Berichtsblatt

1. ISBN oder ISSN

2. Berichtsart
Abschlubericht 2005

3a. Titel des Berichts

Abschlußbericht zu SONNE 171 : Tracerzirkel II Förderkennzeichen: 03G0171A

3b. Titel der Publikation

4a. Autoren des Berichts (Name, Vorname(n))

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4b. Autoren der Publikation (Name, Vorname(n))

5. Abschlußdatum des Vorhabens

6. Veröffentlichungsdatum

7. Form der Publikation

8. Durchführende Institution(en) (Name, Adresse)

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9. Ber.Nr. Durchführende Insitution

10. Förderkennzeichen *)
03G0171A

11a. Seitenzahl Bericht
21

11b. Seitenzahl Publikation

12. Literaturangaben

14. Tabellen
2

15. Abbildungen
11

16. Zusätzliche Angaben

17. Vorgelegt bei (Titel, Ort, Datum)

18. Kurzfassung

Ziele der Messungen im subtropischen und tropischen Atlantik mit FS SONNE waren:

- Ausbreitung von Tiefenwasser im westlichen Randstrom und die Rezirkulation im Beckeninneren
- Tiefenwasseraustausch zwischen West- und Ostatlantik
- Zeitskalen der Ausbreitung von Tiefenwasser
- Einstrom von südhemisphärischem Wasser in die Karibik

Die auf FS SONNE verwendeten Methoden: Messung der Verteilungen von Temperatur, Salzgehalt, Sauerstoff sowie FCKWs, und die Vermessung des Geschwindigkeitsfeldes mit Schiffs-ADCP und lADCP. Verankert werden im Bremer CARIBA Array Strömungsmesser, Schichtungssensoren (MicroCats) und Inverted Echo Sounders mit hochgenauen Bodendrucksensoren (PIES) nördlich von Tobago, westlich von Barbados und östlich von Saint Lucia.
Die neuen Erkenntnisse, die durch dieses Projekt gewonnen wurden, sind die Transporte des klimarelevanten Warmwasserpfads im tropischen Atlantik und seine Aufspaltung in Oberflächen- und Zwischenwasser sowie die Abschätzung der Transporte in die Karibik und im Nordatlantik über 16°N.

19. Schlagwörter
Physikalische Ozeanographie, Tracer-Ozeanographie, Zirkulation, Tiefenwasserausbreitung

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*) Auf das Förderkennzeichen des BMBF soll auch in der Veröffentlichung hingewiesen werden.

Abschlußbericht zu TRACERZIRKEL II – 03G0171A
Die SONNE Reise S171

Projektleitung: Prof. Dr. Monika Rhein
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28359 Bremen

1. Aufgabenstellung

Ziele der Messungen im subtropischen und tropischen Atlantik mit FS SONNE waren:

- Ausbreitung von Tiefenwasser im westlichen Randstrom und die Rezirkulation im Beckeninneren
- Tiefenwasseraustausch zwischen West- und Ostatlantik
- Zeitskalen der Ausbreitung von Tiefenwasser
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Die auf FS SONNE verwendeten Methoden sind die Messung der Verteilungen von Temperatur, Salzgehalt, Sauerstoff sowie FCKWs, und die Vermessung des Geschwindigkeitsfeldes mit Schiffs-ADCP und lADCP. Verankert werden Strömungsmesser, Schichtungssensoren (MicroCats) und Inverted Echo Sounders mit hochgenauen Bodendrucksensoren (PIES) nördlich von Tobago, westlich von Barbados und östlich von Saint Lucia.

2. Voraussetzungen, unter denen das Vorhaben durchgeführt wurde.

Mit der FS SONNE stand eine ausgezeichnete Forschungsplattform zur Verfügung, um das aufwendige Beobachtungsprogramm durchzuführen. Die bewilligten Mittel für Reisen, Transporte und Verbrauch waren für die Durchführung des Vorhabens unerlässlich. Es wurden im Projekt aber KEINE Mittel für die Auswertung zur Verfügung gestellt, die dafür zuerst vorgesehenen Mittel mussten in Reise /Verbrauch / Transporte umgewandelt werden, um die SONNE Reise überhaupt durchführen zu können. Die Personalmittel mussten aus anderen Mitteln zur Verfügung gestellt werden. Dies war mir als Angehörige einer ‚armen' Universität keine leichte Aufgabe. Die wissenschaftliche und technische Expertise der Mitarbeiter war eine wichtige Voraussetzung für die Durchführung der Arbeiten. Die gute Kooperation mit Kapitän und Besatzung ermöglichte die erfolgreichen Arbeiten auf dem Schiff.

3. Planung und Ablauf des Vorhabens

Der im Antrag vorgelegte Arbeitsplan wurde in seinen wesentlichen Teilen eingehalten. Es wurde ein exzellenter Datensatz geschaffen, deren Aufbereitung bereits abgeschlossen ist. Erste Analysen, die diesen Datensatz benutzen, sind bereits veröffentlicht bzw. in Druck. Gemeinsame Veröffentlichungen mit amerikanischen Kollegen, die auch den SONNE 171 Datensatz betreffen, sind in Vorbereitung bzw. geplant.

4. Wissenschaftlicher und technischer Stand

Auf der experimentellen Seite konnte auf die langjährige Erfahrung aus vorangegangenen Experimenten aufgebaut werden, darunter auch die SONNE Reise S-152. Dies schließt eine gut funktionierende Freon-Technik und gut gewartete CTDs mit 10L Schöpfern an einer 24er Rosette mit ein. Neben dem Schiffs - ADCP konnten auch mit Hilfe von gut funktionierenden LADCPs Geschwindigkeitsprofile bis zum Boden gemessen werden. Die Kombination der verschiedenen Datensätze trägt viel zur Interpretation der untersuchten wissenschaftlichen Probleme bei.

5. Zusammenarbeit mit anderen Stellen

Mit W. M. Smethie, Lamont (USA) und R. Fine, RSMAS Miami (USA). Gemeinsame Veröffentlichungen sind in Vorbereitung bzw. geplant.

II Eingehende Darstellung

II.1 Transport von Südatlantikwasser in die Karibik durch die Passagen südlich von Guadeloupe und über 16°N, 2000-20004 (Rhein et al., 2005, im Druck).

We combined the data from the SONNE 171 cruise with all our data collected since November 2000 (SONNE cruise S-152). About 35 Sv of warm South Atlantic Water (SAW) cross the equator into the North Atlantic (Schott et al., 1998). This transport is by far higher than the estimated strength of the thermohaline circulation of 14-23 Sv (Ganachaud and Wunsch, 2000; Ganachaud, 2003), leaving a significant part of that flow to recirculate back into the South Atlantic. The SAW remaining in the North Atlantic forms the warm water path of the meridional overturning circulation. It consists of warm surface and central water with densities $\sigma_\theta < 27.1$ and of Intermediate Water (IW) with densities between $\sigma_\theta = 27.1$ and 27.6. The isopycnal $\sigma_\theta = 27.1$ corresponds roughly to the 8°C isotherm located between 400-600 m depth in the equatorial Atlantic. Due to Macdonald and Wunsch (1996), Ganachaud and Wunsch (2000) and Lux et al. (2001), both layers, the warm water (surface plus central water masses) and the IW have comparable transports. This is in contrast to the results of De Las Heras and Schlitzer (1999) and Lumpkin and Speer (2003), who report a more dominating impact of intermediate water. The upper warm water is thought to flow into the Caribbean to later join the Florida Current. The flow of intermediate water into the Caribbean is more restricted by the narrowness of the passages at deeper levels, so it will mainly flow northwards in the Atlantic. This Atlantic route might also be taken by the surface and central water.

Several pathways for SAW exist to cross the equator and to reach the Caribbean inflow region. SAW is partly transported directly to the Caribbean by a boundary current along the South American Coast (Schott et al. 1998) and partly by eddies created at the retroflection area of the North Brazil Current NBC (Goni and Johns, 2003). The fate of these rings, especially the subsurface ones and their role in transporting South Atlantic water northwards in the Atlantic route is still unclear.

Southern and northern hemispheric source water masses are defined for each density layer and a water mass analysis was carried out to determine the contribution of SAW. We applied an isopycnal mixing approach from $\sigma_\theta = 24.5$ (100 m) to $\sigma_\theta = 27.6$ (1200 m depth). The water masses chosen were: Surface water $\sigma_\theta \leq 24.5$; Salinity Maximum Water (SMW): $24.5<\sigma_\theta\leq 26.3$; Upper Central Water (UCW): $26.3<\sigma_\theta \leq 26.8$; Lower Central Water (LCW): $26.8<\sigma_\theta \leq 27.1$; and Intermediate Water (IW): $27.1<\sigma_\theta \leq 27.6$. (Fig.1) In order to calculate the

Fig.0 *Topographie and location of the CTD/LADCP measurements carried out during the cruises S152 (December 152), M53/3 (June 2002), Atalante cruise 'Caribinflow (April 2003) SONNE cruise S-171 (June 2003) and M62/1, (July 2004).Also included are the WOCE line A22 at 66°W (August 1997 and October 2003, both times from T. Joyce, Woods Hole, USA)*

fractions of northern and southern hemispheric water from T/S alone, one northern and one southern component is permitted. The isopycnal T/S analysis is carried out by taking the two source water masses of the appropriate density and calculate the fraction of each component, necessary to obtain the properties of the sample. The source water masses will have a slightly lower density because of the nonlinearity of the equation of state. The calculations are done in steps of 10dbar. The results are then gridded on a horizontal equally spaced grid.

Transports are calculated from velocity distributions measured with vm-ADCPs. For the depth below the range of the vm-ADCPs, the LADCP profiles were used. The data were interpolated on a regular grid. To obtain the SAW transports, the gridded velocity field between the respective isopycnals was multiplied with the SAW fractions, interpolated on the same grid. The transport through the Grenada passage was inferred from the data taken between Tobago and St. Vincent. We assume that the intermediate water enters the Caribbean, although the passage is only about 750 m deep and the lower limit of the IW is more at 1000 m. From observations along 66°W in the Caribbean (Hernandez-Guerra and Joyce, 2000; Joyce et al., 2001) it is evident, that IW has to enter the Caribbean through the southern passages, the salinity minimum of the AAIW is freshest in the southernmost part of the Caribbean and weakens towards the north. The transports presented here as 'Grenada passage transport' does not include the transport of water denser than $\sigma_\theta = 27.6$.

The velocity distributions in several passages were sampled continuously for a time period of 3 to 24 hours. The effect of tides on the transport was more severe in the passages between St. Vincent and Martinique than in the northern channels. For instance, the inflow through the St. Vincent passage varied between 1.6 Sv and 8.8 Sv during a tidal phase with a mean of 5.5 Sv (April 2003). In using the mean velocity field from the repeats in the passages and relating it to the single CTD realization we assume that the single observation of the SAW fraction is representative for the whole tidal cycle in this passage. The topography of the passages (except Grenada passage) is well known through a survey with a multibeam echosounder, making the calculation of the area – cross - section very accurate. The highest uncertainty is the inflow through the Grenada passage, since the velocity transect used for that purpose is not located in the passage, but at the rim of the deeper Tobago Basin. This affects the estimated inflow of intermediate water, but is presumably of no consequence for the water masses above.

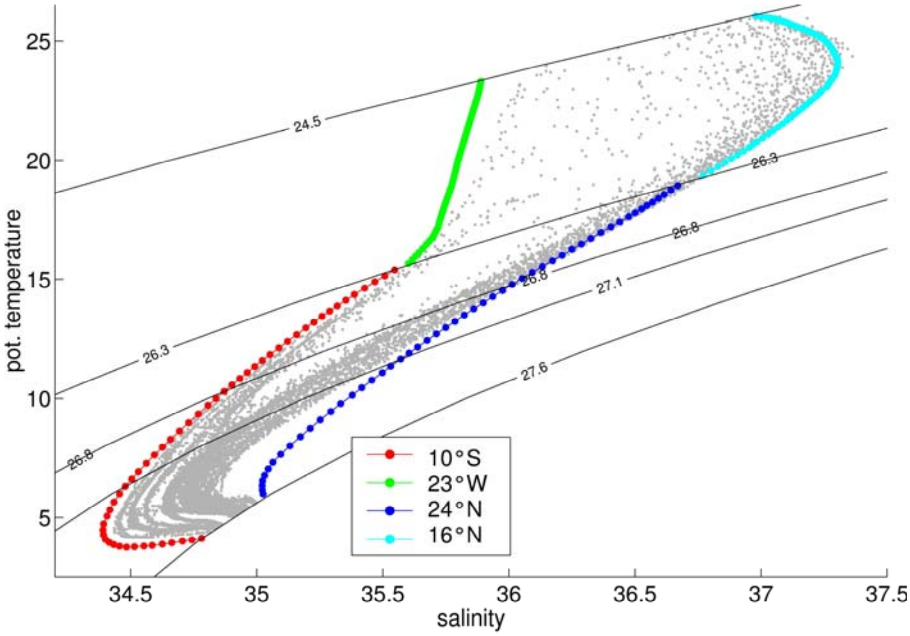


Fig. 1 T/S relationship of source water masses. Coloured dots: blue 24°N data from 1992 (e.g. Lavin et al., 2003) and 1998 (from WOCE), cyan: 16°N (cruise S152, December 2000) red: 10°S (cruise S151, November 2000 (Stramma et al., 2004), green 23°W , April 2000 (cruise METEOR 47, Stramma et al., 2004). As an example for the CTD data from the study region, the data from the METEOR cruise M53/3 are shown as gray dots. From Rhein et al., 2005.

SAW distribution in the passages

Despite the many obvious differences, the distribution of SAW shows some general features in all three surveys (Fig 2) : SAW is more dominant in the intermediate water and lower central water than in the SMW and UCW. More SAW is found in the southern passages (Grenada, St. Vincent, St. Lucia) than in the two northern ones (Dominica and Guadeloupe), confirming the model results from Johns et al. (2002). In the LCW and IW, the higher SAW fractions are often found on the northern slope of the passage, so that inflow of SAW occurs predominantly in the northern half of the channel. When averaging over all passages during an individual cruise, the mean SAW fractions were found to be between 30 and 37% for SMW and the UCW. In the LCW and IW the SAW fractions vary between 47 and 59%. The most striking differences between the repeats are the low SAW fractions in the LCW in the Grenada passage in June 2002. At the same time, both central water masses have smaller SAW contributions also in the St. Vincent and St. Lucia passages (Fig. 2).

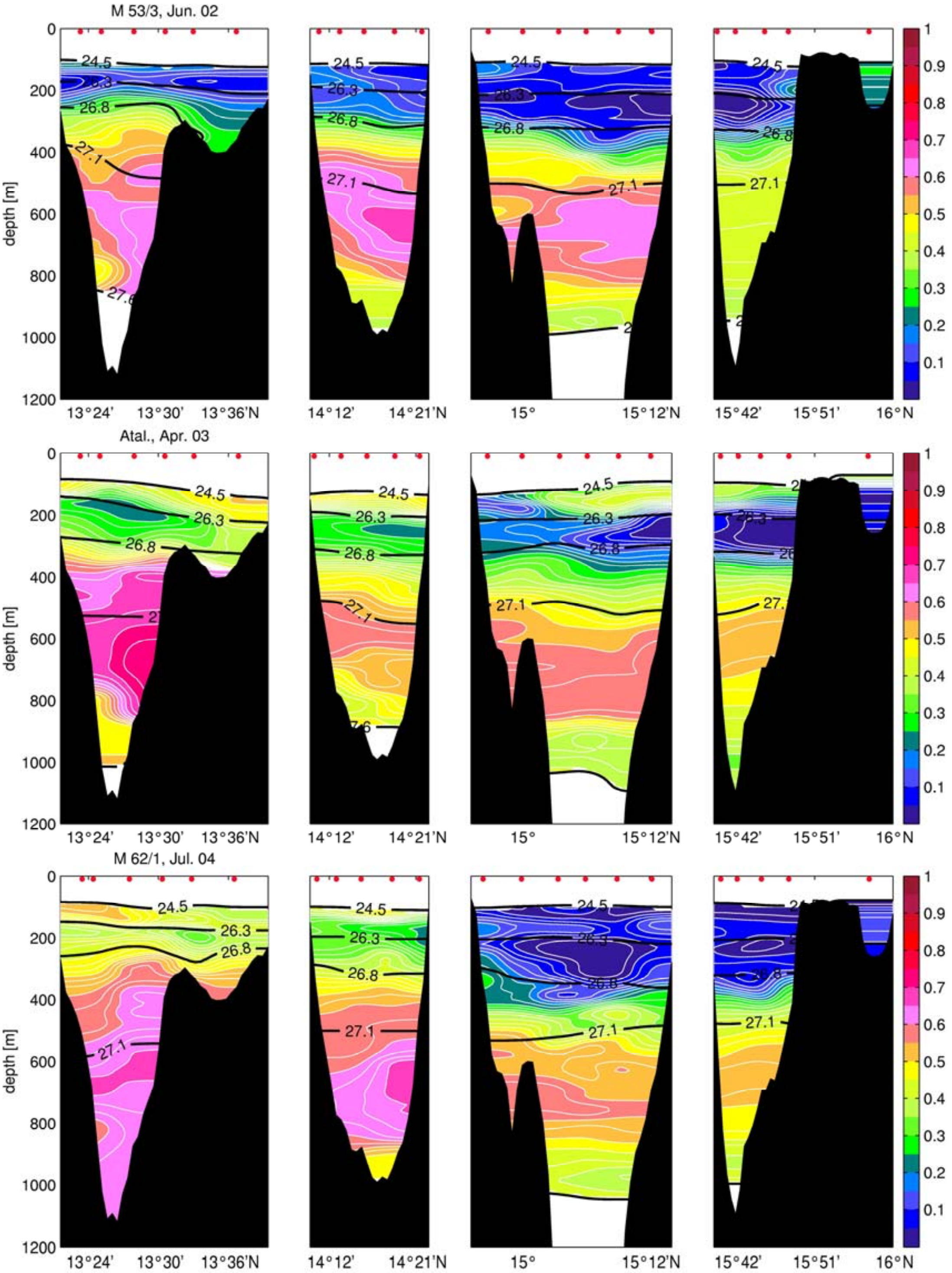


Figure 2: SAW fractions in the passages from St. Vincent passage (left) to Guadeloupe passage (right). The black lines are the isopycnals chosen for water mass boundaries (σ_θ = 24.5, 26.8, 27.1, 27.6), the red dots show the location of the CTD stations. The water above 24.5 is assumed to be of South Atlantic origin, but is not included here. A) M53/3, June 2002; B) L'Atalante, April 2003; C) M62/1, July 2004. From Rhein et al., 2005

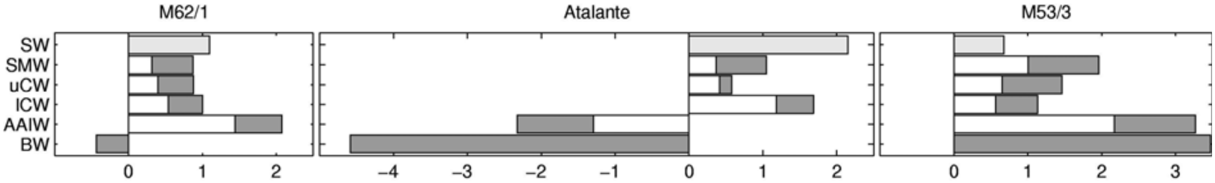


Fig.3 Transports (Sv) through the Grenada passage in July 2004 (M621), April 2003 (Ata) and June 2002 (M533) derived from data along the transect between. Tobago and St. Vincent. SAW transports: white, North Atlantic water transports: dark grey. The surface water is light gray. Positive: inflow, negative: outflow from Rhein et al., 2005

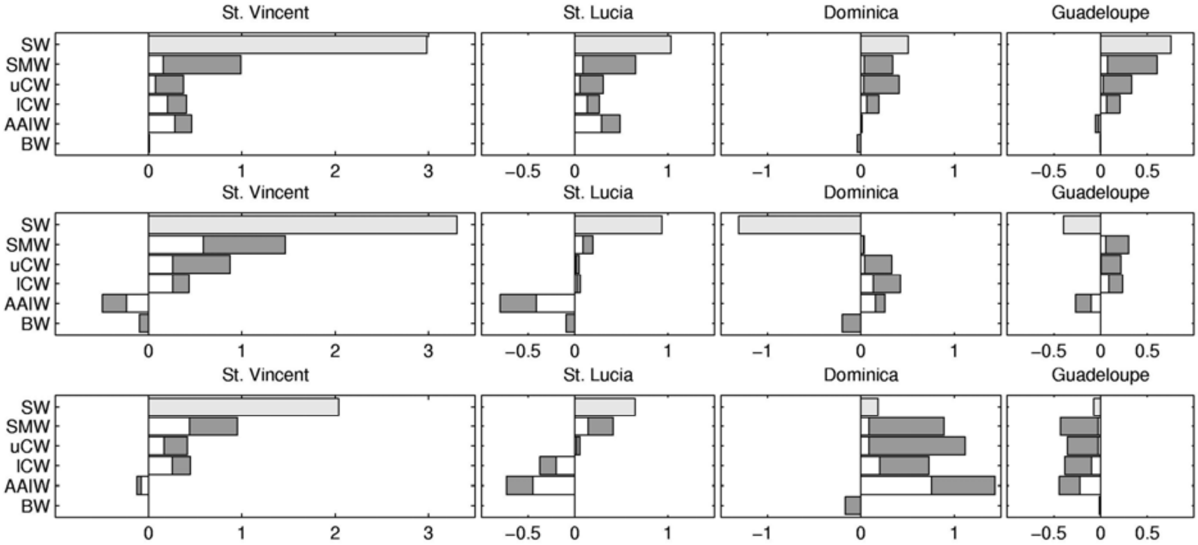


Fig. 4 Transports through the St. Vincent, St. Lucia, Martinique, Dominica, and Guadeloupe passage in a) July 2004; b) April 2003 and c) June 2002 (M533). SAW transports: white, North Atlantic water transports: dark grey. The surface water is light gray. Positive: inflow, negative: outflow (from Rhein et al., 2005)

Table 1: Total transports (Sv) through the Grenada, St. Vincent, St. Lucia, Dominica and Guadeloupe passages in July 2004 (M621), April 2003 (ATA) and June 2002 (M533). The Grenada passage transport was inferred from the measurements between Tobago and St. Vincent, the transport of water below the IW was omitted in that section. Total: the total transport, SW: surface water transport;. SAW:24.5-27.1: SAW transport of the SMW and the two central water masses, SAW:27.1-27.6 transport of SAW in the intermediate layer. SAW total: total SAW transport including the surface layer [Sv] and in % of the total inflow.. Negative: inflow into the Caribbean; positive: outflow. The discrepancy between the sum of the individual terms and the total SAW transport is caused by rounding. *: the outflow of IW was ignored in the calculation of the SAW inflow.

Cruise	total	SW	SAW:24.5-27.1	SAW:27.1-27.6	SAW total Sv	%
M621	-15.2Sv	-3.8Sv	-2.3Sv	-1.5Sv	-7.6 Sv	(50%)
ATA	-10.9Sv	-4.7Sv	-3.5Sv	+1.9Sv*	-8.2 Sv	(75%)
M533	-19.8Sv	-6.0Sv	-3.3Sv	-2.4 Sv	-11.6 Sv	(58%)

Transport through the passages

The transports through the passages decrease from south to north, from about 5 Sv through the Grenada passage (Fig. 3) to about 1-2 Sv in the northern channels (Fig.4). The total transports are highly variable (9.0-19.8 Sv). With one exception (IW in April 2003) the net transport of each of the water masses was into the Caribbean on all three repeats. The 19.8 Sv observed in June 2002 (Table 1.1) are higher than all estimates from the previous surveys, but the second next (17 Sv) was also observed in the same month (June 1993, Wilson and Johns, 1997). In both cases, the transport through Grenada passage was at a maximum (>10 Sv). Stramma et al. (2004) integrated the velocity sections along 44°W done in November 2000 and the December 2000 data along 16°N, resulting in a total inflow into the Caribbean of 23 ± 5 Sv. The inflow originated in part from the NBC retroflection and in part from the North Equatorial Current.

The transports of the SAW follow roughly the features of the total flow: highest in the Grenada passage and decreasing contributions towards the northern passages. A conspicuous feature occurred in April 2003, where IW outflow was observed in the three southern passages (Grenada, St. Vincent, St. Lucia). During the other repeats, these passages show an inflow of SAW in all water masses. Assuming that the surface water is of South Atlantic origin, the net Caribbean inflow of SAW was calculated to 6.3 Sv in April 2003, 7.6 Sv in July 2004, and 11.6 Sv in June 2002 , i.e. 50-75% of the total transport (Table 1.1). The minimum of 6.3 Sv is caused by the outflow of IW (1.9 Sv) at that time. Neglecting the IW, the SAW inflow in April 2003 is 8.2 Sv.

Flow across 16°N

At 16°N, the SAW contributions in the SMW and UCW drop rapidly below 10% east of 58°W, especially in June 2003 (SONNE cruise 171) and July 2004 (Fig.5). For LCW, however, the SAW fractions remain high throughout the western basin with maxima around 40% (Fig 5a,b). In the IW, SAW maxima exceeding 60% are found regularly about 100-200 km apart. The maximum of the SAW percentages is not at the western slope region, but eastward of 60°W. From the five repeats, only two show a net northward flow in the boundary region (Figs.5b,c), the other three have southward flow, confirming that at 16°N no permanent western boundary current in the upper 1200m exist. For the water below the IW, however, a Deep Western Boundary Current was found in the LADCP data (Rhein et al., 2004).

Between about 60°W and 57.30°W, a peculiar feature was observed in winter 2000 (Fig.5a). LCW containing 80% SAW was embedded in an anticyclonic eddy, which had a small imprint on the surface, but the velocity maximum in the LCW. This is most likely a surviving subsurface ring, originating from the NBC retroflection region off Brazil. This was also suggested from interpreting the salinity and oxygen distributions by Stramma et al. (2004). Another ring -- although horizontally more distorted -- was centred at about the same location in June 2003, and the highest SAW fraction was also found in the LCW and IW (Fig. 5d). This anticyclonic ring has surface intensified velocities and a second, weaker maximum in the IW layer. Presumably this is also a ring from the NBC retroflection site. In June 2002 (Fig. 5b), an anticyclonic eddy with surface intensified velocities had its centre at about 60°W in the surface layer and 59°W below 300 m depth. The highest SAW fractions were found in the IW, but higher than normal values (up to 50%) were observed in the two central water masses, and this ring might also originate from the NBC retroflection region.

Based on a 22 months current meter time series at 55°W off Brazil and on several shipboard surveys, Johns et al. (2003) estimated the number of NBC rings and the associated transports. They observed 12 surface and 4 subsurface rings. Deeper rings tend to occur in fall and early winter, while shallower rings are formed in spring and summer. Although subsurface intensified rings were more sparse and smaller in diameter than surface intensified ones, they contain a thicker layer of SAW and contribute to about 40% of the SAW ring transport. The total annualized SAW ring transport was estimated to 9.3 Sv (Johns et al., 2003). Goni and Johns (2003) used 10 years of altimeter data to follow the tracks of 52 rings shed in the retroflection region between October 1992 and December 2001. Once the rings reach 58°W (usually at latitudes between 10°N and 12°N), they turn to the North and pass east of Barbados. Only a few make it into the Caribbean. The trajectories in Goni and Johns (2003) ended at 15°N, and all rings pass 15°N west of 56°N.

In December 2000, the SAW distribution in the IW and LCW east of the subsurface eddy shows ring like features even east of 57°W (Fig.5a). The centre of the high SAW fractions at 56°W, at 54°30’W and at 52°40’N are correlated with the zero velocity isolines with northward flow to the west and southward to the east. Whether theses features also represent surviving NBC rings is unclear. Goni and Johns (2003) did not find any ring trajectories east of 56°W, but the features in Fig. 5a are subsurface intensified with no signal at the surface and therefore undetectable by altimetry.

Judging from the velocity fields, the rings have radii between 107 km and 160 km, comparable to the rings observed by Johns et al. (2003) near the NBC retroflection (100 km – 160 km). Multiplying the volume of the ring in each water mass with the corresponding mean SAW fraction and assuming that this ring crosses 16°N within a year, results in a ring SAW transport of 0.5 Sv for the June 2002 and December 2000 ring and 1.0 Sv for the June 2002 ring. The latter is higher because of its greater horizontal extension (160 km). The contribution of IW on the SAW transport ranges from 50-61%, the higher percentage comes from the subsurface intensified ring.

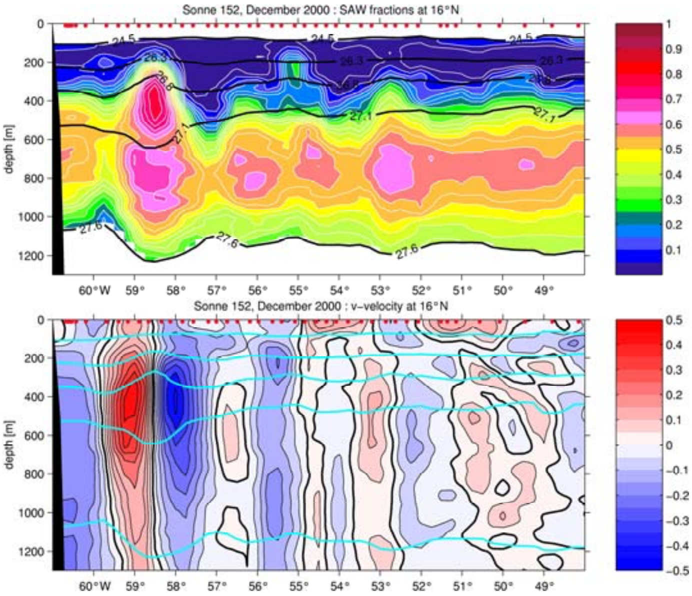
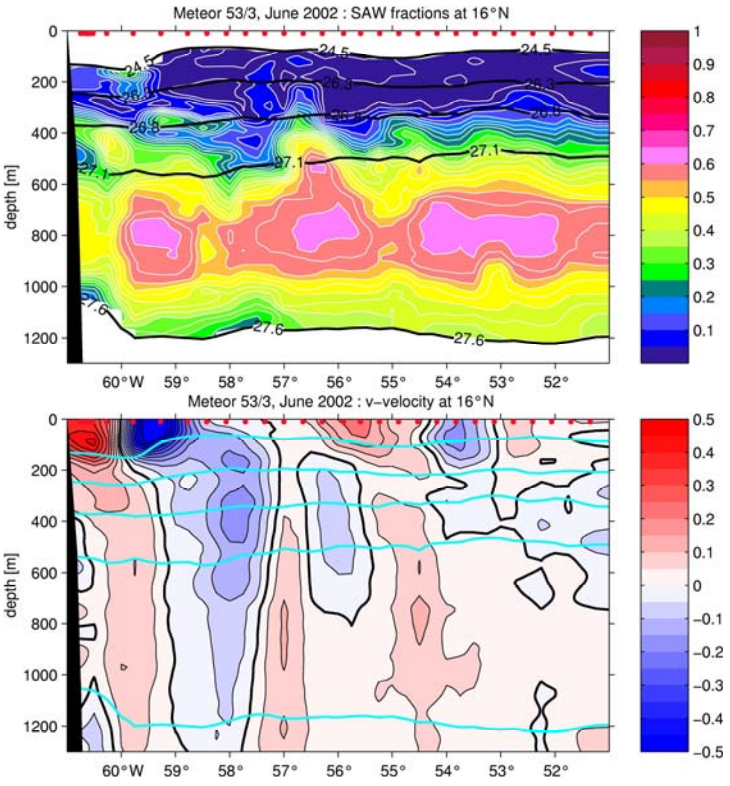
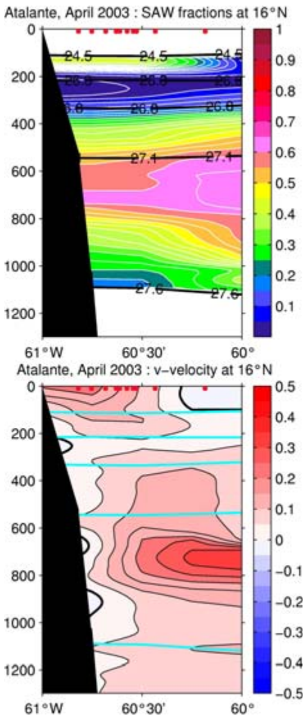
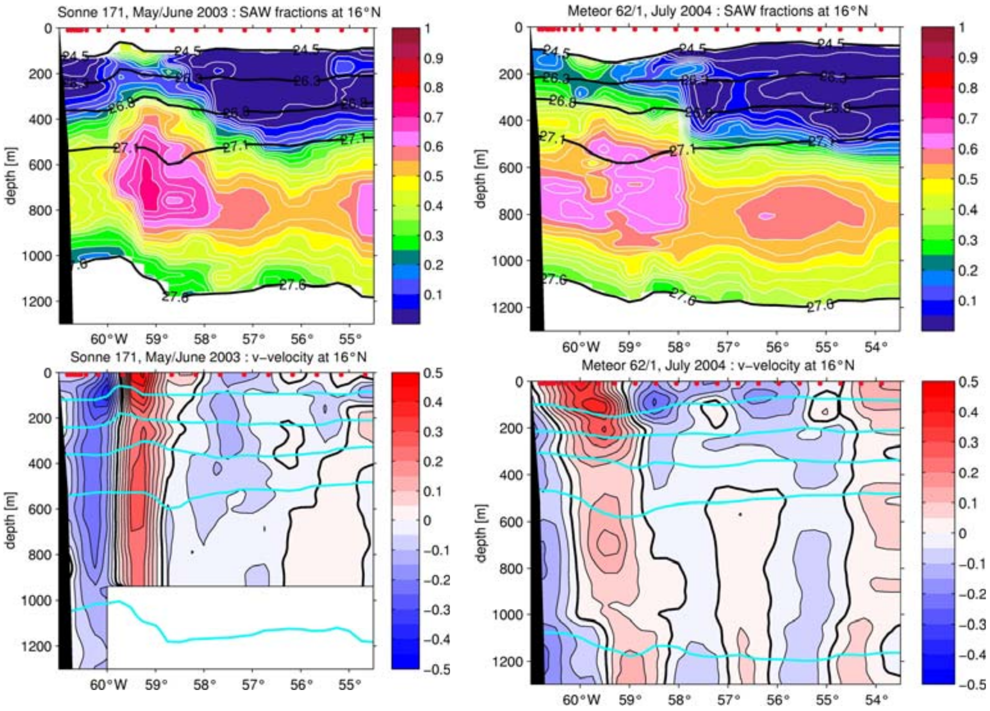


Fig.5a SAW fractions and meridional velocities at 1°N, December 2000 (from Rhein et al., 2005)





left: Fig.5b SAW fractions and meridional velocities at 16°N, June 2002 (from Rhein et al., 2005)
right: Fig. 5c SAW fractions and meridional velocities at 16°N, April 2003.
below left: Fig. 5d SAW fractions and meridional velocities at 16°N, June 2003.SONNE 171
below right: Fig. 5e SAW fractions and meridional velocities at 16°N, July 2004.


Sonne 171, May/June 2003 : SAW fractions at 16°N

Meteor 62/1, July 2004 : SAW fractions at 16°N

Sonne 171, May/June 2003 : v–velocity at 16°N

Meteor 62/1, July 2004 : v–velocity at 16°N

Summary

The mean SAW fraction in the Caribbean inflow was 30-37% for SMW and UCW, and 47-59% for LCW and IW. At 16°N, the percentage of water from the South Atlantic decrease below 10 % in the SMW and UCW, but remain higher for the LCW (maximum : 40%) and the IW (maximum: 70%).

The net SAW inflow into the Caribbean through the passages south of Guadeloupe ranges from 7.6 Sv in July 2004 to 8.2 Sv in April 2003 and to 11.6 Sv in June 2002, and makes up 50-75% of the total inflow. The uncertainty in the contribution of SMW from the Western South Atlantic might add another 0.9-1.6 Sv SAW. The SAW transports calculated here exceeded the limit set by Wilson and Johns (1997) who concluded that no more than 7 Sv SAW enter the Caribbean.

The combined total inflows from our study, from Wilson and Johns (1997) and from Johns et al. (2002), lead to a slightly lower annual mean inflow of 11.1 Sv instead of 12.8 Sv (Johns et al., 2002). The two highest transports are found in June and they are dominated by anomalous high inflow of surface water mainly through the Grenada passage. The lack of transport data during several months and the unknown amplitude of the short-term fluctuations and the interannual variability make it difficult to infer a seasonal cycle. Therefore, higher resolved time series are needed instead of shipboard measurements irregularly spaced in time.

The calculation of the SAW transport across 16°N was hampered by the presence of anticyclonic rings from the North Brazil Current retroflection region. The rings exhibit enhanced contributions of water from the South Atlantic. At least three anticyclonic rings centred at about 58°W were observed in December 2000, June 2002 and June 2003. The ring in December 2000 was subsurface intensified. At this time, three other ring like subsurface features were observed further east. The annual number of rings crossing 16°N cannot be inferred from our observations. Provided that the three rings we observed at 16°N are typical rings and that all rings which are annually produced in the NBC retroflection area reach 16°N, the SAW transport across 16°N due to the NBC rings would be 6.0 Sv, with 3.0-3.6 Sv IW. No permanent western boundary current was found at 16°N, thus the mean northward SAW transport at the western boundary is presumably negligible.

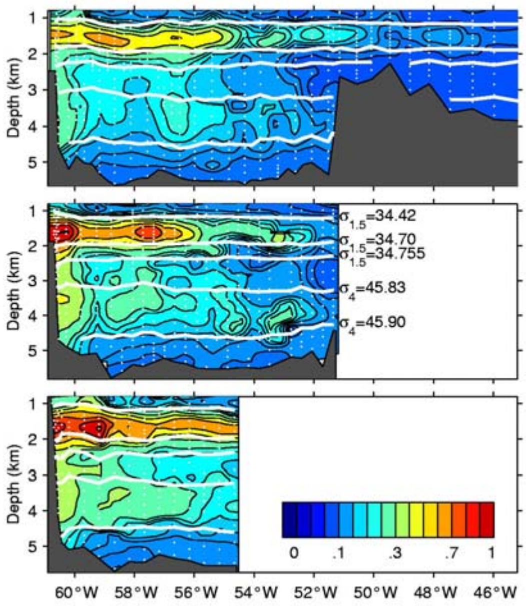
The joint SAW transport from the Caribbean inflow and the flow across 16°N amounts to 15 Sv, which is in the range of the inverse model calculations (e.g. Ganachaud and Wunsch, 2000). About 5-6 Sv of this transport is IW from the South Atlantic, supporting studies which found the contributions of intermediate and upper warm water to be of comparable importance. For the upper warm water ($\sigma_\theta < 27.1$), the Caribbean inflow is the major path (7.9±1.6 Sv), the ring induced transport across 16°N is about 35% of that value. The IW transport is higher across 16°N (3.0-3.6 Sv) than into the Caribbean (60%).

II.2 The Deep Flow (Rhein et al., 2004)

Like everywhere in the North Atlantic (e.g. Rhein et al., 1995), the largest CFC maximum is found in the uLSW, located at about $\sigma_4 = 34.65$ (1500-1700 m depth, Fig. 6). In 2000 and 2002, CFC concentrations >0.5 pmol/kg in the uLSW are restricted to the region west of 56°W (Fig. 6a,b). One year later (June 2003 SONNE cruise 171) concentrations >0.6 pmol/kg extend at least to 54°30‘W, the easternmost station in this year. Several CFC maxima outside the DWBC exist, the location of which varies from cruise to cruise. Maxima outside the DWBC are frequently found in the subtropical and tropical Atlantic (Rhein et al., 1995; 1998) and commonly attributed to recirculation, shifting water from the DWBC into the basin’s interior. In contrast to the general belief that the water in the DWBC is the ‚youngest‘ and therefore has to have the highest CFC concentrations , in two of the three repeats (Dec. 2000 and June 2003), the offshore CFC maxima located at 58°W and 59°W were higher than the concentrations found in the DWBC (Fig. 6a,c).

The salinity and oxygen distributions also show that the water mass characteristic of the DWBC and the region just east of the DWBC are more closely related than the water masses further east (Fig. 7). The mean salinity profiles in the upper NADW in the DWBC (west of 60°W) and between 60°W and 55°W are similar (Fig. 7a), with a conspicuous salinity minimum at about 1700 m depth. The maximum above is caused by admixture of water from Mediterranean origin, which is more pronounced in the DWBC. The salinity minimum is not found east of 55°W. The mean oxygen profiles of the NADW (Fig. 7b) also show high concentrations in the DWBC and only slightly lower values between 60°W and 55°W. East of 55°W, the concentrations decrease throughout the NADW, and the lowest concentrations are observed above the Mid-Atlantic Ridge.

The cLSW is the transition zone between the CFC maximum of the uLSW and the minimum in the mNADW. No second CFC maximum in the cLSW was observed. The mNADW displays a CFC minimum, but within this water mass, the concentrations in the DWBC are higher than farther east, as expected. The deep CFC maximum of the DSOW is strongest in the DWBC during all three cruises. Other CFC cores are found in December 2000 between 56°W-57°W, at 54°W and at 52.5°W, but the concentrations in the maxima diminish with increasing distance to the western boundary. On most occasions – but not always – the uLSW and the DSOW maxima are at the same geographical location (Fig.6). Below $\sigma_4 = 45.90$ (located at about 4500 m depth) the low-CFC Antarctic Bottom Water (AABW) is found.



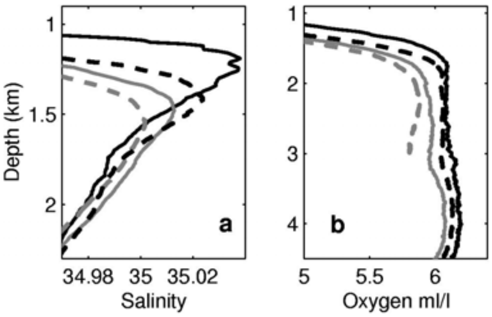


Fig.6. (left) CFC-11 distribution along 16°N a) Dec. 2000 cruise S-152, b) June 2002, cruise M5373; ; c) June 2003 cruise S-171.

Fig. 7 (right) Mean salinity (a) and oxygen (b) profiles in the NADW along 16°N, December 2000. Black bold line: DWBC west of 60°W, black stippled line: 60°W-55°W, gray bold line: 55°W-MAR, gray stippled line: above MAR (bottom of page 10)

The velocity structures in the NADW are in general coherent over several LADCP profiles, hence the horizontal coverage of the profiles seems sufficient to resolve the flow field (Fig. 8). The co-location of the LSW and DSOW CFC maximum cores indicates that the general circulation encompasses all of the NADW from 1000 m to 4500 m depth. This is confirmed by the largely depth independent LADCP flow field measured in 2000, especially west of 55°W (Fig.8). Outside the DWBC, CFC maxima are not always correlated with large southward velocities. This might indicate short term velocity fluctuations not represented in the CFC distribution. For instance, before the date of the measurements, the high CFC water could have been brought there by southward velocities prevailing over weeks. If the velocity slackens or even reverses shortly before measure ment, one still finds high CFC water at that location, but connected to a weak or northward flow.

Because of the steep topography at the continental slope, the DWBC is narrow and confined to the area west of 60°W. The flow is to the south with the highest velocities (exceeding 20 cm/s) between 1000 and 2500 m depth (uLSW/cLSW). The large eddy above 1500 m depth between 59°W and 57°W is intensified in shallower depths and also evident in shipboard ADCP data (not shown).

Because of the pressure limitation of the LADCP at 5000 dbar, only the velocity in the upper part of the AABW was measured. AABW flows mainly northward in the eastern half of the basin (Fig. 8). The high velocities (>20 cm/s, Fig.8b) are similar to those measured with moored current meters in that region (M. McCartney, WHOI, pers.comm.). The strong northward flow reaches far into the DSOW layer and dominates the NADW east of 55°W. This longitude is the easternmost limit of the ridge system bordering the Puerto Rico Trench. The top of the ridge just north of the 16°N section is at about 4000 m depth at 58°W and 4500 m between 56°W and 55°W . This ridge could act as a topographic barrier, limiting the northward flow of AABW (and DSOW) to east of 55°W (Fig. 9). However, in June 2002 the mean NADW flow in the eastern basin was also to the south (Fig. 9c). The region west of 55°W is characterized by CFC concentrations that do not differ much from the ones in the DWBC, i.e. the strongest drop in the concentrations occurs not close to the DWBC, but between 57° and 55°W (Fig. 9 a,b). The direction of the flow in the high CFC region between 60°W and 55°W is predominantly southward (Fig. 6, Fig. 9c), carrying – like the DWBC – young, recently ventilated NADW components downstream. Above the MAR (i.e. east of 51°W), the zonal and meridional velocity components are small (Fig. 9c,d) and no directional preference can be detected. The CFC concentrations in this region are the lowest observed along the 16°N section (Fig. 6a).

In the DWBC, the CFCs in the uLSW and cLSW increased between December 2000 and June 2002 by 26% and 30% per year, respectively. One could tentatively attribute this strong increase to the arrival of LSW that was formed by intense convection in the years 1988-1994. As mentioned above, this LSW arrived at 26.5°N in 1996 (Molinari et al., 1998). For a distance of about 2000 km between the two locations, the mean spreading velocity of the LSW would be roughly 1 cm/s. This velocity is lower than the 2-2.5 cm/s for the region north of 26.5°N (Molinari et al., 1998), but comparable to other tracer based estimates (e.g. Fine et al., 2002; Steinfeldt and Rhein, 2004). In contrast to the 26.5°N data, the arrival of the 1988-94 LSW vintage at 16°N in 2002 was not accompanied by a second CFC maximum at 16°N. This second maximum was also not found upstream at 26.5°N in 1998.

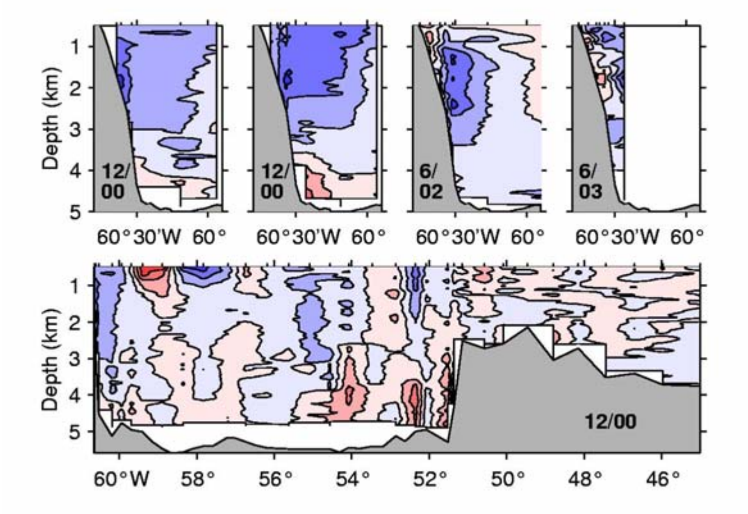
Surprisingly, the CFC increase in the DSOW was of the same amount as in the uLSW/cLSW (26% per year) and this substantial change could not be caused by intensified ventilation in the Labrador Sea. Between June 2002 and June 2003, the CFC concentrations remained constant in the DWBC, but increased between 55°W and 60°W by 13-23% per year. The reason for the constant CFC concentrations in the DWBC could be the anomalous weak DWBC transport in June 2003, which was only 4.5 Sv to the south between 1000 m and 4500 m depth. A weak DWBC transport could only affect the CFC concentrations if the DWBC had been weak for a longer time period. Unfortunately, this cannot be confirmed by our single shipboard section. The increase in velocity toward the easternmost profile of the LADCP transect suggests that a southward flow might exist east of 60°20‘W. The largest CFC maximum in the uLSW was found at 59°W (Fig.6c).

In December 2000, the southward DWBC transport during the two repeats was 25.6 Sv and 28.9 Sv, comparable to that of June 2002 (25.7 Sv). The range of these DWBC transports at

16°N is similar to that further downstream at 0°, 44°W, where Fischer and Schott (1997) found an annual mean deep water (1000 m-3000 m depth) transport of 13 Sv, ranging from 7 Sv in September/October to 25 Sv during January-February. Their estimate excludes the contribution of the DSOW. At 11°N, Friedrichs and Hall (1993) measured a southward DWBC transport of 26.5 Sv, similar to our results from December 2000 and June 2002.

The net meridional transports in the interior were in the same order of magnitude as the DWBC transports: the net southward NADW transport at 16°N between 60°W and 55°W was 26 Sv in December 2000 and 36 Sv in June 2002. The net northward transport in the eastern part of the basin in December 2000 amounted to 21.8 Sv. Although these are only snapshots of the flow field, it is obvious that the transports outside the DWBC cannot be Fomitted when trying to detect climate induced changes in the deep part of the meridional overturning circulation.

Fig 8 Meridional LADCP velocity section a) across the DWBC in Dec. 2000 (two repeats), June 2002 and June 2003 (SONNE cruise S171). b) along 16°N, December 2000. The location of the profiles is indicated at the top. Contour interval is 10 cm/s. Blue denotes southward, red northward flow.



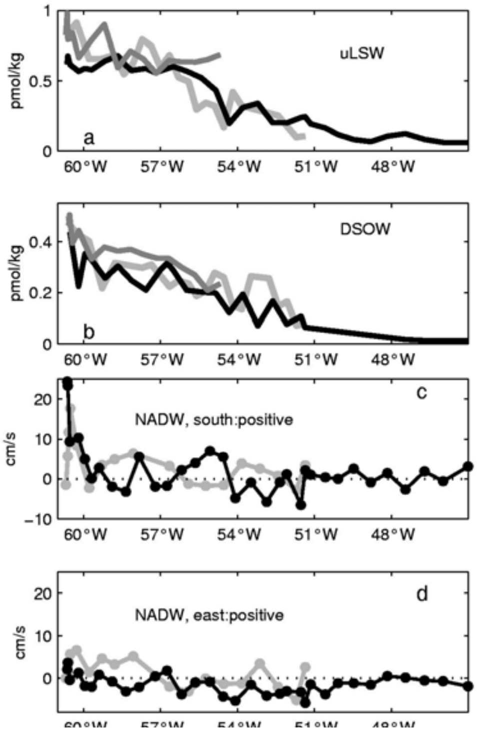


Fig. 9 Zonal distribution of the mean CFC-11 concentration (pmol/kg) along 16°N in a) uLSW and b) DSOW. The mean on each station was calculated by averaging the concentrations in the respective density layers weighted by the vertical distance they represent. c) Mean meridional velocities (cm/s) in the NADW, averaged between 1000m and 4500m depth. Southward velocities are positive (blue in Fig.6). d) Mean zonal velocities (cm/s) of the NADW. Positive is eastward. Black: December 2000; light gray: June 2002, dark gray: June 2003(SONNE cruise S171)

II.3 Correlation between CFC and salinity in the LSW, Labrador Sea – Tropical Atlantic (manuscript in preparation)

The correlation between the CFC concentrations and salinity of the two LSW modes change drastically from the subpolar to the tropical Atlantic: In the subpolar North Atlantic, the LSW is characterized by a CFC maximum and a salinity minimum. While moving towards the subtropical Atlantic, the LSW encounters the somewhat lighter saline, warm and CFC poor Mediterranean Water (MW), with a salinity maximum at 1200-1400m depth. The MW truncates the salinity minimum of LSW below the CFC-11 maximum or even erases it. Further south, the fresh and CFC poor Upper Circumpolar Deep Water (uCDW) flows above the MW/LSW and gradually weakens and truncates the salinity maximum of the MW. At 7°N, off French Guyana, the salinity maximum is found at sig1500= 34.58. Downstream, at 44°W off Brazil at the equator, the salinity maximum coincides with the CFC maximum of the uLSW at sig1500=34.65 (Rhein et al., 1995) and CFCs and salinities show a positive linear correlation (Rhein et al., 1998). This holds also for the cLSW layer, although with a different slope. The CFC and salinity maxima remain at sig1500=34.65 in the South Atlantic DWBC sections at 5°S and 10°S (Rhein et al. 1995) as well as in the zonally flowing NADW at 28°W and 24°W (Rhein and Stramma, 2004).

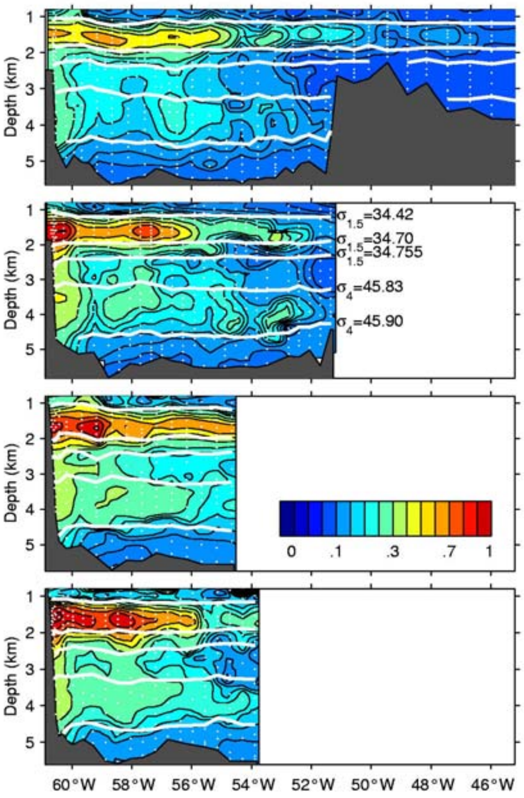
Table 2 *Densities of uLSW and cLSW , subpolar to tropical Atlantic, 55°W : Pickart and Smethie, 1998; 26.5°N: Molinari et al., 1998; equator-10°S: Rhein et al., 1995.*

	at 55°W	at 26.5°N	Equator – 10°S
uLSW	sig_th = 27.68-27.74	sig_15 = 34.54-34.58	sig_15=34.42-.70
cLSW	sig_15= 34.62-34.70	sig_15= 34.65-34.69	sig_15=34.70-755

Temporal change of the CFC concentrations in the deep water at 16°N

In Fig. 10, the CFC distribution at 16°N are presented, starting with the first measurements in December 2000 (uppermost figure), and the M62/1 results are shown in the last figure. In the uLSW level, the M62/1 distribution is characterized by two maxima, one at the DWBC and on located at about 58°W. A similar pattern has been found in June, 2002. In contrast to the 2003 repeat, the high CFC concentrations in the uLSW were limited to the region west of 56°W. The concentrations in the uLSW and cLSW increased, especially in the DWBC, but they remained almost constant in the DSOW.

Fig .10 *CFC-11 distribution at 16°N, a) Dec 2000, b) June 2002; c) July 2003SONNE cruise S171; d) July 2004, cruise M62/1. The white lines denote the isopycnals, chosen as water mass boundaries between the uLSW, cLSW, mNADW and DSOW. upper three panels from Rhein et al., 2004, already presented in Fig.6.*



Change of the salinity signal, Labrador Sea – Tropical Atlantic

The arrival of the cLSW mode (formed in 1988-94) in the subpolar Atlantic at 43°N, 55°W and in the subtropical Atlantic at 26.5°N was inferred from an anomalous increase in CFCs in the cLSW layer compared to the CFC increase in the uLSW, leading occasionally to a 2nd maximum. The associated cooling and freshening at 43°N, 55°W was 0.27°C and 0.06, respectively. At 26.5°N off Abaco the cLSW got fresher by 0.02 and colder by 0.1°C, i.e. the anomalies were reduced 2000km downstream to about one third. One expects that the cooling and freshening at 16°N, more than 1200km further south, will be smaller than at 26.5°N. Our time series of T/S profiles in the Deep Western Boundary Current at 16°N (Fig. 11) show in the cLSW a salinity decrease of about 0.01.

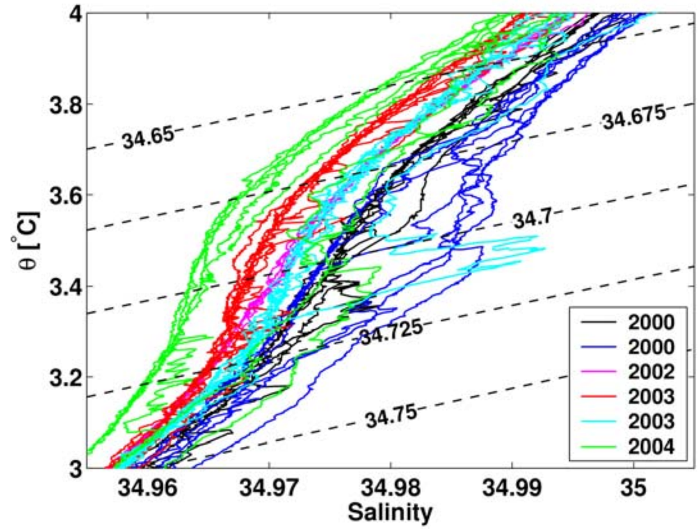


Figure 11 *T/S characteristics in the DWBC at 16°N, 2000-2004. The figure show the density region of the cLSW. The freshest profiles are from the M62/1 cruise, July 2004. Presumably the freshening at these isopycnals is caused by the arrival of cLSW which was formed during years with intensive deep convection in the Labrador Sea in 1989-1994.black: KNORR (M. McCartney, WHOI), January 2000, blue: SONNE 152, December 2000; pink: METEOR M53/3, June 2002; red: Atalante, February 2003;* **light blue: SONNE 171**, *June 2003; green: METEOR M62/1, July 2004. all cruises (except KNORR): Rhein et al.*

This is about 20% of the salinity decrease observed in the Labrador Sea. and about half the signal measured at 26.5°N, i.e. 1000 Kilometers further upstream. From the CFC age spectra, Steinfeldt and Rhein (2004) inferred that at 16°N, the fraction of recently ventilated CLSW in the Deep Western Boundary Current is about 20%. This result was received independent from the temporal salinity decrease (also 20%). The variability in the T/S characteristics of uLSW at 16°N is high, due to mixing of the fresh uLSW with the saline water from the Mediterranean. Up to now the expected salinity decrease due to fresher ULSW cannot be unambiguously detected among the the local variability present. The moored temperature and salinity time series of the MOVE/GAGE array at 16°N show temperature and salinity fluctuations in the uLSW in the order of +-0.01 on weekly time scales, making the detection of an anomaly in the same order of magnitude from shipboard data difficult.

Change of the CFC signal

In Fig. 12, the temporal trend of the CFC concentrations at 16°N in the DWBC is presented. The CFC increase remain strongest in the uLSW, followed by an increase in the cLSW. No double maximum as has been found at 26.5°N has been observed yet. The DSOW concentrations remain rather stagnant in the last years.

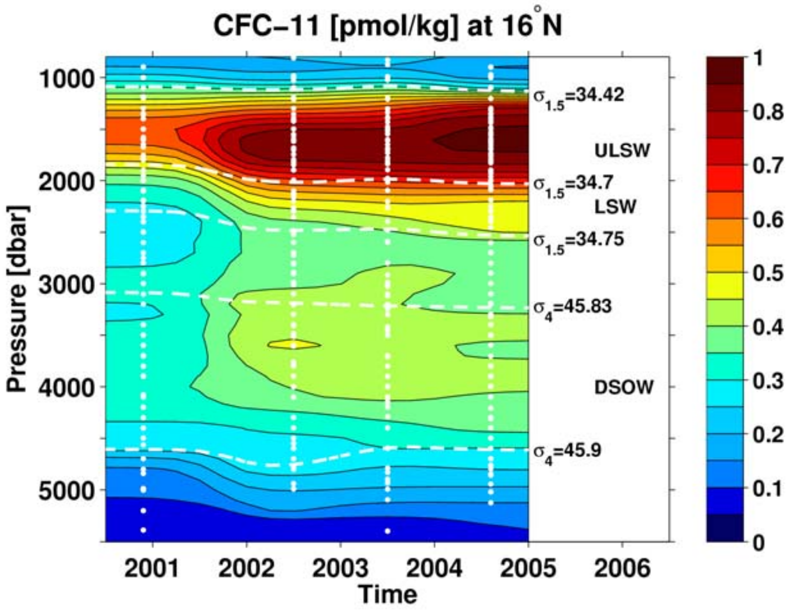


Figure 12 Temporal CFC increase in the Deep Western Boundary Current at 16°N, 2000-2004. The data in the DWBC have been spatially averaged. The white stippled lines denote the isopycnals, which have been chosen as bounds for the deep water components. **SONNE 171 data: 2003**

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II.2 Verwertbarkeit der Ergebnisse und der Erfahrungen

Dies ist ein Projekt der Grundlagenforschung, daher sind keine unmittelbaren wirtschaftlichen Verwertungsmöglichkeiten zu erwarten. Allerdings werden die gewonnenen Erkenntnisse helfen, die Klimarolle des Ozeans besser zu verstehen was mittelfristig zu besseren Vorhersagemodellen führen wird. Dies hat neben den wissenschaftlichen auch wirtschaftliche Konsequenzen.

II.3 . Fortschritt bei anderen Stellen während des Vorhabens

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II.4 Erfolgte und geplante Veröffentlichungen

Rhein, M., M. Walter, C.Mertens, R. Steinfeldt, and D. Kieke, Circulation of North Atlantic Deep Water at 16°N, 2000-2003. Geophys. Res. Lett., 31, LI4305, doi:10.1029/2004 GL019993, 2004

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In Vorbereitung:
Steinfeldt, R. M. Rhein et al., Spreding of deep water along the Deep Western Boundary Current

Smethie, W.M., Rhein et al., The distribution of CFCs in the North Atlantic: CFC inventories and water mass formation rates