Exchanges
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Benchmarks for Atlantic Ocean Circulation[1]

Robert L. Molinari, Roberta Lusic, Silvia L. Garzoli, Molly O. Baringer and Gustavo Goni
NOAA/AOML, Miami, FL, USA
corresponding e-mail: bob.molinari@noaa.gov

Oceanographers frequently decompose the total oceanic circulation into two components: a wind-driven component existing primarily in the horizontal plane and a thermohaline-driven component existing primarily in the vertical plane (also called the meridional overturning circulation, MOC). Although this decomposition is a simplification of the dynamics of the motion in the ocean (the two components are not separable in the complete equations of motion), it provides a framework for describing responses of the ocean to different surface forcing functions. Numerical modelling, paleoclimate and observational studies indicate that both the wind-driven and thermohaline circulation can play an important role in longer-term (greater than decadal) climate variability. The U.S. National Oceanic and Atmospheric Administration addresses both components to satisfy its missions of detecting, attributing and forecasting long-term climate change. We contribute to NOAA's mission by developing and providing observational benchmarks (i.e., indices) for various components of the wind-driven circulation (hereinafter WDC) and MOC in the Atlantic Ocean.

Many early NOAA programmes (e.g. STACS, ACCP) were searching for indices of critical North Atlantic WDC and MOC features to monitor. Although not originally NOAA programs, other studies have considered the contribution of southern hemisphere features to the MOC. For continuity of the upper layer limb of the MOC, exchanges are required: from the Indian Ocean to the South Atlantic; across the South Atlantic; and across the equator. The inter-ocean exchange takes place through the Benguela/Agulhas system, south of South Africa. The Agulhas Current at its retroflection sheds energetic rings that carry salt and warm water into the South Atlantic. Satellite altimetric measurements have been calibrated to provide estimates of the transport of the Agulhas Current and the separated rings. The extension of the Benguela Current brings the Indian Ocean waters to the central South Atlantic as it flow northwestward in the South Atlantic subtropical gyre.

The pathways of the upper limb MOC transport are then complicated by the wind-driven circulation features along the western boundary and the interior tropical Atlantic (i.e., equatorial upwelling, off-equatorial down welling, zonal currents), that provide obstacles for this limb to move from the South Atlantic to the North Atlantic. Currently, there is insufficient understanding and data to identify precisely these pathways. However numerical models do provide some initial guidance. Using an eddy-resolving numerical circulation model, (Fratantoni et al., 2000) concluded that 14 Sv of upper limb MOC flow is partitioned among three pathways connecting the equatorial and tropical wind-driven gyre: a frictional western boundary current accounting for 6.8 Sv; a diapycnal pathway involving wind-forced equatorial upwelling and interior Ekman transport, 4.2 Sv; and North Brazil Current (NBC) rings shed at the NBC retroflection, 3 Sv. The results of an AOML, university observational program indicate that previous estimates both in the numbers of rings per year and in their contribution to hemispheric exchanges were low. Based on the results of this work, a monitoring strategy is being developed to monitor ring formation and propagation.

Both the intensity of the subtropical gyre and a component of the warm upper level poleward flow in the North Atlantic are being monitored by submarine cable observations in the Straits of Florida. Similarly, the characteristics of the cold deep return flow are being tracked by research vessel transects across the DWBC east of the Bahamas. In the North Atlantic Ocean, time-series of both the upper layer temperature structure within the subtropical gyre and total water column changes across the basin are being maintained.

The recent history of these and other components of the MOC and WDC motions are characterized by data collected over the past 10 to 50 years. These benchmarks are designed to serve several purposes. Independently these benchmarks serve as indices for (1) the intensity of various components of the MOC and WDC, thereby providing alerts for dramatic changes in these features and (2) verification of the ability of GCM's to simulate the ocean's role in climate variability. Collectively, when assimilated into GCM's they will provide global benchmarks for detection and attribution of climate change. All the benchmarks presently available are shown in Figure 1). We will now describe a few of these indices, when

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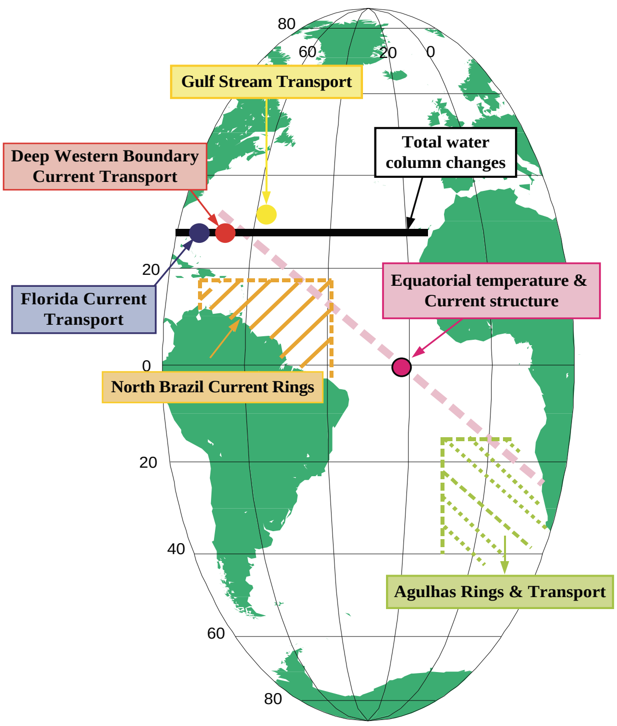

Fig. 1: Benchmarks being monitored and available on http://www.aoml.noaa.gov/benchmarks/index.html.

sufficient data are available we provide a description of the characteristics of various scales of variability.

1. Agulhas Current

Monitoring both the Agulhas transport into the South Atlantic in the upper kilometre of the ocean and the number of rings shed at its retroflection provides a means of detecting any substantial changes in inter-ocean water exchanges. After calibrating the observations with an array of inverted (IES) echo sounds, satellite altimetry has been used to estimate inter-ocean exchange between the Indian and Atlantic Oceans and has been maintained since 1993. The time-series for this transport is shown in figure 2. In addition, ring shedding events can be identified.

Agulhas Current and ring shedding characteristics

After turning to the west, the circulation of this current turns or retroflects back to the east between 15 and 25ºE (Figure2, upper panel). The net westward baroclinic transport across a TOPEX/POSEIDON groundtrack (blue line in the top panel of Figure 2) is estimated using altimetry-derived sea height anomaly and historical hydrographic data within a two-layer reduced gravity scheme.

- *Mean annual transport and number of rings shed:* The mean annual transport of the Aguhlas Current from the coast to 40°S above the 10°C isotherm is 15.7 ± 1.5 Sv, with a maximum of 23 ± 1.5 Sv in 1997 and a minimum of 13 ± 1.5 Sv in 1993. The number of rings shed at the retroflection is between 4 and 7 per year and the transport of the rings varies between 0.8 and 2.4 Sv.

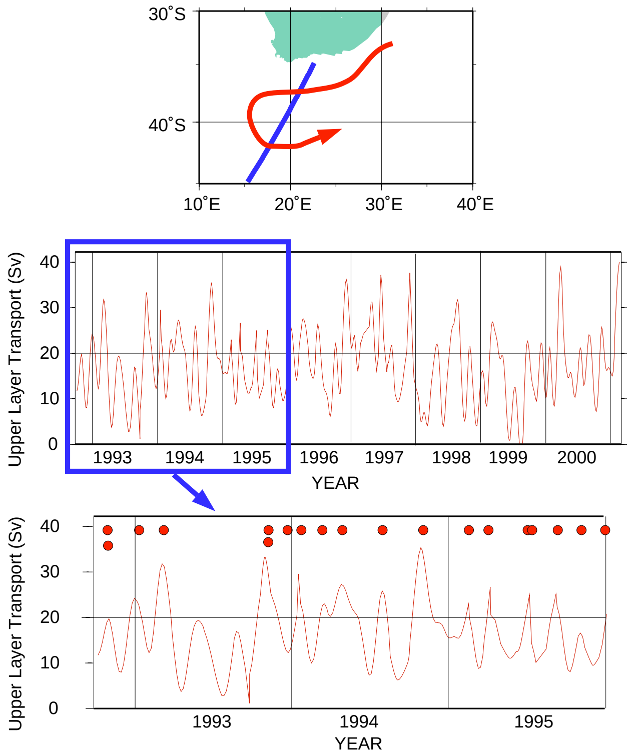

Fig. 2: (top) Schematic of the Agulhas Current retroflection. (center) Baroclinic transport from the surface to the 10 °C isotherm across a selected TOPEX/Poseidon altimeter ground track from the coast to 40 °S. (blue line in top panel). (bottom) Baroclinic transport between 1993 and 1995 showing a strong correspondence between ring shedding (red circles) and maximum transport values.

- *Interannual signal*: Strong interannual variability in the transport time series is primarily related to ring shedding (Figure 2, center panel).

- *Annual signal*: The altimeter-derived Agulhas transport shows no apparent seasonal signal (Garzoli and Goni, 2000), contrary to previous numerical model results (Matano et al., 1998).

2. North Brazil Current

The North Brazil Current is a western boundary current in the tropical Atlantic that transports upper ocean waters across the equator. Particularly during summer and fall, the NBC retroflects from the coast at 6° to 7°N and feeds the North Equatorial Countercurrent and North Equatorial Undercurrent. During this retroflection phase large anticyclonic rings are shed. These features

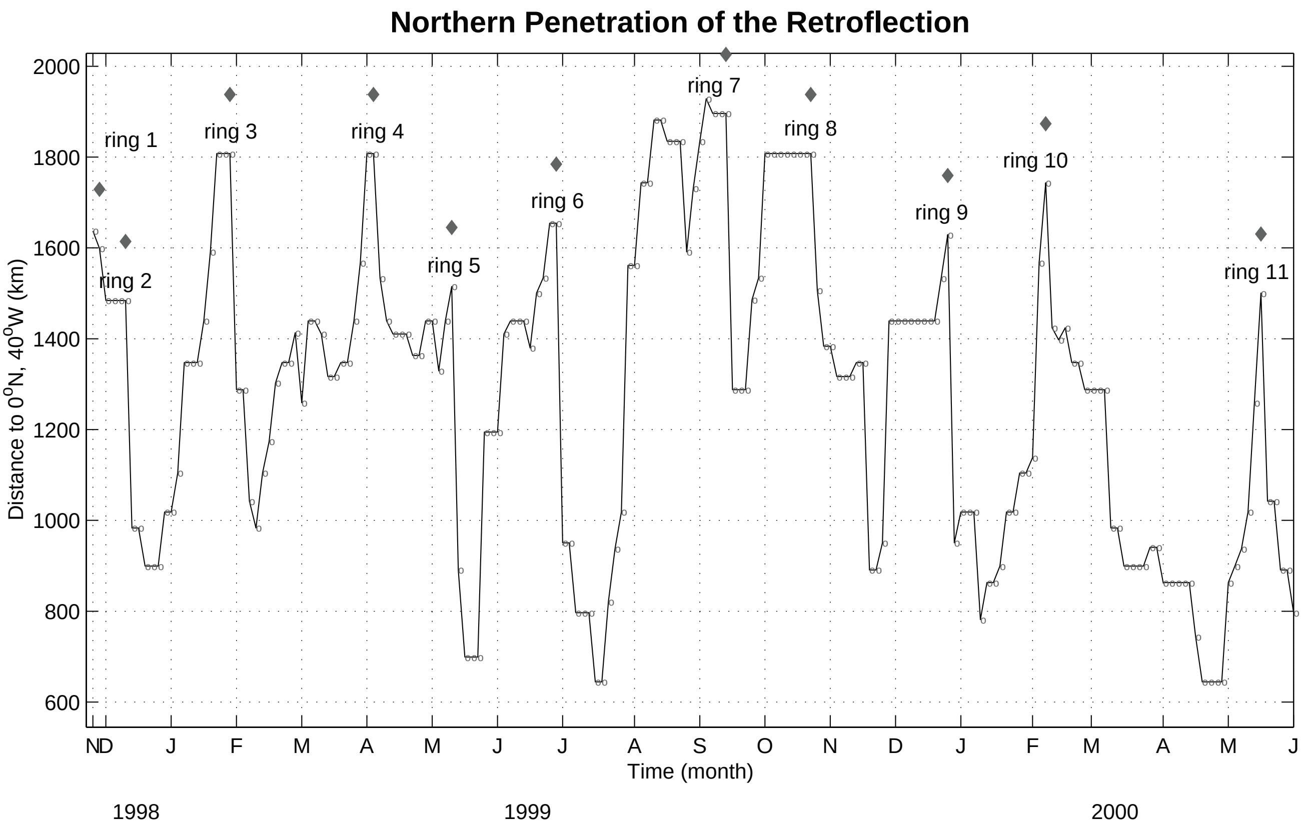

Fig. 3: Time series of the latitude of penetration of the NBC retroflection estimated from synoptic dynamic height maps. It is measured as the distance (in km) between the northern most point of the retroflection and an arbitrary point in space (0°N 40°W). Diamonds indicate the time of a ring shedding. The northward motion can be considered as the motion of the northward penetration (30km/day). The southward motion is only a resetting of the index. As the ring separates, the retroflection reforms further south.

then move northwestward toward the Caribbean Sea, roughly paralleling the South American coastline. As part of the NBC Ring study, an analysis of altimetric data was made (Goni and Johns, 2001). Using a two-layer reduced gravity model, sea height anomaly was converted into upper layer thickness. The thickness maps are used to infer the NBC rings formation and propagation. Analysis of the historical altimetric record indicates that ring shedding is nearly a factor of two greater than previously estimated even though the altimeter does not track all the rings formed at the retroflection, (Garzoli et al., 2002).

North Brazil Current rings characteristics

- *Transport resulting from mean annual ring shedding:* The estimated yearly mass transported by rings is 9 Sv.
- *Interannual variability:* The available time series of ring shedding derived from the altimeter is shown in Figure 3.
- *Annual cycle:* There are insufficient data to determine if there is an annual signal in ring generations. However, the analysis of the IES data obtained during the North Brazil Current ring experiment (Garzoli et al., 2002) indicates that there is no seasonality.

3. Florida Current Transport

The Florida Current (FC) is the western boundary current for the subtropical gyre of the North Atlantic. In addition, to transporting water masses originating in the northern hemisphere, the FC advects water from the southern hemisphere that has crossed both the equator and the North Atlantic's tropical/subtropical gyre boundary. Ultimately, a portion of the FC transport becomes entrained in the subpolar gyre where it contributes to the formation of the deeper water masses. Beginning in the early 1980's, submarine cable observations of voltage differences across the Straits have been calibrated with direct current data to estimate FC transport.

Florida Current characteristics

- *Mean annual transport*: The mean annual transport of the Florida Current at 27°N over the cable record is 32 Sv. Earlier data collected at 26°N during the late

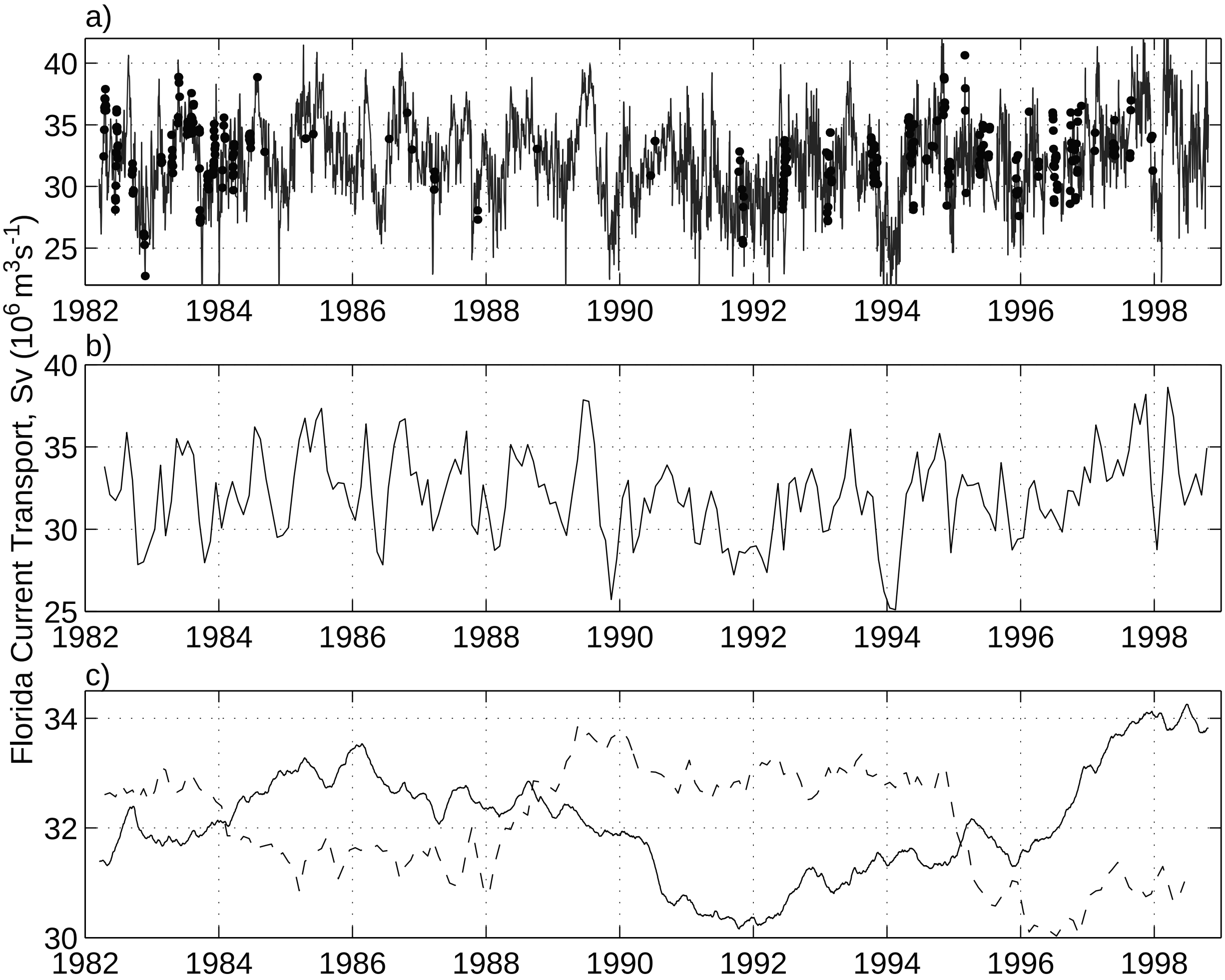

Fig. 4: Time series of Florida Current transport inferred from the cable voltages including (a) the daily transport values (blue line), (b) the monthly average transport, and (c) the two year running means of the daily transport values (solid line). Panel (c) also includes a monthly mean NAO index (Hurrell, 1995) (dashed line). Panel (a) includes in situ observations of Florida Current transport obtained on small boat cruises (solid circles).

1960's early 1970's observed a mean annual transport of 30 Sv (Niiler and Richardson, 1973). Johns et al., (1999) computed a mean annual transport through the NW Providence Channel (located between the two transport sections) of about 1 to 2 Sv. Thus over the past 30+-years the mean annual transport of the Florida Current appears stable.

- *Decadal signals*: A smoothed version of the 20-year time-series is shown in Figure 4. On decadal time-scales, the variability is less than 4 Sv (10-15% of the mean annual signal). This signal in FC transport is visually correlated with a NAO-index with similar time-scales (Figure 4).
- *Annual signal:* Using the 1960/1970's data, (Niiler and Richardson, 1973) estimated an annual signal for FC transport. Largest transports were in the summer and minimum, in the fall. The amplitude of the annual signal was about 3 SV. However, (Behringer and Larsen, 2001) found a larger semi-annual component in the more recent transport data than observed in the earlier records.

4. Lower Layer

The Deep Western Boundary Current (DWBC) provides the main conduit for waters formed in the subpolar and polar Atlantic to the South Atlantic and then on to the other ocean basins. As surface forcing functions change in the formation regions for the DWBC water masses, the characteristics of the water masses will vary downstream. Tracking these changes provides a benchmark for evaluating model simulations of the advective times from the formation regions. For example, a water mass formed in the Labrador Sea (LSW) is advected in the DWBC to 26.5°N, east of Abaco Island, the Bahamas. Time series of the characteristics of LSW

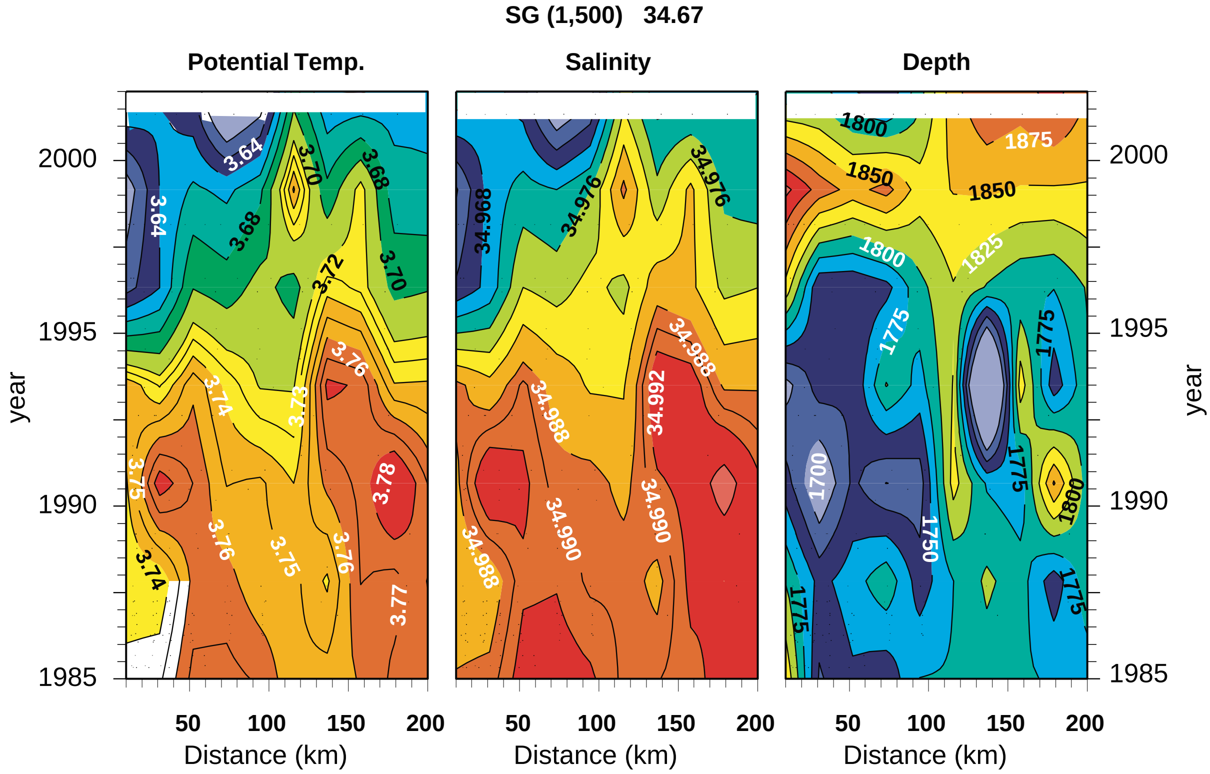

Fig. 5: Time series of T, S and depth along a density surface representing the Labrador Sea Water obtained from historical data collected east of Abaco Island, Bahamas. A pronounced cold, fresh pulse of Labrador Sea water appeared in 1995, less than eight years after it was produced in the Labrador Sea.

at Abaco provide a benchmark for present day advective time-scales from source to subtropical western boundary.

Lower layer characteristics

***Decadal Signal*:** Temperature and salinity characteristics at the depth of LSW in the DWBC at 26.5°N are shown in Figure 5. Late-90 cooling and freshening can be correlated to changes in the characteristics of LSW at its formation region. The comparison indicates the arrival of LSW at Abaco some 8 to 10 years after formation in the Labrador basin. These advective times are somewhat shorter than previously hypothesized but consistent with other observations obtained in the central subtropical and eastern mid-latitude Atlantic (Molinari et al., 1998).

References

Baringer, M.O., and J.C. Larsen, 2001: Sixteen years of Florida Current transport at 27°N. *Geophys. Res. Lett.*, **28**, 3179-3182.

Fratantoni, D.M., W.E. Johns, T.L. Townsend, and H.E. Hurlburt, 2000. Low-Latitude Circulation and Mass Transport Pathways in a Model of the Tropical Atlantic Ocean. *J. Phys. Oceanogr.*, **30** (8), 1944-1966.

Garzoli, S.L., Q. Yao, and A. Ffield, 2002: North Brazil Current rings and the variability in the latitude of retroflection. In: *Interhemispheric Water Exchange in the Atlantic Ocean*, G. Goni and P. Malanotte-Rizzoli (Eds.), Elsevier Science, submitted.

Garzoli, S.L., and G. Goni, 2000: Combining altimeter observations and oceanographic data for ocean circulation studies. In: *Satellites, Oceanography and Society*, Halpern, D., (ed.) Elsevier Science B. V., 79 -97.

Goni G., and W.E. Johns, 2001: A Census of North Brazil Current Rings Observed from TOPEX/POSEIDON Altimetry: 1992 – 1998. *Geophys. Res. Lett.*, **28**, 1-4.

Hurrell, J.L., 1995: Decadal Trends in the North Atlantic Oscillation: Regional Temperatures and Precipitation. *Science*, **269**, 676.

Johns, E., W.D. Wilson, and R.L. Molinari, 1999: Direct observations of velocity and transport in the passages between the Intra-Americas Sea and the Atlantic Ocean, 1984-1996. *J. Geophys. Res.*, **104**, 25805-25820.

Matano, R.P., C.G. Simionato, W.P. de Ruijiter, P.L. van Leeuween, P.T. Strub, D.B. Chelton, and M.G. Schlax, 1998: Seasonal variability in the Agulhas retroflection region. *Geophys. Res. Lett.*, **25**, 4361-4364.

Molinari, R.L., R.A. Fine, W.D. Wilson, R.G. Curry, J. Abell, and M.S. McCartney, 1998: The arrival of recently formed Labrador Sea Water in the Deep Western Boundary Current at 26.5°N. *Geophys. Res. Lett.*, **25**, 2249–2252.

Niiler, P.P., and W.S. Richardson, 1973: Seasonal variability of the Florida Current. *J. Mar. Res.*, **31**, 144-166.