STATE OF THE CLIMATE IN 2010

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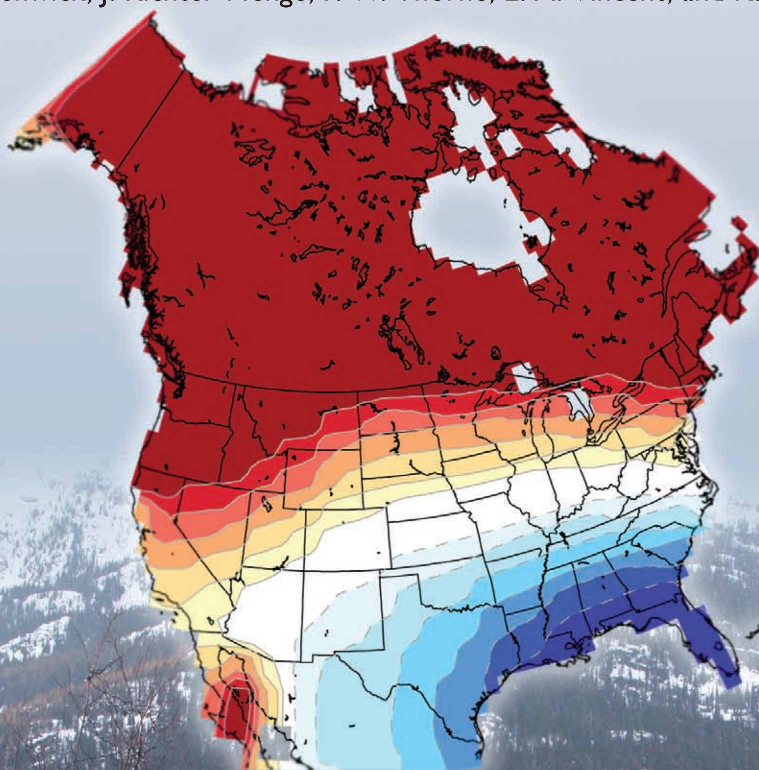

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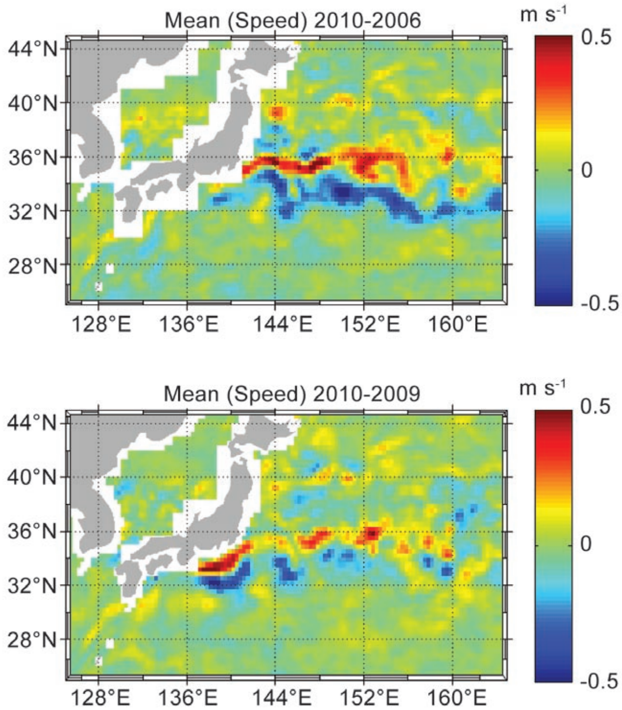

Fig. 3.21. Mean speed of the Kuroshio Current, 2010 minus 2006 (top) and 2010 minus 2009 (bottom) from OSCAR. Differences between 2010 and 2007–2008 (not shown) are similar.

basin, and were present across the basin in August–September. Eastward anomalies persisted through the remainder of the year in the center of the basin, albeit with less organization than seen in late boreal summer.

3) Atlantic Ocean

In the tropical Atlantic, near-equatorial surface currents were anomalously westward in February–April, with peak values of 20 cm s^{-1}–40 cm s^{-1} east of 30°W in mid-March, associated with anomalously cold SSTs of -0.5°C to -0.7°C at 12°W–18°W (the western half of the Atlantic cold tongue). Through boreal summer, equatorial current anomalies were less organized, although westward anomalies tended to dominate in the eastern half of the basin. In September, eastward anomalies began to develop across the basin, reaching ~25 cm s^{-1} by mid-October. These eastward anomalies persisted through November and weakened through December.

The North Brazil Current (NBC) plays an important role the Atlantic Meridional Overturning Circulation by periodically shedding rings which transfer water of Southern Hemisphere origin to the Northern Hemisphere. In 2010, the NBC demonstrated extremely anomalous conditions, with very high values of annually-averaged sea height in the ring corridor region, superimposed on the higher-frequency sea height peaks of anticyclonic rings shed from the current (Fig. 3.22). Anomalies of this magnitude have not been seen previously in the altimeter time period (1993–present).

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. The location of this front exhibits strong fluctuations at time scales from intraseasonal and seasonal to interannual and decadal (Goni and Wainer 20001; Lumpkin and Garzoli 2010). The front shifted south approximately 1° in latitude between late 1992 and 1998, while its annual-averaged position did not change significantly from 1998 to 2009. In 2010 the annual mean location of the Confluence at the South American continental shelf break was 37.5°S, further north than has been seen since 1997. The 1992–98 trend in the Confluence location may be part of a multidecadal oscillation related to surface temperature anomalies advected from the Indian Ocean into the Atlantic via the Agulhas-Benguela pathway (Lumpkin and Garzoli 2010).

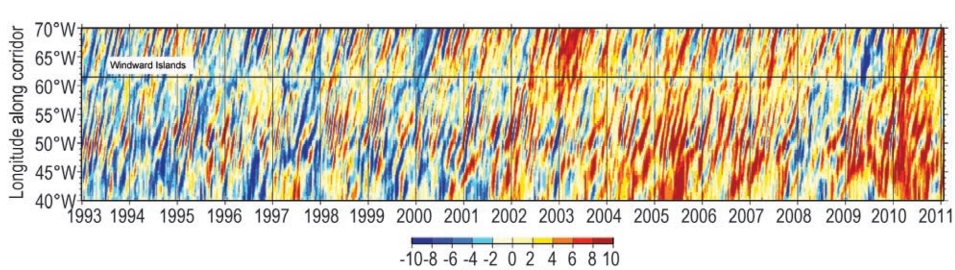

Fig. 3.22. Sea height residual (annual signal removed) from AVISO altimetry in the ring shedding corridor region of the North Brazil Current (NBC), 0°–15°N. Propagating high (red) signals indicate anticyclonic NBC rings. The longitude of the Windward Islands, which separates the Atlantic from the Caribbean, is indicated by a horizontal line.

h. Meridional overturning circulation observations in the subtropical North Atlantic—M. O. Baringer, T. O. Kanzow, C. S. Meinen, S. A. Cunningham, D. Rayner, W. E. Johns, H. L. Bryden, E. Faika-Williams, J. J-M. Hirschi, M. P. Chidichimo, L. M. Beal, and J. Marotzke

The meridional redistribution of mass and heat associated with the large-scale vertical circulation within an ocean basin such as the Atlantic is typically called the meridional overturning circulation (MOC).

The most common definition of the strength of the MOC is 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. Substantial progress has been made on developing a coordinated observing system to begin to measure the MOC, through plans outlined 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). A small portion of the recommended observing system has been in place since April 2004 spanning the subtropical gyre in the North Atlantic near 26.5°N. The system is composed of UK-NERC RAPID MOC moorings, US-NSF Meridional Overturning Circulation Heat-Transport Array (MOCHA), and the US-NOAA Western Boundary Time Series program (see also Chidichimo et al. 2010; Rayner et al. 2011). For the rest of the global ocean, changes in the complex, global MOC can also be inferred only from observations of individual components of the MOC (for example, a specific current or ocean layer; e.g., Dong et al. 2009), which are not discussed here.

The estimates of the MOC from the 26.5°N array include data from April 2004 to April 2009 (see also Kanzow et al. 2010). Over this time period the MOC has averaged 18.5 Sv with a high of 34.0 Sv, a low of 3.2 Sv, 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); note Sv is a Sverdrup, equal to 10^6 m^3 s^{-1}, a unit commonly used for ocean volume transports]. These data suggest no statistically significant trend in the strength of the MOC for this extremely temporally limited dataset (-0.8 ± 1.6 Sv decade^{-1}, with 95% confidence limits). After five years of data, however, a clear seasonal signal is beginning to emerge (Fig. 3.23), with a low MOC in April and a high MOC in October with peak to trough range of 6.9 Sv. The MOC can be divided into three components: the northward western boundary Florida Current, the wind-driven Ekman transport, and the southward "interior" transport (upper ocean geostrophic flow between the Bahamas and Africa). 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. Of note is that all the MOC transport values estimated from five repeated CTD (Conductivity, Temperature, Depth) sections by Bryden et al. (2005) can be found within the seasonal range of the MOC time series (values ranged from 22.9 Sv in 1957 to 14.8 Sv in 2004). In fact, Kanzow et al. (2010) demonstrated that removing the seasonal cycle estimates from Bryden et al. would effectively eliminate a statistically significant trend in the transport.

These results do not disprove the presence of a long-term trend in the strength of the MOC [e.g., Longworth et al. (2011) and Wunsch and Heimbach (2006) both found significant long-term decreases in the MOC], but they do suggest that a careful error analysis must be performed that includes the impact of the underlying higher-frequency variability of the MOC on trend estimates (see also Baehr 2010; Baehr et al. 2008; Brennan et al. 2008). Other recent studies of the MOC trend are contradictory, with some reporting a decrease in the MOC [e.g., Wunsch and Heimbach (2006), using data assimilating models; Longworth et al. (2011), using end-point hydro-

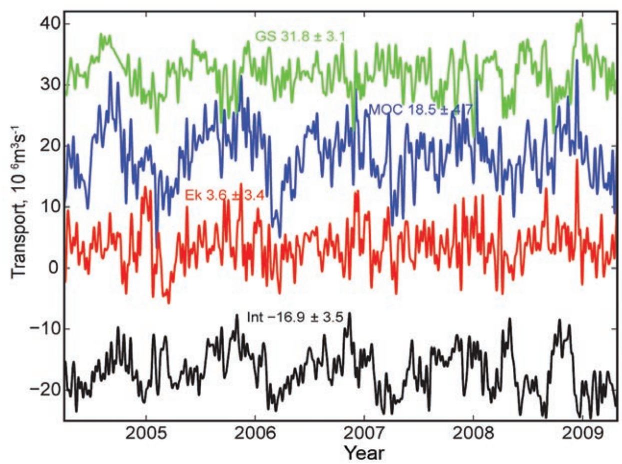

Fig. 3.23. Daily estimates of the strength of the meridional overturning circulation (MOC: blue line) and its components, the Florida Current (GS: green), wind-driven Ekman transport (Ek: red) and the geostrophic interior (Int: black), as measured by the UK National Environmental Research Council (NERC) Rapid Climate Change Program, the National Science Foundation Meridional Overturning and Heat Transport Array, and the long-term NOAA funded 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 April 2009 (see also Kanzow et al. 2010), with a ten-day low pass filter applied to the daily transport values. Smooth curves are the annual climatology of each component estimates from the full five years of data.

graphic observations following the 26°N mooring design principles] while others suggest no change or even an increase [e.g., Lumpkin et al. (2008), using hydrographic sections]. Some estimates showing an increase (C. Wang et al. 2010) and no trend (e.g., Schott et al. 2009) did not include basin-wide estimates of the MOC. Clearly, while disagreement remains over the details of findings from any particular observing systems (e.g., Kanzow et al. 2009), agreement exists that longer time series at multiple locations, particularly of the deep transport components, are needed (e.g., Zhang et al. 2010; Zhang 2008). New efforts are focusing on the use of state estimation models and "fingerprints" of other readily observed variables linked to changes in the MOC (e.g., Msadek et al. 2010; Lorbacher et al. 2010; Baehr 2010). Trends in the MOC can also be determined through proxies of the MOC strength, such as paleo observations (e.g., Y. Luo et al. 2010), tracers (e.g., Nelson et al. 2010; LeBel et al. 2008) and water mass characteristic (e.g. Kouketsu et al. 2009; Zhang 2008). For example, temperature and salinity observations in the Labrador Sea showed an abrupt return of deep convection between 2007 and 2008 (Våge 2009). Using water mass properties, Yashayaev and Loder (2009) showed that the enhanced deep convection in the Labrador Sea in the winter of 2008 was the deepest since 1994 and included the largest heat loss from the ocean to the atmosphere since the mid-1990s, exceeding the long term mean by 50%. Such anomalous local events may be a precursor to changes in the MOC strength (e.g., Lohmann et al. 2009).

One of the main contributions to the MOC estimate near 26.5°N is the Florida Current transport, the longest transport time series of an ocean circulation feature directly linked to the MOC. Near this latitude in the Atlantic, the bulk of the warm upper limb of the Atlantic MOC is thought to be carried to the north in the Florida Current through the Straits of Florida and the majority of the cold lower limb is believed to be carried to the south in the Deep Western Boundary Current (DWBC) just east of the Bahamas (e.g., Meinen et al. 2010; Baringer and Larsen 2001). Since 1982, Florida Current transport has been monitored using a submarine cable across the Straits of Florida in combination with regular hydrographic sections. In 2010, the mean transport through the Florida Straits continued the decrease over the past four years to 30.7 ± 1.5 Sv (95% confidence limits), lower than the 2009 31.3 ± 1.2 Sv, 2008 31.7 ± 2.2 Sv , and 2007 32.1 ± 1.0 Sv mean transports (error bars represent standard error of daily values using degrees of freedom calculated for each year, representing a typical decorrelation time scale of around 20 days). The annual mean of 2010 falls within the lowest quartile of mean annual values (32 ± 0.14 Sv). Note that while recently the annual means appear to have decreased (trend of -0.88 ± 0.85 Sv decade^{-1} from April 2004 to April 2009, 95% significance), there is only a very small significant long-term trend to the Florida Current transport (Fig 3.24; trend for full time series is -0.14 ± 0.06 Sv per decade).

The daily fluctuations of the Florida Current transport throughout the year are fairly similar to 2009 and generally fall within 90% confidence levels (Fig. 3.24). There were, however, a few unusual low transport events during the year (Fig. 3.24; the most significant or occurring over three-day or more

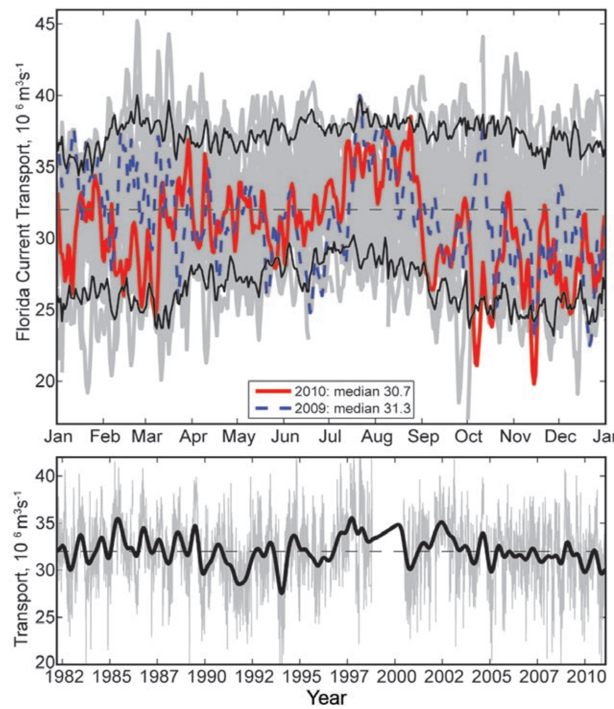

Fig. 3.24. (top) Daily estimates of the transport of the Florida Current during 2010 (red solid line) compared to 2009 (dashed blue line). The daily values of the Florida Current transport for other years since 1982 are shown in light gray and the 90% confidence interval of daily transport values computed from all years is shown in black (solid line); the long-term annual mean is dashed black. The mean transport in 2010 of 30.7 ± 1.5 Sv decreased for the fourth year in a row, below 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 (light 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 black).

events during 25–27 May, 5–9 October, 15–17 October, 15-17 November, and 8–10 December with values as low as 19.8 Sv). In comparison, only the transport on 24 August was higher than the 90% confidence range, with a daily average transport of 38.5 Sv. Due to the fact that these events were relatively short-lived, it is likely they are 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). These transient fluctuations can have important environmental consequences. As examples, 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. (2009) 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 2010, the low transport events could reasonably be inferred to have influenced sea level along the eastern U.S.; as of this report no relationship has been documented. For longer time scales, the same mechanical effect due to a reduction in ocean currents causes sea-level changes associated with geostrophy; Yin et al. (2010) showed that the dynamical response to MOC reductions associated with carbon dioxide (CO_2) emission scenarios would lead to approximately 20 cm rise in regional sea-level along the East Coast of the U.S. due to this sort of circulation change alone. Yin et al (2010) suggest that this region may be in greater jeopardy from regional effects of ocean circulation changes on top of the global mean sea-level rise predicted by climate models.

i. Sea level variations—M. Merrifield, G. Mitchum, E. Leuliette, D. Chambers, S. Nerem, P. Woodworth, S. Holgate, L. Miller, and S. Gill

Sea surface height (SSH) variations exhibited weak-to-moderate amplitudes during 2010, with the most evident patterns associated with a transition from a weak La Niña during most of 2009 to a weak El Niño (in terms of sea level) that peaked in late 2009 to early 2010 (Fig. 3.25a), returning to La Niña conditions during the remainder of 2010. In the annual mean SSH for 2010 (Fig. 3.26a), this sequence of events led to a dominant La Niña pattern in the tropical Pacific, consisting of low SSH anomalies (relative to a 1993–2010 baseline) in the central equatorial region and high SSH anomalies in the western tropical Pacific, particularly north of the Equator. SSH anomalies in other regions of the ocean that stand out in 2010 (relative to the 1993–2010 mean) include negative anomalies in the Southern Ocean to the west of South America, negative anomalies in the North Atlantic, and positive anomalies in the northwest Pacific with negative anomalies farther east (Fig. 3.26a).

The SSH tendency during 2010 is measured by the difference between the 2010 and 2009 annual means (Fig. 3.26b). The tendency in the tropical Pacific reflects the transition from El Niño to La Niña conditions, with falling SSH in the central equatorial Pacific and in the South Pacific Convergence Zone region. Other SSH tendencies of note during 2010 include negative changes in the North Pacific in the region of the Aleutian Low, with positive coastal sea level anomalies along Alaska and Canada. A similar pattern arises with falling SSH in the North Atlantic, with positive sea level anomalies along the

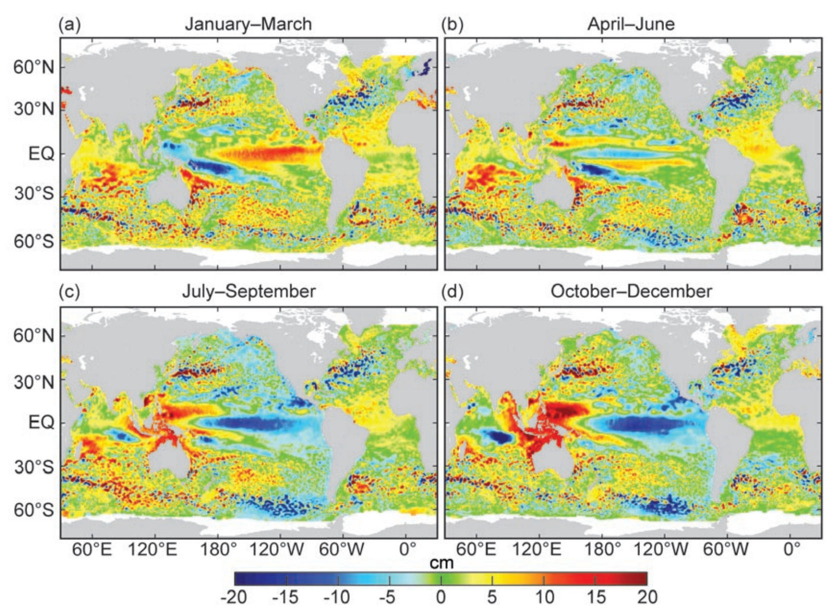

Fig. 3.25. Seasonal SSH anomalies (cm) for 2010 relative to the 1993–2010 baseline average are obtained using the multimission gridded sea surface height altimeter product produced by Ssalto/Duacs and distributed by AVISO, with support from CNES (http://www.aviso.oceanobs.com).