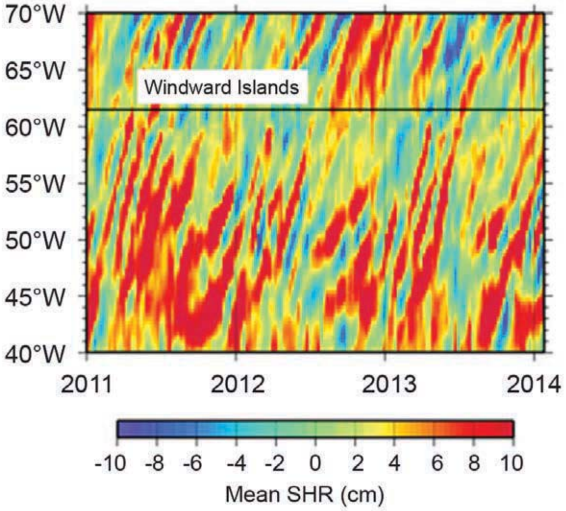

Fig. 3.20. Space-time diagram of de-seasoned sea height residual values (cm) along the NBC ring corridor during 2011–14. (Source: http://www.aoml.noaa.gov/phod/altimetry/cvar/nbc.)

rings that carry waters from the Southern Hemisphere into the North Atlantic basin, exhibited an annual transport close to climatology and shed eight rings, a larger-than-average value (Goni and Johns 2003). Sea height anomalies in the region, which have generally increased since 2001 (apart from the anomalous low years of 2003 and 2008), continued to exhibit higher-than-average values in 2013 (Fig. 3.20).

In the southwest Atlantic Ocean, the Brazil Current carries waters from subtropical to subpolar regions. The separation of the Brazil Current front from the continental shelf break continued to exhibit annual periodicity driven by wind stress curl variations (c.f., Goni and Wainer 2001). However, the annual mean separation of the front was at its average (1993–present) latitude after having exhibited extreme southward anomalies of up to 2° latitude during 2002–11 (http://www.aoml.noaa.gov/phod/altimetry/cvar/mal/BM_anm.php). That southward shift was related to a multidecadal oscillation or was in response to a secular trend in South Atlantic temperatures (c.f., Lumpkin and Garzoli 2010; Goni et al. 2011).

h. *Meridional overturning circulation observations in the North Atlantic Ocean*

—M. O. Baringer, G. McCarthy, J. Willis, M. Lankhorst, D. A. Smeed, U. Send, D. Rayner, W. E. Johns, C. S. Meinen, S. A. Cunningham, T. O. Kanzow, E. Frajka-Williams, and J. Marotzke

The ocean's meridional overturning circulation (MOC) is the large-scale "conveyor belt" that redistributes heat, fresh water, carbon, and nutrients around the globe. Variability in the MOC dominates the variability of transported properties (not variability in the properties themselves), and so the discussion here is focused on the mean and variability of the MOC. For discussion of the importance of the MOC and the state of understanding of this the reader is referred to previous *State of the Climate* reports (e.g., Baringer et al. 2013) and recent reviews such as Macdonald and Baringer (2013), Lozier (2012), and Srokosz et al. (2012). This section reports the results provided by three MOC observing systems in the North Atlantic at 16°N, 26°N, and 41°N.

As part of the 26°N system, the Florida Current (FC, as the Gulf Stream is called at this latitude) has been measured since 1982. Measurements continued through 2013; however, the computer recording system failed twice, leading to two brief gaps in the time series during 28 October–4 November 2013 and during 15 December 2013–3 January 2014. The median transport (from 1982 to 2013) of the Florida Current is 32.0 ±0.26 Sv (standard error of the mean based on an integral time scale of about 20 days) with an insignificant downward trend of −0.25 ±0.28 Sv decade^{-1} (errors using 95% significance with a decorrelation time scale of about 20 days). In 2013 the annual median was 31.7 ±1.7 Sv with the annually-averaged transport essentially equivalent to the long-term average; the 2013 median is within the middle 50% of all annual averages. The daily FC transport values as compared to all previous years (Fig. 3.21a) indicate that 2013 was unusual in that there were several low transport values (extremes defined as outside the 95% confidence limits) during 8–14 March, 10–17 October, and early December. The lowest transport observed (19.7 Sv) occurred on 11 March. This low value was the ninth lowest transport recorded since 1982. During 2013 there was only one high transport event that exceeded the 95% confidence limits: during 10–12 June the transport reached 40.2 Sv.

The RAPID-MOC/MOCHA/WBTS 26°N mooring array continues to provide a twice-daily estimate of basin-wide MOC strength (Fig. 3.22) and is the most complete MOC existing observing system, measuring the full water column across the full basin and absolute transports in boundary currents (see Rayner et al. 2010 for details). McCarthy et al. (2012) noted statistically significant low MOC transport in the winter of 2009/10, showing that the low transport was predominantly caused by both a decrease in the northward Ekman transport and particularly by an increase in the southward interior transport: the overturning weakened as the gyre strengthened. Downturns in the overturning circulation such as

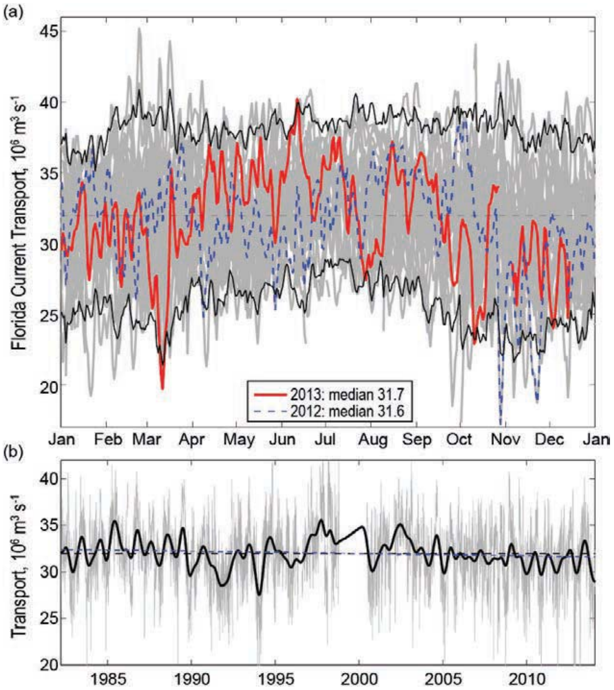

Fig. 3.21. (a) Daily estimates of the transport (×10⁶ m³ s⁻¹) of the Florida Current during 2013 (red solid line) compared to 2012 (dashed blue line). Daily values for years since 1982 are shown in light gray and the 95% confidence interval of daily transport values computed from all years is shown in solid black line; the long-term annual mean is dashed black. (b) Daily estimates of the Florida Current transport (×10⁶ m³ s⁻¹) for the full time series record (light gray), a smoothed version of transport (heavy black line; using a 12-month second-order butterworth filter), the mean transport for the full record (dashed black) and the linear trend from 1982 to present (dashed blue).

this have been shown to cool the subtropical North Atlantic (Cunningham et al. 2013). The MOC and interior transports data (INT) presented in Fig. 3.22 extend the record reported last year from April 2011 through October 2012, while FC and Ekman transport data are available through 2013; MOC estimates based on mooring data require substantially more lead time because a ship is typically required to go to the site to retrieve the data. During this period there was significantly low MOC transport from 4 May to 20 June 2012 (average MOC of 10.8 Sv vs. the long-term mean of 17.3 Sv). The FC contributes about the same reduction during this period as the Ekman transport (about –1.5 Sv), which is half the size of the interior transport contribution (about –3.2 Sv). It is the sum of the Ekman, Florida Current, and interior components that makes up the MOC at this latitude and the 2012 low transport shows a clear dominance of the interior transport changes driving low MOC values. The long-term trend of the MOC is –5.4 ±4.5 Sv decade^{-1} (using 95% confidence assuming a 45-day decorrelation scale); this means there is 95% confidence the decrease in the MOC is greater than 0.8 Sv decade^{-1}. Smeed et al. (2014) examine in detail this downward trend in the MOC and note that the largest changes have occurred since 2008 (as can be readily seen from the annual averages noted on Fig. 3.22).

The 26°N array is not the only array estimating the strength of the MOC in the North Atlantic. At 41°N the MOC in the North Atlantic is being estimated using a combination of profiling Argo floats (that measure the ocean temperature and salinity in the upper 2000 m on broad spatial scales) and altimetry derived surface velocity (see Willis and Fu 2008 for complete details). The data sources for this MOC

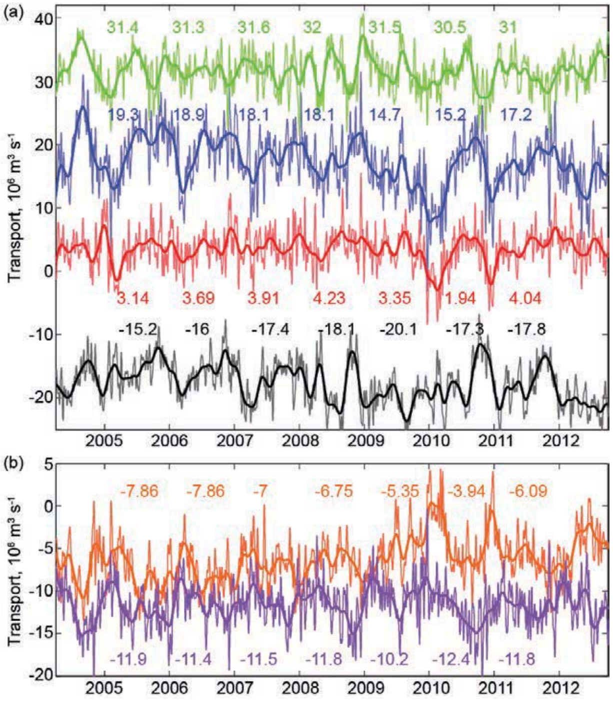

Fig. 3.22. Daily estimates of the (a) strength (×10⁶ m³ s⁻¹) of the meridional overturning circulation (blue line) and its components, the Florida Current (green), wind-driven Ekman transport (red), and the geostrophic interior (black), as measured by the UK National Environmental Research Council (NERC) Rapid Climate Change Program (RAPID-WATCH), the NSF's Meridional Overturning and Heat transport Array proposal, and the NOAA Western Boundary Time Series project (WBTS), and (b) Lower North Atlantic Deep Water (3000–5000-m depth; orange line) and Upper North Atlantic Deep Water (1100–3000-m depth; purple line). The volume transports have a 10-day low pass filter applied to the daily values (Rayner et al. 2010) and the annual averages of the transports for each year are shown in the associated color text (in Sv).

estimate are available in near real-time and hence the time series has been extended from May 2012 (reported last year) to October 2013 (Fig. 3.23). Furthermore, near 16°N, the MOC is being estimated by a mooring array of inverted echo sounders, current meters, and dynamic height moorings that measure the deep circulation that is the southward flowing part of the MOC conveyor belt that sends North Atlantic Deep Water towards the equator (see Send et al. 2011 for further details). For this report, the 16°N data has been updated from June 2011 to October 2013, the date of the last cruise. The updated data from all three latitudes were 90-day low-pass filtered and plotted in Fig. 3.23. The mean MOC based on these estimates decreases to the north (22.8 Sv at 16°N; 17.3 Sv at 26°N; 13.8 Sv at 41°N). Similarly, the variability decreases to the north (as described by the standard deviation: 4.2 Sv at 16°N; 3.4 Sv at 26°N; 2.9 Sv at 41°N). All three time series have a seasonal cycle, which is most prominent at 26°N and 41°N (Fig. 3.23). There are different phases for each, with 41°N having a maximum MOC in May–July, 26°N having a broad maximum in July–November (Kanzow et al. 2010), and 16°N having a maximum southward flow (and hence stronger MOC) in November–January. Of note with the most recent data, the 16°N data has stronger southward flow, reaching filtered values above −34 Sv; the new 26°N data is slightly lower than the long-term average and the newest 41°N data is similar to the long-term average. Various authors have reported longer-term MOC trends ranging from zero (Willis 2010 using the first seven years of data from 41°N) to a −3 Sv decade^{-1} decrease (Send et al. 2011 using the first 9.5 years of data from 16°N), to the largest decrease of −5.4 Sv decade^{-1} (Smeed et al. 2014 using the first 8.5 years of data from 26°N). Using the overlapping time period of these observations (2 April 2004 to 2 October 2012) which includes more recent data than reported by Willis (2010) and Send et al. (2011), there is an insignificant trend in the MOC of −3.3 ±6.5 Sv decade^{-1} at 41°N, while at 26°N there is a strong decrease in the MOC of −5.1 ±4.1 Sv decade^{-1} (using 95% confidence limits; Fig. 3.23). However, at 16°N the deep southward flow has recently been increasing, suggesting a possible increase of the MOC at 8.4 ±5.6 Sv decade^{-1}. At 26°N where both the upper and deep southward flows are measured, the decreasing MOC is seen to be compensated by a reduction in the southward export of lower North Atlantic Deep Water (LNADW) in the depth range of 3–5 km (perhaps surprisingly there is no trend in export of upper North Atlantic Deep Water in the depth range 1.1–3 km). The decrease in export of LNADW is 4.6 ±3.9 Sv decade^{-1} (Fig. 3.22b; Smeed et al. 2014). From the full time series from 41°N and 16°N, the MOC trends decrease, becoming insignificant (−0.9 ±4.6 Sv decade^{-1} at 41°N and −2.3 ±2.9 Sv decade^{-1} at 16°N). At these time scales, there appears to be no consistent trend in the MOC at these latitudes. Note that statistically significant changes can be found using various subsets of these time series; however, the interpretation of any trend should consider regional, interannual, and decadal variability that may not be linked to longer-term trends.

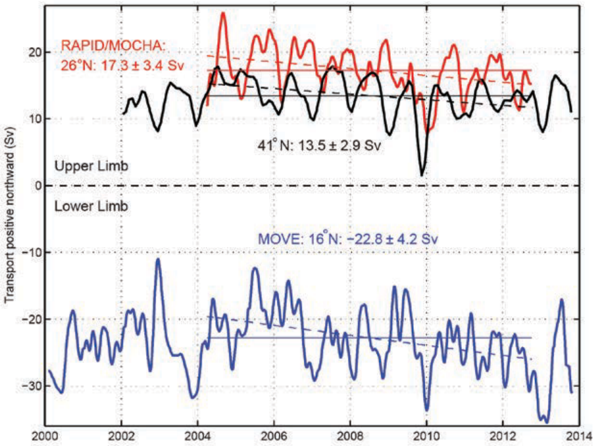

Fig. 3.23. Estimates of the MOC (Sv) in the Atlantic Ocean from the Argo/Altimetry estimate at 41°N (black; Willis 2010), the RAPID-WATCH/MOCHA/WBTS 26°N array (red; Rayner et al. 2010), and the German/NOAA MOVE array at 16°N (blue; Send et al. 2011). All time series have a three-month second-order butterworth low pass filter applied. Horizontal lines are the mean transport during similar time periods as listed in the corresponding text. Dashed lines are the trends for each series over the same time period. For the MOVE data the net zonal and vertical integral of the deep circulation represents the lower limb of the MOC (with a negative sign for the southward flow) and hence a stronger negative southward flow represents an increase in the MOC.

i. Meridional oceanic heat transport in the Atlantic Ocean—M. O. Baringer, W. E. Johns, S. Garzoli, S. Dong, D. Volkov, and W. R. Hobbs

The meridional overturning circulation is related to the meridional heat transport (MHT) in the oceans, and the variability of MHT can impact heat storage, sea-level rise, and air-sea fluxes, and hence influence local climate on land. Time series of the oceanic heat transport are more rare than time series of the meridional overturning circulation because they involve the product of temperature and velocity to be resolved across a trans-basin section where