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Accelerated sea level rise and Florida Current transport

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Abstract

The Florida Current is the headwater of the Gulf Stream and is a component of the North Atlantic western boundary current from which a geostrophic balance between sea surface height and mass transport directly influence coastal sea levels along the Florida Straits. A linear regression of daily Florida Current transport estimates does not find a significant change in transport over the last decade, however, a nonlinear trend extracted from empirical mode decomposition suggests a 3 Sv decline in mean transport. This decline is consistent with observed tide gauge records in Florida Bay and the Straits, all exhibiting an acceleration of mean sea level rise over the decade. It is not known whether this recent change represents natural variability or the onset of the anticipated secular decline in Atlantic meridional overturning circulation, nonetheless, such changes have direct impacts on the sensitive ecological systems of the Everglades as well as the climate of western Europe and eastern North America.

1 Introduction

The Florida Current is a progenitor of the Gulf Stream, a component of the North Atlantic subtropical gyre western boundary current, and a surface component of the Atlantic meridional overturning circulation (AMOC). This current is climatically important (Jackson et al., 2015) with model simulations predicting a decrease in AMOC in response to increasing greenhouse gases (Solomon et al., 2007; Liu et al., 2015). Models also suggest the potential for significant sea surface height (SSH) changes across the western North Atlantic in response to AMOC dynamics (Brunnabend et al., 2014). In terms of mass transport Thomas et al. (2012) find that a weakening AMOC would be manifested as a reduction in southward deep water transport balanced by a decline in the northward upper ocean western boundary current. A decrease in AMOC since 2004 has been reported by Robson et al. (2014) and Smeed et al. (2014), find-

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ing a weakening of the southward flowing lower North Atlantic deep water. It is then reasonable to expect a concurrent decrease in western boundary transport.

Not only is the Florida Current important in terms of meridional heat transport, it is tightly confined in the Straits of Florida and geostrophic balance between transport and western boundary sea surface height exert a significant influence on coastal sea levels as noted by Montgomery (1938). More recent investigations corroborate the transport–SSH link, e.g. Blaha (1984); Sweet et al. (2009), and quantify transport variations (Leaman et al., 1987). These coastal sea level variations have important implications on ecological and anthropogenic responses along the Florida Straits and eastern seaboard of North America, including the fresh water resources of the environmentally critical ecosystems of the Everglades.

Gulf Stream dynamics in the Middle Atlantic Bight region of North America are also known to express similar influences. Ezer et al. (2013) analyzed the SSH elevation gradient across the western boundary of the Gulf Stream in the Middle Atlantic Bight north of Cape Hatteras, Florida Current transport, and coastal sea level at ten tide gauges in the Chesapeake Bay and middle Atlantic coast concluding that the Gulf Stream has shifted from a 6–8 year oscillation cycle to a continuous weakening trend since about 2004, and that this trend may be responsible for recent acceleration of middle Atlantic coast sea level rise (Sallenger et al., 2012). Subsequently, Rossby et al. (2014) reported two decades of ship-based velocity measurements across the Gulf Stream finding no significant decrease based on a *linear* regression. We note that Ezer et al. (2013) based their results on empirical mode decomposition (EMD), a component of the Hilbert–Huang transform (Huang and Wu, 2008) capable of extracting nonlinear trends in an area limited to the US East Coast, while Rossby et al. (2014) analyzed stream–wide transects from the East Coast to Bermuda.

The question of whether or not such changes are secular has not yet been answered. Kopp (2013) examined tide gauge records along the middle Atlantic coast along with the Atlantic multidecadal oscillation (AMO) and North Atlantic oscillation (NAO) indices, finding that all are currently within the bounds of 20th century variability and that an-

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other decade of observations are required to determine whether the recent middle Atlantic coast sea level acceleration represents the onset of trend, or an extension of historical variability. Specific to sea level rise acceleration, Haigh et al. (2014) indicate that interannual to multidecadal variability dominates the records such that in most locations several additional decades are needed to reliably quantify any tide gauge accelerations.

Transport estimates

Daily transport estimates derived from electromotive induction voltages in a submarine cable spanning the Florida Straits near 27° N have been made since 1982 (Fig. 1), with independent ship-based calibration measurements obtained on a recurring basis. A review of Florida Current transport measurements including details on the cable observational program and data can be found in Meinen et al. (2010) along with an assessment of the temporal variability of Florida Current transport. Specifically, two thirds of the variance is at sub-annual time scales, less than 10 % annually, 13 % interannually (13–42 months), and less than 10 % at periods longer than 42 months. Meinen et al. (2010) also found no evidence for a long-term linear trend in Florida Current transport based on data for 1982–2007, and variability on decadal time scales of roughly ±1 Sv during 1982–2007.

Garcia and Meinen (2014) recently assessed accuracy of the cable transport estimates, finding that annual transport averages are accurate to within 0.3 Sv and that the cable is capable of observing small but important climate-induced changes in Florida Current transport. The focus of this paper is to examine recent data linking Florida Current transport and coastal SSH anomalies.

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2 Florida Current trend

Daily estimates of Florida Current transport from the cable, as well as ship-based dropsonde or lowered acoustic Doppler profiler measurements are available from the NOAA Climate Observation Division as part of the Western Boundary Timeseries project (NOAA, 2015a). Figure 2 shows daily data from 18 March 1982 through 19 November 2014 along with data reconstruction (gray vertical bands) over the period 23 October 1998 through 18 June 2000 when data was not collected, and five other periods with gaps greater than 30 days (2 July to 16 August 1995; 27 May to 8 August 1996; 21 November 2001 to 2 February 2002; 2 September to 8 October 2001; 3 September to 29 October 2004). Reconstructed data are uniformly sampled from probability distributions estimated with Gaussian kernels of all available data for each missing yearday. All other data gaps (46 one day gaps, 33 between 2 and 5 days, 21 between 6 and 30 days) are filled with linear interpolation. The ship data have no reconstruction applied.

A linear regression of the ship data results in a decline of 0.77 ± 0.22 Sv from 1982 through 2014 with a p value of 0.17, suggesting an 83 % probability that a linear model decline is not a random artifact. A linear model of cable transport from 1982 through September 2014 finds a decrease of 1.08 ± 0.46 Sv (p value less than 0.001), while from October 2004 through October 2014 a linear regression decrease of 0.57 ± 0.38 Sv (p value 0.002). Since decadal transport variability of the Florida Current has been estimated as ± 1 Sv, linear regressions of the data, which are less than 1 Sv decade^{-1}, can lead one to conclude that there has been no significant change in mean transport.

However, a linear model can be biased by incomplete modal oscillations, is not data-adaptive within the record (there is only one fit coefficient) and may provide an incomplete picture for the complex dynamics of coupled nonlinear processes, providing motivation to employ empirical mode decomposition (EMD) in an effort to extract time-varying trends in the data. EMD is a heuristic, basis-free, data-adaptive modal decomposition which extracts modes in order of increasing oscillatory scales (lower instantaneous frequencies) into intrinsic mode functions (IMFs). It is essentially a mod-

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ern implementation of Chrystal's graphical method of residuation (Chrystal, 1906), with an excellent introduction and review provided by Huang and Wu (2008). In contrast to Fourier decomposition employing time-invariant sinusoidal bases, wavelet transforms using scale-invariant wavelets, or empirical orthogonal functions based on eigenmodes, EMD is a recursive residuation extracted from envelopes of the data itself. It performs well on non-stationary and nonlinear signals, and is suited to the extraction of time-adaptive nonlinear trends (Wu et al., 2007).

The black line in Fig. 2 shows the sum of the EMD residual with IMFs 11 through 17 (the seven longest scale modes), and blue lines plot the EMD residuals representing trends. The trend in the cable data from 1982 through 2004 exhibits a ±1 Sv variation, while the most recent decade indicates a 3 Sv decline. In contrast, the ship data residual decreases by 0.5 Sv over the entire record. The divergence in these estimates over the last decade has not been attributed and needs further study. One factor is that the cable estimates are based on an integrated measurement of electromotive flux across the entire cable, whereas ship measurements are sampled with spatially limited vertical profiles.

Since the mean transport decline of the cable data over the last decade is consistent with the change of Gulf Stream SSH gradient in the Middle Atlantic Bight as found by Ezer et al. (2013), with a reduction in AMOC since 2004, and also with coastal SSH anomalies in South Florida (discussed below), there is observational evidence to support a recent decline in mean transport as detected in the cable data and we will focus on it in the remainder of the analysis.

3 Climate indices

The El-Niño Southern Oscillation (ENSO), NAO and AMO express global teleconnections influencing atmospheric and oceanic circulation, as well as coastal sea levels. We examine each of these in relation to the Florida Current transport in the following sections. NAO data are available at www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/

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nao.shtml, AMO data at www.esrl.noaa.gov/psd/data/timeseries/AMO/, and the multivariate ENSO index (MEI) at www.esrl.noaa.gov/psd/enso/mei/.

3.1 North Atlantic Oscillation

Barringer and Larsen (2001) noted that decadal changes in transport were inversely correlated to the North Atlantic Oscillation Index over the period 1982–1998, motivating DeNezio et al. (2009) to propose that wind stress curl forcing of fast propagating Rossby waves was a causative mechanism. Concurrently, Peng et al. (2009) suggested that the correlation is phase-dependent such that a strong positive NAO initiates a transport peak in May, while a strong negative NAO delays the transport peak until July, and concluded that transport variability is influenced by variability of internal ocean dynamics forced by NAO, rather than by NAO directly. More recently, Meinen et al. (2010) examined a longer data record (through 2007) than available to Barringer and Larsen (2001), concluding that the NAO-transport correlation is not evident outside the 1982–1998 time frame, and the mechanism proposed by DeNezio et al. (2009) may be only one of several mechanisms contributing to interannual and longer variability in the Florida Current.

A comparison of EMD residual trends, as well as decadal and interannual IMFs of the Florida Current, NAO, AMO and MEI climate indices are shown in Fig. 3. There does not appear to be relationship between EMD residuals of Florida Current and NAO, however in (b) we identify decadal scale IMFs of Florida Current and NAO which are approximately anti-phased from 1985–2006, while beyond 2006 the NAO mode appears to be increasing in period and decreasing in amplitude. We note that Meinen et al. (2010) made their determination of NAO and transport synchronization by comparison of 3 and 5 year centered–means (their Fig. 7). Examination of their 5 year mean timeseries suggests a stable anti-correlation from 1986–2002. Since an arithmetic mean can not discriminate contributions to the mean from longer period cycles, it may be that decadal–scale IMFs provide a more complete representation of decadal cycles, and is perhaps why we find the anti-correlation to hold beyond 2002. Nonetheless, the finding

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by Meinen et al. (2010) that a synchronous relation between transport and NAO on decadal time scales is not persistent is consistent with the EMD analysis.

3.2 Atlantic Multidecadal Oscillation

The AMO is coherently related to North Atlantic coastal SSH anomalies (Frankecombe and Dijkstra, 2009; Park and Dusek, 2013) and it has been suggested that it is a manifestation of the AMOC (Knight et al., 2005; Latif et al., 2004). Since the Florida Current is a component of the AMOC we examine EMD residuals and decadal IMFs of Florida Current and AMO Index in Fig. 3c and d. While there is no clear association between the Florida Current and AMO EMD residuals, there appears to be a link between decadal modes with Florida Current transport leading the AMO Index by an average of 1.7 years. This is physically reasonable since the Florida Current transports warm water into the North Atlantic.

3.3 El-Niño Southern Oscillation

Regarding interannual scales, the ENSO globally influences oceanic processes and is readily apparent in geostrophic transport time series spectra of the Florida Current (NOAA, 2015b). We note a positive Florida Current anomaly coincident with the strong 1997–1998 El-Niño in Figs. 2 and 3e, however there is no evidence of a Florida Current anomaly during the 1982–1983 El-Niño suggesting that ENSO influence on Florida Current transport is indirect and only one component of a complex system.

It is also interesting to note that inspection of MEI IMFs during the 1982–1983 and 1997–1998 El-Niño's (Fig. 3f) indicate that strong El-Niño events correspond to a synchronization of MEI IMFs 4 through 7. While this observation does not appear to be directly relevant to the SSH-transport link, it may nonetheless provide a useful starting point for investigations of physical forcings associated with the respective IMFs and their episodic synchronization into El-Niño's.

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4 Sea level

Rising sea levels are a major concern from both ecological and sociological perspectives, and understanding impacts from Florida Current variability can provide valuable information for modeling efforts and decision makers. Figure 4 plots monthly mean sea levels from March 1982 through October 2014 from the NOAA tide gauge at Vaca Key Florida, from January 1994 through January 2015 at the Virginia Key Florida NOAA gauge (data and station information available at tidesandcurrents.noaa.gov), and from October 1993 through October 2014 at a National Park Service station in Florida Bay within Everglades National Park (Little Madeira Bay, 25.17580° N 80.63269° W). Sea level rise (SLR) rates are determined by a linear regression of monthly means with the seasonal cycles removed (Zervas, 2009), as shown by the dashed lines. EMD residuals are shown with the solid red (Vaca Key), blue (Florida Bay) and green (Virginia Key) curves, suggesting SLR rates above the linear trend over the last decade.

The Florida Current influences coastal sea levels through a geostrophic balance of transport and SSH:

$$\Delta\zeta = \frac{-fL}{g}\overline{V}_s \qquad (1)$$

where $\Delta\zeta$ is the change in sea surface height across the width of the channel L, f the Coriolis parameter, g the vertical acceleration and $\overline{V}_s$ the mean transport velocity (Wunsch et al., 1969). The cross–sectional area of the Florida Straits at 27° N is approximately 42.96 Mm^2 and with a nominal transport of 32 Sv results in a mean current of 0.745 $\mathrm{m\,s^{-1}}$ and an equivalent 1 Sv current of 0.023 $\mathrm{m\,s^{-1}}$. Evaluating Eq. (1) at 27° N (L = 90 km) with a mean current of $\overline{V}_s = 0.023\,\mathrm{m\,s^{-1}}$ results in a SSH factor of $-1.4\,\mathrm{cm\,Sv^{-1}}$. This of course neglects nonlinear effects and assumes a barotropic uniform flow.

Leaman et al. (1987) assessed variability of the Florida Current finding that the while the northward component of flow is not homogeneous across the strait, the flow is

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well–structured with northward components more than an order of magnitude stronger than eastward components, with SD typically 20 % or less of the mean flow velocity. They also found that barotropic modes dominate over baroclinic modes, with good coherence between the spatial structure of density (σT) and temperature across the strait. This suggests that the assumption of uniform barotropic flow is reasonable for first order estimates of transport.

Figure 5a plots sea surface height anomaly (demeaned EMD residual) at Vaca Key, Florida Bay and Virginia Key, as well as an estimated SSH anomaly for the Florida Current at 27° N computed from the Florida Current demeaned EMD residual multiplied by $-1.4\,\mathrm{cm\,Sv^{-1}}$. Subtraction of this Florida Current SSH anomaly (black curve) from the tide gauge anomalies are shown in Fig. 5b providing an estimate of the component of SLR not attributed to Florida Current transport where we have assumed that the transport–SSH relationship deduced at 27° N applies at the tide gauges.

The dashed lines in Fig. 5b plot linear regressions to the SSH changes with the transport changes removed, finding values of 3.5, 3.0 and $2.7\,\mathrm{mm\,yr^{-1}}$ at Vaca Key, Florida Bay and Virginia Key respectively. Note that the data used to compute EMD residuals in Fig. 5a do not have the seasonal cycle removed, whereas the linear trends previously estimated do (Fig. 4). Since the linear rates estimated on EMD tidal residuals with the transport component removed are a significant fraction of the linear rates determined from the monthly mean data with the seasonal cycle removed (3.8 and $3.9\,\mathrm{mm\,yr^{-1}}$), we expect that the seasonal cycle is dominated by Florida Current transport variability.

Regarding the nonlinear trends in sea level, from October 2004 through October 2014 the Vaca Key, Florida Bay and Virginia Key mean sea level (MSL) EMD residuals increased by 7.4, 7.1 and 5.9 cm respectively, while the Florida Current SSH anomaly increase is 4.3 cm, which is 58, 60 and 73 % of the respective MSL rise at each station. Compared to the long term linear rates of 3.8 and $3.9\,\mathrm{mm\,yr^{-1}}$, MSL rises of 7.4, 7.1 and 5.9 cm over a decade are roughly twice the linear rate.

We note that the seasonal cycle of MSL that is removed from the monthly means in order to estimate a long term linear rate (Fig. 4) is computed as an average of the

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monthly mean sea level for each month over the period of record assuming that the cycle is stationary in frequency and amplitude. Given that the seasonal anomalies are influenced by atmospheric pressure, ocean temperature, salinity and transport, this is likely an untenable assumption as evidenced by Meinen et al. (2010) who report significant variability in the structure of the annual cycle of Florida Current transport during different years. Since the EMD analysis suggests that at Vaca Key the annual seasonal cycle as determined above is dominated by Florida Current transport, we would like to examine the relation between transport and MSL on an annual scale without the assumption of a stationary seasonal cycle. IMF 4 of the Vaca Key MSL and IMF 11 of cable transport capture annual scale oscillations, and we select sections of these IMFs with periods corresponding to Hilbert instantaneous frequencies between 9 and 15 months with the resultant modes shown in Fig. 6. Here we note a general inverse relationship between transport and MSL on the annual scale, supporting the idea that Florida Current transport is an important influence on MSL in the Florida Straits.

5 Conclusions

Florida Current transport is dynamically linked to coastal sea level anomalies through geostrophic balance between SSH and mass transport. Empirical mode decomposition of daily transport estimates indicates a ±1 Sv variation in mean transport from 1982 through 2004, but a 3 Sv decline from 2004 through 2014, however, direct measurement of velocities from ship surveys lack this dramatic decline over the last decade. This conflict needs resolution to better understand geophysical processes associated with Florida Current Transport. Nonetheless, the decline suggested by the cable data are consistent with changes in Middle Atlantic Bight SSH gradient, sea level rise at Vaca Key, Florida Bay, Virginia Key, and a decline in AMOC since 2004.

Examination of concurrent NAO and Florida Current decadal modes for 1982–2014 is consistent with the analysis of Meinen et al. (2010) which considered data for

1982–2007 and found that outside the 1982–1998 window the anti-correlation between Florida Current transport and NAO does not appear to hold. However, their centered–average approach could include effects from longer period cycles whereas an IMF will not, and we find that decadal IMFs are approximately in anti-phase synchronization from 1985–2006. While there is some tension between these estimates, they both support the notion that the NAO and Florida Current transport are not perennially anti-correlated on decadal time scales.

Regarding sea surface temperatures, we find that decadal modes of Florida Current lead the AMO Index by an average of 1.7 years. Since decadal SSH anomalies along the southeastern US coast are coherent with the AMO Index (Park and Dusek, 2013), a connection to Florida Current transport with a reasonable lead time may prove useful for prognosis of long term SSH anomalies along the coast. One must be cautious that both the NAO and AMO relationships encompass only a few cycles in the data, there is no reason to warrant that these relationships will be maintained. Influences of ENSO are confusing at best. The 1982–1983 El-Niño was not observed to be coincident with a Florida Current Anomaly, whereas the 1997 event was.

EMD residuals of monthly mean sea levels at Vaca Key, Florida Bay and Virginia Key indicate an acceleration of sea level over the last decade coincident with the mean transport decline detected in the cable data. To estimate the transport–SSH relationship at 27° N we neglected nonlinear effects and assumed a barotropic uniform flow across the channel. We further assumed that the transport–SSH relationship deduced at 27° N applies at the tide gauges. These assumptions allow for a simple model, but clearly are points of deficiency. Further work is needed to validate or repudiate them.

The transport–SSH relationship of $-1.4\,\mathrm{cm\,Sv^{-1}}$ was used to estimate the SSH anomaly at 27° N based on the EMD residual of Florida Current transport, which when subtracted from the EMD residual MSL largely recovers the long term linear trend with the average seasonal cycle removed. This suggests that the seasonal cycle is dominated by Florida Current variability, and examination of annual modes of transport and MSL with instantaneous frequencies corresponding to periods between 9 and

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15 months finds an inverse transport–SSH relationship. If this mechanism is causative, it suggests that 60 % of the roughly 7 cm MSL change in South Florida over the last decade could be related to a mean decline in Florida Current transport.

It must be remarked that even if the 3 Sv mean transport detected here in the cable data is verified, we cannot say whether or not this represents a secular climatic shift or the result of natural variability. Kopp (2013) reminds us that at least another decade of MSL observations are needed in the Middle Atlantic Bight to separate detected accelerations from 20th century variability, and Haigh et al. (2014) finds that several decades may be required before acceleration detection methods reveal discernible accelerations in individual tide gauge records here, primarily due to the considerable interannual to multidecadal variability of oceanic processes.

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References

Barringer, M. O. and Larsen, J. C.: Sixteen years of Florida Current transport at 27° N, Geophys. Res. Lett., 28, 3179–3182, 2001. 557

Blaha, J. P.: Fluctuations of monthly sea level as related to the intensity of the Gulfstream from Key West to Norfolk, J. Geophys. Res., 89, 8033–8042, 1984. 553

Brunnabend, S.-E., Dijkstra, H. A., Kliphuis, M. A., van Werkhoven, B., Bal, H. E., Seinstra, F., Maassen, J., and van Meersbergen, M.: Changes in extreme regional sea surface height due to an abrupt weakening of the Atlantic meridional overturning circulation, Ocean Sci., 10, 881–891, doi:10.5194/os-10-881-2014, 2014. 552

Chrystal, G.: On the hydrodynamical theory of Seiches, T RSE Earth, 41, 599–649, doi:10.1017/S0080456800035523, 1906. 556

DeNezio, P. D., Gramer, L. J., Johns, W. E., Meinen, C. S., and Barringer, M. O.: Observed interannual variability of the Florida Current: wind forcing and the North Atlantic Oscillation, J. Phys. Oceanogr., 39, 721–736, 2009. 557

Ezer, T., Atkinson, L. P., Corlett, W. B., and Blanco, J. L.: Gulf Stream's induced sea level rise and variability along the U.S. mid-Atlantic coast, J. Geophys. Res.-Oceans, 118, 685–697, 2013. 553, 556

Frankecombe, L. M. and Dijkstra, H. A.: Coherent multidecadal variability in North Atlantic sea level, Geophys. Res. Lett., 36, L15604, doi:10.1029/2009GL039455, 2009. 558

Garcia, R. F. and Meinen, C. S.: Accuracy of Florida Current volume transport measurements at 27° N using multiple observational techniques, J. Atmos. Ocean. Tech., 31, 1169–1180, 2014. 554

Haigh, I. D., Wahl, T., Rohling, E. J., Price, R. M., Pattiaratchi, C. B., Calafat, F. M., and Dangendorf, F.: Timescales for detecting a significant acceleration in sea level rise, Nat. Commun., 5, 1–11, 2014. 554, 563

Huang, N. E. and Wu, Z.: A review on Hilbert–Huang transform: method and its applications to geophysical studies, Rev. Geophys., 46, RG2006, doi:10.1029/2007RG000228, 2008. 553, 556

Jackson, L., Kahana, R., Graham, T., Ringer, M., Woollings, T., Mecking, J., and Wood, R.: Global and European climate impacts of a slowdown of the AMOC in a high resolution GCM, Clim. Dynam., 44, 1–18, doi:10.1007/s00382-015-2540-2, 2015. 552

Knight, J. R., Allan, R. J., Folland, C. K., Vellinga, M., and Mann, M. E.: A signature of persistent natural thermohaline circulation cycles in observed climate, Geophys. Res. Lett., 32, L20708, doi:10.1029/2005GL024233, 2005. 558

Kopp, R. E.: Does the mid–Atlantic United States sea level acceleration hot spot reflect ocean dynamic variability?, Geophys. Res. Lett., 40, 3981–3985, 2013. 553, 563

Latif, M., Roeckner, E., Botzet, M., Esch, M., Haak, H., Hagemann, S., Jungclaus, J., Legutke, S., Marsland, S., Mikolajewicz, U., and Mitchell, J.: Reconstructing, monitoring and predicting decadal-scale changes in the North Atlantic thermohaline circulation with sea surface temperature, J. Climate, 17, 1605–1614, 2004. 558

Leaman, K. D., Molinari, R., and Vertes, P.: Structure and variability of the Florida Current at 27° N: April 1982–July 1984, J. Phys. Oceanogr., 17, 566–583, 1987. 553, 559

Liu, Y., Lee, S.-K., Enfield, D. B., Muhling, B. A., Lamkin, J. T., Muller-Karger, F. E., and Roffer, M. A.: Potential impact of climate change on the Intra-Americas Sea: Part-1. A dynamic downscaling of the CMIP5 model projections, J. Marine Syst., 148, 56–69, 2015. 552

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Meinen, C. S., Barringer, M. O., and Garcia, R. F.: Florida Current transport variability: an analysis of annual and longer-period signals, Deep-Sea Res. Pt. I, 57, 835–846, 2010. 554, 557, 558, 561

Montgomery, R. B.: Fluctuations in monthly sea level on Eastern U.S. coast as related to dynamics of western North Atlantic Ocean, J. Mar. Res., 1, 165–185, 1938. 553

NOAA: Western Boundary Time Series, Florida Current Transport Time Series and Cruises, available at: http://www.aoml.noaa.gov/phod/wbts/index.php, last access: 24 April 2015, 2015a. 555

NOAA: Florida Current spectral analysis, available at: http://www.aoml.noaa.gov/phod/altimetry/cvar/fl/spectra.php, last access: 24 April 2015, 2015b. 558

Park, J. and Dusek, G.: ENSO components of the Atlantic multidecadal oscillation and their relation to North Atlantic interannual coastal sea level anomalies, Ocean Sci., 9, 535–543, doi:10.5194/os-9-535-2013, 2013. 558, 562

Peng, G., Garraffo, Z., Halliwell, G. R., Smedsted, O. M., Meinen, C. S., Kourafalou, V., and Hogan, P.: Temporal Variability of Florida Current Transport at 27° N, Nova Science Publishers Inc., 2009. 557

Robson, J., Hodson, D., Hawkins, E., and Sutton, R.: Atlantic overturning in decline?, Nat. Geosci., 7, 2–3, 2014. 552

Rossby, T., Flagg, C. N., Donohue, K., Sanchez-Franks, A., and Lillibridge, J.: On the long-term stability of Gulf Stream transport based on 20 years of direct measurements, Geophys. Res. Lett., 41, 114–120, 2014. 553

Sallenger, A. H., Doran, K. S., and Howd, P.: Hotspot of accelerated sea-level rise on the Atlantic coast of North America, Nat. Clim. Change, 2, 884–888, 2012. 553

Smeed, D. A., McCarthy, G. D., Cunningham, S. A., Frajka-Williams, E., Rayner, D., Johns, W. E., Meinen, C. S., Baringer, M. O., Moat, B. I., Duchez, A., and Bryden, H. L.: Observed decline of the Atlantic meridional overturning circulation 2004–2012, Ocean Sci., 10, 29–38, doi:10.5194/os-10-29-2014, 2014. 552

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L. : Climate Change 2007: The Physical Science Basis, Cambridge University Press, Cambridge, UK and New York, NY, USA, 2007. 552

Sweet, W. V., Zervas, C., and Gill, S.: Elevated East Coast Sea Level Anomaly: June–July 2009, Tech. Report NOS CO-OPS 051, United States Department of Commerce, National Oceanic and Atmospheric Administration, Silver Spring, Maryland, USA, 2009. 553

Thomas, M. D., de Boer, A. M., Stevens, D. P., and Johnson, H. L.: Upper ocean manifestations of a reducing meridional overturning circulation, Geophys. Res. Lett., 39, L16609, doi:10.1029/2012GL052702, 2012. 552

Wu, Z., Huang, N. E., Long, S. R., and Peng, C.-K.: On the trend, detrending and variability of nonlinear and non-stationary time series, P. Nat. Acad. Sci. USA, 104, 14889–14894, 2007. 556

Wunsch, C., Hansen, D. V., and Zetler, B. D.: Fluctuations of the Florida Current inferred from sea level records, Deep-Sea Res., 16, 447–470, 1969. 559

Zervas, C.: Sea Level Variations of the United States 1854–2006, Tech. Report NOS CO-OPS 053, United States Department of Commerce, National Oceanic and Atmospheric Administration, available at: http://www.tidesandcurrents.noaa.gov/publications/Tech_rpt_53.pdf (last access: 24 April 2015), 2009. 559

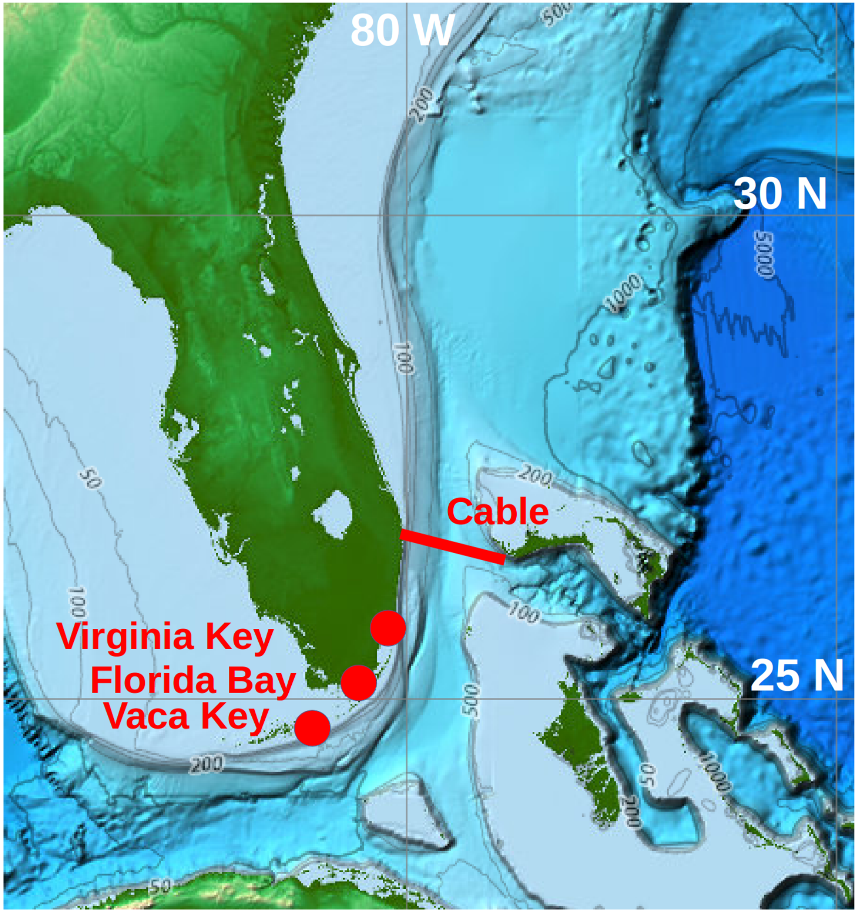

Figure 1. Map of Florida Straits with the cable and tide gauge locations. Bathymetry contours are in meters.

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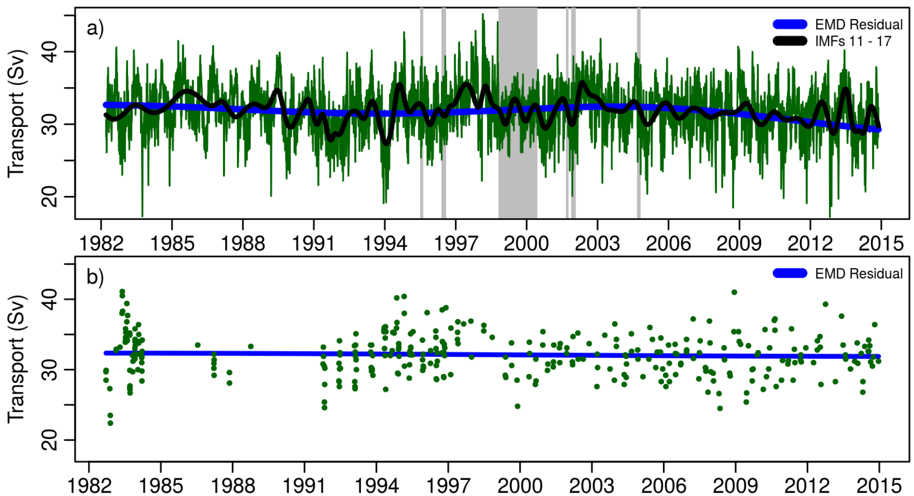

Figure 2. (a) Florida Current daily transport estimates from induced cable voltages at 27° N (green). The gray background bounds missing measurements and data reconstructed from daily distributions across all available years. Also shown are the sum of the EMD residual and IMFs 11–17 (black), and the EMD residual itself (blue). The total number of IMFs is N_{IMF} = 17. **(b)** Florida Current transport estimates from ship–based measurements (green) and EMD residual (blue).

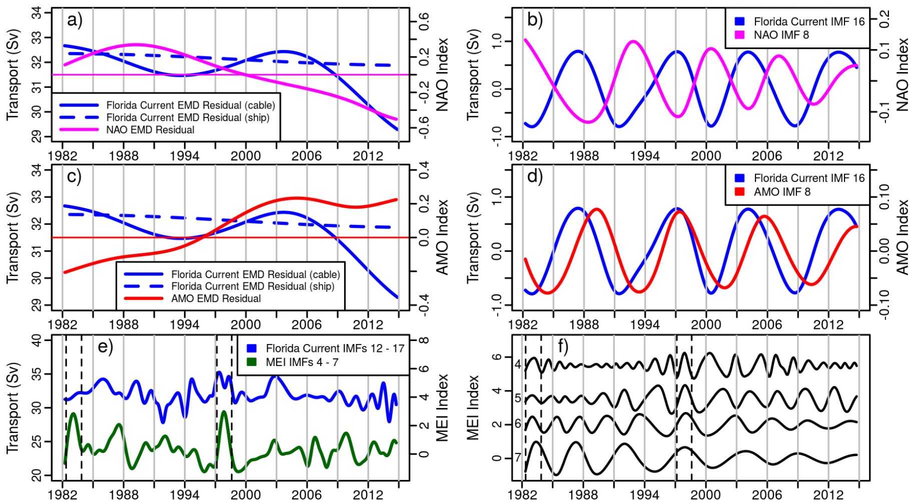

Figure 3. Comparison of Florida Current IMFs with the NAO, AMO and MEI indices. **(a)** Florida Current and NAO Index EMD residuals. **(b)** Decadal scale IMFs of Florida Current ($N_{\mathrm{IMF}} = 17$) and NAO Index ($N_{\mathrm{IMF}} = 10$). **(c)** Florida Current and AMO Index EMD residuals. **(d)** Decadal scale IMFs of Florida Current and AMO Index ($N_{\mathrm{IMF}} = 9$). **(e)** Sum of Florida Current IMFs 12–17 (blue) and sum of MEI IMFs 4–7 (green, $N_{\mathrm{IMF}} = 9$). **(f)** MEI IMFs 4–7. IMFs are vertically offset for clarity. The dashed vertical lines in (**e** and **f**) bracket strong El-Niño events in June 1982–October 1983, and March 1997–August 1998.

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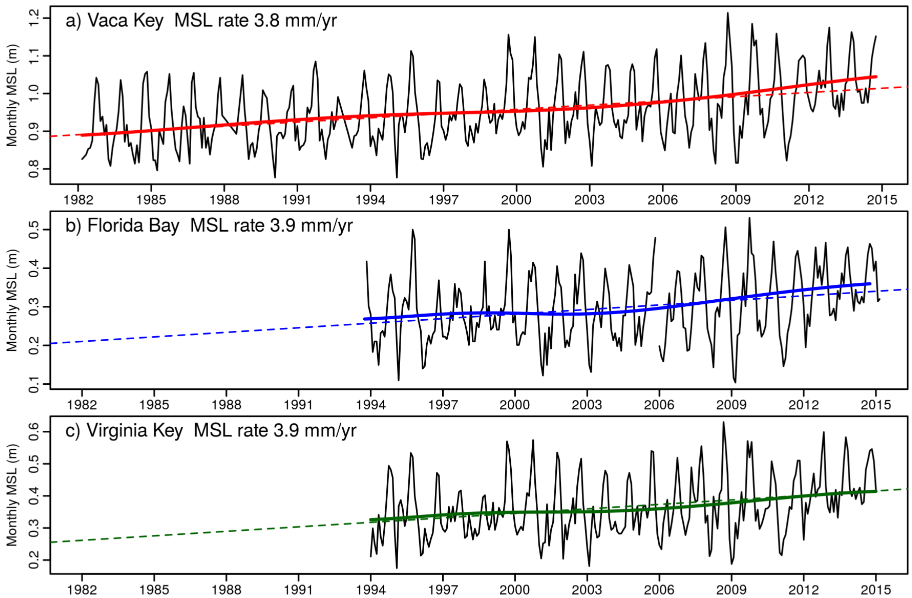

Figure 4. Monthly mean sea levels at **(a)** Vaca Key Florida, **(b)** Florida Bay and **(c)** Virginia Key Florida. Solid lines show the EMD residual (red at Vaca Key, blue in Florida Bay, green at Virginia Key), dashed lines plot linear regression of the monthly mean sea level with the annual cycle removed.

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Florida Current and coastal sea level

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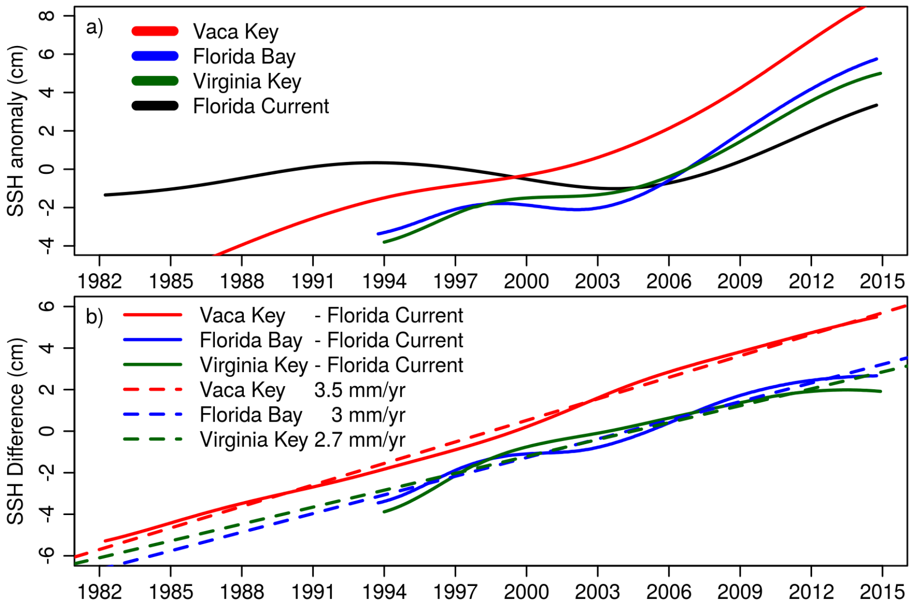

Figure 5. (a) SSH anomalies at Vaca Key, Florida Bay and Virginia Key from EMD residuals, and for the Florida Current at 27° N assuming a SSH/transport rate of $-1.4\,\mathrm{cm\,Sv^{-1}}$. **(b)** Difference of the Florida Current SSH anomaly from the SSH anomalies at Vaca Key, Florida Bay and Virginia Key. Dashed lines are linear regressions to the SSH differences.

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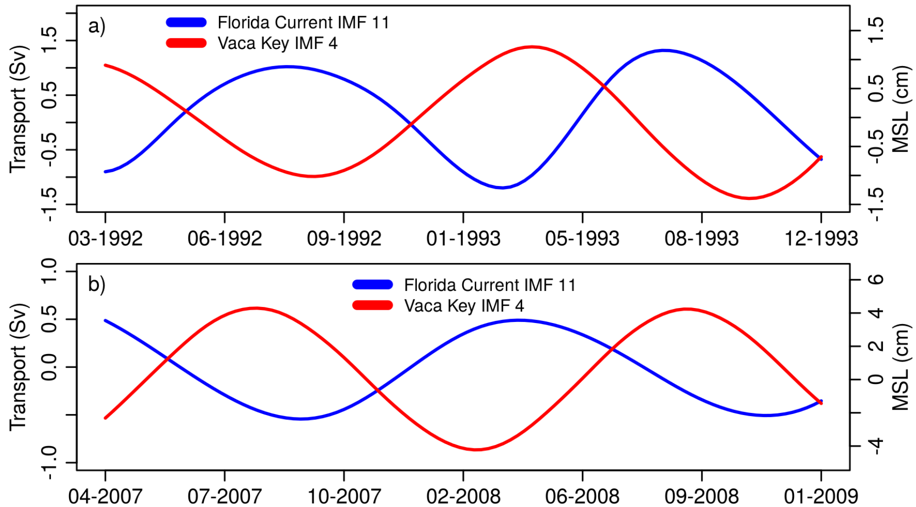

Figure 6. Florida Current transport ($N_{\text{IMF}} = 17$) and Vaca Key MSL ($N_{\text{IMF}} = 9$) IMFs with Hilbert spectrum instantaneous frequencies between 9 and 15 months. **(a)** March 1992–December 1993. **(b)** April 2007–January 2009.

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