STATE OF THE CLIMATE IN 2011

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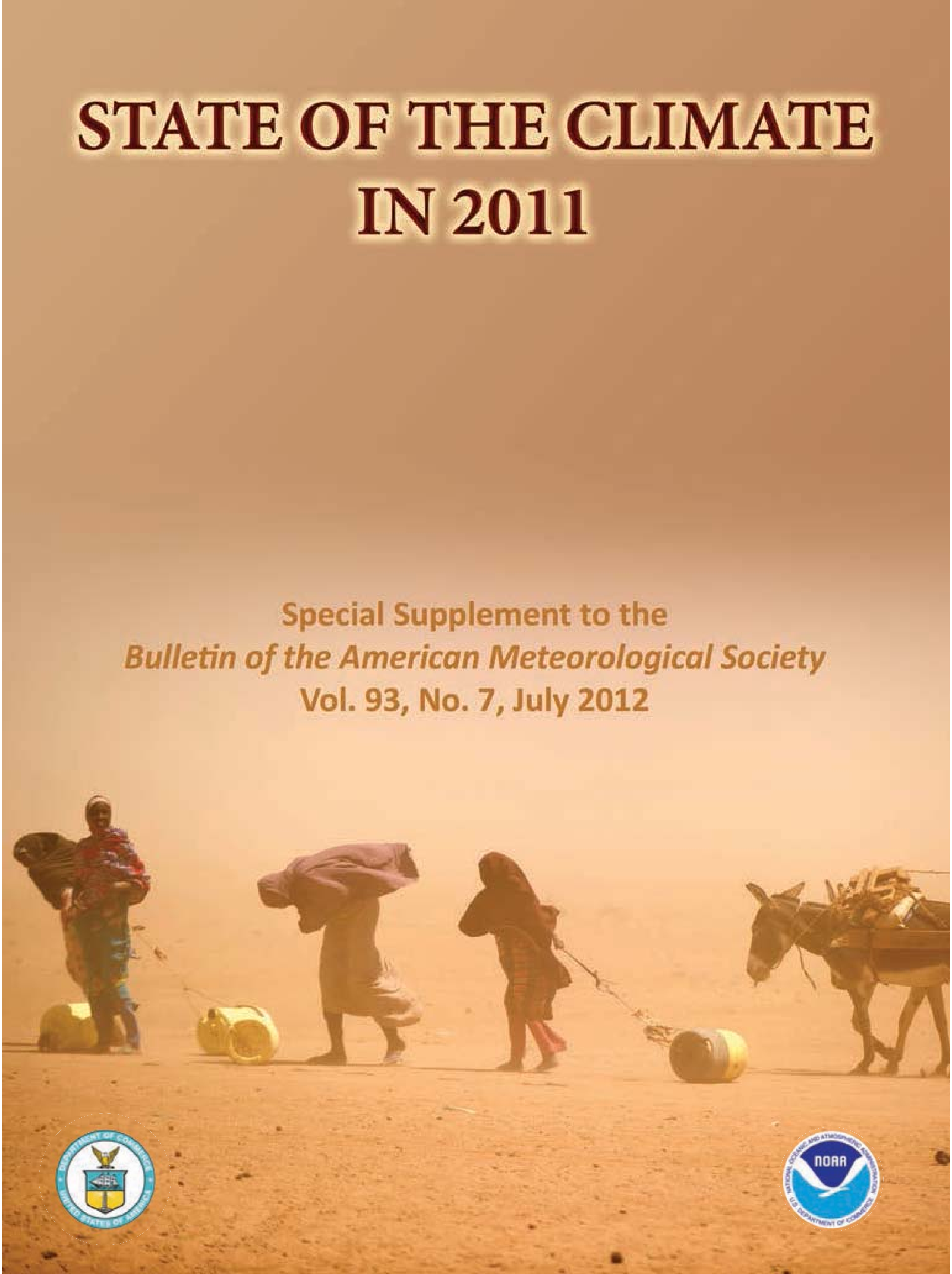

Against the east coast of South America, the southward-flowing warm, salty Brazil Current meets the northward flowing cold, fresh Malvinas Current to create the Confluence Front. During 2011, the separation of the front from the continental shelf break continued to exhibit annual periodicity driven by wind stress curl variations (cf., Goni and Wainer 2001). The annual mean position of the front in 2011 was 38.5°S, a shift to the south from the 37.5°S position in 2010. This location is as far south as the annually-averaged front has been seen since the launch of the TOPEX/Poseidon altimeter in 1992, and was matched by only one other year (2004). Since 1992, the front has shifted significantly southward in response to wind stress curl changes driven by SST anomalies advected from the Indian Ocean (Lumpkin and Garzoli 2010; Goni et al. 2011).

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

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

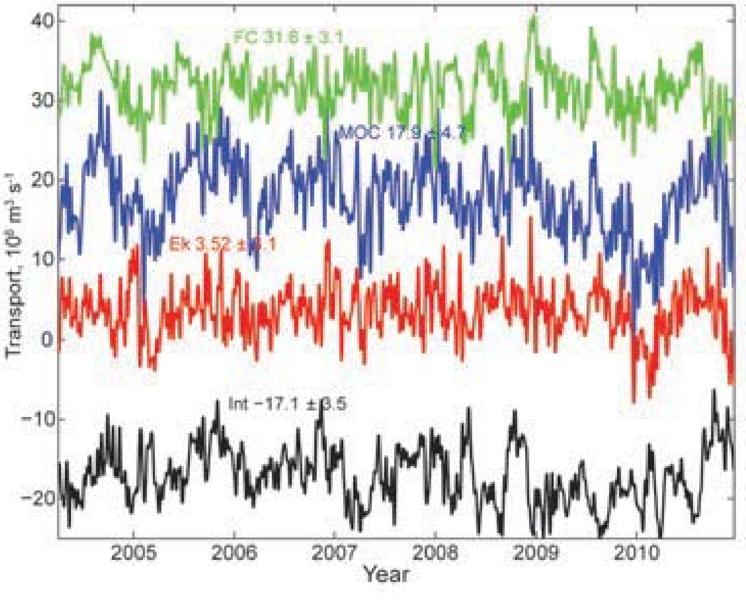

Fig. 3.21. Daily estimates of the strength of the meridional overturning circulation (MOC; blue line) and its components, the Florida Current (FC; green), wind-driven Ekman transport (Ek; red), and the geostrophic interior (Int; black), as measured by the UK National Environmental Research Council Rapid Climate Change Program, the National Science Foundation's Meridional Overturning and Heat transport Array, and the NOAA Western Boundary Time Series Program. The interior volume transport estimate (accurate to 1 Sv, Cunningham et al. 2007) is based on the upper ocean transport from April 2004 to December 2010 (see also Rayner et al. 2010; Kanzow et al. 2010), with a 10-day low pass filter applied to the daily transport values.

For several years, this section has reported on the meridional redistribution of mass associated with the large-scale vertical circulation within ocean known as the meridional overturning circulation (MOC). Here, the MOC is defined as the maximum of the vertically integrated basin-wide stream function, which changes as a function of latitude and time and is influenced by many physical systems embedded within it. It is related to the meridional transport of heat (MHT) in the oceans, although the relationship may not be direct and can vary with latitude; for example, where horizontal gyre circulation is strong, the heat transport can largely be ascribed to the wind-driven circulation. Variability in oceanic MHT can in turn contribute to heat storage, sea-level rise, and air-sea fluxes and hence influence local climate on land. Therefore, closing the ocean heat budget is a central area of study for understanding and predicting societally-relevant impacts from the oceans. Changes in MOC and MHT can be inferred from "fingerprint" changes in ocean temperature, sea-level rise, and changes in individual current systems (see Baringer et al. 2011 and previous *State of the Climate* reports for more discussion). This annual report focuses on the longest time series observations of ocean heat and mass transport currently available and what can be inferred from them about the current state of the MOC and MHT.

Recommendations for a coordinated observing system to begin to measure MOC were presented at the international conference OceanObs'09 in September 2009 (e.g., Cunningham et al. 2010; Rintoul et al. 2010) and subsequent planning workshops focused on expanding existing observations to include the subpolar North and South Atlantic (e.g., Garzoli et al. 2010). The most complete MOC observing system has been in place since April 2004, and spans the subtropical gyre in the North Atlantic near 26.5°N. The system is composed of UK-NERC RAPID-WATCH moorings, US-NSF Meridional Overturning Circulation Heat-Transport Array (MOCHA), and the US-NOAA Western Boundary Time Series program (see also Rayner et al. 2010; Chidichimo et al. 2010).

The estimates of MOC from the 26.5°N array include data from April 2004 to December 2010 (see also Rayner et al. 2010), shown in Fig. 3.21. Over this time period, the MOC had a mean transport of 18.1 Sv with a high of 31.6 Sv, a low of -2.6 Sv in December 2009 and a standard deviation of 4.7 Sv (using the twice daily values filtered with a 10-day cutoff as described in Cunningham et al. 2007). From early December 2009 through the end of April 2010, the MOC sustained low values with a mean of 9.8 Sv. At the end of the time series in December 2010, the MOC was again relatively low, with a transport of about 13 Sv. These two low MOC "events" were produced by a combination of changes occurring on different time scales (e.g., short-term Ekman and Florida Current transport changes) and long-term changes in the southward geostrophic flow. Overall, the Florida Current and Ekman (EK) transport were about 2 Sv less northward than usual and the southward thermohaline circulation was about 2 Sv stronger, leading to a year-long anomaly of about 5 Sv – 6 Sv in the MOC. With these two events present at the end of the multiyear time series, a linear regression of MOC versus time yields a decrease of -6 ± 0.3 Sv decade^{-1} (95% confidence). A linear trend estimated with the time series ending in December 2009 has a trend of only -4.8 Sv decade^{-1}. Baringer et al. (2011) reported an insignificant trend through April 2009 of -0.8 ± 1.6 Sv decade^{-1}. It is clear that 2010 was an unusual year for MOC transport across 26°N, but given the large variability of MOC estimates, it would be imprudent to ascribe too much to the last year of values in determining a decadal trend. After six years of data, however, a clear seasonal signal is beginning to emerge (Kanzow et al. 2010), with a low MOC in April and a high MOC in October with peak to peak range of 6.9 Sv. The seasonal cycle of the MOC appears to be largely attributable to seasonal variability in the interior rather than Ekman or Florida Current fluctuations; Kanzow et al. (2010) show that the interior seasonal cycle is likely due to seasonal upwelling through a direct wind-driven response off Africa.

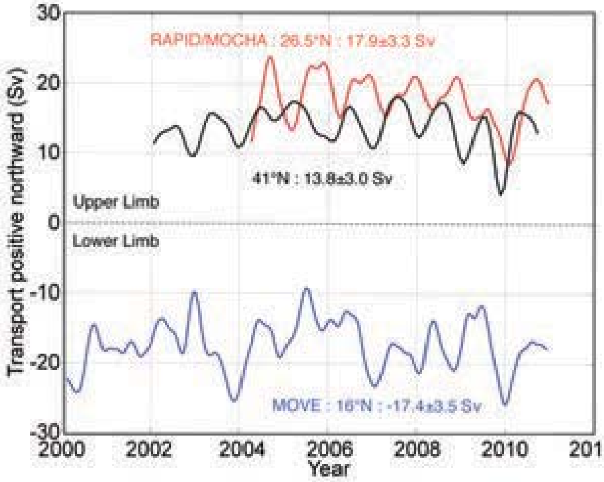

Fig. 3.22. Estimates of the MOC in the Atlantic Ocean from the Argo/Altimetry estimate at 41°N (black; Willis 2010), the Rapid/MOC/MOCHA/WBTS 26°N array (red; Cunningham et al. 2007), and the German/NOAA MOVE array at 16°N (blue; Send et al. 2011) are shown for 2000–12. All time series have a three-month running mean applied.

Two other approaches for estimating Atlantic MOC were developed by Willis and Fu (2008) and Send et al. (2011). Near 41°N, Willis and Fu (2008) used a combination of Argo data and satellite altimetry (measuring sea-surface height fluctuations on 10-day global grid) to determine the absolute geostrophic transports in the upper 2000 m of ocean referenced to subsurface Argo drift velocities. The use of altimetry data, which is well resolved in time, helps to reduce aliasing from the Argo profile data. The MOC time series from 41°N following Willis (2010) is shown in Fig. 3.22 with a three-month running mean applied. The mean value is 13.8 Sv, with similar, slightly smaller variability than found in the 26°N MOC time series (3.0 Sv vs. 3.3 Sv). The decrease in mean MOC strength with increasing latitude is a common feature of observations and models (e.g., Ganachaud and Wunsh 2000; Wuncsh and Heimbach 2009). Willis (2010) reported an insignificant trend in the MOC from 2002 to 2009, consistent with the insignificant trend in the 26°N data to April 2009, before the relatively low transport "event" in late 2009–early 2010. Of note is that the low MOC "event" described earlier in the 26°N data, appears in the 41°N data slightly earlier in time. Both time series have relatively strong annual cycles, slightly shifted in phase. Further examination of the causes of this likely basin-scale "event" and the causes of the shift of seasonal variability is needed.

Since 2000, an array of dynamic height moorings and one current meter mooring have been in place near 16°N to measure the transport fluctuations of the North Atlantic Deep Water (NADW; Kanzow et al. 2008). This NADW time series provides transport estimates of the deepest part of the MOC and has been shown by Kanzow et al. (2008) to be a reasonable index for the strength of the MOC at 16°N for multiannual timescales (e.g., a stronger southward negative flow of NADW corresponds to an increased MOC). The NADW transport time series shows substantial variability (on the order of 3.5 Sv), with a weaker annual cycle than at 26°N or 41°N (Fig. 3.22). There is some suggestion of a decrease in the southward NADW of 20% over the observation period that would imply a decrease in the MOC (Send et al. 2011). This is consistent with the trend computed from the complete 26°N time series; however, multidecadal fluctuations of the MOC are expected from natural variability and cannot as yet be ascribed to climate change (Send et al. 2011).

Another time series of a major ocean current that contributes to the MOC variability is also the longest open ocean transport time series. Figure 3.23 shows the time series of the Florida Current, which has been measured since 1982 using a submarine cable across the Straits of Florida in combination with regular hydrographic sections Bahamas (e.g., Meinen et al. 2010; Baringer and Larsen 2001). In 2011, the median transport through the Florida Straits was 31.4 ± 1.1 Sv. For the previous four years, the annual average Florida Current transport decreased from 32.1 ± 1.0 Sv in 2007 to 30.7 ± 1.5 Sv in 2010 (error bars represent the standard deviation of daily values divided by the square root of the degrees of freedom calculated for each year where typical decorrelation time scales are about 20 days). The annual mean of 2011, no longer falls within the lowest quartile of mean annual values (long-term median annual average and interquartile range of 31.8 ± 0.5 Sv). Note that while recently the annual means appear to have decreased (April 2004 to December 2010 trend of -1.9 ± 0.2 Sv decade^{-1}, 95% significance), there is only a small significant long-term trend to the Florida Current transport (Fig. 3.23, bottom; trend for complete daily time series is -0.2 ± 0.06 Sv decade^{-1}). The daily fluctuations of Florida Current transport generally fall within 95% confidence levels (32.0 ± 1.0 Sv); the 95% confidence range of daily transport values is shown in Fig. 3.23. There were, however, five extreme low transport events during the year (Fig. 3.23); the most significant events lasting over three days or more occurred during 17–19 July and 30 July–2 August, with values as low as 25.1 Sv. In comparison, there were only three events with transport higher than the 95% confidence range, and no such event lasted for more than a day. Due to the fact that these events were relatively short lived, it is likely they were local responses to atmospheric forcing and coastally-trapped wave processes and are not particularly indicative of a climatically important shift (e.g., Mooers et al. 2005). Nevertheless, these transient fluctuations can have important environmental consequences due to dynamic sea-level changes. For example, it was previously reported that in the summer of 2009, the east coast of the United States experienced a high sea-level event that was unusual due to its unexpected timing, large geographic scope, and coastal flooding that was not associated with any storms (Sweet et al. 2009). Sweet et al. showed that this anomalous event was related to the anomalously low Florida Current transport; a reduced Florida Current transport corresponds to a lower sea-surface height gradient across the front and hence higher sea-level onshore. In 2011, the low transport events could reasonably be inferred to have influenced sea-level along the eastern US; however, as of this report, no relationship has been documented.

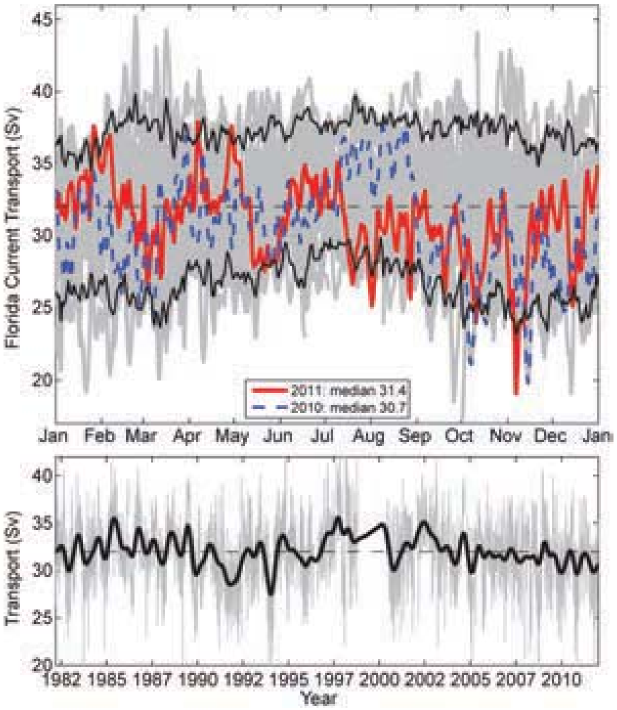

Fig. 3.23. (Top) Daily estimates of the transport of the Florida Current during 2011 (red solid line) compared to 2010 (dashed blue line). The daily values of the Florida Current transport for other years since 1982 are shown in gray and the 95% confidence interval of daily transport values computed from all years is shown in black (solid line); the long-term annual mean is dashed gray. The mean transport in 2011 was 31.4 ± 1.1 Sv, which is less than the long-term mean for the daily values of the Florida Current transport (32.2 Sv). (Bottom) Daily estimates of the Florida Current transport for the full time series record (gray), a smoothed version of transport (heavy black line; using a 30-day running mean six times) and the mean transport for the full record (dashed gray).

In the South Atlantic, a time series of MOC and MHT has been maintained since 2002 (Fig. 3.24), using a high-density expendable-bathythermograph (XBT) line (Garzoli and Baringer 2007; Dong et al. 2009). The mean heat transport across 35°S is 0.55 ± 0.14 PW (petawatt, 1 PW = 10^{15} watts). Following an increase in heat transport since 2008, the year 2011 had a substantial increase in the mean annual

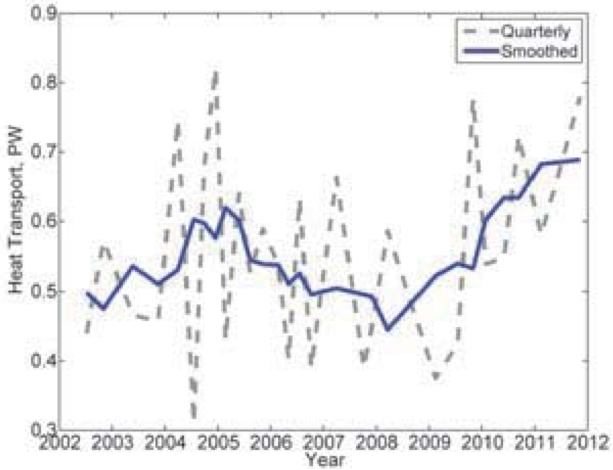

Fig. 3.24. Heat transport in the South Atlantic near 35°S derived from quarterly transects along the high-density line AX18 (gray dashed line) and smoothed values of heat transport (using a five-point running mean; blue solid line). Heat transport values are computed following the methodology of Baringer and Garzoli (2007).

transport value (0.68 PW), the highest recorded annual mean (however, still within one standard error of the mean). According to Dong et al. (2009) the changes in MHT are well correlated with changes in the MOC. This correlation implies an increase in the MOC in the South Atlantic since 2008. The meridional coherence of changes in MOC and heat transport and the relative lead/lag is an active area of research. Heimbach et al. (2011) found that changes in the upper ocean near 35°S could be precursors to changes in the MOC across 26°N as early as four years into the future.

i. Sea level variability and change—

M. A. Merrifield, P. Thompson, D. P. Chambers, G. T. Mitchum, M. Menéndez, R. S. Nerem, E. Leuliette, L. Miller, S. Holgate, J. J. Marra, and W. Sweet

Sea level is a primary indicator of climate variability and change over a wide range of time and space scales. Global mean sea level provides a measure of volume changes associated with ocean heat content changes and water mass exchange with the land. Regional sea level variations reflect changes in the wind-forced circulation and transports of heat and salt. Extreme sea levels reflect storm patterns and their variation from year to year, as well as sea level extremes associated with ENSO and other climate modes of variability. Not only is sea level change a key climate indicator, it is also potentially one of the more important impacts of climate change.

Sea level variability during 2011 is characterized by first examining seasonal anomalies (Fig. 3.25), which highlight changes associated with variable winds and climate modes of variability. Annual mean sea level deviations and changes from the previous year are considered (Fig. 3.26), and global mean sea level is shown to have been significantly below the long-term trend during 2011 (Fig. 3.27), but is trending sharply back upwards late in the year. Ongoing assessments of the sea level budget are reviewed (Fig. 3.28) to provide context for the 2011 sea level drop in terms of the La Niña conditions that dominated the year. Lastly, extreme sea level conditions during 2011 are characterized based on 30-plus-year tide gauge records (Fig. 3.29). Data for this assessment were obtained from the multimission gridded sea surface height (SSH) altimeter product produced by Ssalto/Duacs and distributed by AVISO, with support from CNES (http://www.aviso.oceanobs.com), and from the University of Hawaii Sea Level Center (http://uhslc.soest.hawaii.edu/), with support from the NOAA Climate Observations Division.

The regional sea level patterns (Fig. 3.25) show that La Niña conditions prevailed during 2011. The La Niña event peaked during the winter of 2010/11

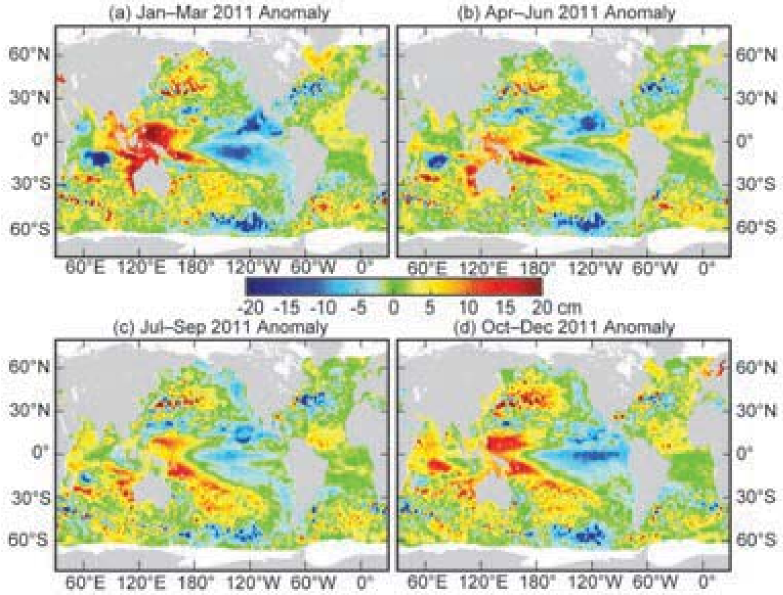

Fig. 3.25. Seasonal SSH anomalies (cm) for 2011 relative to the 1993–2011 base period are obtained using the multimission gridded sea surface height altimeter product produced by Ssalto/Duacs and distributed by AVISO, with support from CNES (http://www.aviso.oceanobs.com).