STATE OF THE CLIMATE IN 2009

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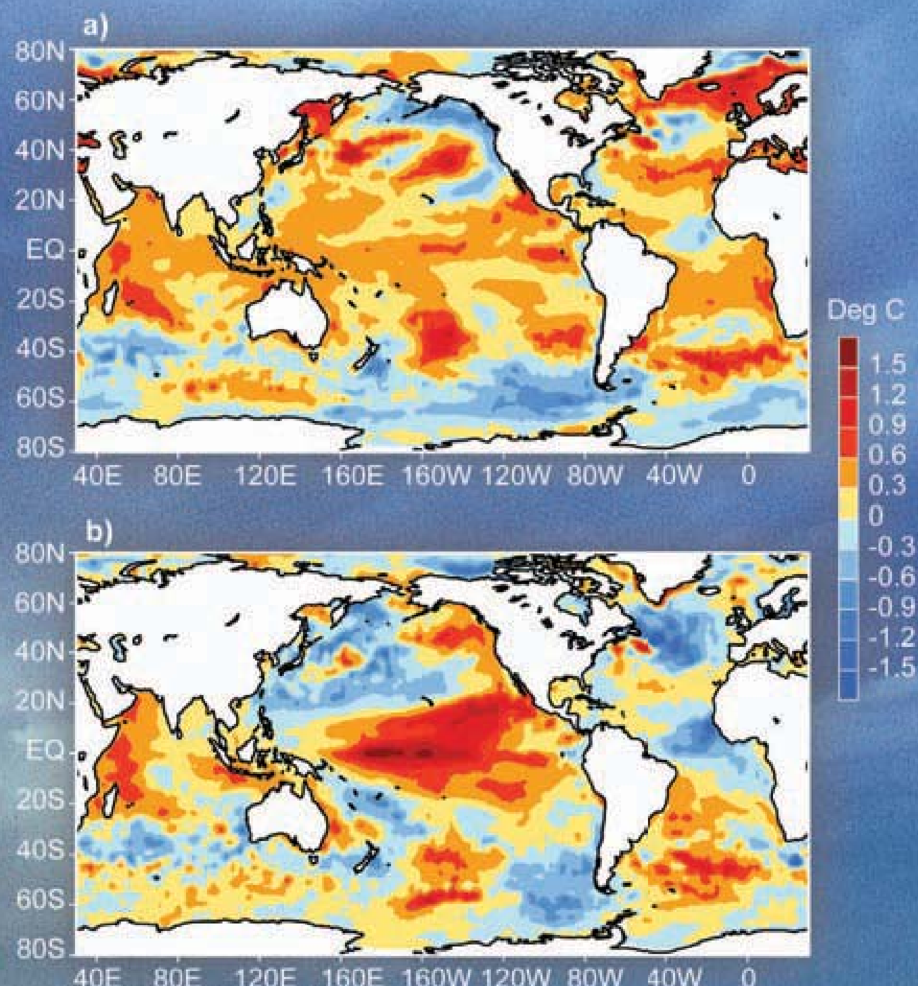

(a) Yearly mean sea surface temperature anomalies (SSTA) in 2009 and (b) SSTA differences between 2009 and 2008. Anomalies are defined as departures from the 1971-2000 climatology. Refer to Chapter 3, Figure 3.1 for a more detailed description.

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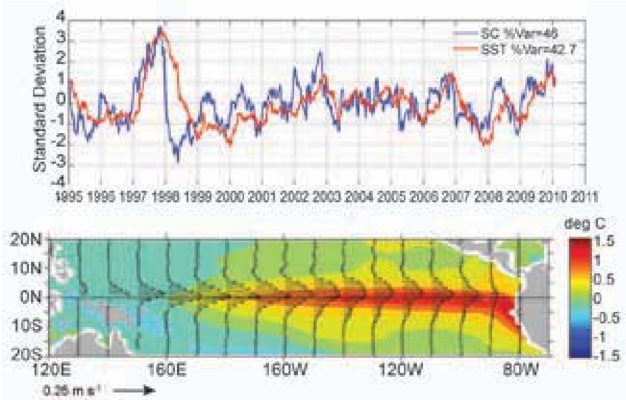

Fig 3.17. Principal empirical orthogonal functions (EOF) of surface current (SC) and of SST anomaly variations in the Tropical Pacific. (top) Amplitude time series of the EOFs normalized by their respective standard deviations. (bottom) Spatial structures of the EOFs.

seen clearly in the first principal EOF of surface current anomaly and separately of SST anomaly in the tropical Pacific basin (Fig. 3.17). By the end of 2009, the values of the normalized surface current and SST EOFs were reaching values approaching those of the 2002 El Niño, the strongest El Niño since the massive 1997–98 event.

The year ended with another strong wave pulse at the beginning of January 2010, together with a southward shift in westerly wind anomalies (Fig. 4.4), often associated with the onset of the termination of El Niño conditions (Lagerloef et al. 2003).

2) Indian Ocean

The Agulhas Current in the southwestern Indian Ocean is the major western boundary current linking the Indian and South Atlantic basins. Its transport can be estimated on a monthly basis using a combination of altimetry and hydrographic climatology (see http://www.aoml.noaa.gov/phod/altimetry/cvar/index.php). In 2009, the baroclinic transport of the Agulhas decreased from a maximum seen in 2007, to ~48 Sv[2], a value similar to those of the 1993–2000 period (Fig. 3.18, top). The generation of Agulhas rings, which carry Indian Ocean water into the Atlantic, decreased from the peak seen during 2007/08 (Fig. 3.18, bottom) to the more typical long-term average of ~5 rings yr^{-1}.

3) Atlantic Ocean

In the tropical Atlantic, 2009, surface currents were close to climatology except during boreal spring. Eastward anomalies of up to 50 cm s^{-1} occurred along the equatorial Atlantic in April through May, in response to weaker than normal Trade Winds that were also associated with anomalously cold SSTs in the northeastern Tropical Atlantic. This eastward anomaly pattern was disrupted in June–July, when westward anomalies developed east of 20°W in the Guinea Current region. By July, these currents had returned to normal climatological values.

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.

Over the last 15 years, the location of this front has shifted to the south at a mean speed of nearly 1° latitude per decade (Goni et al. 2010, manuscript submitted to *Deep-Sea Res.*; Lumpkin and Garzoli 2010, manuscript submitted to *J. Geophys. Res.*). However, most of this shift occurred in the early part of the altimeter-derived time series; while it exhibits strong intraseasonal to seasonal fluctuations (Goni and Wainer 2001), its annual-averaged position has not changed significantly since 1998, and in 2009 it fluctuated between 37° and 39°S.

g. The meridional overturning circulation—M. O. Baringer, T. O. Kanzow, C. S. Meinen, S. A. Cunningham, D. Rayner, W. E. Johns, H. L. Bryden, J. J-M. Hirschi, L. M. Beal, and J. Marotzke

The meridional redistribution of mass and heat associated with the large-scale vertical circulation within the oceans is typically called the meridional overturning circulation (MOC). The most common definition of the strength of the MOC at any particular latitude is the maximum of the vertically integrated basinwide stream function, which changes as a function of latitude and time and is influenced by many physical systems embedded within it. There are several available estimates of the steady-state global mass, fresh water, and heat transport based on the best available hydrographic data (Talley 2008; Lumpkin and Speer 2007; Ganachaud and Wunsch 2003), as well as a few local estimates of the MOC from one-time full water column hydrographic sections and western boundary arrays (e.g., McDonagh et al. 2008; Kanzow et al. 2008); however, true time-series observations of basinwide MOC transports are logistically very challenging to collect.

Substantial progress has been made on developing a coordinated observing system to measure the MOC through the international conference called OceanObs09 held September, 2009. The conference resulted in numerous community white papers and

[2] Sv is a Sverdrup or $10^6\ m^3\ s^{-1}$, a unit commonly used for ocean volume transports.

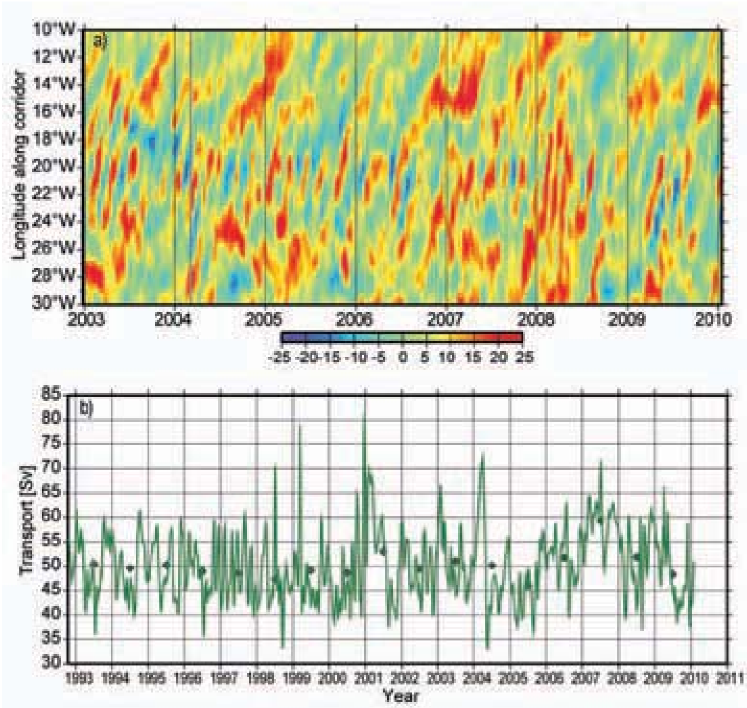

Fig. 3.18. (a) Time–longitude plot of sea height anomaly (SHA) in cm along the corridor of Agulhas ring propagation into the Atlantic Ocean, showing the presence of rings as high SHA (red colors). (b) monthly transport of the Agulhas Current (solid line) and annual averages (dots).

conference summary papers aimed at synthesizing recommendations for a sustained observing system including measurements of the MOC (e.g., Cunningham et al. 2010; Rintoul et al. 2010). Presently, quantifying changes in the complex, global MOC are being inferred only from observations of one component of the MOC (e.g., a specific current or ocean layer; e.g., Kanzow et al. 2008), at discrete locations (e.g., at 26.5°N in the Atlantic; Cunningham et al. 2007; Kanzow et al. 2007; Johns et al. 2008), or from indirect measurements such as air-sea fluxes thought to force the MOC (e.g., Marsh 2000; Speer 1997), or indirect measurements thought to be influenced by changes of the MOC, such as deep property fields like temperature or salinity (e.g., Johnson et al. 2008b). A prototype for the recommended observing system has been in place since April 2004, spanning the subtropical gyre in the North Atlantic near 26.5°N, hence this note concentrates on those observations. 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 Kanzow et al. 2007; Kanzow et al. 2008; Cunningham et al. 2007).

The most up-to-date estimates of the MOC from the 26.5°N array include data from April 2004 to April 2008[3] (Cunningham et al. 2007; Kanzow et al. 2010, manuscript submitted to *J. Climate*). Over this time period the MOC has averaged 18.7 Sv with a high of 32.1 Sv, a low of 3.2 Sv, and a standard deviation of 4.8 Sv (using the twice daily values filtered with a 10-day cutoff as described in Cunningham et al. 2007). The data suggest no significant trend in the strength of the MOC. After four years of data, a seasonal signal is beginning to emerge (Fig. 3.19) with a low MOC in April and a high MOC in October and peak to trough range of about 7 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, manuscript submitted to *J. Climate*). Of note is that all the MOC transport values estimated from five repeated CTD 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 2004 to 14.8 Sv in 1957). These results do not disprove the presence of a long-term trend in the strength of the MOC (e.g., as suggested by Bryden et al. 2005; Wunsch and Heimbach 2006), 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 (e.g., Baehr et al. 2008; Baehr et al. 2007; Brennan et al. 2008). Other related studies of the MOC trend are, so far, contradictory with some reporting a decrease in the MOC or components of the MOC (e.g., Wunsch and Heimbach 2006; Longworth et al. 2010, unpublished manuscript) while others suggest no change or even an increase (e.g., Köhl and Stammer 2008; Zhang 2008; Olsen et al. 2008; Lumpkin et al. 2008; Schott et al. 2009). Clearly, while disagreement remains over the details of findings from any particular observing systems (e.g., Kanzow et al. 2009), agreement exists

[3] Observations of the strength of the MOC from the 26.5° mooring array are available only with a time delay as the moorings are recovered over 12 to 18 month intervals.

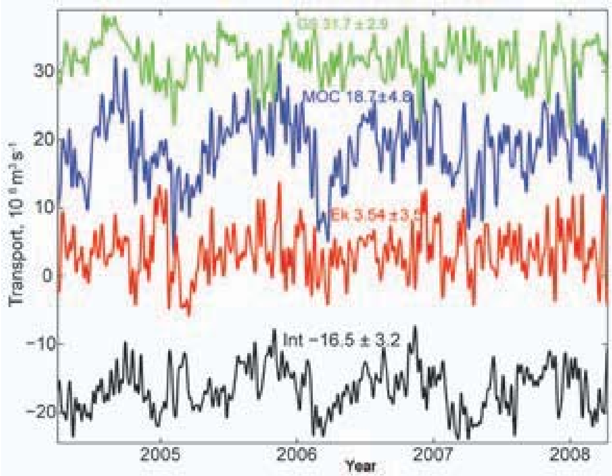

Fig. 3.19. Daily estimates of the strength of the meridional overturning circulation (MOC; blue line) and its components, the Florida Current (GS: green), wind-driven Ekman transport (Ek: red) and the geostrophic interior (Int: black), as measured by the United Kingdom's National Environmental Research Council (NERC) Rapid Climate Change Program, the National Science Foundation's 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 2008 (see also Kanzow et al. 2009), with a 10 day low-pass filter applied to the daily transport values.

that longer time series at multiple locations, particularly of the deep transport components, is needed (e.g., Wunsch 2008).

One of the main components of 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 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., Baringer and Larsen 2001; Meinen et al. 2010). Since 1982, variations in an important contributor to the upper limb of the Atlantic MOC have been monitored by measuring the Florida Current transport using a submarine cable across the Straits of Florida in combination with regular hydrographic sections. In 2009 the median transport through the Florida Straits was 31.3 ± 1.2 Sv[4], slightly lower than the 31.7 ± 2.2 Sv median transport in 2008, but well within the middle range of mean annual values (32.2 Sv median transport of the Florida Straits from 1982 to 2008 with 50% of the annual means within +/- 2.2 Sv). There were, however, several unusual high-frequency events during the year (Fig. 3.20): anomalously low-transport (outside of two standard deviations of the daily averaged values) events during 20–22 May, 18–27 June, 14–15 November, and 21–22 December, with values as low as about 23 Sv and an unusually high transport 11–12 July, with values as high as about 38 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). However, these transient fluctuations can have important environmental consequences. In the summer of 2009, the east coast of the United States experienced a high sea level event that was unusual due to it 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. Changes in Florida Current transport and the associated MOC have been similarly shown to affect sea level along the east coast of the United States through other studies such as Bingham and Hughes (2009) and Yin et al. (2009).

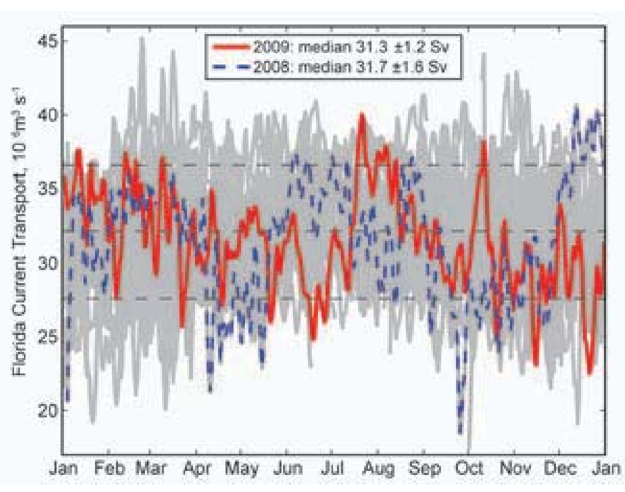

Fig. 3.20. Daily estimates of the transport of the Florida Current during 2009 (red solid line) compared to 2008 (dashed blue line). The daily values of the Florida Current transport for other years since 1982 are shown in light grey. The median transport in 2009 decreased slightly relative to 2008, and is slightly below the long-term median for the Florida Current (32.2 Sv).

[4] Standard error of the mean represents 95% confidence limits.

Trends in the MOC can also be determined through proxies of the MOC strength, such as paleo observations (e.g., Carlson et al. 2008), tracers (e.g., LeBel et al. 2008), and water mass characteristics (e.g., Kouketsu et al. 2009; Lohmann et al. 2008; Hawkins and Sutton 2007). For example during the past year, temperature and salinity observations in the Labrador Sea showed an abrupt return of deep convection between 2007 and 2008 (Våge et al. 2009). 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; Bellucci et al. 2008). Large-scale changes in temperature and salinity can also provide an indication of circulation changes; for example, Kouketsu et al. (2009) and Johnson et al. (2008a) showed that deep water temperature changes are consistent with a slowing of the deep circulation.

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

The dominant changes in sea level during 2009 were associated with a moderate El Niño event that peaked at the end of the year. We first describe quarterly sea level anomalies, which illustrate the sea level signature of the El Niño event, followed by the 2009 annual mean relative to a long-term mean and to the 2008 mean, which we treat as the present sea level tendency. We conclude with an update on global sea level rise and a brief description of daily sea level extremes observed at coastal and island tide gauges in 2009.

The La Niña event that developed in 2007 and persisted through 2008 was still evident during January–February–March 2009 (JFM 09) with high/low sea surface height (SSH) anomalies in the western/eastern tropical Pacific (Fig. 3.21). Positive anomalies extended throughout the Indonesian Archipelago into the tropical Indian Ocean and southward along the west coast of Australia. The La Niña weakened noticeably along the western equatorial Pacific during April–May–June 2009 (AMJ 09) with the excitation of a downwelling Kelvin wave that created positive SSH anomalies in the central and eastern equatorial Pacific. The size of the positive SSH anomalies in the western Pacific warm pool region also began to diminish during AMJ 09 presumably due to weakening trade winds to the east. The high SSH anomalies in the eastern tropical Pacific increased in amplitude during July–August–September 2009 and peaked in October–November–December 2009 (OND 09). By OND 09 the high water levels in the western equatorial Pacific had largely subsided to background levels with the exception of a branch of high water level near the South Pacific Convergence Zone. Most of these changes in equatorial sea level are associated with changes in regional ocean heat content (see section 3c.).

Averaged over the entire year, the SSH anomaly includes contributions from the weakening La Niña state and the strengthening El Niño with high water levels across the equatorial Pacific (Fig. 3.22, top panel). The low levels along the Pacific coast of North America with high levels in the central North Pacific suggest the dominance of the negative phase of the PDO. High anomalies occur along the paths of the Gulf Stream and Kuroshio extensions, suggesting either a strengthening or meridional shift of those currents. In general, sea level appears to be unusually high in the Indian Ocean relative to the 1993–2002 baseline with the exception of the mid- to high-latitude North Pacific and North Atlantic and in the

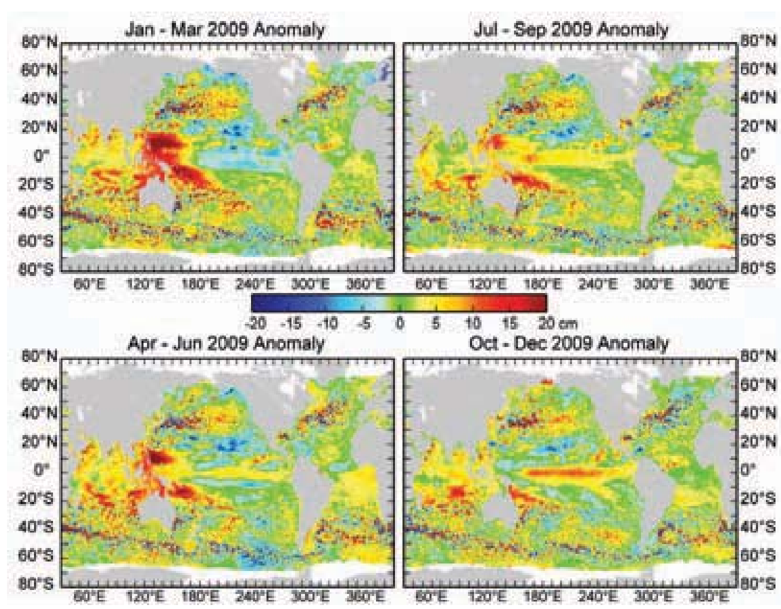

Fig. 3.21. Seasonal SSH anomalies for 2009 relative to the 1993–2007 baseline average are obtained using the multimission gridded sea surface height altimeter product produced by Ssalto/Duacs and distributed by Aviso, with support from CNES (www.aviso.oceanobs.com).