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Key Points:

- Vessel-mounted ADCPs measure currents and transport accurately
- Gulf Stream shows no weakening unlike recent assertions in literature
- Clear need for more comprehensive measurements of ocean currents

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On the long-term stability of Gulf Stream transport based on 20 years of direct measurements

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Abstract In contrast to recent claims of a Gulf Stream slowdown, two decades of directly measured velocity across the current show no evidence of a decrease. Using a well-constrained definition of Gulf Stream width, the linear least square fit yields a mean surface layer transport of 1.35×10^5 m^2 s^{-1} with a 0.13% negative trend per year. Assuming geostrophy, this corresponds to a mean cross-stream sea level difference of 1.17 m, with sea level decreasing 0.03 m over the 20 year period. This is not significant at the 95% confidence level, and it is a factor of 2–4 less than that alleged from accelerated sea level rise along the U.S. Coast north of Cape Hatteras. Part of the disparity can be traced to the spatial complexity of altimetric sea level trends over the same period.

1. Introduction

The Gulf Stream off the U.S. East Coast is an integral link in the meridional overturning circulation (MOC) in the North Atlantic. It is the sole pathway by which the North Atlantic can transfer warm salty water from low to high latitudes. In addition, as a western boundary current, the Gulf Stream provides closure to the wind-driven subtropical gyre circulation [e.g., *Stommel*, 1958]. Off the U.S. East Coast, the wind-driven and MOC contributions to the Gulf Stream transport are not identifiable as separate constituents of the current, but east of the Grand Banks at 50°W the north turning branch of the Gulf Stream emerges as a distinct link in the MOC. The wind-driven part of the Gulf Stream continues east and south. In this note Gulf Stream refers to the current just downstream from Cape Hatteras and thus includes both the wind-driven and MOC components.

Over the last 20+ years a growing body of literature has addressed the stability of the MOC. Early papers, based on the sedimentary record of past climate variability, point to evidence of rapid climate change in association with the shutdown of the MOC [e.g., *Broecker*, 1997; *Clark et al.*, 2002]. The physical basis for this is that high-latitude warming leads to increased ice melt and freshwater flow, both of which might reduce or prevent the production of dense deep water in the Nordic Seas and hence the demand for warm salty North Atlantic water. This would lead to climatic cooling across the North Atlantic into central and northern Europe, a matter of enormous societal concern. In more recent years, as knowledge of ocean dynamics and modeling skills have improved, it is more widely thought that the MOC might weaken to some degree, but neither shut down nor increase in strength [*Intergovernmental Panel on Climate Change Fourth Assessment Report*, 2007; *Yin et al.*, 2009]. While comforting, considerable uncertainty remains, especially given indications of increased ice melt on Greenland [e.g., *Jungclaus et al.*, 2006], hence the need for continued and improved observation and further research [e.g., *Srokosz et al.*, 2012]. Because oceanic variability is substantially driven by shifting wind patterns in the subtropics [e.g., *Sturges and Hong*, 1995] and buoyancy fluxes at higher latitudes [e.g., *Häkkinen and Rhines*, 2004], and further constrained by topography in subpolar waters [e.g., *Bower et al.*, 2002; *Knutsen et al.*, 2005], it becomes difficult to identify MOC variability from single zonal sections across the Atlantic. Thus, to fully understand the dynamics of the MOC a more comprehensive approach is warranted, such as to monitor poleward flow in both subtropical and subpolar waters, and to do so over long time [*Srokosz et al.*, 2012].

Recently, two papers have suggested that the MOC may be weakening based on the well-documented accelerated sea level rise (SLR) along the U.S. East Coast [*Sallenger et al.*, 2012; *Ezer et al.*, 2013]. They infer that observed coastal SLR reflects a decreased sea level difference across the Gulf Stream. *Sallenger et al.* [2012]

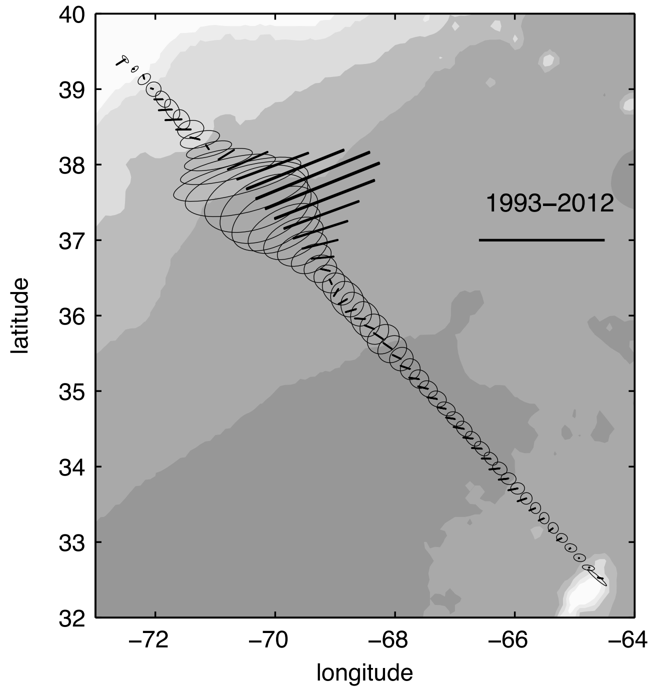

Figure 1. Mean velocity and variance ellipses between the mid-Atlantic Bight shelf break and Bermuda at 52/55 m depth for the 1993–2012 period. The bar corresponds to 1 m s^{-1} and 0.5 m^2 s^{-2}, respectively. The depth contours range from 1000 to 5000 m.

examine a large number of tide gauges along the US East Coast and estimate an accelerated sea level rise of up to 4 mm yr^{-1} over the last 40 years between Cape Hatteras and Cape Cod. *Ezer et al.* [2013] also note the coastal SLR north of Cape Hatteras. They report decadal variations that after 2004 turned into a decreasing trend in sea level gradient across the Gulf Stream between 70 and 75.5°W based on an analysis of AVISO (Archiving, Validation, and Interpretation of Satellite Oceanographic data) satellite altimetry. While changes in coastal sea level are well documented, it is not clear why the Gulf Stream per se should be implicated as it is a large-scale connected flow-through system whereas the documented SLR is limited to the mid-Atlantic Bight between Cape Hatteras and Nova Scotia [*Boon*, 2012]. In contrast to these recent assertions of a weakening Gulf Stream, our direct measurements of Gulf Stream currents for the past 20 years indicate no such trend, as we show in section 2. The discussion in section 3 seeks to provide at least some partial answers to the different findings about Gulf Stream transport.

2. Results

Between 1992 and 2012, we completed 20 years of operations measuring currents between the U.S. East Coast and Bermuda, spanning the outer shelf, the Slope Sea (between the continental shelf and the Gulf Stream), the Gulf Stream, and the Sargasso Sea. Currents were measured with an acoustic Doppler current profiler, which profiles currents to roughly 200–300 m depth (a 150 kHz acoustic Doppler current profiler (ADCP), between 1992 and 2004) and to 500–600 m depth (75 kHz, 2005 to present). Here we consider currents at a shallow depth just below the Ekman layer as an indicator of the Gulf Stream's overall transport: 55 m for the 150 kHz and 52 m for the 75 kHz ADCP. The installation and methodology of operation are discussed in detail in *Flagg et al.* [1998]. Over 1000 transects are now available in the archive (http://po.msrc.sunysb.edu/Oleander/) of which ~750 give good coverage of the Gulf Stream itself. Figure 1 shows the 20 year mean velocity and variance at 52/55 m depth [*Rossby et al.*, 2010], here updated through the end of 2012.

Here we define the extent of the Gulf Stream for each transect as the region in which the velocity component parallel to the maximum velocity is of the same sign. The transport then is the total flow through the section within this region. This definition corresponds in hydrographic or altimetric terms to finding the maximum dynamic height or sea level difference across the current [e.g., *Iselin*, 1936; *Worthington*, 1976; *Halkin and Rossby*, 1985; *Sato and Rossby*, 1995; *Lillibridge and Mariano*, 2013]. Typically, limits are 50 km to the north and

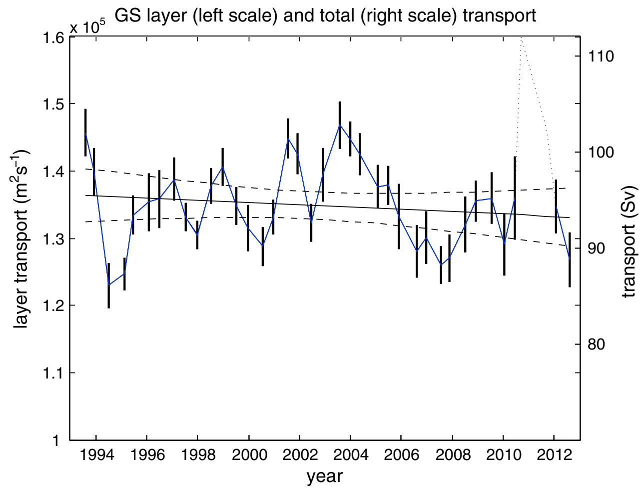

Figure 2. Annually averaged layer transport stepped every half year. The mean = $(1.34 \pm 0.6) \times 10^5$ $m^2\,s^{-1}$. The slope of the line = -173 ± 377 $m^2\,s^{-1}\,yr^{-1}$, equivalent to a decrease in sea level difference of 1.5 ± 3.3 mm yr^{-1} or 0.03 m over the 20 year observing period. The dashed lines indicate the 95% confidence limits of the linear fit. Note the large ~8% extrema around 1994, 2003, 2007, and 2012. The right axis shows 0–2000 m transport assuming a scale factor of 700. The dotted line in 2011 reflects a scarcity of data due to an extended dry dock period and difficulties starting up the ADCP afterward.

150 km to the south normal to the direction of flow. Since the ship rarely crosses the current at right angles, we follow past practice [e.g., *Halkin and Rossby*, 1985] and make the operational assumption that the current is flowing locally straight such that all vectors can be projected onto a line normal to the current.

The sampling frequency varies over time for a number of reasons including weather, equipment failure, and vessel dry dock periods, Gulf Stream transport is estimated in 1 year segments stepped at half-year intervals to give roughly equal weight to all parts of the 20 year record. On average, 36 sections contribute to each 1 year estimate, but the actual amount varies from year-to-year, the smallest being 18 (the first half of 2012). Integrating downstream velocity (i.e., the component parallel to the maximum velocity vector) for each section yields layer transport by the Gulf Stream. We then bin-average these on a yearly basis to produce the time series in Figure 2. The overall mean transport for a 1 m thick layer is $0.135 \times 10^6\ m^2\,s^{-1}$. Given that the Gulf Stream has long been understood to be in geostrophic balance [e.g., *Stommel*, 1958], which has been demonstrated observationally [*Johns et al.*, 1989], one can use the average cross-stream momentum balance $f < v > = g\ \Delta H/L$ where $< v >$ represents the average downstream velocity, f the local Coriolis parameter ($=0.9 \times 10^{-4}\ s^{-1}$), g acceleration due to gravity, and L cross-stream width to determine sea level difference, ΔH, across the current:

$$\Delta H = f/g < v > L = f/g \bullet \text{layer transport} = 1.17\ \text{m}.$$

The linear least square fit to layer transport (straight line) yields a 0.13% negative trend per year such that over the 20 year observation period layer transport may have decreased 2.6%. However, this estimate is clearly not significantly different from zero at the 95% confidence level (Figure 2). And this estimate may be biased slightly negative due to insufficient data in 2011 (due to vessel overhaul and equipment problems).

3. Discussion

Key to the above results is the ability to monitor the ocean with high horizontal resolution on a repeat and regular basis. The ADCP enables us to scan ocean currents at high horizontal resolution, here every 2.4 km (16 knot vessel speed × 5 min ensemble-averaged profiles). Considering that the radius of deformation (which characterizes the scale of the energetic mesoscale eddy field in the ocean) increases from about 19 to 34 km (north to south) across the Gulf Stream, this resolution means that the dynamical structure of the current can be resolved in considerable detail [e.g., *Rossby and Zhang*, 2001]. It also means that the limits of integration for each of the transport estimates used here can be accurately determined. This is relevant particularly for the northern limit due to the sharp lateral shear between the stream and the Slope Sea. Stopping the integral short will miss some of the Gulf Stream transport while integrating too far will pick up some westward flow, in either case biasing the transport downward. Thus, scanning the Gulf Stream at high

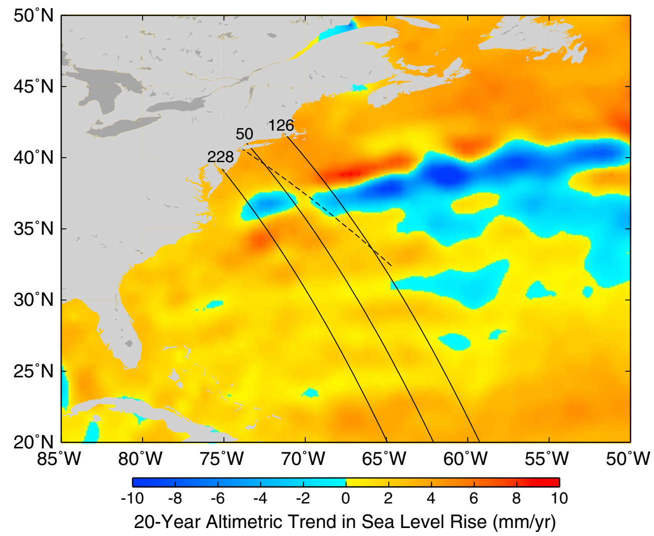

Figure 3. Sea level rise estimated from the TOPEX/Poseidon, Jason-1, and Jason-2 satellites over the 1992–2012 time period, in mm yr^{-1}. The three solid lines indicate descending tracks 228, 50, and 126 going from west to east. The dotted line shows the *Oleander* route between Bermuda and New Jersey. The large region of negative SLR (dark blue) corresponds to a net southward movement of the GS axis over this two-decade period.

resolution permits an accurate unbiased estimate of upper ocean transport or, equivalently, geostrophic sea level difference. A single ADCP mounted on a vessel in regular service enables us to efficiently obtain a very large number of independent measurements of velocity and transport. We do not get time series in the sense of moored measurements, but the repeat sampling delivers the degrees of freedom needed to estimate the climatically important interannual and longer-term variations.

The scatter of individual transport estimates relative to an annual mean is about 15%, reflecting mesoscale and submesoscale activity in and adjacent to the stream [*Rossby et al*., 2010]. Repeat sampling reduces this uncertainty significantly so that we can determine that the standard deviation of annual averages for the 20 year period is 4.5% of the overall mean. Note that the extrema around years 1994, 2003, 2007, and 2012 are quite a bit larger, Figure 2. The fact that transport is measured and that the uncertainty of estimation is kept small by the large ($>$20) number of independent samples in the yearly ensembles allows surface transport and geostrophic sea level difference to be determined quite accurately. The possible 0.13% negative trend per year of the linear fit in Figure 2 corresponds to a 0.03 m decrease in sea level across the Gulf Stream over this 20 year period of observation. This is a factor 2 smaller than the 0.056 ± 0.022 m $((3.8 \pm 1.06) - (0.98 \pm 0.33) = (2.82 \pm 1.11)$ mm $yr^{-1})$ accelerated SLR between Cape Hatteras and Cape Cod estimated by *Sallenger et al*. [2012] for the 1970–2009 period. We might add that the mean flow north of the Gulf Stream up to the continental shelf edge is westward. The corresponding mean and standard deviation of sea level difference across it (estimated from the *Oleander* velocity data) are 0.15 ± 0.03 m with no trend over the past two decades (not shown).

Using the AVISO altimetric data set, *Ezer et al*. [2013] find that sea level difference across the Gulf Stream is decreasing at an accelerated rate since 2004. Inspection of their Figure 5 (panel of remaining trend) yields $>$0.1 m over the 1993–2011 interval, a factor 3 greater than our direct estimate. While we cannot determine the specific reasons for this discrepancy (e.g., exact location and analysis methods) [*Ezer et al*., 2013], we show here the difficulty in estimating Gulf Stream transport change from local altimetric analysis due to the continual shifting of the narrow swift Gulf Stream over a continuum of spatial and temporal scales. The problem is knowing where the limits of the Gulf Stream are at any given time. *Worst* [2011] shows good agreement between *Oleander* and mapped AVISO estimates of sea level difference across the current for both data sets when sampled at the same time and position. But we do not in general have that information. To illustrate the challenge of estimating SLR across the Gulf Stream, Figure 3 shows the rate of SLR over the past 20 years estimated from TOPEX/Poseidon, Jason-1, and Jason-2 altimetry data in the western N. Atlantic. There is significant regional variability in the SLR rates, with regions of both positive and negative SLR in excess of 1 cm yr^{-1} (compared to a globally averaged SLR of about +3 mm yr^{-1}). Note the region of positive sea level rise just off Cape Hatteras and a long west-to-east swath of negative sea level farther east; the latter plausibly due to a slight

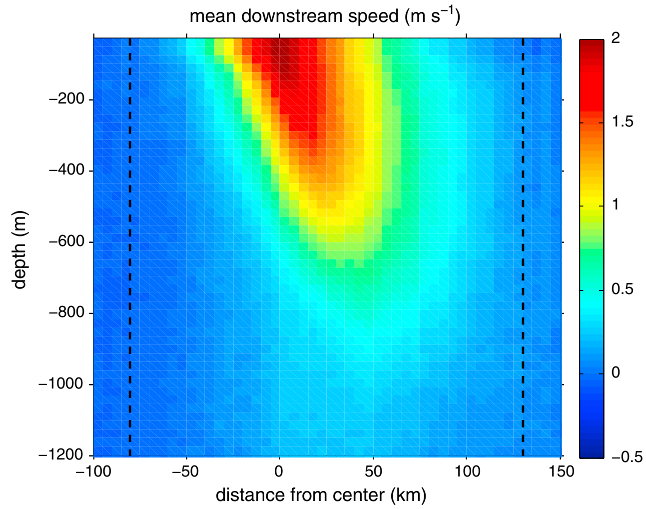

Figure 4. Mean downstream velocity (m s^{-1}) in the Gulf Stream in stream coordinates along the *Oleander* line constructed from 31 *Explorer of the Seas* sections in years 2006–2007. The dashed vertical lines define the lateral limits for the integration of transport (see text).

southward shift of the Gulf Stream. Sampling sea level differences without a specific definition of the Gulf Stream runs the risk of picking up nearby sea level variations that reflect local and regional changes, in addition to that of the Gulf Stream itself. To put this in more quantitative terms, we estimate sea level difference across the Gulf Stream along the three altimetry tracks shown by solid lines in Figure 3. The middle line (pass 50) crosses the *Oleander* line (dashed line) and was used to analyze seasonal and interannual variability in the Gulf Stream by *Lillibridge and Mariano* [2013]. Absolute sea surface height (SSH) from each satellite pass was analyzed in stream coordinates, using the location of the 25 cm height contour as a representative proxy for the current's axis. The height level of the inshore side of the Gulf Stream (Slope Sea) is estimated by the median of SSH values 0.5–2.5° of latitude north of the axis. Median averaging attenuates the effects of local mesoscale variability along the altimetry line. The height of the offshore side (Sargasso Sea) is similarly estimated as the median SSH between 1 and 3° of latitude south of the axis. This averaging procedure is designed to get an estimate of SSH just beyond the north and south edges of the stream, and provides height estimates and their difference every 10 days between 1992 and 2012. From west to east the rate of change in sea level difference across the Gulf Stream goes from strongly positive (4.22 mm yr^{-1}) to weakly positive (1.32 mm yr^{-1}) to negative ($-$0.66 mm yr^{-1}), in agreement with the regional variability seen in Figure 3. These variations in SLR illustrate the difficulty of estimating transport from altimetry in a highly energetic boundary current region. The time series of transport from altimetry across the middle line does not even agree very well with the *Oleander* data, despite their overlap. The conclusion we draw from this is that estimates of Gulf Stream transport from altimetry and its variability over time cannot be made reliably without knowing exactly where the meandering current is located. It also means that the directly measured short-term variability in Figure 2 reflects local and regional variations in recirculation along the Gulf Stream itself. They do not reflect increases or decreases in strength of the MOC as a whole. Interestingly, a recent paper by *Kopp* [2013] notes that the observed SLR is still within the bounds of twentieth century variability and concludes that it is "premature to validate the hypothesis of *Sallenger et al*. [2012] that the current regionally high rates of SLR along the U.S. East Coast represent the start of a long-term reorganization of the GS, and it will take about two decades of additional observations before the sea level effects of such a reorganization can be identified in tide gauge records as very likely exceeding the range of past variability".

A recently published paper [*Ezer*, 2013] analyzes tide gauge records along the U. S. East Coast and compares these with the Bermuda tide gauge for the same 30 year period. While all stations undergo significant interannual variability, they also exhibit similar sea level rise. Thus, on the longest time scales, sea level rise is about the same along the coast and at Bermuda. This would accord with our Gulf Stream findings as well as with *Worst* [2011], who finds no long-term or secular trend in layer transport between the shelf break and Bermuda.

Lastly, we should note that it is not sufficient to consider layer transport near the surface as a proxy for the MOC. These waters will have cooled and dispersed from the Gulf Stream long before it and its extension, the North Atlantic Current, reach the Nordic and Labrador Seas [*Brambilla and Talley*, 2006; *McGrath et al*., 2011].

The warm limb of the MOC is advected by the upper ocean baroclinic Gulf Stream. We can estimate mean volume transport by using directly measured currents to 1200 m to determine a vertical scale factor to yield transport to 2000 m, a depth often used for reporting Gulf Stream transport. *Rossby et al*. [2010] determined the scale factor between surface transport and transport to 600, 1200, and 2000 m from the 1980–1983 Pegasus data set at 73°W [*Halkin and Rossby*, 1985] 416, 548, and 605 m, respectively. We combine this information with a 38 kHz ADCP data set from the Royal Caribbean Cruise Line (RCCL) cruise ship the *Explorer of the Seas*, which operates in summer and fall between New Jersey and Bermuda along the *Oleander* line, Figure 4. The scale factors to 600 and 1200 m from that data set are 478 and 638 m, respectively, which are ~16% larger than those at the Pegasus line due to entrainment of water from both sides of the Gulf Stream as noted by *Halkin and Rossby* [1985]. Assuming the 16% increase applies at 2000 m as well gives us a scale factor ~700 m. Thus, the mean 0–2000 m transport at the *Oleander* line from 20 years of data would be $= 0.135 \times 10^6\ \mathrm{m^2\,s^{-1}} \times 700\ \mathrm{m} = 94.5$ sverdrup where 1 sverdrup $= 10^6\ \mathrm{m^3\,s^{-1}}$ (see Figure 2, right-side scale). However, the assumption of a constant scale factor is not at all certain since the Gulf Stream includes both wind-driven and MOC components, and their characteristics and trends may well differ. We know very little about variability of water column transport in relation to surface transport. For example, *McCarthy et al*. [2012] note a 30% reduction in the MOC from early 2009 to mid-2010, a very large signal that does not appear in the *Oleander* surface transport. On the other hand, it does show up in sea level difference between Bermuda and the U. S. East Coast [*Ezer*, 2013]. Profiling currents to and across the main thermocline would enable us to distinguish between surface and internal modes of variability and study their characteristics more effectively than we can today.

While the conundrum of accelerated SLR occurring along the US East Coast between Cape Hatteras and the Gulf of Maine remains, direct measurement of Gulf Stream surface transport over the last 20 years reveals no significant secular trend. In fact, in contrast to the insignificant decrease over this 20 year period, *Rossby et al*. [2010] noted a slight increase in transport based on the first 17 years of measurement. Estimates of transports and trends are relevant only to the period of observation; by themselves they have no predictive value.

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References

Boon, J. D. (2012), Evidence of sea level acceleration at U.S. and Canadian tide stations, Atlantic coast, North America, *J. Coastal Res.*, *28*(6), 1437–1445, doi:10.2112/JCOASTRES-D-12-00102.1.

Bower, A. S., B. Le Cann, T. Rossby, W. Zenk, J. Gould, K. Speer, P. Richardson, M. D. Prater, and H. M. Zhang (2002), Directly measured mid-depth circulation in the northeastern North Atlantic Ocean, *Nature*, *419*, 603–607.

Brambilla, E., and L. Talley (2006), Surface drifter exchange between the North Atlantic subtropical and subpolar gyres, *J. Geophys. Res.*, *111*, C07026, doi:10.1029/2005JC003146.

Broecker, W. (1997), Thermohaline circulation, the Achilles heel of our climate system: Will man-made CO_2 upset the current balance?, *Science*, *278*, 1582–1588.

Clark, P. U., N. G. Psias, T. F. Stocker, and A. J. Weaver (2002), The role of the thermohaline circulation in abrupt climate change, *Nature*, *415*, 863–869.

Ezer, T. (2013), Sea level rise, spatially uneven and temporally unsteady: Why the U.S. East Coast, the global tide gauge record, and the global altimeter data show different trends, *Geophys. Res. Lett.*, *40*, 1–6, doi:10.1002/2013GL057952.

Ezer, T., L. P. Atkinson, W. B. Cortlett, and J. L. Blanco (2013), Gulf Stream's induced sea level rise and variability along the U.S. mid-Atlantic coast, *J. Geophys. Res. Ocean*, *118*, 685–697, doi:10.1002/jgrc.20091.

Flagg, C., G. Schwartze, E. Gottlieb, and T. Rossby (1998), Operating an acoustic Doppler current profiler (ADCP) aboard a container vessel, *J. Atmos. Ocean. Technol.*, *15*, 257–271.

Häkkinen, S., and P. B. Rhines (2004), Decline of subpolar North Atlantic circulation during the 1990's, *Science*, *304*, 555–559, doi:10.1126/science.1094917.

Halkin, D., and H. T. Rossby (1985), The structure and transport of the Gulf Stream at 73°W, *J. Phys. Oceanogr.*, *15*, 1439–1452.

Intergovernmental Panel on Climate Change Fourth Assessment Report (2007), *The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., pp. 747–845, Cambridge Univ. Press, Cambridge, U.K., and New York.

Iselin, C. O'D. (1936), A study of the circulation of the Western North Atlantic, *Pap. Phys. Oceanogr. Meteor.*, *4*(4), 101.

Johns, E., R. Watts, and T. Rossby (1989), A test of geostrophy in the Gulf Stream, *J. Geophys. Res.*, *94*, 3211–3222.

Jungclaus, J. H., H. Haak, M. Esch, E. Roeckner, and J. Marotzke (2006), Will Greenland melting halt the thermohaline circulation?, *Geophys. Res. Lett.*, *33*, L17708, doi:10.1029/2006GL026815.

Knutsen, Ø., H. Svendsen, S. Østerhus, T. Rossby, and B. Hansen (2005), Direct measurements of the mean flow and eddy kinetic energy structure of the upper ocean circulation in the NE Atlantic, *Geophys. Res. Lett.*, *32*, L14604, doi:10.1029/2005GL023615.

Kopp, R. E. (2013), Does the mid-Atlantic United States sea level acceleration hot spot reflect ocean dynamic variability?, *Geophys. Res. Lett.*, *40*, 3981–3985, doi:10.1002/grl.50781.

Lillibridge, J. L., and A. J. Mariano (2013), A statistical analysis of Gulf Stream variability from 18+ years of altimetry data, *Deep Sea Res. Part II*, 127–146, doi:10.1016/j.dsr2.2012.07.034.

McCarthy, G., E. Frajka-Williams, W. E. Johns, M. O. Baringer, C. S. Meinen, H. L. Bryden, D. Rayner, A. Duchez, C. Roberts, and S. A. Cunningham (2012), Observed interannual variability of the Atlantic meridional overturning circulation at 26.5°N, *Geophys. Res. Lett.*, *39*, L19609, doi:10.1029/2012GL052933.

McGrath, G., T. Rossby, and J. Merrill (2011), Drifters in the Gulf Stream, *J. Mar. Res.*, *68*, 699–721.

Rossby, T., and H. M. Zhang (2001), The near-surface velocity and potential vorticity structure of the Gulf Stream, *J. Mar. Res.*, *59*, 949–975.
Rossby, T., C. Flagg, and K. Donohue (2010), On the variability of Gulf Stream transport from seasonal to decadal timescales, *J. Mar. Res.*, *68*, 503–522.
Sallenger, A. H., Jr., K. S. Doran, and P. A. Howd (2012), Hotspot of accelerated sea-level rise on the Atlantic coast of North America, *Nat. Clim. Change*, *2*, 884–888.
Sato, O., and T. Rossby (1995), Seasonal and secular variations in dynamic height anomaly and transport of the Gulf Stream, *Deep Sea Res.*, *42*, 149–164.
Srokosz, M., M. Baringer, H. Bryden, S. Cunningham, T. Delworth, S. Lozier, J. Marotzke, and R. Sutton (2012), Past, present, and future changes in the Atlantic meridional overturning circulation, *Bull. Am. Meteorol. Soc.*, *93*, 1663–1676.
Stommel, H. (1958), *The Gulf Stream: A Physical and Dynamical Description*, pp. 202, Univ. of California Press, Berkeley, Calif., and Cambridge Univ. Press, London.
Sturges, W., and B. G. Hong (1995), Wind forcing of the Atlantic thermocline along 328 N at low frequencies, *J. Phys. Oceanogr.*, *25*, 1706–1715.
Worst, J. S. (2011), Long-term monitoring of the NW Atlantic through altimetry and an acoustic Doppler current profiler. M.S. thesis, Grad. School Oceanography, Univ. Rhode Island, Kingston, RI.
Worthington, L. V. (1976), *On the North Atlantic Circulation*, vol. 6, Oceanographic studies, pp. 1–110, The John Hopkins University, Baltimore, Md.
Yin, J., M. E. Schlesinger, and R. J. Stouffer (2009), Model projections of rapid sea level rise on the northeast coast of the United States, *Nat. Geosci.*, *2*, 262–266, doi:10.1038/NGEO462.

