Global and Planetary Change 129 (2015) 23–36

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Detecting changes in the transport of the Gulf Stream and the Atlantic overturning circulation from coastal sea level data: The extreme decline in 2009–2010 and estimated variations for 1935–2012

Tal Ezer *

Center for Coastal Physical Oceanography, Old Dominion University, 4111 Monarch Way, Norfolk, VA 23508, USA

ARTICLE INFO

Article history:
Received 21 January 2015
Received in revised form 3 March 2015
Accepted 9 March 2015
Available online 13 March 2015

Keywords:
Atlantic Meridional Overturning Circulation
Gulf Stream
sea level
climate change

ABSTRACT

Recent studies reported weakening in the Atlantic Meridional Overturning Circulation (AMOC) and in the Gulf Stream (GS), using records of about a decade (RAPID project) or two (altimeter data). Coastal sea level records are much longer, so the possibility of detecting climatic changes in ocean circulation from sea level data is intriguing and thus been examined here. First, it is shown that variations in the AMOC transport from the RAPID project since 2004 are consistent with the flow between Bermuda and the U. S. coast derived from the Oleander measurements and from sea level difference (SLDIF). Despite apparent disagreement between recent studies on the ability of data to detect weakening in the GS flow, estimated transport changes from 3 different independent data sources agree quite well with each other on the extreme decline in transport in 2009–2010. Due to eddies and meandering, the flow representing the GS part of the Oleander line is not correlated with AMOC or with the Florida Current, only the flow across the entire Oleander line from the U.S. coast to Bermuda is correlated with climatic transport changes. Second, Empirical Mode Decomposition (EMD) analysis shows that SLDIF can detect (with lag) the portion of the variations in the AMOC transport that are associated with the Florida Current and the wind-driven Ekman transport (SLDIF-transport correlations of ~0.7–0.9). The SLDIF has thus been used to estimate variations in transport since 1935 and compared with AMOC obtained from reanalysis data. The significant weakening in AMOC after ~2000 (~4.5 Sv per decade) is comparable to weakening seen in the 1960s to early 1970s. Both periods of weakening AMOC, in the 1960s and 2000s, are characterized by faster than normal sea level rise along the northeastern U.S. coast, so monitoring changes in AMOC has practical implications for coastal protection.

1. Introduction

Recent findings of acceleration in sea level rise (SLR) along the U.S. East Coast north of the separation point of the GS at Cape Hatteras, North Carolina (Boon, 2012; Ezer and Corlett, 2012; Sallenger et al., 2012; Ezer, 2013; Ezer et al., 2013; Kopp, 2013), suggest that this acceleration may be a dynamic response to changes in ocean circulation. (See Appendix A for definitions of all the acronyms used.) The stretch of the North American coast between Cape Hatteras and Cape Cod has been labeled a "hotspot for accelerated sea level rise" (Sallenger et al., 2012) and a "hotspot for accelerated flooding" (Ezer and Atkinson, 2014), thus it is important to study the implications of regional climatic changes for flood-prone coastal communities (Atkinson et al., 2013; Nicholls and Cazenave, 2010; Cazenave and Cozannet, 2014; Goddard et al., 2015) and better understand the forcing mechanism behind those changes. Note that part of the hotspot region, especially the lower Chesapeake Bay area, has additional contribution to the relative SLR from land subsidence associated with the Glacial Isostatic Adjustment (GIA) and other geological and hydrological processes (Boon et al., 2010; Kopp, 2013; Miller et al., 2013), but the GIA impact has a time-scale of thousands of years, which is distinguishable from shorter-term ocean dynamics-driven variability studied here. The spatial pattern of this hotspot is consistent with dynamic sea level changes that have been seen in different numerical ocean models (Ezer, 1999, 2001; Levermann et al., 2005; Yin et al., 2009; Yin and Goddard, 2013; Griffies et al., 2014; Goddard et al., 2015). However, the regional pattern of sea level anomaly associated with changes in AMOC may be complicated and depends on the time scales of interest; there is a clear sea level response pattern near the GS due to interannual changes, but much broader spatial response of sea level to multidecadal variations (Lorbacher et al., 2010). Therefore, the study will use an analysis method that separates oscillations on different time scales.

Because of the sea level gradient across the GS (i.e., sea level is lower/higher on the onshore/offshore side of the GS), changes in the path and strength of the GS are expected to impact coastal sea level variations along the U.S. East coast; this idea is behind the main motivation of our study to estimate changes in offshore ocean currents from coastal

* Tel.: +1 757 683 5631.
E-mail address: tezer@odu.edu.

http://dx.doi.org/10.1016/j.gloplacha.2015.03.002
0921-8181/

tide gauge measurements. Over the years, several studies found significant correlations between variations in the GS and coastal sea level (Blaha, 1984; Ezer, 2001, 2013; Sweet et al., 2009; Ezer et al., 2013; Ezer and Atkinson, 2014), suggesting that the recent SLR acceleration may be driven by weakening AMOC and the GS (Sallenger et al., 2012; Ezer et al., 2013). However, the mechanism in which large-scale changes in ocean circulation affect the pattern of coastal sea level rise is complex, as it involves several processes such as changes in the southward flowing coastal slope current (Rossby et al., 2010), wind-driven changes in the GS and the Subtropical Gyre (Zhao and Johns, 2014), wind forcing on the shelf (Woodworth et al., 2014), climatic change in subpolar regions (Hakkinen and Rhines, 2004) and vertical divergence of large-scale ocean currents (Thompson and Mitchum, 2014). Some of these processes, as well as changes in the North Atlantic Oscillations (NAO) contribute to changes in the Atlantic Meridional Overturning Circulation (AMOC; McCarthy et al., 2012; Srokosz et al., 2012; Smeed et al., 2013). The GS, as part of the upper branch of the AMOC, may serve as a mean to transfer signals originated by climatic changes in the open ocean far away from coasts, into signals that can be detected at the coast — a recent example is the extreme sea level anomaly observed along the U.S. northeastern coast in 2009–2010 (Sweet et al., 2009; Goddard et al., 2015). Therefore, three elements are studied here and compared, AMOC, GS and sea level. The possibility of detecting changes in AMOC and the GS from sea level data is especially intriguing, given that from the 3 elements, only sea level had been continuously measured for more than a century.

While a weakening in the AMOC under warmer climate conditions is expected (Hakkinen and Rhines, 2004; Lorbacher et al., 2010; McCarthy et al., 2012; Sallenger et al., 2012; Srokosz et al., 2012; Smeed et al., 2013), there is ongoing debate whether or not this change can be detected from past observations. Continuous direct observations of all the components contributing to the AMOC transport are available from the RAPID project for only ~10 yrs, since 2004 (McCarthy et al., 2012; Srokosz et al., 2012; Baringer et al., 2013; Smeed et al., 2013), so they cannot resolve decadal or multidecadal variations which dominate the Atlantic Ocean dynamics (Sturges and Hong, 1995, 2001; Ezer, 1999, 2001, 2013; Rossby et al., 2014). Various attempts have been made to reconstruct the variations of AMOC in the past, for example, using sea surface temperature (SST) data (Klöwer et al., 2014), which captures the heat flux-driven part of AMOC. A different approach is proposed here, using observations of sea level difference across the GS. Observations of the GS flow by the Oleander container ship (Rossby et al., 2010, 2014) and by altimeter data (Ezer et al., 2013) span ~20 yrs and observations of the Florida Current (FC) at the Florida Strait (Baringer et al., 2013) span ~30 yrs of data. However, all the above data records are still short relative to the ~60-year cycle that may be associated with the Atlantic Multidecadal Osillations (AMO) (Chambers et al., 2012). Sea level data from tide gauges (Woodworth and Player, 2003; Church and White, 2011; Woodworth et al., 2014) have been monitored at a much higher rate (as frequent as hourly or daily) and have been recorded for much longer periods (in some locations over 100 yrs) than the AMOC or GS observations, so these data will be used here to reconstruct a longer proxy of the AMOC record. However, even in the long sea level records, decadal and multidecadal variations make the detection of long-term acceleration or identifying the sources of changes in trends difficult (Haigh et al., 2014).

Because of the different lengths of the records and the different instrumentations used, as mentioned above, there are sometimes discrepancies between different studies of the GS which may create confusion. For example, Rossby et al. (2014) claim that the Oleander data does not provide evidence that the GS is slowing down, a claim that appears to contradict evidence from other data showing recent slowing down of the GS (Sallenger et al., 2012; Ezer, 2013; Ezer et al., 2013) and weakening AMOC (Smeed et al., 2013). However, a close examination here will show that there is no real contradiction between different data sources. On the one hand, Rossby et al. (2014) looked at the average linear trend of the upper GS flow over 20 yrs, which indicates a small downward trend that is not statistically significant at 95% confidence level given the large variability in the GS flow. On the other hand, Sallenger et al. (2012) and Ezer et al. (2013) looked at non-linear changes, indicating that weakening of the GS and AMOC is not constant, but may have accelerated in recent years (Ezer et al., 2013, noticed a particular faster decline in the GS strength after ~2004). There is no reason to expect that climate trends will continue at the same rate over long period of time, so one has to look at the variability, not just the long-term mean trend; this is one of the goals of this study.

Comparing the variations and trends in different data sets is not a straight forward task when observations use different instruments, different sampling intervals and different locations (Fig. 1). For example, defining the upper GS flux and front position in the Oleander section between Bermuda and the U.S. coast (Rossby et al., 2014) is a complex task, as seen in Fig. 1. The GS is meandering, the flow field includes

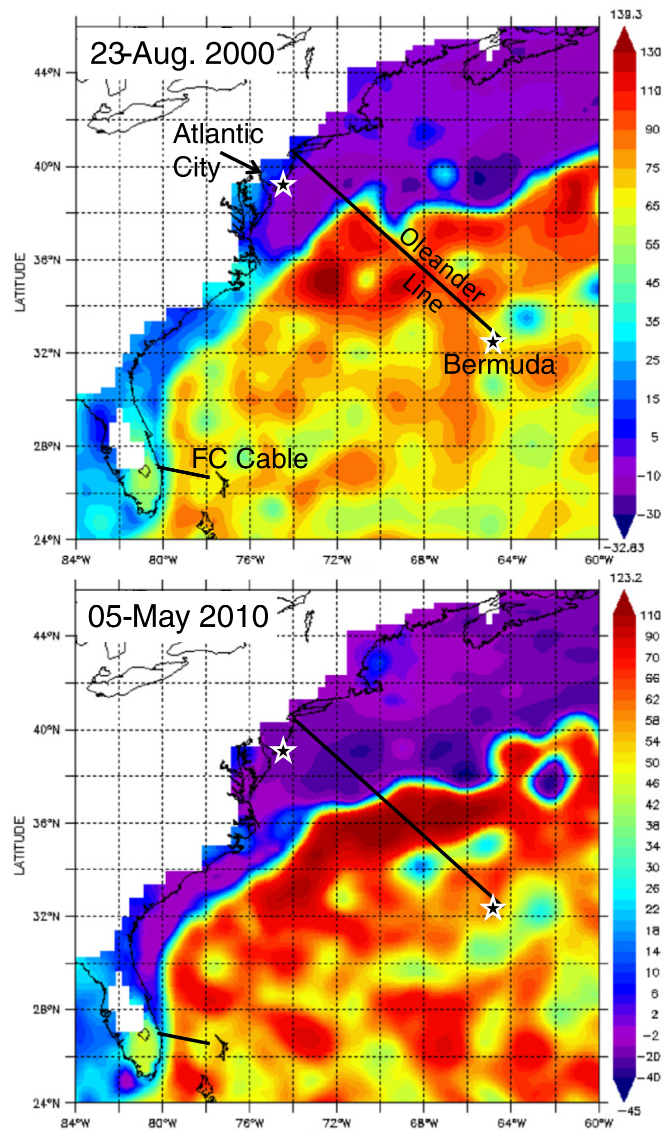

Fig. 1. Examples of absolute sea surface height (cm; in color) from altimeter data. Top: August 23, 2000, when the Gulf Stream front was farther north. Bottom: May 5, 2010, when the Gulf Stream front was farther south. Also shown are approximated locations of data used in the study: the Oleander section, the Florida Current section and the tide gauges (marked as stars).