Discovery and quantification of the Atlantic Meridional Overturning Circulation: the importance of 25ºN

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Abstract

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 24ºN, 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 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 1200 m 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 25ºN, 25ºW (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 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 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 50ºN to 50ºS (reviewed by Reid, 1981). Defant's flow field at 2000m shows a continuous current from the Labrador Sea to 35ºS 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 10º x 10º boxes covering the Atlantic from 60ºN to 60ºS 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 3(i) and (ii)): 10 Sv of NADW formation but with 4 Sv recirculating north of 40ºN, and 1 Sv 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 30ºS to 50ºN, 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 40ºN (Figure 5), 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 4ºC 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 10ºS and 30ºS (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 35ºN 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 30ºN 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 27ºN 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 27ºN 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 36ºN 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* 25ºN 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 25ºN 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 25ºN 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 7ºC, 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 in the following section). Furthermore, Wunsch (1980), using model circulations and the inverse method on a dataset of meridional and zonal hydrographic sections in the North Atlantic between 10º and 60ºN found a conversion of 16 Sv of the 31 Sv Florida Straits transport to waters colder than 4.6ºC 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* 25ºN 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 25ºN 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 6 (ii)) 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 6(i)), we see net northward and southward flows above and below 1150m respectively comprising the meridional overturn (Figure 6(iii)). 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 4ºC from 7 Sv to 15.6 Sv, and an additional 3 Sv in the 4-7ºC waters (Table 1) corresponding to NADW transport. Hall and Bryden (1982) also quantified the northward flow of AAIW as 7-12ºC waters that had not featured in Worthington's (1976) 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 4ºC, rather than in the upper layers at temperatures warmer than 17ºC (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 25ºN, 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, 25ºN 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 25ºN 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 25ºN has provided a robust description of transports in the subsequent sections. The slowed overturning recently reported by Bryden et al. (2005b) from observations at 25ºN in 1998 and 2004 remains contested (e.g. Levi, 2006).

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 4.0ºC Sv 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 24ºC and the rest between 7 and 12ºC). A 13 Sv northward interbasin exchange in the upper water column is also consistent with a net southward deep transport of 13 Sv at 32ºS 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 50ºW 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 3.5ºC across 25ºN (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 25ºN section (e.g. Lavín et al., 1998) suggests that the 25ºN 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 3-5Sv 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 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 25ºN 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 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; Lavín 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. Lavín 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* 25ºN 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 25ºN 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.

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Figure and Plate Captions

Plate 1 Discovery leaving Woods Hole, Massachusetts in 1957.

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

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.

Figure 3 The North Atlantic circulation according to Worthington (1976) of the total water column (i) and the deep waters (colder than 4ºC) only (ii). (i) does not show the 1 Sv of Mediterranean Water formation. The side insert of (ii) 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.

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 6. 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.

Figure 6 Meridional zonally integrated volume transport per unit depth at 24ºN across the Florida Straits (i), the mid-ocean (ii) and combined Florida Straits plus mid-ocean (iii). Figure produced from Table 5 of Hall and Bryden (1982).

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

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

Figure 9 Circulation cartoons for waters warmer than 7ºC (i) and 1.8-4ºC (ii). Transports are in Sv, triangles denote upwelling and squares sinking in or out of the respective layer. In (ii) 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.

Tables

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

Table 1 Meridional volume transports across 25ºN 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.

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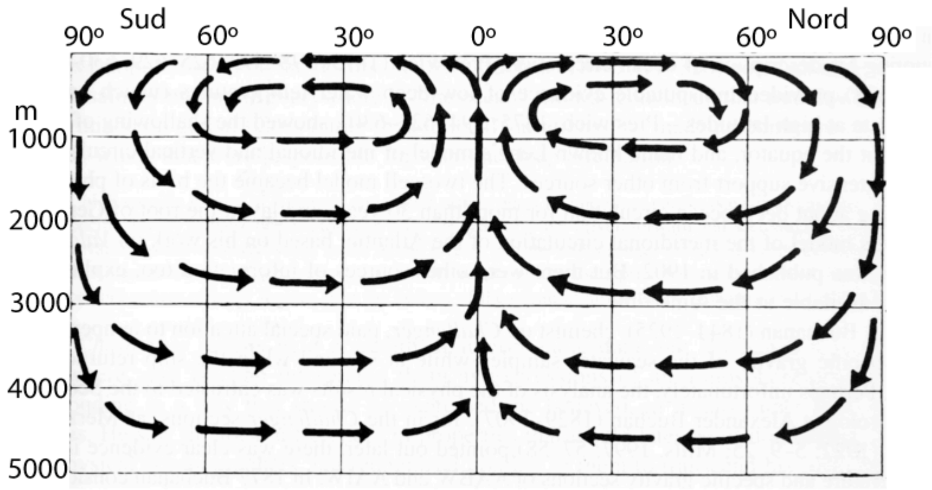
Plate 1 Discovery leaving Woods Hole, Massachusetts in 1957.



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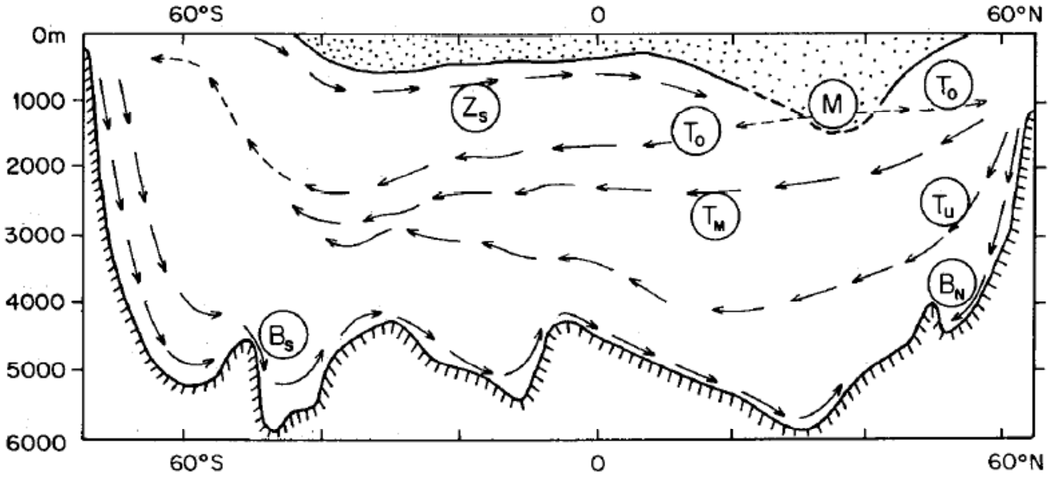

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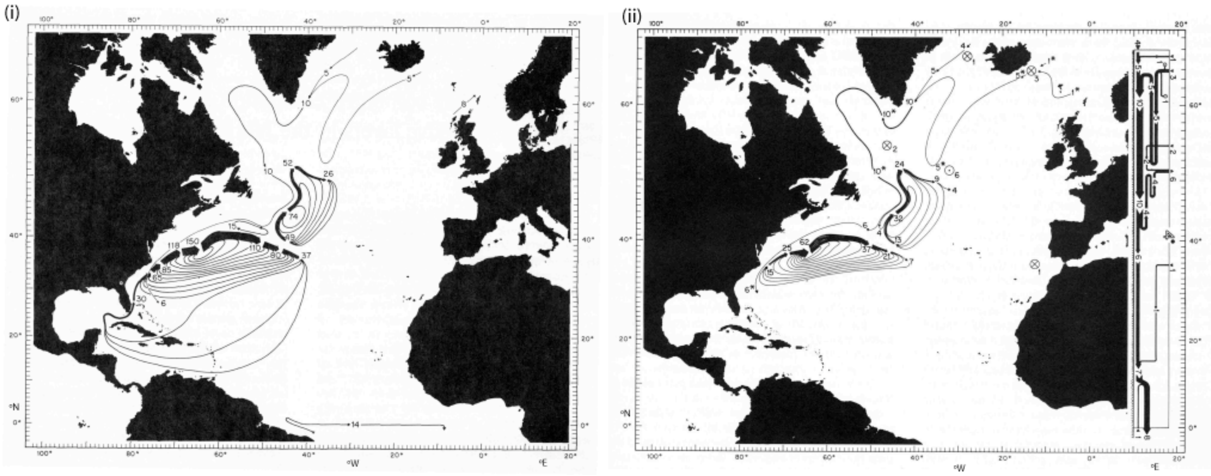

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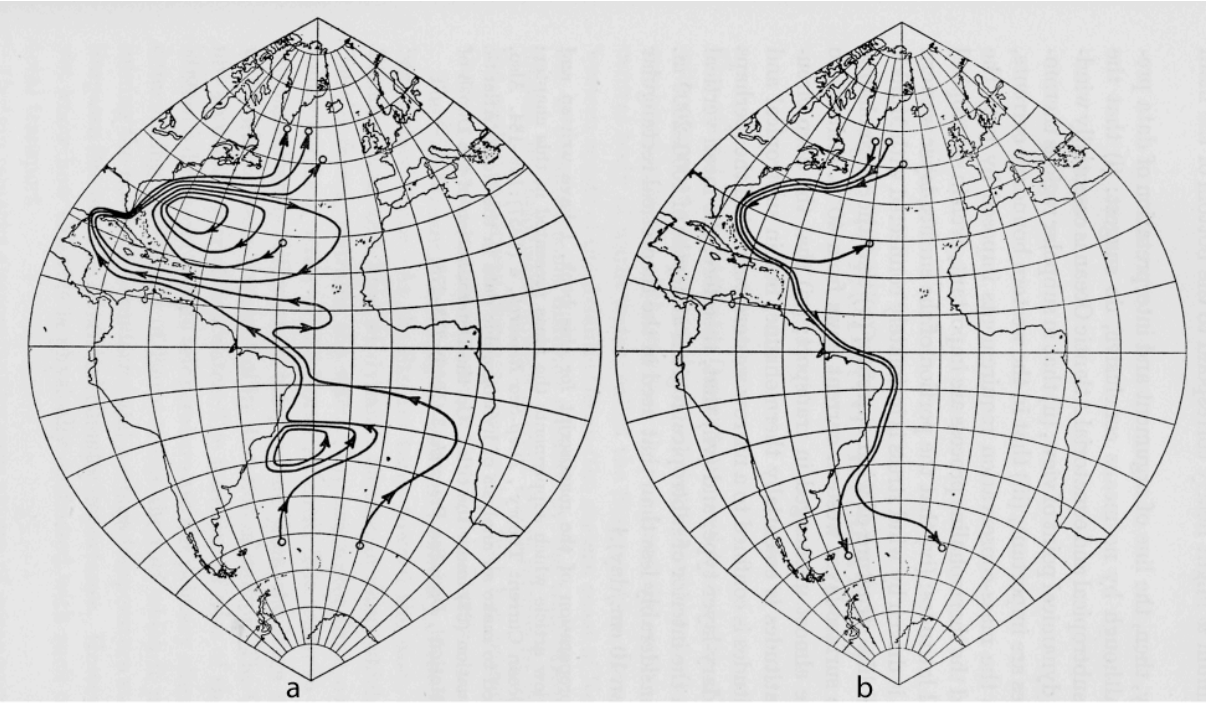

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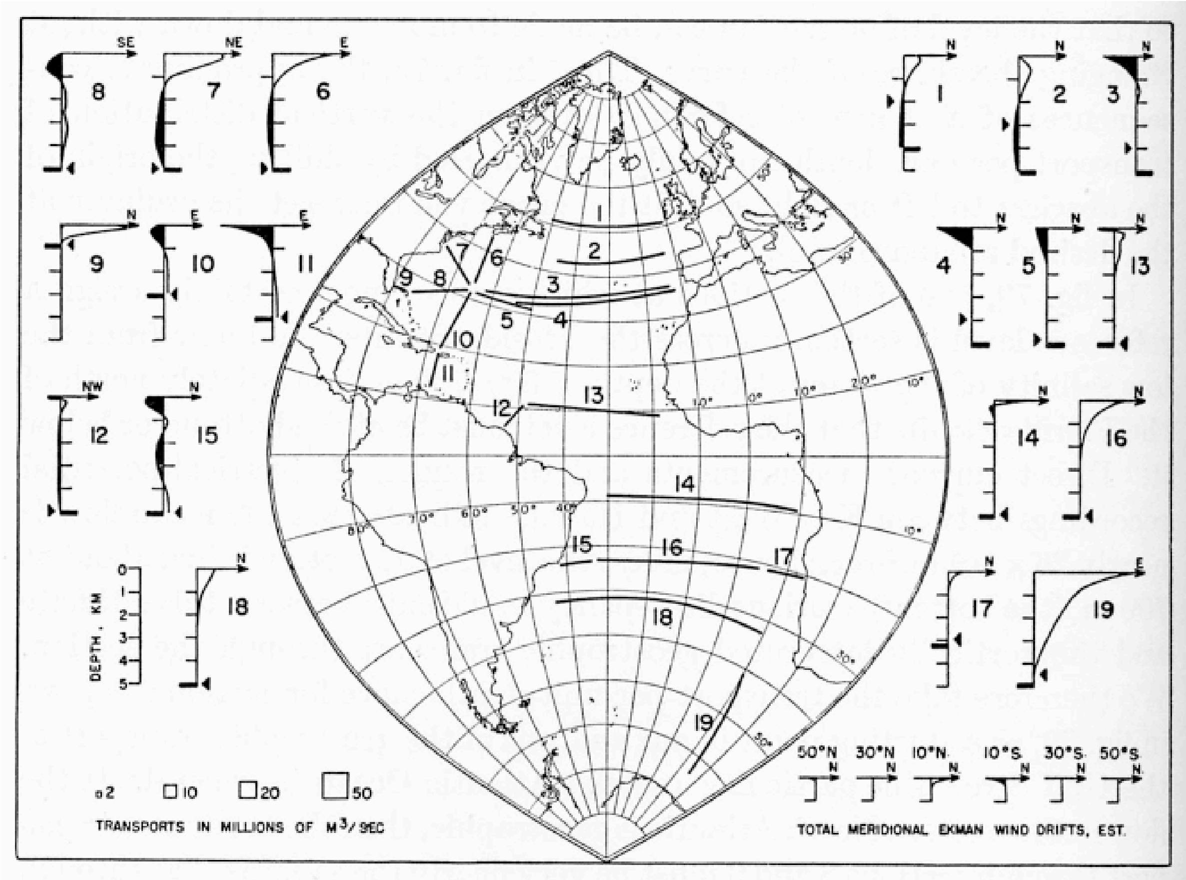

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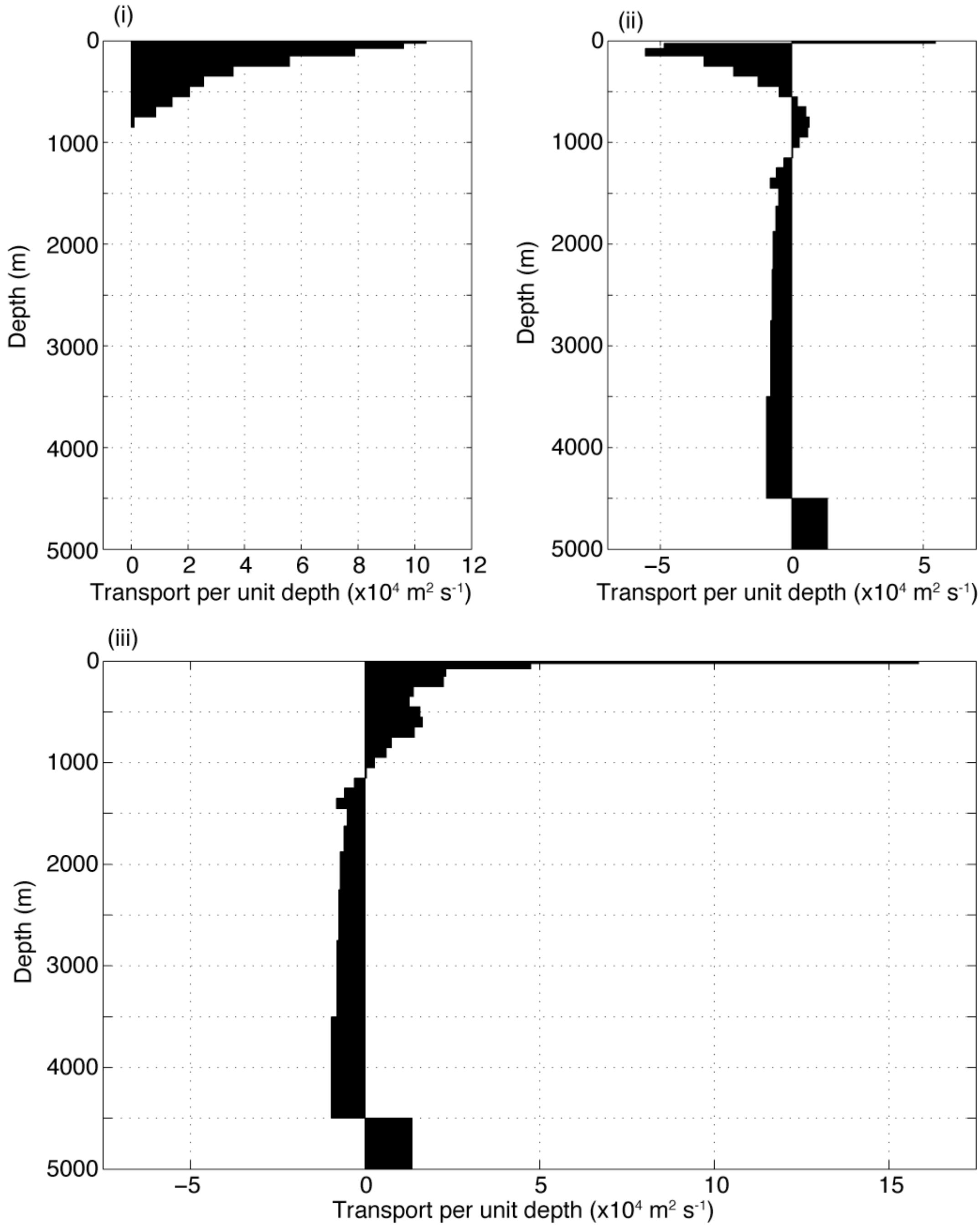

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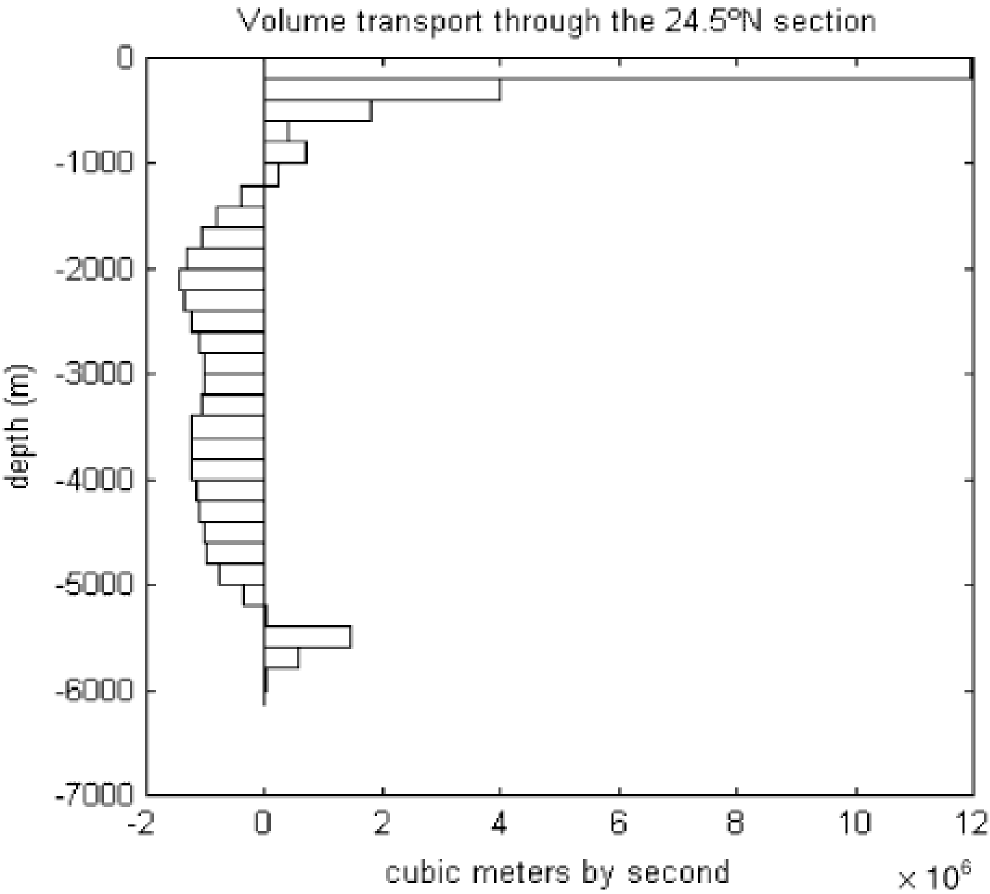

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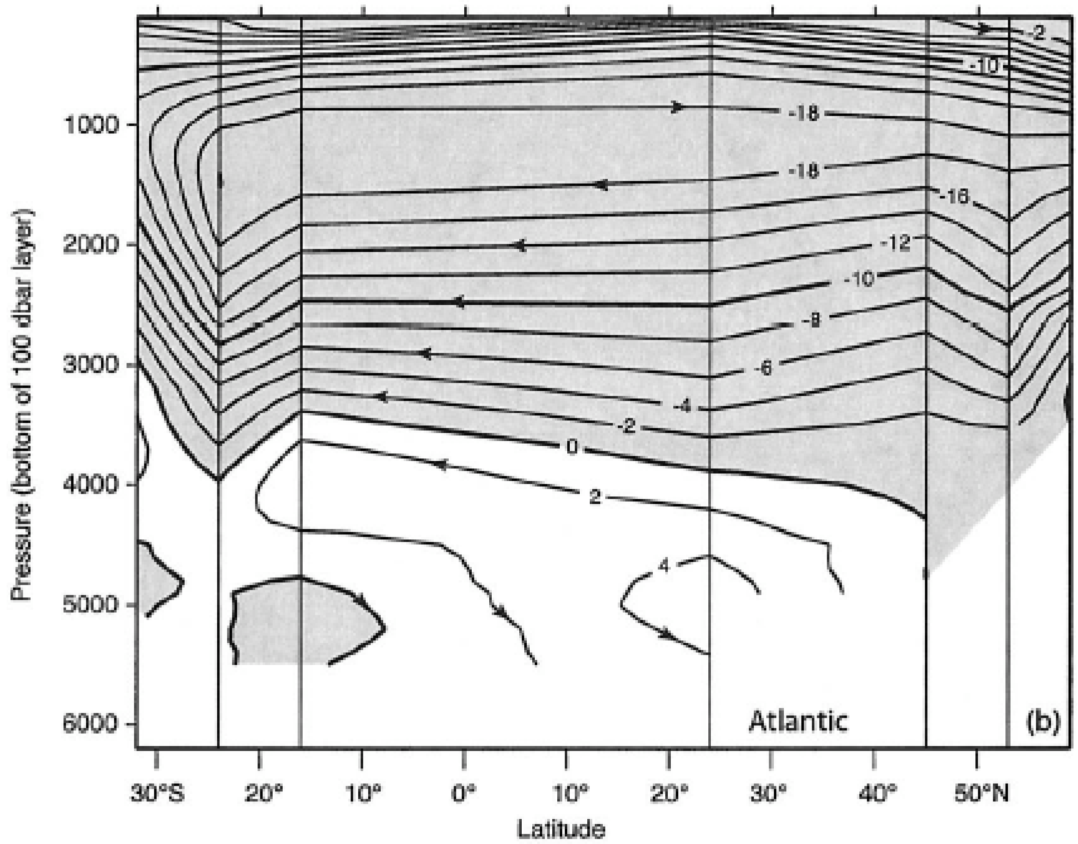

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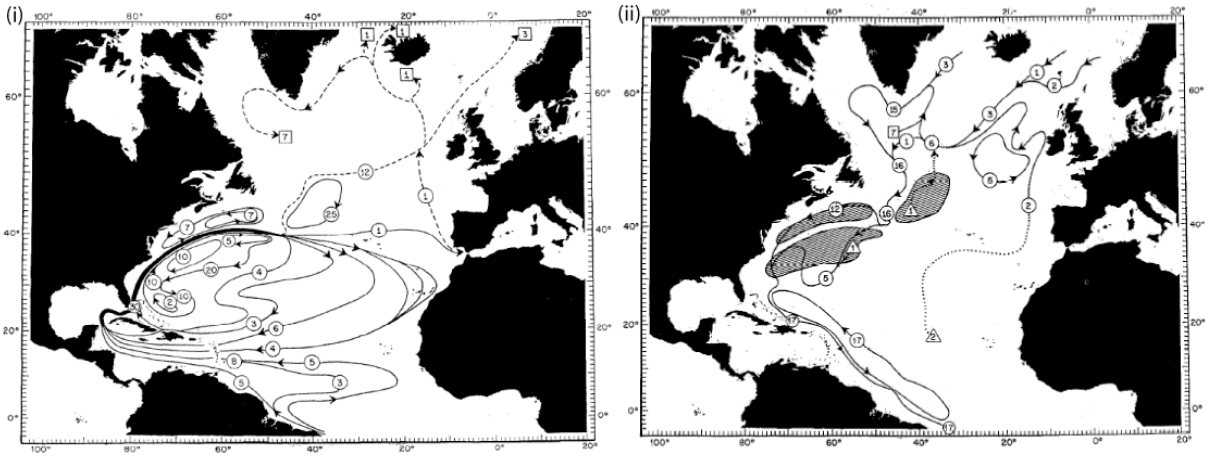

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