# MERIDIONAL CIRCULATION IN THE TROPICAL NORTH ATLANTIC

by

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B.A., Middlebury College, 1989

submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

and the

WOODS HOLE OCEANOGRAPHIC INSTITUTION

September, 1992



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Submitted to the Joint Program in Physical Oceanography
Massachusetts Institute of Technology
Woods Hole Oceanographic Institution
on August 19, 1992, in partial fulfillment of the
requirements for the degree of Master of Science

## Abstract

A transatlantic CTD/ADCP section nominally located at 11°N was carried out in March 1989. In this paper relative geostrophic velocities are computed from these data via the thermal wind balance, with reference level choices based primarily on water mass distributions. Mass is conserved by requiring the geostrophic transport to balance the sum of the Ekman and shallow western boundary current transports.

A brief overview of the meridional circulation of the upper waters resulting from these analysis techniques is presented, and indicates a North Brazil Current transport of nearly 12 Sv. Transports of the shallow waters are found to support the results of Schmitz and Richardson (1991) who found nearly half of the Florida Current waters to be derived from the South Atlantic. Schematic circulation patterns of the NADW and AABW are also presented. The deep waters of the western basin are dominated by a cyclonic recirculation gyre, consisting of a southward DWBC transport of 26.5 ± 1.8 Sv, with nearly half of this flow returning northward along the western flank of the MAR. A particularly notable result of the deep western basin analysis is the negligible net flow of middle NADW. Although the northward flows of upper and lower NADW along the western flank of the MAR are believed to be associated with the local recirculation gyre, the northward flow of middle NADW, which nearly balances the southward flow of this water mass along the western boundary, may be derived from the eastern basin of the South Atlantic. The deep waters of the eastern basin are also dominated by a large cyclonic recirculation gyre, consisting primarily of lower NADW and supplemented by middle NADW and AABW. Each of these water masses, as well as the upper NADW, have small net northward flows within the eastern basin. The AABW most likely enters the eastern basin by means of the Vema Fracture Zone, while the lower NADW enters primarily through the Kane Gap.

Although the components of the horizontal circulation discussed above agree well with results from previous CTD, current meter, and float studies, the meridional overturning cell (5.2 ± 1.6 Sv) and the net heat flux ($2.3 \pm 1.6 \times 10^{14}$ W) calculated in this study are considerably lower, and the net freshwater flux (-0.60 ± 1.5 Sv) is slightly higher than previous estimates. These discrepancies may be attributed to: (1) differences in methodologies, (2) the increased resolution of this section (as compared to earlier IGY sections), and (3) temporal (including decadal, synoptic, and most importantly, seasonal) variability. Annual average meridional overturning (12 Sv), heat flux ($11 \times 10^{14}$ W), and freshwater flux (-0.35 Sv), are computed based on annual average Ekman and NBC transports, temperatures, and salinities, and agree well with most previous annual estimates. The large difference between the March and the annual estimates is indicative of the importance of seasonal variability within the tropical North Atlantic.

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## Acknowledgments

I am grateful to my thesis advisors Mindy Hall and Harry Bryden for helpful suggestions made throughout this work. I would also like to thank my other committee members, Breck Owens, Paola Rizzoli, Phil Richardson, and Nelson Hogg, for useful comments on the final drafts of this thesis. Stimulating conversations with Mike McCartney throughout the entire past year are also gratefully acknowledged. This work has been supported by the Office of Naval Research through the American Society for Engineering Education.

## Table of Contents

## 1. Introduction

One of the best ways of examining large scale oceanic circulation, and a proven method of directly computing meridional heat and freshwater fluxes, is the analysis of zonal coast to coast hydrographic sections. The data previously used for such studies in the Atlantic have primarily been the International Geophysical Year (IGY) data of the 1950's (Hall and Bryden 1982; Roemmich 1983; Roemmich and Wunsch 1985; Rintoul 1991). Although these sections can give us some insight as to the net mass, heat, and freshwater transports in the Atlantic, the poor horizontal (and vertical) resolution of these transects makes it difficult to identify the nature of the horizontal circulation.

In this study we reexamine the circulation of the tropical North Atlantic by analyzing a much more recent hydrographic section nominally located at 11°N. As a result of the high horizontal resolution of this section (four to five times greater than that of the IGY transects), a detailed analysis of the horizontal circulation across this section *is* possible. Thus, a primary goal of this study is to quantify some of the known circulation patterns in the tropical Atlantic, such as the magnitude of the Deep Western Boundary Current (DWBC) and its recirculation, as well as bring to light new elements of the circulation such as the possible net northward flow of middle North Atlantic Deep Water (NADW). Comparison between the horizontal circulation results of this study and those from other float, current meter, and CTD data analyses helps us to paint a definitive picture of the meridional flow patterns in this region.

Since this transect reaches all the way from French Guiana to Senegal, direct computations of heat and freshwater transports are also possible. Partly as a result of the lack of direct heat flux estimates (there have only been a couple direct computations of heat flux (Roemmich 1983; Wunsch 1984) in the tropical North Atlantic), heat transport estimates obtained indirectly via surface heat budgets and general circulation models vary widely. Although integrations of evaporative fluxes provided by Baumgartner and Reichel (1975) and Schmitt et al. (1989) indicate a maximum of freshwater transport in the tropical North Atlantic (Wijffels et al. 1992), freshwater transport has never been directly calculated within this region. Therefore an important part of this paper will be to provide direct estimates of heat and freshwater fluxes with which the many indirectly calculated fluxes can be compared.

The tropical North Atlantic is particularly complicated by the strong seasonal variability of the winds (and the resulting Ekman transport) and the North Brazil Current (NBC). Although the horizontal circulation patterns of the intermediate, deep and bottom waters are relatively independent of the Ekman and western boundary current transports, the strength of the meridional overturning cell is extremely dependent on these factors. As a result, the net volume, heat and freshwater fluxes are highly sensitive to seasonal changes. From previous observational studies we can approximate the Ekman and NBC transports at other times of the year, and thus we are also able to estimate the magnitude of the seasonal variability in these net meridional fluxes. Although it is more difficult to assess, the possibility of decadal variability (between for instance the 1950's IGY data and our 1989 section) will also be discussed.

In this study, volume, heat, and freshwater transports are calculated by integrating velocities obtained by means of the dynamic method. Since such geostrophic calculations determine only vertical shear, and not absolute velocities, one needs to know the absolute velocity a priori at one depth for each station pair in order to determine absolute velocities. There are a number of ways in which the velocity at such a 'reference level' can be determined. If long-term current meter records or acoustic doppler current profiler (ADCP) measurements are available in the vicinity of the hydrographic stations, the geostrophic velocities can, in theory, be referenced to these absolute velocities. Beta spiral and inverse methods can also be used. Although some of these other methods may be applied to this data set in the future, in this paper we use the more traditional method of choosing a level (or levels) of no motion based primarily on water mass distributions and using these as a reference for the geostrophic velocity calculations. Mass conservation is then satisfied by balancing the geostrophic transport with the sum of the shallow NBC transport and the ageostrophic Ekman transport. The consistency of our results with available direct velocity measurements and other CTD studies in the area justifies our analysis methods a posteriori.

In the next section we provide a brief description of the data used in this study, followed by a discussion of some of the subtleties in the data analysis. In section 3 the horizontal circulation across this transect is described and the net heat and freshwater fluxes are calculated. Possible explanations for the relatively low values we obtain for these latter fluxes, in comparison to other direct, indirect and model estimates, are discussed in Section 4. Section 5 contains a brief summary.

## 2. Data and Analysis Techniques

*a. Data*

In March 1989, D. Roemmich, M. Hall, and T. Chereskin carried out a CTD/hydrographic/ADCP zonal section across the tropical North Atlantic Ocean, repeating the track of a basin-wide deployment of SOFAR (Sound Fixing and Ranging) floats completed by P. Richardson and W. Schmitz the previous month. The 4000 km cruise track, shown in Figure 1, consisted of 84 CTD stations, each of which extended from the surface down to within 10 m of the bottom. The average station spacing was 50 km, with shorter spacing of 15 - 25 km near the coasts and in regions of strongly variable topography. Beginning at the 200 m isobath off Senegal, the ship angled slightly southwestward for a short segment before heading due west along 11°12'N. In order to approach the South American coast perpendicularly, the ship made a second turn toward the southwest at roughly 46.5°W. The last station was located near the 200 m isobath off French Guiana. To the west of this CTD, the ADCP was used in bottom-tracking mode in order to determine the transport of the NBC over the wide shallow shelf, illustrated in Figure 2.

Although later work on this project will synthesize the hydrographic data with the SOFAR float and ADCP data, in this work we employ the traditional method of choosing a reference level based primarily on water mass distributions, and referencing the geostrophic velocity calculations to this assumed level of least motion. When using this method there are a number of choices that must be made. For instance, one must decide what velocity to attribute to the bottom triangles, and how to account for intervening topography. (The details of this part of the analysis are given in the Appendix.) The Ekman and shallow western boundary transports must also be computed using either climatological data or in situ ADCP data obtained during the cruise. A reference level, or combination of reference levels, must also be chosen in order to obtain absolute velocities from the relative velocities given by the application of the thermal wind relationship. All these choices must be made in such a manner that mass is conserved, i.e. total geostrophic mass transport across the section must balance the shallow western boundary and Ekman transports. The remainder of this section describes ways in which these complications have been addressed in the past, as well as how they are specifically dealt with in this study.

*b. Ekman and shallow western boundary transport*

Ekman transport is a major component in the meridional circulation, heat and freshwater balances of the tropical North Atlantic. For example, using IGY 8°N data, Roemmich (1983) found the heat flux due to the Ekman transport to be greater in magnitude than that due to the geostrophic transport. This condition was not found at the sections Roemmich examined at 24°N, 8°S and 24°S.

Chereskin and Roemmich (1991) computed the Ekman transport across the 11°N transect (to the east of the first CTD located at the 200 m isobath) using three different methods. The difference between the geostrophic shear and the shear measured by the ADCP data yielded an estimate of 12.0 ± 5.5 Sv and is in good agreement with that estimated from the shipboard winds, 8.8 ± 1.9 Sv. Using the mean monthly winds of Hellerman and Rosenstein (1983) for the month of March, they obtained a third estimate of 13.5 ± 0.3 Sv. Since the cruise period was characterized by particularly low winds, it is not surprising that the calculations using the in situ data yielded smaller estimates of Ekman transport. In this examination of the March 1989 circulation across 11°N, the best estimate of Ekman transport is assumed to be a weighted mean of the two in situ estimates: 9.1 ± 1.8 Sv. In order to yield a more accurate representation of the circulation for March in general, calculations using the climatological estimate will also be shown where appropriate.

Along the western boundary of this transect, the northwestward flow of the NBC is evident from the data of the shallowest few CTD's. Using the ADCP in bottom tracking mode, this O(1 $m \cdot s^{-1}$) flow was observed to extend across the wide shallow shelf where no CTD data was taken (Chereskin and Roemmich 1991). (See Figure 2.) The across track component of the flow between the coast and the first CTD station, i.e. the 200 m isobath, is hereafter referred to as the 'shallow NBC transport'. Using the ADCP data over the shelf, Chereskin (pers. comm.) calculated the net shallow NBC transport to be 4.5 ± 1 Sv. Absolute velocities were integrated from the bottom to 30 m (2.7 Sv), and a slab extrapolation was applied between 30 m and the surface (1.8 Sv). Of this net flow, 3.3 Sv was found to be in water depths of less than 100 m, in good agreement with the shallow transports of the North Brazil Current obtained by Candela et al. (1992) using ADCP and CTD data from March 1990.

The remaining calculations in this paper are performed assuming that the geostrophic component of the flow (to the east of the first CTD) must balance the sum of the net northward Ekman transport and the shallow western boundary transport, i.e. 13.6 ± 2.1 Sv. Error bars on the geostrophic transports will include the propagation of the uncertainty in this sum.

*c. Reference levels*

1) APPLICATION OF HISTORICAL REFERENCE LEVELS

Selecting a reference level of no motion is a fundamental aspect of transport analyses based on geostrophic velocity calculations; a change in reference level of only a few hundred meters can sometimes change even the sign of the net transport across a hydrographic section. It is common practice to examine property distributions across hydrographic sections, and to choose reference levels of no motion between known water masses flowing in opposite directions. Using seven IGY sections in the Atlantic, Wright (1970) chose a reference level which approximated the boundary between the NADW and the AABW. This boundary was determined by examining temperature-depth and salinity-depth profiles, and selecting the level where a discontinuity in the profiles occurred. The result of this analysis was a reference level that sloped from roughly 4400 m at the 16°N section to 3400 m at the 32°S section, and nominally coincided with the 1.9°C isotherm. (All temperatures throughout this paper refer to *potential* temperatures.) In their study in the vicinity of the Greater Antilles Outer Ridge north of Puerto Rico, Tucholke et al. (1973) experimented with a reference level of 4700 m, also roughly approximating the boundary between the NADW and the AABW. A level of no motion at $\theta = 1.9$°C was also used by Whitehead and Worthington (1982) (as well as by McCartney (1992a) in a recent update of their analysis) for a group of hydrographic stations in a 300 km wide gap at 4°N between the Mid-Atlantic Ridge (MAR) and the Ceara Rise.

Reference levels have also been chosen in the upper water column. In his comprehensive dynamic calculations using six Meteor sections, Wust (1955; 1957) was one of the first to choose an intermediate reference level. His choice was based on an approximation of the boundary between the Antarctic Intermediate Water (AAIW) and the upper NADW, and sloped from less than 1000 m at 19°N to about 2000 m at 33°S. More recently, Molinari et al. (1992) have found the 4.7°C isotherm to be a useful approximation to the level of no motion in their examination of the DWBC in the western tropical North

Atlantic. Bennett and McCartney (1990) also suggest "fairly unambiguous choices for levels of no motion" to be between the 4° and 5°C potential temperature surfaces in this region of the Atlantic Ocean.

As discussed above, in past hydrographic studies of the tropical Atlantic, a single reference level was often chosen to approximate either (1) the boundary between lower NADW and AABW (roughly 4500 db or $\theta \approx 1.8 - 1.9$°C) or (2) the boundary between AAIW and upper NADW (roughly 1200 db or $\theta \approx 4.7$°C). For comparison, both of these reference levels are applied to the full 11°N section, and the transport results for different water masses are shown in Figure 3. Isothermal boundaries for the water masses are determined from the θ-S diagrams shown in Figure 4. Corresponding definitions of water masses are listed in Table 1. Station pairs which include at least one station shallower than the reference level are referenced to the deepest common level. In each case mass is balanced by requiring the geostrophic transport to be equal and opposite to the sum of the Ekman and shallow NBC transports. This is done by adding a small uniform velocity, $v_o$, across the entire section, thus changing the reference level from a level of 'no' motion to a level of 'known' motion, i.e. $v_o$, and simultaneously shifting the zero velocity surface to a slightly different depth. Error bars on the transports in Figure 3 are based on the uncertainties in the bottom triangle transports (see Appendix), as well as in the sum of the Ekman and shallow NBC transports.

Although a deep reference level can sometimes give reasonable results (Wright 1970; Tucholke et al. 1973; Whitehead and Worthington 1982; McCartney 1992a), it appears that this is probably not the best possible approximation to the level of no motion at 11°N. As a result of the rather large mass imbalance of 38 Sv caused by choosing (initially) 4500 db to be a level of no motion, a uniform velocity of $v_o = -0.21$ cm/s must be added to the section. This is equivalent to raising the average level of no motion by 1000 db which places it in the center of the lower core of NADW! As expected, results from such a calculation, as shown in Figure 3a, show very little NADW flowing south. (If a 1.8°C isothermal reference level had been used in place of the 4500 db isobaric reference level, the net NADW transport would be northward.) Equally problematic is the relatively large *southward* flow of AABW caused by the use of this deep reference level.

As described above, shallow reference levels approximating the boundary between the AAIW and the upper NADW have also frequently been used in the tropical North Atlantic (Wust 1955; Wust 1957; Molinari et al. 1992; Bennett and McCartney 1990). The mass imbalance caused by a reference level of 1200 db is considerably smaller, and requires a velocity of only $v_0$ = 0.08 cm/s to be added uniformly to the section. The addition of such a small velocity changes the level of no motion by less than 20 m and immediately indicates that this reference level choice is likely to give more reasonable results. However, Figure 3b only shows a slightly larger southward transport of deep water, and once again an anomalously large southward transport of AABW. Such circulation patterns lead us to continue our search for a more appropriate reference level.

2) REFERENCE LEVELS USED IN THIS STUDY

The possibility of other more carefully chosen reference levels producing more realistic transports of AABW and NADW is now considered. Figure 5 shows the total transport of AABW and NADW plotted as a function of reference level. For each reference level shown, a velocity $v_0$ has been added uniformly to the entire section in order to maintain mass conservation. It is important to note that if a constant reference level is chosen across the entire section, the maximum possible northward flow of AABW is 0.4 Sv. This is considerably smaller than previous estimates of transequatorial bottom water transport which exceed 4 Sv (McCartney and Curry 1992; McCartney 1992a). Furthermore, if the AABW is required to flow northward, the resulting transport of total NADW is still only between 4 and 5.5 Sv. This is a surprisingly low value, since deep water transports of roughly 17 Sv have been found both at 24°N (Hall and Bryden 1982) as well as at 32°S (Rintoul 1991).

Although Figure 5 shows the transport results for a number of different reference levels, the realm of possible reference level choices is not yet exhausted. In the analysis above, a single reference level was chosen to best approximate the level of least motion for all station pairs. In an attempt to determine whether the small northward transport of AABW and the small southward transport of NADW found above are real or are simply artifacts of using a constant reference level across the entire section, we now allow for the possibility that different regions of the 11°N transect may have different levels of no motion. (In fact, it is likely that each station pair has a different level of no motion; however, due to the limited number of known constraints, it is only possible to rationalize the use of a few different reference levels.) As a result, the western and eastern basins will now be examined separately. Since more previous work has been carried out in the western basin than in the eastern basin, the discussion of reference level choice will begin there.

Numerous studies in the past few decades indicate that the circulation within the western basin of the tropical North Atlantic varies tremendously from west to east. On the eastern side the AABW flows northward (McCartney 1992a), while on the western side the NADW flows southward along the Brazil coast (Johns et al. 1992a; McCartney 1992b). Furthermore, the core of the upper NADW is typically found inshore of the core of lower NADW (Molinari et al. 1992). Thus it is conceivable that the best approximation to the level of no motion may also differ considerably across the western basin. Therefore, the western basin is divided into three subsections with different reference levels allowed within each region.

One reasonable location to subdivide the western basin is at the abrupt change in topography and increase in depth near 46.5°W (or equivalently ~850 km offshore of the shelf break) where the cruise track slightly changes direction, as shown in Figure 1. This division is illustrated in Figure 6 and is reinforced by observations which indicate that in the tropical North Atlantic the NADW extends at least 800 km offshore (Molinari et al. 1992). Furthermore, within the deep waters of the 11°N transect the highest values of dissolved oxygen and the lowest values of silicate and phosphate, which are indicative of the NADW, lie primarily in the westernmost 850 km as illustrated in Figure 7. A second division of the basin is imposed in order to allow the upper and lower cores of NADW to have different reference levels. A division positioned near 50°W (or equivalently ~175 km offshore of the shelf break, as shown in Figure 6) appears to separate the inshore core of upper NADW at 1800 m depth from the offshore core of lower NADW. Such a boundary is also useful in that it marks the location of a significant change in the bottom slope. It must be remembered, however, that such divisions are primarily convenient methods by which reference level possibilities can be examined. Even if such separations existed they probably would not be uniform with depth, but might be tilted with the slope of the surrounding bathymetry.

Since logical divisions between the eastern, middle and western parts of the west basin have now been established, the reference levels must be decided upon for each of these regions. One method of determining a level of least motion is to examine current meter data. There are two sets of current meter data off the coast of S. America that are relevant to our 11°N section: Whitehead and Worthington's array at 4°N, and the array of Johns et al. (1992a) at 8°N. (Because neither of these arrays were coincident in time or space with our section, it is not logical to reference our geostrophic velocities directly to these current meter measurements.) Since all the current meters at 4°N are below 4000 m, it is not possible to determine from these data alone whether a shallow or a deep level of no motion would be more appropriate. However, these data do indicate that at depths of 4000 m or so there is a strong periodic variability with roughly a 60-day time scale and amplitudes of up to 20 cm/s. The data at 8°N also show considerable vertical excursion of isotherms with a similar periodic oscillation. In some instances, AABW as cold as 1.4°C was observed to flow southward. The strong temporal variability of NADW and AABW transports at these locations introduces some doubt as to whether a reference level between these two water masses is the best choice for the western side of the western basin.

Another reason to exclude the deep reference levels from consideration in the western basin is that this part of the 11°N section crosses the hypothesized Guiana Abyssal Gyre (McCartney 1992b; Johns et al. 1992a). It is believed that within the western basin of the tropical North Atlantic, the bottom water flows northward along the MAR and returns southward along the western boundary, while the deep water flows southward along the western boundary and recirculates back northward along the western side of the MAR. This recirculation of both the NADW and the AABW appears to extend southward to the Ceara Rise (~ 4°N) and northward to at least 14°N (Molinari et al. 1992). Thus it is likely that within the entire western basin the AABW is flowing in the same direction as the lower NADW, and a reference level between these water masses is not suitable as a level of no motion.

Evidence of the Guiana Abyssal Gyre is shown in the potential temperature contours of Figure 7a. Here the isotherms both above 1.8° (NADW) and below 1.8° (AABW) slope upward toward the coast. If a reference level of $\theta = 1.8$°C is chosen, the resulting NADW flow would be *northward* - in disagreement with almost all tracer and current meter data in the DWBC. Furthermore, although the strong maximum of dissolved oxygen provides indisputable evidence for the presence of NADW (Figure 7c), this maximum is associated with isotherms ($\theta = 1.8$° - 2.4°C) rising towards the western boundary; these are indicative of a southward flowing water mass only if a reference level above the lower core of NADW (i.e. shallower than 3000 db) is chosen. Similarly on the eastern side of the western basin, the high silicate values of the AABW (Figure 7d) lie near the bottom of the western basin and are coincident with isotherms ($\theta = 1.4$° - 1.9°C) sloping upward against the MAR; these are indicative of a northward flowing water mass only if a reference level above 3000 db is chosen.

Although deep reference levels have now been eliminated from consideration, which reference levels are preferable? In order to gain insight into this question, transport per unit depth relative to the bottom is plotted in Figure 8. Transport per unit depth for the section as a whole is shown in Figure 8a, and that for the individual Regions 1 - 3 are shown in Figures 8(b, c, and d) respectively.

Figure 8b indicates two distinct water masses in Region 1: one located at 800 m depth and the other at 1800 m. The upper layer is identified as AAIW by its strong oxygen minimum (Figure 7c), while the silicate maximum of the lower core (Figure 7d) indicates that it must be of northern origin. Because the long term mean flows of these two water masses are expected to be in opposite directions, a reference level of 1100 db is chosen.

Figures 8c and 8d do not show any clear levels of least motion and thus a different method must be used to determine the reference levels for Regions 2 and 3. Since deep reference levels have already been eliminated from consideration, only those between 1000 db and 3000 db are allowed. If reference levels of 100 db increments are considered, there are 441 possible combinations for the western basin alone. Each of these 441 combinations were examined, and those with southward flow of AABW with a magnitude greater than 0.5 Sv were rejected. Since McCartney et al. (1991) predict a northward flow of roughly 2 Sv in the western basin across 11°N, our initial constraint is a mild one; at this point we only reject absurdly large southward flows of bottom water. (Also note that mass cannot yet be balanced since a reference level for Region 4 has not yet been chosen; however, as a result of the small area that the AABW occupies, the addition of a typical $v_o$ ($O(+.1\ cm \cdot s^{-1})$) will increase the western basin bottom water transport by only 0.2 Sv.) This single constraint eliminates 293 combinations from further consideration.

Figure 9 illustrates the western basin NADW and AABW transport for all the possible reference level combinations discussed above. The combinations rejected due to large southward transports of AABW are shaded, and, as shown in Figure 9b, correspond to the largest southward transports of NADW. As a result of the anomalously low transports of NADW shown in Figure 5, we now select from the remaining (unshaded) 148 combinations the 20% (i.e. 30 levels) that have the greatest transport of NADW. These 30 choices are shown by asterisks in Figure 9b. (Note that after mass is balanced by uniformly adding a typical positive $v_o$ to the section, the southward flowing western basin NADW transport will decrease in magnitude by roughly 3 Sv.)

Eastern basin reference levels are now chosen such that total NADW transport (across the entire section) is maximized for each of these 30 combinations. All levels between 1000 db and 5000 db (in 100 db increments) are examined. For every one of the

30 combinations found above, the eastern reference level that maximizes total NADW transport (after balancing mass), is located at 2100 db.

In summary, levels of no motion have been chosen that give "reasonable" western basin AABW transport and simultaneously maximize total NADW transport. These criteria yield reference levels of 1100 db for Region 1, 2100 db for Region 4 and thirty possible reference level combinations for Regions 2 and 3, as depicted in Figure 9b, and listed in Table 2. The resulting net transports are shown in Figure 10. Error bars include the uncertainties in the bottom triangle, Ekman, and shallow NBC transports. The error due to reference level choice is assumed to be equal to the standard deviation of the thirty different reference level calculations, and in this case is insignificant in comparison to the other sources of error.

The transport results shown in Figure 10 are clearly more reasonable than the initial results shown in Figure 3. For instance, the net transport of AABW is now northward, in agreement with previous current meter, tracer and CTD data. Although the southward transport of deep water has doubled, it is still considerably smaller than that obtained in previous mid-latitude studies of IGY data (Hall and Bryden 1982; Rintoul 1991). Further discussion of the discrepancy in these results is postponed to Section 4. In the following section we first examine in detail the circulation patterns resulting from the data analysis methods described above, and compare these with other results of recent float, current meter and CTD studies.

## 3. Results

### *a. Horizontal circulation*

Volume transport in seven temperature classes is computed for each of the reference level combinations described in Table 2. The results for the four different regions are shown in Figures 11 (a, b, c, and d) respectively. The error bars on these transports include the uncertainties in the bottom triangle (see Appendix), Ekman, and shallow NBC transports, as well as the error in our reference level choice which again is assumed to be equal to the standard deviation of the thirty estimates. In contrast to the net transport calculations (Figure 10), the reference level errors dominate the error bars of Figure 11. The bottom triangle errors are significant only in the AABW transports, and the uncertainties in the Ekman and shallow NBC transports are important only in the eastern basin. Before beginning a detailed description of the deep and bottom water circulation, a brief overview of the shallow water circulation will be presented.

1) SHALLOW WATERS: $\theta > 4.7°C$

Due to the strong temporal variability of shallow tropical waters, the circulation of the upper waters near 11°N is not well known; however, one aspect of the tropical North Atlantic circulation that has been the subject of a number of recent investigations (Candela et al. 1992; Johns et al. 1992b) is the North Brazil Current (NBC). Although this current is strongly seasonal (Cochrane 1979; Philander and Pacanowski 1986) the magnitude of the seasonal variation is not yet well defined. Recent studies indicate, however, that the NBC may range from roughly 10 Sv in the spring to as much as 30-35 Sv in the fall (Candela et al. 1992; Johns et al. 1992b). An estimate of the NBC transport, which is herein defined to include the northwestward flow of $\theta > 12°C$ waters located within 250 km of the western boundary, can also be obtained from the 11°N section. The portion of this flow located over the 150 km wide shelf was determined from the ADCP data to be 4.5 Sv (T. Chereskin, pers. comm.), while the component of this shallow flow in deeper waters (200 m - 3000 m) was calculated from the first six CTD pairs to be 7.3 Sv. The total NBC transport is thus estimated to be 11.8 Sv, and agrees well with the recent March estimates of 10 - 15 Sv obtained by Candela et al. (1992) and Johns et al. (1992b).

In order to examine the horizontal circulation of the shallow waters in greater detail, we divide these waters into 4 temperature classes: surface water ($\theta > 24°C$), thermocline water ($12° < \theta < 24°C$), lower thermocline water ($7° < \theta < 12°C$), and AAIW ($4.7° < \theta < 7°C$). The horizontal circulation of each of these temperature classes will now be examined individually.

Integrated transport of the surface water is shown in Figure 12a. The NBC is evident as a strong northwestward flowing current banked up against the western boundary and extending roughly 250 km offshore. Of the total 11.8 Sv NBC transport, 9.3 Sv is at temperatures greater than 24°C. Farther offshore an even larger 13.5 Sv southward counterflow exists. At first glance this current resembles the shallow NECC retroflection. However, a number of previous studies have shown that typically the NECC does not begin to form until May, and is nearly non-existent in March (Richardson and Walsh 1986; Philander and Pacanowski 1986). It is difficult to determine from this study alone whether this flow represents a particularly early formation (or late weakening) of the NECC, a retroflection eddy that has been pinched off from the NBC retroflection, or some other unrelated strong southward flow. The remainder of the western basin is characterized by a 5 Sv net northward flow. The eastern basin is almost entirely composed of waters colder than 24°C. Summing the shallow NBC transport over the shelf (4.5 Sv), the Ekman transport (9.1 Sv), and the net geostrophic transport across the entire section of $\theta > 24°C$ waters (-7.4 Sv), yields a net transport of surface waters across the section of 6.2 Sv. If the climatological Ekman transport value of 13.5 Sv were used (which is higher than the Ekman transport value derived from in situ data since the 11°N cruise was characterized by particularly low winds), this estimated net surface water transport would increase to 10.6 Sv.

Integrated transport of the thermocline water, shown in Figure 12b, closely resembles that of the surface water. The NBC also penetrates down to this temperature class and supplements the 9.3 Sv of $\theta > 24°C$ NBC water with an additional 2.5 Sv, yielding a total NBC transport of 11.8 Sv. The southward transport offshore of the NBC that was evident in the surface water is also evident in the thermocline water, with the combined ($\theta > 12°C$) transport reaching -20.3 Sv. As was the case for the surface water, the eastern portion of the western basin is dominated by a net northward flow of thermocline water, and only small net flows occur within the eastern basin. The net transport of thermocline water across 11°N is -2.6 Sv.

As shown by Figure 12c, the NBC does not penetrate down to the lower thermocline water; however, the southward flow offshore of the NBC does extend down to this temperature class (250 - 650 m) and yields a total of -25.4 Sv for this current. It is interesting to note that the magnitude of this southward flowing current is more than twice the size of the northward NBC. The flow pattern across the remainder of the section resembles that of the surface and thermocline water, with northward transport over the western side of the MAR, southward flow over the eastern side of the MAR, and only small net flows within the eastern basin. The net transport of lower thermocline water across 11°N is -0.6 Sv.

A number of the results discussed above can be compared to the results of a recent study by Schmitz and Richardson (1991). Using hydrographic data from a number of Caribbean passages as well as from the Straits of Florida, they were able to determine the origin of the surface, thermocline and lower thermocline water within the Florida Current. They found 8.9 Sv of $\theta > 24°C$ water flowing northward in the Florida Current. Of this transport, they determined that only 1.8 Sv comes from the North Atlantic, and 7.1 Sv flows in from the South Atlantic. As discussed above, we find 10.6 Sv of surface water