stream at the western boundary of the North Atlantic [*Wunsch*, 1978]. *Wunsch* [1978] explicitly stated his interest in comparison of the flow solution which resulted when an initial reference level of the sea-floor was used e.g. as done by *Worthington* [1976], compared to a mid-depth reference level that had been favoured earlier, e.g. by *Stommel* [1958]. His personal preference was for the mid-depth reference level, which not only gave a stronger southward Western Boundary Undercurrent of waters colder than 4°C through the box formed by the sections, but also found the undercurrent waters to originate from further north than the recirculations offshore of Bermuda as in the scheme with the sea-bed reference level [*Wunsch*, 1978]. Additional support for a reference level between 1500 and 2000m came from *Swallow and Worthington's* [1957, 1961] float observations of isobar slopes [*Stommel*, 1958]. One may wonder whether, if *Worthington* [1976] had referenced transports to a mid-depth level, the net export of deep waters from the North Atlantic would have been stronger, i.e. he may have found a MOC strength in line with *Stommel's* [1958] earlier work, and whether he would have had to resort to permitting deviations from geostrophy, which *Wunsch* [1977] attributes to his "arbitrary selection of a level of no motion".

We suggest that the "reliable circulation diagrams for the North Atlantic" sought by Worthington had a number of shortcomings that impacted upon the MOC proposed, while Stommel as early as 1958 through the use of full zonal hydrographic sections and a mid depth reference level in the western boundary was able to gain significant insight into the nature of the meridional, thermohaline transports. Stommel's work at the end of the 1950's presented a strong case for the thermohaline (overturning) circulation in the Atlantic comprising a DWBC transporting NADW from formation sites in the high latitude northern hemisphere, fed by a return flow in the upper waters of the western boundary, with 15-25 Sv net meridional transport in each layer. Stommel was not however the first to suggest stronger DWBC transport than the authors of Section 3. As early as 1955, Wüst's calculations of top to bottom flow speeds from the South Atlantic *Meteor* expedition sections show a DWBC with average speed of 9.2 cm s^{-1} between 10°S and 30°S [*Wüst*, 1955], broadly consistent with the DWBC strength of 22 Sv later computed by *Amos et al.* [1971] off the Blake Bahamas Outer Ridge, or 24 Sv near 35°N by *Richardson* [1977]. The advantage of *Stommel's* [1958] study was the computation of section-wide zonally integrated transports. These permit direct inference of the MOC strength, unlike DWBC transports alone which were not always interpreted in the wider context of interbasin exchange, and which we now know are sensitive to offshore recirculation gyres [e.g. *Lee et al.*, 1996]. We suggest that it is most unfortunate that Stommel's early insights, bearing many similarities with the definitive papers of MOC strength of the 1980s [e.g. *Roemmich*, 1980; *Hall and Bryden*, 1982], took so many years to be followed up.

5. THE MOC AND ITS MERIDIONAL HEAT TRANSPORT

It took almost 20 years from the publication of *Wüst's* [1935] Atlantic MOC schematic for its potential role in ocean heat transport to be recognised (*Jung*, 1952]. Having noted that "closed mean vertical circulations in meridional planes might transport large amounts of energy, even though the average velocities are extremely small", *Jung* [1952] set about quantifying this for the Atlantic. Firstly he constructed a hypothetical model of closed vertical circulation in a meridional plane near 30°N with northward surface flow above 950m and return flow satisfying continuity to the bottom (4250m) and realistic temperature profiles from the western basin. Oceanic poleward heat transport was approximately a third of that of the global ocean heat transport estimated from radiation data with the residual method [*Jung*, 1952]. A direct calculation using *Sverdrup et al*. [1942] and *Riley's* [1951] meridional velocity profiles at 27°N and temperature data from the *Meteor* was consistent with the model calculation, but uncertainties about mass balance were large and southward transport was confined to depths above 2400m. Although Jung overestimated the global significance of the total meridional heat transport, being seemingly unaware of the absence of a similar overturning circulation in the Pacific and at least weaker deep water formation in the Indian [*Sverdrup et al*., 1942], the importance of the MOC in energy balance calculations was identified, necessitating determination of its magnitude.

Jung [1955] did follow up his 1952 paper with publication (in an obscure technical report) of mass transport maps of the North Atlantic circulation in three layers and identified exchanges between layers. This was the first analysis of its kind based on a comprehensive data set, but total deepwater transport across 27°N in the Atlantic of 8.3 Sv is consistent with the other computations of that time [e.g. *Sverdrup et al*., 1942]. *Bryan* [1962] provided further support for Jung's assessment of the importance of an overturning circulation for meridional heat transport and simultaneously suggested a stronger overturning circulation. Again Bryan used the direct method to estimate heat transport and computed circulation according to Sverdrup transport, thus avoiding selection of a contentious reference level. Specifically the 36°N section showed significantly stronger meridional heat transport by the overturning circulation than the more vigorous horizontal circulation by virtue of vertical temperature gradients. Notable is the 15 Sv overturn at this latitude, although this was not the focus of Bryan's paper and seemingly not expanded upon.

Bryan [1962] did not include the 1957 *Discovery II* 25°N section in his heat flux calculations and it was not until the early 1980's that interest was renewed in the problem. A number of authors [e.g. *Bryden and Hall*, 1980; *Roemmich*, 1980] made use of the ideally placed 25°N section in conjunction with the well constrained transport of the Gulf Stream through the Florida Straits at this latitude [*Niiler and Richardson*, 1973] as had been first done by Stommel in 1958 (Figure 5), although he had used different, non-synoptic sections. *Roemmich* [1980] applied the inverse methods for ocean circulation developed by *Wunsch* [1977; 1978] to these observations and computed a 1.2 PW meridional oceanic heat transport, 0.7 PW of which was attributed to the MOC. Of the 30 Sv northward transport through the Florida Straits, 14 Sv retuned south after conversion to deep water at high latitudes while the remaining 16 Sv returned south in the mid ocean at densities less than the maximum in the Florida Current associated with the subtropical gyre. The latter carried only 0.1 PW northward supporting *Jung* [1952] and *Bryan* [1962]'s analyses. The remaining 0.4 PW of meridional heat transport was driven by northward Ekman transport at this latitude and its barotropic southward compensation. That *Roemmich* [1980] obtained a 16 Sv MOC from this study is noteworthy.

Roemmich's work was in fact done at the same time as that of *Bryden and Hall* [1980] who used the same 1957 25°N hydrographic section to compute a meridional oceanic heat transport of 1.1 PW. Roemmich regarded the use of inverse methods a progression in that they permitted description of the heat flux mechanisms and resolution of velocity on broad scales [*Roemmich*, 1980]. *Hall and Bryden* [1982] however, through presentation of transport in the mid ocean and Florida Straits in depth and temperature classes, supported Roemmich's findings showing that of the 28.5 Sv Florida Current transport warmer than 7°C, 18 Sv were converted to deep water before their southward return across then section, with the remaining 10.5 Sv recirculating in the upper waters of the mid-ocean section (see Table 1). Furthermore, *Wunsch* [1980], using model circulations and the inverse method on a dataset of meridional and zonal hydrographic sections in the North Atlantic between 10° and 60°N found a conversion of 16 Sv of the 31 Sv Florida Straits transport to waters colder than 4.6°C in the return flow.

We see that from the drive to quantify the meridional heat transport associated with the MOC, started by *Jung* [1952], a new picture of the Atlantic MOC strength emerged around 1980, with most progress originating from the use of the 1957 *Discovery* 25°N hydrographic section. The 16-18 Sv overturn, notably stronger than *Worthington's* [1976] 7 Sv and the calculations preceding this, is consistent in structure with *Stommel's* [1958] model while the principal development in understanding was associated with better constraint on the strength of the overturn and associated heat transport.

6. TODAY'S PICTURE OF THE ATLANTIC MOC FROM THE 25°N SECTION

The new consensus of a 16-18 Sv Atlantic overturning [*Roemmich*, 1980; *Hall and Bryden*, 1982; *Wunsch*, 1980] was accompanied by significant advancement in our understanding as discussed by *Hall and Bryden* [1982] relative to the key North Atlantic circulation text of the 1970's [*Worthington*, 1976] (Table 1 and Figure 6).

Hall and Bryden [1982]'s zonally integrated mid-ocean layer transports (Figure 6) clearly show the *Wüst* [1935] components of meridional exchange. In the mid ocean (Figure 6b) southward return flow of the subtropical gyre is seen above 550m (apart from the upper 25m northward wind-driven transport), with the northward core of AAIW sitting below this to 1150m. From 1150 to 4500m NADW flows southward, then AABW moving north is seen beneath 4500m. Combining this with the northward transport through the Florida Straits from the surface to 850m (Figure 6a), we see net northward and southward flows above and below 1150m respectively comprising the meridional overturn (Figure 6c). Also included is the wind driven surface Ekman transport of 5 Sv.

Hall and Bryden discussed computed meridional flow strengths in the context of *Worthingon* [1976], which was arguably the key reference text for the North Atlantic circulation at that time. Their main finding in this respect was an increase in the southward transport of waters colder than 4°C from 7 Sv to 15.6 Sv, and an additional 3 Sv in the 4-7°C waters (Table 1) corresponding to NADW transport. *Hall and Bryden* [1982] also quantified the northward flow of AAIW as 7-12°C waters that had not featured in *Worthington's* [1976]

Table 1. Meridional volume transports across 25°N in the Atlantic by temperature class, following *Hall and Bryden* (1982). Northward Ekman transport of 5 Sv is included in the warmest class of the mid-ocean. *Worthington* (1976)'s scheme is based on 30 Sv northward transport through the Florida Straits.

Temperature Class	Transport (Sv)			
	Hall and Bryden (1982)			*Worthington* (1976)
	Total	Florida Straits	Mid-ocean	Mid-ocean
$\theta > 17°C$	8.9	18.4	–9.5	–15
$12°C < \theta < 17°C$	2.5	5.4	–2.9	–5
$7°C < \theta < 12°C$	6.6	4.7	1.9	–4
$4°C < \theta < 7°C$	–2.3	1.0	–3.3	0
$\theta < 4°C$	–15.6	–	–15.6	–7

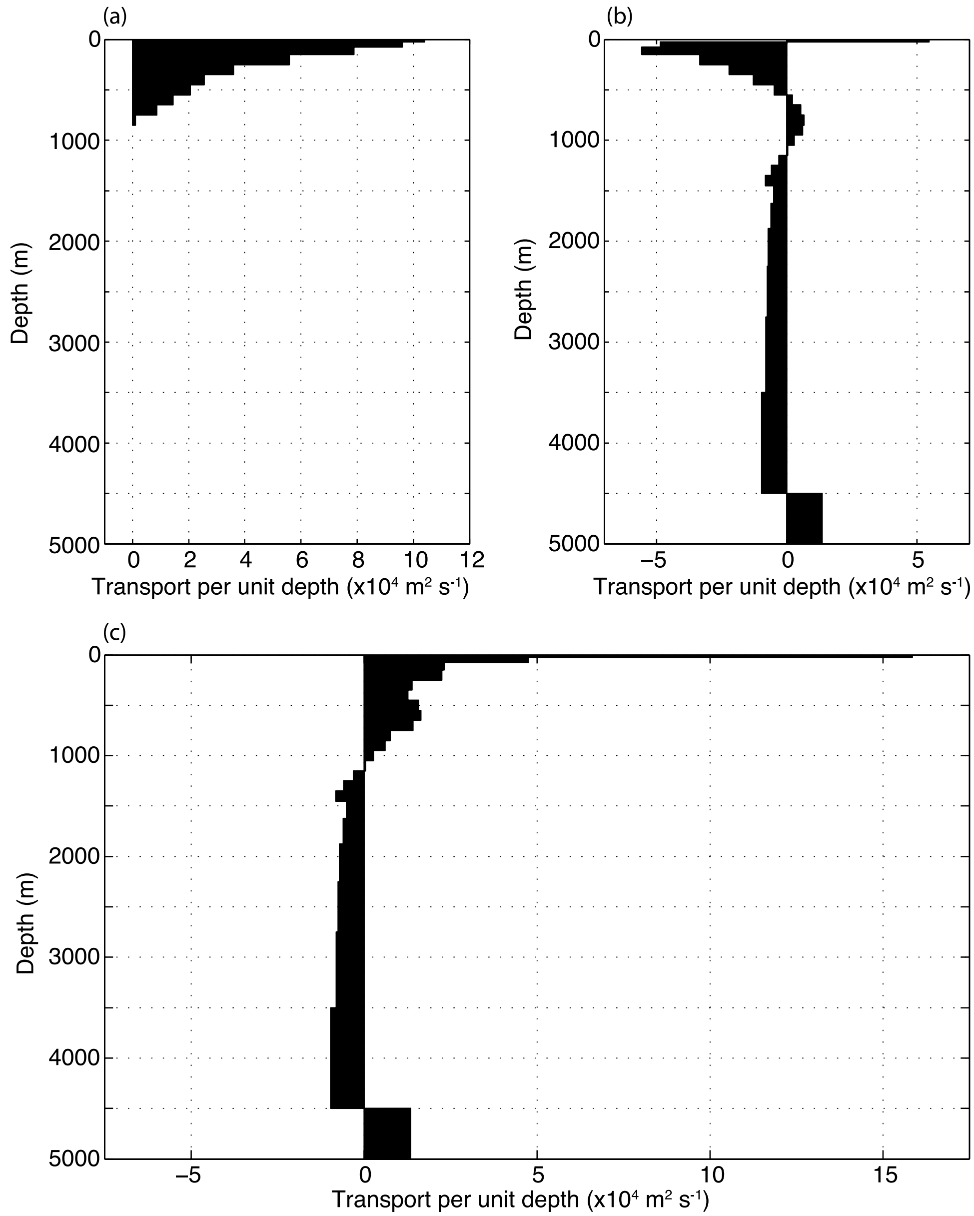

Figure 6. Meridional zonally integrated volume transport per unit depth at 24°N across the Florida Straits (a), the mid-ocean (b) and combined Florida Straits plus mid-ocean (c). Figure produced from Table 5 of *Hall and Bryden* (1982).

calculations at approximately 2 Sv. *Hall and Bryden* [1982] showed that the required southward transport in the mid-ocean to satisfy mass balance with northward Florida Straits transport of 29.5 Sv, occurs predominantly in the lower waters colder than 4°C, rather than in the upper layers at temperatures warmer than 17°C [*Worthington*, 1976]. This reflects the importance of the meridional transport's thermohaline component obtained by *Hall and Bryden* [1982] which was comparable to *Stommel's* [1958] circulation scheme, but more rigorously computed.

The principles of the method developed by *Bryden and Hall* [1980] have been broadly employed to determine overturning strength on subsequent occasions at 25°N, this being arguably best latitude to quantify the meridional cell [*Roemmich*, 1980]. Close to the boundary between ocean heat gain from the atmosphere in the tropics and loss to the atmosphere in the high latitudes, 25°N is near the latitude of maximum heat transport [*Bryden*, 1993]. Errors in geostrophic velocity are reduced relative to the equatorial regions while further north the rougher topography of the Mid-Atlantic Ridge increases noise and smaller vertical density gradients decrease the number of layers and thus the information content of the data in inverse calculations. From knowledge of Florida Current transport from years of monitoring by submarine cable and calibration cruises [*Niiler and Richardson*, 1973; *Larsen*, 1992; *Baringer and Larsen*, 2001] and assuming the Atlantic north of this latitude to be an essentially closed basin, northward transport through the Florida Straits and in the Ekman layer (computed from wind stress climatologies) must be compensated for by southward flow across the mid ocean (Bahamas to Africa). Mass balance may therefore be achieved through imposition of a uniform barotropic compensation velocity. Alternatively a reference level may be identified with the inverse method and additional constraints, for example as done by *Roemmich and Wunsch* [1985]. The subjectivity associated with selection of absolute levels of no motion is thus removed, giving confidence in the zonally integrated transports obtained relative to the earlier transport estimates.

Subsequent sections across 25°N were made in 1981, 1992, 1998 and 2004 [*Roemmich and Wunsch*, 1985; *Parilla et al.*, 1994; *Baringer and Molinari*, 1999; *Bryden et al.*, 2005b], from which the main addition to our understanding of the MOC has resulted from increased vertical resolution due to replacement of bottle samples and reversing thermometers with continuous recording CTD systems; in particular the two-lobe structure of NADW can be better delineated [*Roemmich and Wunsch*, 1985]. The upper lobe centred around 2100m (Figure 7) originates in the Labrador Sea and the lower around 3800m in the Nordic seas. Aside from this, despite employment of a hierarchy of geostrophic models [*Roemmich and Wunsch*, 1985] and incorporation of silica constraints [*Lavín et al.*, 2003] the zonally integrated profile of meridional velocities proposed by *Hall and Bryden* [1982] associated with an overturning circulation of 16-18 Sv at 25°N has provided a robust description of transports in the subsequent sections. The slowed overturning recently reported by *Bryden et al.* [2005b] from observations at 25°N in 1998 and 2004 remains contested [e.g. *Levi*, 2006].

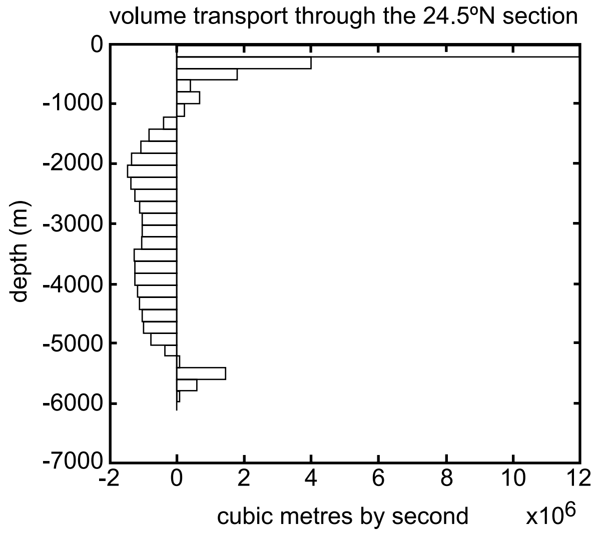

Figure 7. Total volume transport through the 24°N 1992 section by depth classes of 200m, including Florida Straits, Ekman layer and mid-ocean section. From *Lavín et al.* (2003).

7. INDEPENDENT VERIFICATION FOR THE 16-18 SV ATLANTIC MOC

The identification of water masses constituting the DWBC transport [*Roemmich and Wunsch*, 1985] permitted quantitative links to be made with high latitude studies. *McCartney and Talley's* [1984] box model study of warm to cold water conversion in the high latitude North Atlantic provided independent support for the 16-18 Sv strength subtropical Atlantic MOC. They considered the 11.1 Sv DWBC, consisting of 8.5 Sv LSW and 2.5 Sv from the Norwegian Seas, to be in agreement with *Hall and Bryden's* [1982] deep southward transport of 15.6 Sv below 4.0°C with entrainment as the boundary current moves southward.

Additionally an analysis of water mass properties in the Florida Straits and Caribbean passages reinforced the new overturn strength further, through consideration of the rate of replacement of South Atlantic origin waters that feed NADW formation [*Schmitz and Richardson*, 1991]. With a 29 Sv Florida Current, *Schmitz and Richardson* [1991] showed that the subtropical gyre circulation contributed 16 Sv while the remaining 13 Sv was part of the thermohaline circulation originating in the South Atlantic [identified by virtue of its low salinity with 7.1 Sv warmer than 24°C and the rest between 7 and 12°C). A 13 Sv northward interbasin exchange in the upper water column is also consistent with a net southward deep transport of 13 Sv at 32°S with flows of 17 Sv NADW and 4 Sv AABW northward [*Rintoul*, 1991].

Global circulation schemes are a natural progression from the calculation of single section zonally integrated flows, which were so important in determining the strength of the MOC. *Wunsch* [1978] stated that the inverse solution to circulation west of 50°W in the subtropical North Atlantic was in fact a first step towards the production of a circulation budget for the entire Atlantic and ultimately the world oceans. The completed global inversions of WOCE hydrographic sections found 16 ± 5 Sv of net southward transport below 3.5°C across 25°N [*Macdonald and Wunsch*, 1996], a value confirmed by *Ganachaud and Wunsch's* [2000] update but with errors decreased to ± 2 Sv. The global inversion arguably provides a better representation of the mean state of the overturning circulation than a single section through forced consistency between section transports separated both temporally and spatially, and is thus less susceptible to anomalous conditions. The notably good agreement between this global inversion and MOC strength as estimated from the 25°N section [e.g. *Lavìn et al.*, 1998] suggests that the 25°N section and Florida Straits transport are strong constraints in the large scale inversions.

A complementary approach and result were provided by construction of the first Atlantic MOC streamfunction (a diagnostic commonly used in modelling the MOC) from in situ data [*Talley et al.*, 2003]. Argued to be no more subjective than the inverse method, meridional geostrophic velocities computed from observations spanning the period from 1957 to the WOCE sections with adjustments based on observed property distributions are integrated from bottom to top (Figure 8). As expected, the zonally integrated Atlantic MOC is dominated by NADW, including LSW, and AABW cells, transport of the former is 18 Sv with an error of 3-5 Sv at most latitudes. It is expected that future determinations of the streamfunction with global inversions or data assimilation will have an improved accuracy [*Talley et al.*, 2003].

The zonal mean representation (e.g. Figure 8) is useful for an overview of the MOC but conceals the fact that meridional exchange is concentrated in western boundary currents of the upper and deep waters. To complement this we therefore present an update of *Worthington's* [1976] circulation maps

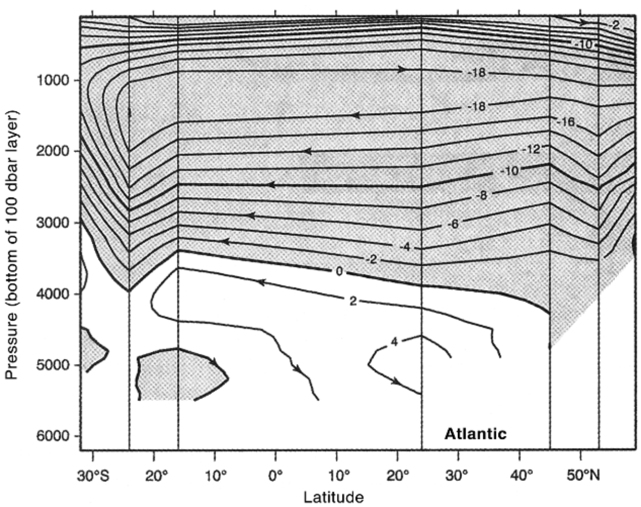

Figure 8. Atlantic meridional overturning streamfunction including Ekman transport, based on observational data. From *Talley et al.* [2003].

(Figure 9), derived from synthesis of many of the aforementioned studies and more, by *Schmitz and McCartney* [1993]. The similarity with *Stommel's* [1958] schematic is notable, but complexity has increased. Recirculation gyres complicate the picture, and their exact offshore extent is unknown even at 25°N and likely to be temporally variable [*Bryden et al.*, 2005a]. The construction of streamlines as in earlier works [e.g. *Worthington*, 1976] is therefore not possible, however desirable.

Finally we note that the strength of the Atlantic MOC has been constrained not only by the traditional water properties of temperature and salinity but also radiocarbon observations [*Broecker*, 1991]. The flux of NADW to the deep North Atlantic is calculated by dividing the deep water volume by

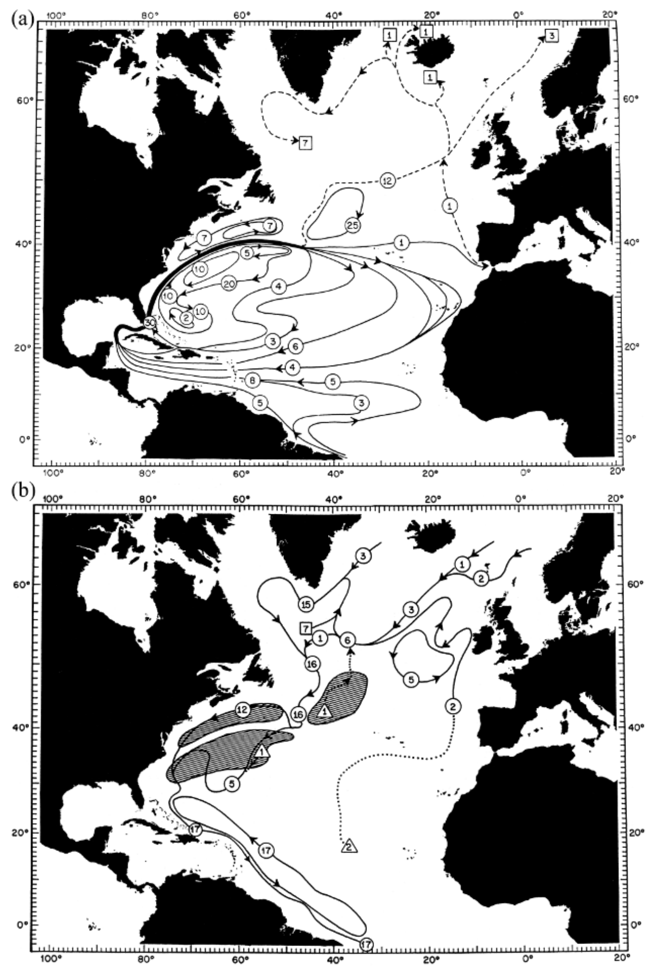

Figure 9. Circulation cartoons for waters warmer than 7°C (a) and 1.8-4°C (b). Transports are in Sv, triangles denote upwelling and squares sinking in or out of the respective layer. In (b) detail of recirculation gyres is omitted and their general position shaded. Additional cartoons for AAIW and AABW are available in *Schmitz and McCartney* [1993], from which we take this figure.

a radiodecay-based residence time with correction for atmospheric carbon ratio changes and the proportion of AABW (estimated from phosphate concentration). *Broecker* [1991] found a NADW flux of 20 Sv, not inconsistent with hydrographic-based transports when the error of order 25% is allowed.

8. SUMMARY

The discovery and quantification of the Atlantic MOC has a long and interesting history. The initial proposition was intuitive; high latitude sinking in both hemispheres with equatorial upwelling produced two equatorially symmetric cells forced by the meridional heat flux gradient. Later contested following observation of cross equatorial flows, Wüst's classical picture of interhemispheric exchange evolved [*Wüst*, 1935]. High latitude sinking is found in both hemispheres but NADW formation dominates interhemispheric exchange. This shows a layered structure: schematically northward in the surface waters and southward at depth with northward AABW and AAIW flow in southern and low northern latitudes. Obtained through water mass analysis and the definition of core layers that identified the spreading path of waters from their formation site, Wüst's circulation scheme was broadly confirmed through analysis of later hydrographic sections with geostrophic velocities expressed as a zonal integral [e.g. *Stommel*, 1958; *Hall and Bryden*, 1982; *Lavìn et al*., 1998].

A strength of 16-18 Sv (definitions vary among references but can be broadly regarded as the net meridional deep water transport) is supported by observational studies with data encompassing single hydrographic sections [e.g. *Lavìn et al*., 1998], regional and global inversions [e.g. *Roemmich and Wunsch*, 1985; *Ganachaud and Wunsch*, 2000], water mass property analysis [*Schmitz and Richardson*, 1991] and radiocarbon observations [*Broecker*, 1991]. While it was Stommel's insightful two layer circulation scheme of the late 1950's [*Stommel*, 1957] which first proposed an overturning two to three times stronger than the previous 6-8 Sv cross equatorial deep water transport, it was not until analysis of the 1957 *Discovery* 25°N section in the 1980's that the 16-18 Sv overturning was formally computed and thus gained widespread recognition. Early works were largely inhibited by controversial choice of reference level velocities in geostrophic calculations, later avoided through employment of mass balance starting with *Stommel* [1958] and later by the many authors working with the 1957 25°N section.

We have here only reviewed the steady state case since all independent observations are consistent within the errors estimated: even *Bryden et al*. [2005b]'s changes are at the limit of the 6 Sv error associated with analysis of single hydrographic sections [*Ganachaud*, 2003]. The large error of many estimates clearly reflects variability in the system: quantification and interpretation of such variability presents numerous current and future challenges. To date work in this field has been hampered by limited observations, but nonetheless potential variability sources have been identified. The dominant mode of atmospheric variability in the North Atlantic, the North Atlantic Oscillation (NAO) can affect the strength and character of the Atlantic thermohaline circulation through altered air sea exchange of heat and freshwater [*Hurrel et al*., 2001] and transport of the North Atlantic Current, which supplies the high latitude NADW sinking sites, varies as a lagged response to the NAO [*Curry and McCartney*, 2001]. Freshening of the Nordic Sea overflows since 1965 [*Dickson et al*., 2002] is anticipated to be accompanied by changes in the overturning strength and has been linked to an increasingly positive state of the NAO [*Dickson et al*., 2003]. Observations of the Faroe Bank Channel overflow have indeed shown this not to have been constant over the last 50 years [*Hansen et al*., 2001]. Furthermore feedback mechanisms between LSW formation and the strength of the MOC have been suggested [*Koltermann et al*., 1999]. At the southern end of the system, Agulhas leakage, which in part feeds the NADW return flow, contributes to the salty thermocline of the Atlantic and thus NADW formation [*Gordon et al*., 1992]. Agulhas leakage may influence the MOC through the effect of the lateral buoyancy flux on the available potential energy [*Weijer et al*., 1999] and is itself temporally variable. All such mechanisms causing variability in the Atlantic overturning await conclusive study.

REFERENCES

Amos, A.F., A.L. Gordon, and E.D. Schneider, Water masses and circulation patterns in the region of the Blake-Bahama Outer Ridge. *Deep-Sea Research*, 18, 145-165, 1971.

Baringer, M.O., and R.L. Molinari, Atlantic Ocean baroclinic heat flux at 24 to 26°N. *Geophysical Research Letters*, 26, 353-356, 1999.

Baringer, M.O., and J.C. Larsen, Sixteen years of Florida Current transport at 27°N. *Geophysical Research Letters*, 28, 3179-3182, 2001.

Broecker, W.S., The Great Ocean Conveyor. *Oceanography*, 4, 79-89, 1991.

Bryan, K., Measurements of meridional heat transport by ocean currents. *Journal of Geophysical Research*, 67, 3403-3414, 1962.

Bryden, H.L., Ocean heat transport across 24°N latitude. *Interactions Between Global Climate Subsystems: The Legacy of Hann*, G.A. McBean and M. Hantel, Eds., American Geophysical Union, pp.65-75, 1993.

Bryden, H.L., and M.M. Hall, Heat transport by currents across 25°N latitude in the Atlantic Ocean. *Science*, 207, 884-886,1980.

Bryden, H.L., W.E. Johns, and P.M. Saunders, Deep western boundary current east of Abaco: Mean structure and transport. *Journal of Marine Research*, 63, 35-57, 2005a.

Bryden, H.L., H.R. Longworth, and S. Cunningham, Slowing of the Atlantic meridional overturning circulation at 25°N. *Nature*, 438, 655-657, 2005b.

Curry, R.G., and M.S. McCartney, Ocean gyre circulation changes associated with the North Atlantic Oscillation. *Journal of Physical Oceanography*, 31, 3374-3400, 2001.

Deacon, M., *Scientists and the Sea 1650-1990. A study of marine science.* Academic press, London, 1971.

Deacon, M., An early theory of ocean circulation: J.S. von Waitz and his explanation of the currents in the Strait of Gibraltar. *Progress in Oceanography,* 31, 3374-3400, 1985.

Defant, A., Quantitative Untersuchungen zur Statik und Dynamik des Atlantischen Ozeans. Die relative Topographie Einzelner Druckflachen im Atlantischen Ozean (The Relative Topography of individual pressure surfaces of the Atlantic Ocean). *Wissenschaftliche Ergebnisse der Deutschen Atlantischen Expedition auf dem Forschungs und Vermessungsschiff "Meteor" 1925-1927.* 6: 2nd Part, 1941.

Dickson, B., I. Yashayaev, J. Meincke, B. Turrell, S. Dye, and J. Holfort, Rapid freshening of the deep North Atlantic Ocean over the past four decades. *Nature*, 416, 832-837, 2002.

Dickson, R.R., R. Curry, and I. Yashayaev, Recent changes in the North Atlantic. *Philosophical Transactions of the Royal Society of London A*, 361, 1917-1934, 2003.

Ganachaud, A., Error budget of inverse box models: The North Atlantic. *Journal of Atmospheric and Oceanic Technology*, 20, 1641-1655, 2003.

Ganachaud, A. and C. Wunsch, Improved estimates of global ocean circulation, heat transport and mixing from hydrographic data. *Nature*, 408, 453-456, 2000.

Gordon, A.L., R.F. Weiss, W.M.J. Smethie, and M.J. Warner, Thermocline and intermediate water communication between the South Atlantic and Indian Oceans. *Journal of Geophysical Research*, 97, 7223-7240, 1992.

Hall, M.M., and H.L. Bryden. Direct estimates and mechanisms of ocean heat transport, *Deep-Sea Research*, 29(3A), 339-359, 1982.

Hansen, B., W.R. Turrell, and S. Østerhus, Decreasing overflow from the Nordic seas into the Atlantic Ocean through the Faroe Bank channel since 1950. *Nature*, 411, 927-930, 2001.

Hurrell, J.W., Y. Kushnir, and M. Visbeck, The North Atlantic Oscillation. *Science*, 291, 603-605, 2001.

Jung, G.H., Note on the meridional transport of energy by the oceans. *Journal of Marine Research*, 11, 139-146, 1952.

Jung, G.H., *Heat Transport in the North Atlantic Ocean*. Ref 53-54T, Department of Oceanography, A and M College of Texas, Texas, U.S.A, 1955.

Koltermann, K.P., A.V. Sokov, V.P. Tereschenkov, S.A. Dobroliubov, K. Lorbacher, and A. Sy, Decadal changes in the thermohaline circulation of the North Atlantic. *Deep-Sea Research II*, 46, 109-138, 1999.

Larsen, J.C., Transport and heat flux of the Florida Current at 27°N derived from cross-stream voltages and profiling data: theory and observations. *Philosophical Transactions of the Royal Society of London A*, 338, 169-236, 1992.

Lavín, A., H.L. Bryden, and G. Parrilla, Meridional transport and heat flux variations in the subtopical North Atlantic. *The Global Atmosphere and Ocean System*, 6, 269-293, 1998.

Lavín, A.M., H.L. Bryden, and G. Parrilla, Mechanisms of heat, freshwater, oxygen and nutrient transports and budgets at 24.5°N in the subtropical North Atlantic. *Deep-Sea Research I*, 50, 1099-1128, 2003.

Lee, T.N., W.E. Johns, R.J. Zantopp, and E.R. Fillenbaum, Moored observations of Western Boundary Current variability and Thermohaline Circulation at 26.5°N in the Subtropical North Atlantic. *Journal of Physical Oceanography*, 26, 962-983, 1996.

Levi, B.G., Is there a slowing in the Atlantic Ocean's overturning circulation? *Physics Today*, 59, 26-28, 2006.

Macdonald, A.M., and C. Wunsch, An estimate of global ocean circulation and heat fluxes. *Nature*, 382, 436-439, 1996.

McCartney, M.S., and L.D. Talley, Warm-to-cold water conversion in the northern North Atlantic ocean. *Journal of Physical Oceanography*, 14, 922-935, 1984.

Mills, E.L., From *Discovery* to discovery: the hydrology of the Southern Ocean, 1885-1937. *Archives of Natural History*, 32, 246-264, 2005.

Niiler, P.P., and W.S. Richardson, Seasonal variability of the Florida Current, *Journal of Marine Research,* 31, 144-167, 1973.

Parilla, G., A. Lavìn, H. Bryden, M. Garcia, and R. Millard, Rising temperatures in the subtropical North Atlantic Ocean over the past 35 years. *Nature*, 369, 48-51, 1994.

Reid, J.L., On the mid-depth circulation of the World Ocean. *Evolution of Physical Oceanography*, B.A. Warren and C. Wunsch, Eds., Massachusetts Institute of Technology, pp.70-111, 1981.

Richardson, P.L., On the crossover between the Gulf Stream and the Western Boundary Undercurrent. *Deep-Sea Research,* 24, 139-159, 1977.

Riley, G.A., Oxygen, phosphate and nitrate in the Atlantic Ocean. *Bulletin of the Bingham Oceanographic Collection*, 13, 1-126, 1951, 1951.

Rintoul, S.R., South Atlantic interbasin exchange. *Journal of Geophysical Research*, 96, 2675-2692, 1991.

Roemmich, D.H., Estimation of meridional heat flux in the North Atlantic by inverse methods, *Journal of Physical Oceanography*, 10, 1972-1983, 1980.

Roemmich, D., and C. Wunsch, Two transatlantic sections: meridional circulation and heat flux in the subtropical North Atlantic Ocean. *Deep Sea Research*, 32, 619-664, 1985.

Schmitz, W.J., On the interbasin-scale thermohaline circulation. *Reviews of Geophysics,* 33, 151-173, 1995.

Schmitz, W.J. Jr., and M.S. McCartney, On the North Atlantic Circulation. *Reviews of Geophysics*, 31, 29-49, 1993.

Schmitz, W.J., and P.L. Richardson, On the sources of the Florida Current. *Deep Sea Research*, 38, S379-S409, 1991.

Stommel, H., A survey of ocean current theory. *Deep-Sea Research,* 4, 149-184, 1957.

Stommel, H., *The Gulf Stream*. Cambridge University Press, pp.153-172, 1958.

Stommel, H. and A.B. Arons, On the abyssal circulation of the world ocean-I. Stationary planetary flow patterns on a sphere. *Deep-Sea Research*, 6, 140-154, 1960a.

Stommel, H. and A.B. Arons, On the abyssal circulation of the world ocean-II. An idealized model of the abyssal circulation pattern and amplitude in oceanic basins. *Deep-Sea Research*, 6, 217-233, 1960b.

Stommel, H., A.B. Arons, and A.J. Faller, Some examples of stationary planetary flow patterns in bounded basins. *Tellus*, 2, 179-187, 1958.

Sverdrup, H.U., M.W. Johnson, and R.H. Fleming. *The Oceans: their Physics, Chemistry and General Biology*. Prentice-Hall, Englewood Cliffs, N.J. 1087 pp., 1942.

Swallow, J.C., and L.V. Worthington, Measurements of deep currents in the western North Atlantic, *Nature,* 179, 1183-1184, 1957.

Swallow, J.C., and L.V. Worthington, An observation of a deep countercurrent in the western North Atlantic. *Deep-Sea Research,* 8, 1-19, 1961

Talley, L.D., J.L. Reid, and P.E. Robbins, Data-based meridional overturning streamfunctions for the Global Ocean. *Journal of Climate*, 16, 3213-3226, 2003.

Warren, B.A., Deep circulation of the World Ocean. *Evolution of Physical Oceanography*, B.A. Warren and C. Wunsch, Eds., Massachusetts Institute of Technology, pp.6-41, 1981.

Weijer, W., W.P.M. de Ruijter, H.A. Dijkstra, and P.J. van Leeuwen, Impact of Interbasin Exchange on the Atlantic Overturning Circulation. *Journal of Physical Oceanography*, 29, 2266-2284, 1999.

Worthington, L.V., *On the North Atlantic circulation*. Vol. 6, *The John Hopkins Oceanographic Studies*, The John Hopkins University Press, 110 pp., 1976.

Worthington, L.V., Oceanographic Data from the RRS Discovery II during the International Geophysical Year, Woods Hole Oceanographic Institution Technical Report 58-30, Woods Hole MA, 58p, 1958.

Wunsch, C., Determining the general circulation of the oceans: A preliminary discussion. *Science*, 196, 871-875, 1977.

Wunsch, C., The North Atlantic General Circulation West of 50°W Determined by Inverse Methods. *Reviews of Geophysics and Space Physics*, 16, 583-620, 1978.

Wunsch, C., Meridional heat flux of the North Atlantic Ocean, *Proceedings of the National Academy of Sciences, U.S.A.,* 77, 5043-5047, 1980.

Wüst, G., Schichtung und Zirkulation des Atlantischen Ozeans, Die Stratospháre. *Wissenschaftliche Ergebnisse der Deutschen Atlantischen Expedition auf dem forschuungs und Vermessungsschiff "Meteor" 1925-1927.* 6: 1st Part. 180pp (*The stratosphere of the Atlantic Ocean*, WJ Emery (ed), 1978, Amerind, New Delhi, 112pp), 1935.

Wüst, G., Stromgeschwindigkeiten im Tiefen- und Bodenwasser des Atlantischen Ozeans auf Grund dynamischer Berechnung der *Meteor*-Profile Deutschen Atlantischen Epedition 1925/27. *Deep Sea Research,* 3 (Supplement), 373-395, 1955.

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A Simple Theory of the Pycnocline and Overturning Revisited

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A simple theory linking the pycnocline depth and volume transport of the thermohaline overturning to winds, eddies, surface densities and diapycnal diffusion was proposed by *Gnanadesikan* (Science, 283:2077-2079, 1999). This paper revisits this theory, with eye to understanding which predictions are robust, and which may be limited by the geometric simplification required to derive such a simple theory. We show that the theory works extremely well for diagnostic models, in which surface density is fixed. It thus appears that the model can be used as a diagnostic framework for understanding mechanisms behind circulation changes. The key insight of the theory that the Southern Ocean, rather than the tropics, can serve as a pathway for transformation of dense water to light water is supported by the observed distribution of radiocarbon. However, we demonstrate that changes in forcing do more than simply scale the magnitude of the circulation up and down, producing changes in pycnocline shape and circulation geometry. In particular, the roles of buoyancy forcing and stationary eddies are more complicated than would be expected from the simple theory. Such changes must be taken into account when interpreting measurements at individual locations.

1. INTRODUCTION

Understanding variability in the meridional overturning circulation requires linking changes in surface forcing and internal mixing to modifications of the thermal structure, differences in the rate of formation of deep waters, and shifts in the locations where these waters are formed. It is thus closely linked to the question of how the ocean circulation is "driven"—which has been debated for many years. In his classic "Physical Geography of the Oceans" (reprinted in 1963), Matthew Fontaine Maury argued that the dominant mechanism for driving such currents was the heating of the tropics and cooling of polar latitudes. In such a picture, one would primarily look to changes in the hydrological cycle or surface heat balance to explain changes in overturning, as in the classic box models of *Stommel* [1961]. By contrast, Maury fulminated against those who supposed that the ocean circulation was wind-driven, arguing that the variable winds of the Atlantic could never produce the steady Gulf Stream.

The idea of a thermally-driven overturning was challenged by *Sandstrom* [1908] who argued that in a domain where heating occurs at the same level as cooling, a large-scale circulation cannot be generated in the absence of

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diffusion. While various parts of "Sandstrom's theorem" appear to be incorrect [*Coman et al*., 2006], his work contains a fundamental insight. When buoyancy is added at the same level at which it is removed, the vertical buoyancy flux, and hence the buoyancy work is zero [*Papparella and Young*, 2002; *Gnanadesikan et al*., 2005]. Thus even insofar as the ocean overturning is affected by buoyancy forcing, some source of energy is required to provide the mechanical driving for the system—particularly over long time periods and relatively large vertical length scales [*Munk and Wunsch*, 1998; *Huang*, 1999].

Two such sources have been proposed. One is the internal mixing driven by breaking internal waves. In a seminal paper, *Bryan* [1987] discussed the dynamics of an overturning whose magnitude is controlled by the vertical diffusion—which in turn is governed by the internal wave field controlled by winds and tides. The second possible source of energy is the work done by the wind on the surface geostrophic currents. There are two types of circulation schemes that make use of this idea. The first [most clearly expressed by *Toggweiler and Samuels*, 1993, 1998] suggests that it is the winds within the Southern Ocean that are most important. Within this scheme, the dominant location where water is transformed from dense to light is the Southern Ocean and changes in the density in the north would be expected to change only the pycnocline depth. A second set of schemes, as described by *Salmon* [1990], *Samelson and Vallis* [1997] and *Vallis* [2000], link the depth of the pycnocline to mid-latitude Ekman pumping. In these schemes the balance is between the wind stress curl- which pumps light water down into the interior, and boundary currents which return it to higher latitudes.

Gnanadesikan [1999, henceforth G99] developed a simple theory that melded the *Bryan* [1987] and *Toggweiler and Samuels* [1993] ideas for determining the depth of the pycnocline as well as including the impact of mesoscale eddies. This paper revisits the G99 theory, reviewing some of the ways in which it succeeds in describing ocean models—and some ways in which it falls short. Section 3 demonstrates that the theory works well in a diagnostic sense to explain the overall circulation and that the distribution of radiocarbon supports the idea that the Southern Ocean is in fact the principal region of dense-to-light water conversion in the present-day ocean. However, in the following sections we demonstrate that theory does not capture some aspects of the circulation that are important in interpreting past measurements. Section 4 examines how the geometry of the circulation changes in response to changes in forcing, highlighting the role of stationary eddies. Section 5 discusses the role of the reduced gravity in setting the geometry and sensitivity of the solutions. Finally Section 6 shows that the shape of the pycnocline may change in response to forcing changes. Section 7 concludes the paper.

2. THEORY AND MODELS

The basic idea behind the G99 theory is illustrated in Figure 1. Closures for the northern overturning M_n and tropical upwelling flux M_u in terms of the pycnocline depth D, which is defined as the depth above which ~80-90% of the density anomaly is found. For purposes of this paper we will adopt the definition

$$D = 2\frac{\int_{z=-2500}^{0} (\sigma_2(z) - \sigma_2(z=-2500))z\,dz}{\int_{z=-2500}^{0} (\sigma_2(z) - \sigma_2(z=-2500))\,dz} \tag{1}$$

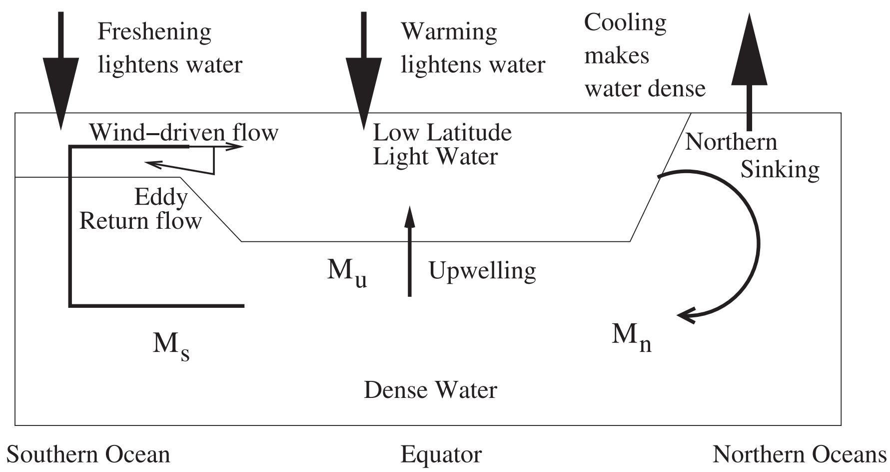

Figure 1. A schematic of the overturning circulation in the G99 model.

A depth of 2500m is used to avoid spurious effects due to topography as most of the ocean ridges (at least in the coarse models we use here) lie below these depths. When calculated from the World Ocean Atlas for the region from 30°S to 40°N, D has a value of 894m. Closures to link D with the overturning fluxes may be taken following *Bryan* [1987] and *Park* [1999] as

$$M_n = g'D^2/\varepsilon \tag{2a}$$

$$M_u = 2K_v A/D \tag{2b}$$

Where g' is the density contrast associated with the pressure gradient driving the overturning, ε is a "resistance coefficient" which embodies the effects of friction and geometry, K_v is the vertical diffusive coefficient, and A is the area of the tropical oceans. G99 added two other terms in the Southern Ocean, an Ekman upwelling term M_{ek} and an eddy-induced advection term M_{eddy}.

$$M_{ek} = \tau L_x/\rho f \tag{3a}$$

$$M_{eddy} = A_I L_x D/L_y \tag{3b}$$

Where τ is the mean wind stress at the tip of Drake Passage, L_x is length of the latitude circle, ρ is the density, f the Coriolis parameter, A_I the Gent-McWilliams diffusion coefficient and L_y the horizontal scale over which the pycnocline shallows in the south. Assuming a steady-state mass balance then leads to

$$g'D^2/\varepsilon + A_I L_x D/L_y = \tau L_x/\rho f + 2K_v A/D \tag{4}$$

This equation has several revealing limiting cases. If the Southern Ocean terms are set to zero, one recovers the result of *Bryan* [1987] that the overturning

$$D = (2K_v A\varepsilon/g')^{1/3} \tag{5a}$$

$$M_n = M_u = (g'K^2{}_v A^2/\varepsilon)^{1/3} \tag{5b}$$

This classic result suggests that increasing the density contrast between the polar North Atlantic and the tropics will result in reducing the pycnocline, but increasing the overturning. It also requires a relatively large vertical diffusion to supply the roughly 18 Sv of North Atlantic Deep Water (NADW) formation. If A is the area of the oceans between 30°S and 40°N (2.0×10^{14} m^2) and D=894m, then the required diffusion is 4×10^{-5} m^2/s. Following recent calculations by *St. Laurent and Simmons* [2006] the energy required to support such a high mixing coefficient is 2.2 PW for the pycnocline alone, far larger than the approximately 1 PW supplied by winds. A key prediction of this model is thus that tidal mixing should play a major role in overturning and climate. A second prediction which is relevant to paleoclimate is that changes in the hydrological cycle will produce opposite changes in the pycnocline depth and overturning. The only way to get both the overturning and pycnocline depth to decrease [as for example *Lynch-Stieglitz et al*., 1999, suggest occurred during the last Ice Age] is to decrease the diapycnal diffusion coefficient.

A second limit of the theory is when K_v is set to 0 and, as in *Marshall and Radko* [2003], the vertical diffusion coefficient depends on the slope of the pycnocline ($A_I \sim D$). In this limit the pycnocline depth goes as the square root of the wind stress, with the fraction of upwelling supplied by diapycnal transformation or transient eddy fluxes remaining constant. This limit qualitatively describes eddy-resolving models of the Southern Ocean [*Hallberg and Gnanadesikan*, 2001, 2006] in cases where the Ekman flux is not significantly larger than the buoyancy transformation. In this version of the theory, both pycnocline depth and overturning can decrease if the Southern Ocean winds decrease and the pycnocline depth goes as the square root of the wind stress.

It has been noted that the G99 theory does not include a representation of the effects of mid-latitude wind stress curl. One reason for this may be found in the contemporaneous simulations reported in *Gnanadesikan and Hallberg* [2000] that look at the impact of changes in wind stress and wind stress curl on the transport of the Antarctic Circumpolar Current. In this work, wind stress offsets that changed the Ekman flux, but not the Ekman pumping, were compared with increases and decreases in the magnitude of the wind stress. As seen in Figures 10 and 14 of *Gnanadesikan and Hallberg* [2000], the runs with offsets are not significantly different from the runs with winds scaled up and down, suggesting that it is the stress and not the wind stress curl that matters (at least in diagnostic models).

There have been a number of tests of the theory in addition to the qualitative evaluation of G99. One particular area of concern has been the degree to which the northern overturning and density structure responds to Southern Ocean winds. *Klinger et al*. [2003] demonstrated that the G99 theory worked in a set of idealized ocean-only models, but argued that the wind effect was relatively small. *Vallis* [2000] also found a relatively small effect from changing Southern Ocean winds but a noticeable impact of changing the low-latitude wind stress curl. *Gnanadesikan et al*. [2003] presented an evaluation of the theory for a relatively limited set of coarse-resolution global runs arguing that dominance of tropical upwelling seen in *Klinger et al*. [2003] and *Vallis* [2000] was a result of using a small basin. This study did not, however, look at how well the theory predicted the response to changes in winds.

A second area of concern regards the role of density (subsumed in the g′ parameter), which may be more complicated than allowed for in the G99 theory. In general, the buoyancy