In: Ocean Circulation and El Nino: New Research
Editors: J. A. Long, D. S. Wells, pp. 119-137

ISBN: 978-1-60692-084-8


*Chapter 5*

# TEMPORAL VARIABILITY OF THE FLORIDA CURRENT TRANSPORT AT 27°N

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## ABSTRACT

The variability of annual cycle of the Florida Current transport and its relationship to variability of large-scale atmospheric forcing is examined using time series of daily Florida Current transport based on submarine cable voltage measurements from 1982 to 2005. To investigate the impact of large-scale atmospheric forcing variations represented by the North Atlantic Oscillation (NAO), two NAO regimes, strong positive and strong negative, are defined in order to isolate basic characteristics of the annual cycles of the Florida Current transport associated with those two regimes. The strong positive (negative) NAO regime is defined as being when the NAO index is greater (less) than 0.8 (-0.8). A minimum of 30.46 Sv in the Florida Current transport is found in January and a maximum of 33.71 in July with a mean of 32.12 Sv based on daily composites of all cable data, which is consistent with previous studies. A distinct difference between those two opposing NAO regimes occurs in late winter, with a minimum (maximum) for the strong positive (negative) NAOs in March. As for the summer peak, it occurs in May for the strong positive NAOs and in July for the strong negative NAOs, as in the normal year. There is a 5% fluctuation in the mean Florida Current transport values between those two strong NAO regimes.

Using daily transport time series for the Florida Current calculated from various model experiments for the year 2004, along with the Florida Current transport derived from cable and in-situ measurements from research cruises, we have shown that the Florida Current transport is not sensitive to the resolution of local atmospheric forcing or

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to the model vertical resolution. However, the major influence on fluctuations on time scales of a few days to several weeks is found to be linked to basin-scale variability in the North Atlantic Ocean.

The decadal variability of the Florida Current transport is examined using a 54-year time series of Florida Current transport anomaly from a 1/3o North Atlantic model simulation. The model Florida Current transport anomaly is found to be loosely correlated with the NAO anomaly. The time series of the sea surface height difference (sshdif) between the subtropical gyre and subpolar gyre, however, is strongly correlated with the NAO anomaly, with NAO leading by about 2.5 years. The results also show that the sshdif is well correlated with the model Florida Current transport anomaly, with sshdif leading by about 3.5 years. This suggests that the decadal variability of the Florida Current transport is largely controlled by the variability of the internal ocean dynamics forced by the NAO variability rather than by the NAO variability itself.

## INTRODUCTION

The Florida Current is a part of the western boundary current for the subtropical gyre of the North Atlantic. It includes both the wind-driven subtropical circulation and the upper layer limb of the meridional overturning circulation, which transports heat polewards, and supplies the warm waters to the Gulf Stream system. Thus, it is one of the important components in closing the large-scale North Atlantic wind-driven circulation and the Atlantic Overturning circulation (Johns and Schott, 1987; Baringer and Larsen, 2001). Because of its importance and easy accessibility, the Florida Current near 27°N has been extensively studied. The mean transport of the Florida Current is well-established by various types of observations at about 32 Sv, with typical fluctuation magnitudes of 2 to 3 Sv (Niller and Richardson, 1973; Johns and Schott, 1987; Molinari et al., 1983; Lee et al., 1985; Schott and Zantopp, 1985; Baringer and Larsen, 2001). Seasonal variations of an early spring minimum and a summer maximum have been observed and examined by a number of investigators (Niller and Richardson, 1973; Leaman et al., 1987; Johns and Schott, 1987; Schott and Zantopp, 1985; Baringer and Larsen, 2001). Using sixteen years of submarine cable data, Baringer and Larsen (2001) have shown that the annual cycle of the Florida Current transport is not stable, especially the onset time of the summer maximum. The larger variations on shorter time scales of several days to weeks are also documented, mainly through measurements obtained as a part of National Oceanic and Atmospheric Administration (NOAA)'s Subtropical Atlantic Climate Study (STACS) during 1982 to 1984 (Brooks, 1979; Lee et al., 1985; Schott and Zantopp, 1985; Johns and Schott, 1987). Local synoptic-scale wind forcing has been suggested to be potentially associated with those variations (Wunsch and Wimbush, 1977; Duing et al., 1977; Lee et al., 1985). However, Johns and Schott (1987) found no strong correlation between those variations of the Florida Current transport on the time scales of several days to weeks and local wind forcing using the STACS data set. Mooers et al. (2005) showed that these variations could be associated with the passage of coastally trapped waves forced along the southeastern U. S. coast, which could result in transport changes of 10 Sv in 3 days.

A study of temporal variability of the Florida Current transport near 27°N is presented here. This chapter is organized as follows. An outline of observational data is given followed by an outline of the model. Annual cycle of the Florida Current transport near 27°N is first examined in relationship to strong positive and negative North Atlantic Oscillation (NAO) regimes, using 24 years of daily Florida Current transport derived from the cable data. The variability on transport fluctuations with time scales ranging from several days to a few weeks is investigated next using an ocean circulation model with sensitivity to resolution of local atmospheric forcing, model vertical resolution, and boundary conditions. Then, a time series of fifty-four years of the model based Florida Current transport at about $27^{\circ}$N is used to examine links between decadal Florida Current transport variability and both the NAO variability and fluctuations of the North Atlantic subtropical and subpolar gyres, followed by conclusion.

## DATA OUTLINE

In a program running nearly continuously from 1982 to the present, the NOAA Florida Current project measures the voltage induced on a submarine telephone cable across the Straits of Florida at 27N by the flow of ions in the Florida Current through the Earth's magnetic field (e.g. Larsen and Sanford, 1985; Larsen, 1992; Baringer and Larsen, 2001). These voltage measurements are then calibrated into estimates of the Florida Current volume transport using data from shipboard cruises. During the early years of the program the shipboard velocity measurements were collected using a Pegasus velocity profiler (e.g. Leaman et al., 1987), while beginning around 1990 the program turned to one of the older, less expensive systems for measuring the velocity, the Dropsonde float (e.g. Richardson and Schmitz, 1965). The primary data set used in the present study will be the daily transport values derived from the cable measurements from 1982 to 2005, while the 157 dropsonde section transport estimates from the 1991-2005 periods will be used where needed. Additional information about the program is available at the project web site (www.aoml.noaa.gov/phod/floridacurrent/) where the cable and section transport estimates are made freely available.

## MODEL AND SIMULATION OUTLINE

A state-of-art community model, the Hybrid Coordinate Ocean Model (HYCOM), is utilized in this study. HYCOM is a finite-difference primitive equation model that uses a hybrid isopycnal/sigma/z vertical coordinate (Bleck and Chassginet 1994; Bleck 2002; Chassignet et al. 2003; Halliwell 2004; Chassignet et al. 2006). It is isopycnal in the open stratified ocean, but reverts to a terrain following (sigma) coordinate in shallow coastal regions, and to a z-level coordinate near the surface in the mixed layer or unstratified seas. This generalized vertical coordinate approach involves a dynamical transition between different coordinate types via the layered continuity equation. In doing so, the model combines the advantages of different types of coordinates and can be applied to open-ocean basins and coastal regions in a same model domain, thus making it suitable for simulating the interaction between the open ocean and the South Florida coastal ocean.

To analyze inter-decadal climate simulations, HYCOM is configured for the North Atlantic basin from $98^{\circ}$W to $20^{\circ}$E and from $28^{\circ}$S to $70^{\circ}$N with horizontal resolutions of $1/3^{\circ}$

(Garraffo et al., 2008). The Mediterranean Sea is not resolved explicitly, but transport and water property are prescribed through a relaxation zone. There are 28 hybrid layers in vertical with the minimum top layer thickness of 3m. The model topography is based on the Earth-Topography-Five-Minute (ETOPO5) Gridded World Ocean Elevation Dataset from the National Geophysical Data Center with the coastline at the 20m isobath. A free-running simulation is performed from the beginning of 1948 to the end of 2003, forced by the National Center for Environmental Prediction (NCEP) 2.5-degree, 6-hourly atmospheric reanalysis. To analyze higher-frequency variability, a sequence of nested models is employed during the year 2004 to downscale basin–scale fluctuations to the South Florida coast. The basin-scale is represented by two products: realistic 1/12° Atlantic nowcasts (ATL) that assimilate the observed sea surface height (SSH) fields using an optimal interpolation (OI) scheme (Chassignet el al., 2007), and a 1/12° Atlantic climatology generated by averaging several years of realistically-forced free-running HYCOM Atlantic basin simulations. The 1/12° Atlantic basin domain is similar to the 1/3° Atlantic domain but with the eastern boundary extended to about 36°E to resolve the Mediterranean Sea. Simulations are forced by 1-degree, 3-hourly atmospheric forcing provided by the Navy Operational Global Atmospheric Prediction System (NOGAPS, Hogan and Rosemond, 1991). Nesting within both products permits the contribution of wind-driven basin-scale variability to FC transport to be assessed. To downscale this basin variability, a Gulf of Mexico (GOM) nowcast system with a horizontal resolution of 1/25° from 77.36°W to 98°W and from 18.09°N to 30.71°N is nested within the Atlantic climatology. This nowcast system assimilates various types of observed fields including SSH, sea surface temperature, and temperature profiles using the Navy Coupled Ocean Data Assimilation (NCODA) system which utilizes the multivariate OI scheme (MVIO, Cummings, 2005; Chassignet el al., 2007). The GOM nowcast system is forced by the NOGAPS 1-degree, 3-hourly atmospheric forcing as well. Finally, a 1/25° South Florida coastal region (FLA) from 77.36°W to 83.76°W and from 22.78°N to 28.61°N is used to model the South Florida coastal domain (Kourafalou et al. 2008). It is nested within the GOM and the ATL nowcast systems to assess the influence of basin-scale wind-driven variability through boundary conditions. The topography in both GOM and FLA domains is based on the 2-minute Digital Bathymetric Data Base (DBDB2) from the Naval Oceanographic Office /Naval Research Laboratory with the minimum depth of 2m. The depth values in shallow areas around the Florida Keys reef tract have been corrected in FLA to resolve better the Atlantic shelf along the Florida Keys and major passages between the Florida Keys and Florida Bay.

These topographic details are not included in the outer GOM and ATL models and have been shown to be important in improving representation of both shelf and deep sea flows (Kourafalou et al. 2008). In addition to the NOGAP 1-degree forcing, a 27 km, 3-hourly atmospheric forcing data set from the Coupled Ocean Atmosphere Prediction System (COAMPS, Hodur et al. 2002) is also used to examine the impact of resolution of local atmospheric forcing on the synoptic and seasonal variability of the Florida Current transport. The attributes for the model experiments can be found in Table I. The bathymetry in the FLA domain is shown in Figure 1 along with sections that are used to compute the Florida Current transport from cable measurements and model results.

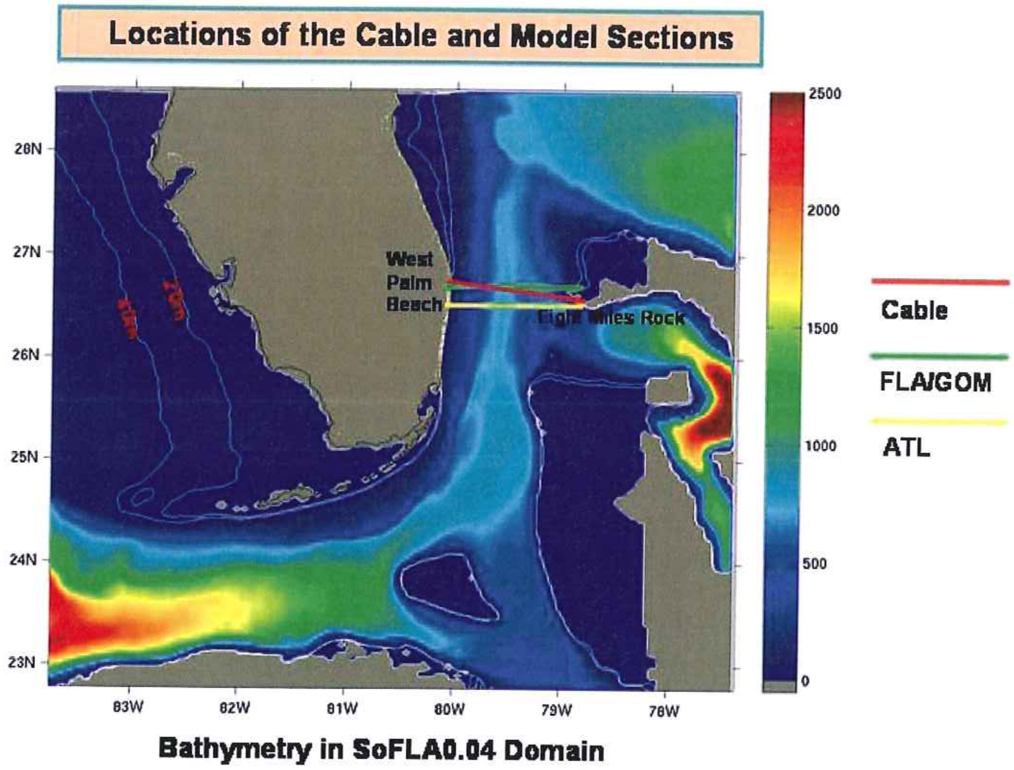


Figure1. The bathymetry in the South Florida Model domain. Contours are for 20 and 40 m isobaths. The sections used to compute the Florida Current transport from the cable measurements and model results are also shown.

**Table I, Attributes for Model Experiments**

| RunId | Domain | Grid | Layer | Forcing | Run type | Nesting/ relaxation |
|---|---|---|---|---|---|---|
| ATLd091 | N. Atlantic | 1/12° | 20 | nogaps 1-deg | OI | Levitus climatology |
| GOMh200 | Gulf of Mexico | 1/25° | 20 | nogaps 1-deg | NCODA | ATLd091 climatology |
| FLAh291 | So. FLA | 1/25° | 20 | nogaps 1-deg | Free | GOMh200 |
| FLAh271 | So. FLA | 1/25° | 20 | coamps 27km | Free | GOMh200 |
| FLAh025 | So. FLA | 1/25° | 26 | coamps 27km | Free | GOMh200 |
| FLAh391 | So. FLA | 1/25° | 20 | coamps 27km | Free | ATLd091 |
| ATLn303 | N. Atlantic | 1/3° | 28 | NCEP | Free | Levitus climatology |

## RESULTS

### (i) Annual Cycles from the Submarine Cable Data

Using sixteen years of daily Florida Current transport (1982-1998) inferred from the cable data, Baringer and Larsen (2001) showed that there is a minimum of 30 Sv in January and a maximum of 35 Sv in July. They have also demonstrated that this annual cycle is not stable and pointed out a possible link between the variation in the annual cycle and changes in the basin-scale circulation forcing associated with the NAO. A good negative correlation between the long-term Florida Current transport and NAO index was found (Baringer and Larsen, 2001). In this section, we will repeat their analysis by extending the cable data to year 2005 (total 24 years).

Figure 2a displays the time series of the daily Florida Current transport derived from the daily submarine cable voltage measurements (solid line) and in-situ observations (marked by an 'x') while monthly running means using both cable and in-situ data are presented in Figure 2b. Variations on the seasonal and inter-annual time scales are quite obvious.

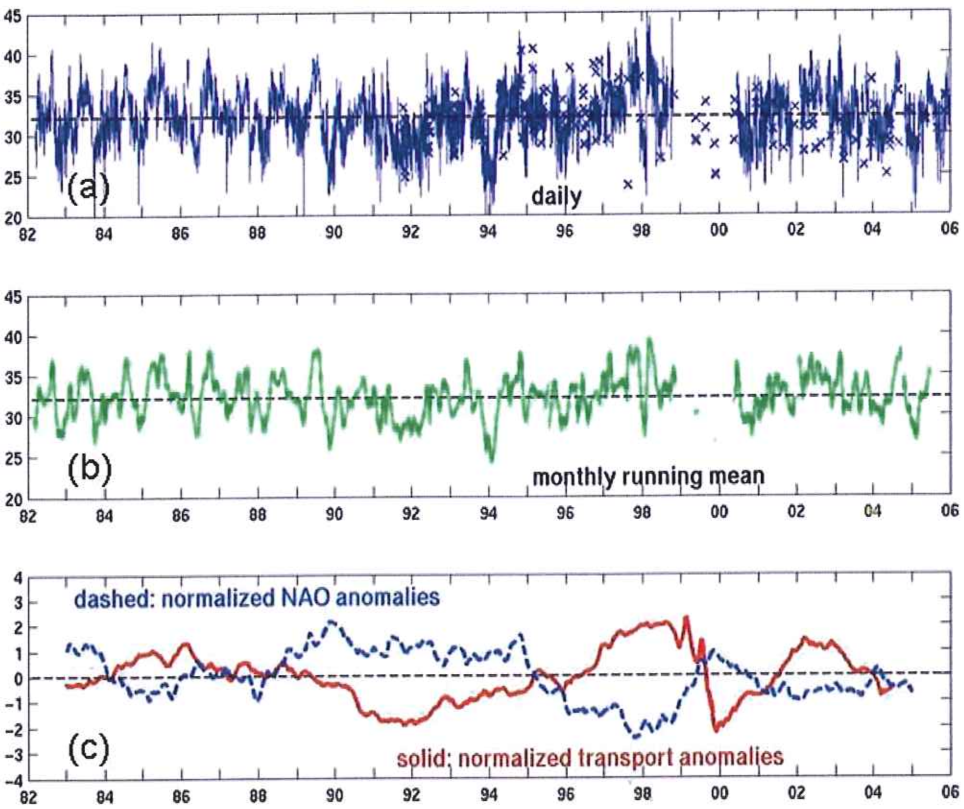


Figure 2. (a) Time series of daily Florida Current transport inferred from the daily submarine cable voltage measurements. The transport values computed from the in-situ observations are marked by 'x'. (b) Time series of the monthly running mean from both cable and in-situ measurements. (c) Time series of normalized anomalies of the Florida Current transport inferred from the daily submarine cable and in-situ data (solid) and monthly NAO index (dashed). The anomalies are from the two-year running means and normalized by their respective standard deviations.

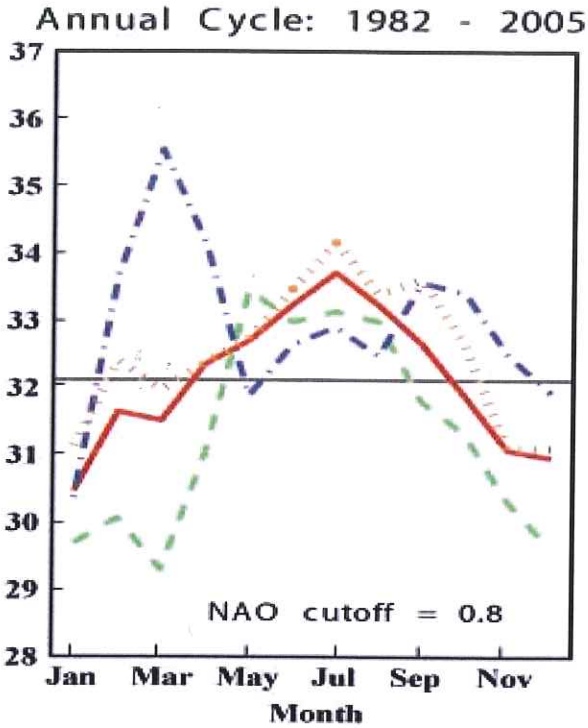


Figure 3. Annual cycle of cable-derived Florida Current transport for all NAOs (solid), strong positive NAOs (dashed), strong negative NAOs (dash-dotted), and all other NAOs (dotted).

Figure 2c shows normalized anomalies of Florida Current transport and NAO from their two-year running means based on monthly values. The negative correlation is visually stronger between the two time series during the periods of well-established and persistent NAO periods that last more than 3 years (1984-1987; 1989-1994; 1996-1999; 2001-2004). The correlation is much weaker during the transition periods. This implies that the correlation between the variations of the Florida Current transport and NAO should not be expected to hold on a year-to-year basis. As in weather forecasts, there are periods of high predictability such as those of established high or low NAO regimes and periods of low predictability such as transition periods.

Baringer and Larsen (2001) decomposed sixteen years of daily Florida Current transport into two eight-year periods. The summer peaks were found to be out of phase between those two periods. There is a high peak in May-June for the first eight-year period and a low in June for the second eight-year period (see Figure 4 in Baringer and Larsen, 2001). Unfortunately, those two periods do not offer a clear separation between positive and negative NAOs. Furthermore, the records from the transition periods are also included which could smear out signals that separate the characteristics of negative and positive NAO regimes. To isolate the impact of strong NAO years (both negative and positive) on the variability of the annual cycle of the Florida Current transport, we have defined a normal NAO regime by fitting the annual cycle of all records eliminating strong negative and positive NAO periods to the annual cycle of all records.

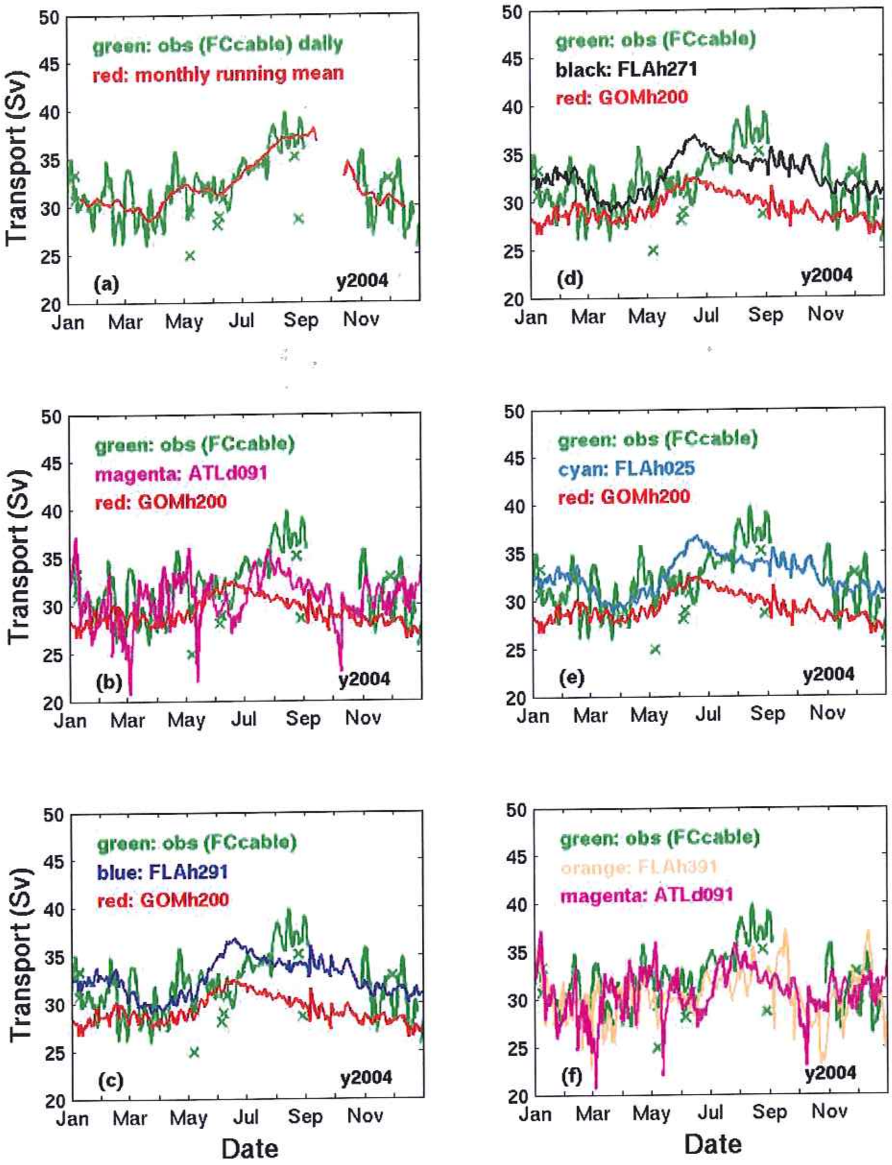


Figure 4. Time series of the Florida Current transport for year 2004: (a) daily transport from the cable data (cable, green) and the monthly running mean (red); (b) daily transport from cable (green), Atlantic HYCOM 1/12-degree simulation (ATLd091, magenta), and Gulf of Mexico HYCOM 1/25-degree nowcast (GOMh200, red); (c) daily transport from SoFLA HYCOM1/25-degree simulation forced by NOGAPS 1-degree atmospheric forcing with 20 model layers and nested to GOMh200 (FLAh291, blue) superimposed with cable and GOMh200; (d) same as (c) except the simulation is forced by COAMPS 27-km atmospheric forcing (FLAh271, black); (e) same as (d) except the model layer is increase to 26 from 20 (FLAh025, cyan); and (f) same as (e) except nested to ATLd091 (FLAh391, orange).The transport values from cruise sections are marked by 'x' in the plots.

The cut-off NAO value is found to be 0.8. We then define strong positive NAO periods as being when the NAO index is higher than 0.8 and strong negative NAO periods as being when the NAO index is lower than -0.8. (This is very subjective and the NAO cut-off value is up for debate.

**Table II. Statistic characteristics of Florida Current transport based on the cable data (1982 – 2005)**

| | Mean | Min | Max | STD |
|---|---|---|---|---|
| ALL NAO | 32.12 | 30.46 | 33.71 | 1.02 |
| Strong Positive NAO | 31.31 | 29.3 | 33.46 | 1.54 |
| Strong Negative NAO | 32.92 | 30.37 | 35.54 | 1.3 |
| Others | 32.51 | 31.1 | 34.16 | 1.04 |

It may require a further fine tuning as a longer time-series of cable data becomes available.) Again, there is a minimum of 30.46 Sv in January and a maximum of 33.71 in July for all NAOs with a mean of 32.12 Sv (Figure 3; table II). In addition, there is a weak maximum in February and a weak minimum in March (Figure 3). Surprisingly, the distinguishing feature between strong positive and negative NAO regimes is the large difference during late winter and early spring that peaks in March: a minimum of 29.3 Sv associated with strong positive NAOs and a maximum of 35.54 Sv associated with strong negative NAOs. As to the summer peak, the difference between these two regimes involves timing: the peak occurs in May for the strong positive NAOs and in July for the strong negative NAOs, with the latter case displaying a minimum in May. The mean for the strong positive NAOs is 31.31 Sv, which is 2.5% lower than that of all NAOs. On the contrary, the mean for the strong negative NAOs is 32.92 Sv, which is 2.5% higher than that of all NAOs (table II). The difference in the mean transport between the strong positive and negative NAOs is 1.61 Sv. This represents 5% of the mean of all NAOs for the period of 1982 to 2005. It is on the same order as inter-annual variation and accounts for nearly half of seasonal variation in the Florida Current transport.

## (ii) Year 2004 Florida Current Transport from Model Output

Daily values of Florida Current transport from various model simulations for year 2004 (see Table I for run attributes) are used in this section to examine the sensitivity of Florida Current transport to resolutions of atmospheric forcing, vertical resolutions of the model, and nesting boundary conditions.

Figure 4a shows the daily and filtered Florida Current transport from the cable data for year 2004. (The data are missing from September 4 to October 28, 2004, and in-situ observations are marked by an 'x'). The fluctuations on time scales of a few days to weeks are distinct. The smoothed time series displays a minimum in late March and early April and a second minimum occurs in the middle of June 2004. As the values of the Florida Current transport from the data peaked in late August through early September before the cable went out of service, it is hard to judge if the transport values continue to increase or decrease from there. However, based on the daily transport values from the cable data and the in-situ section measurements from the research cruises as well as the trend of their monthly running mean, it is fairly safe for us to speculate that the transport peaked in late summer in 2004.

Both the Gulf of Mexico (GOM) and the North Atlantic (ATL) nowcasts (GOMh200 and ATLd091, Table I) realistically represent the mean magnitude of the Florida Current transport (Figure 4b). However, fluctuations on the scale of a few days to several weeks are much smaller in GOMh200 than in ATLd091. As a result, the South Florida coastal model (FLA) simulations (FLAh291, FLAh271, and FLAh025) nested within GOMh200 all yield small fluctuation magnitude (Figures 4c-e). The magnitudes of the FLA transport time series are, however, somewhat closer in magnitude to the observations than that of GOMh200, signifying the importance of topographic details and interaction with coastal flow around the Florida Keys and along the Straits of Florida. All FLA runs nested within GOMh200 have a minimum in late March, which is consistent with the cable data, and a maximum in mid-June, which is more than two months earlier than that of the cable data (Figures 4c-e). The time series of the Florida Current transport from the simulation forced by the NOGAPS 1-degree atmospheric forcing (FLAh291) is very close to that from the one forced by the COAMPS 27 km atmospheric forcing (FLAh271) (comparing Figure 4c to Figure 4d). The results from the simulations forced by the same atmospheric forcing with the same boundary conditions but with 20 (FLAh271) and 26 (FLAh025) model layers, respectively, are very similar as well (comparing Figure 4d to Figure 4e). Thus, the Florida Current transport is not sensitive to the resolution of the atmospheric forcing or to the vertical resolution of the model.

Both ATLd091 and FLAh391, the FLA simulation nested within ATLd091, produce larger fluctuations than GOMh200 and the FLA simulations nested within GOMh200. Those fluctuations are also more consistent with observations. The transport from ATLd091 has a summer peak in late July 2004 and a minimum in early October (Figure 4f). The transport from FLAh391, which uses ATLd091 as the nesting boundary condition extends the ascending trend all the way to the middle of September 2004. The fall minimum appears in late October. Both the Florida Current transport from ATLd091 and FLAh391 produce secondary lows in the middle of May and June 2004 (Figure 4f), which are consistent with the observations. On the other hand, the transports from GOMh200, and all the FLA simulations using GOMh200 as the nesting boundary conditions, produce a peak in the middle of June 2004. Noting that GOMh200 uses the climatology of multi-years of the free-running ATL simulations as its boundary conditions, which is shown to be good enough for producing reasonable circulation in the Gulf of Mexico (Kourafalou et al. 2008), the variability filtered out by time-averaging, and synoptic variability that is not assimilated into the model in the ATL domain, are apparently more important to inducing the Florida Current transport fluctuations on the time scales of a few days to weeks. Thus, variability in the North Atlantic basin plays an important role in influencing, and possibly inducing the variability of Florida Current transport at 27°N. Consequently, ATLd091 and FLAh391 are generally more realistic compared to observations than simulations nested within the ATL climatology since ATLd091 contains the remotely forced variability in ocean circulation that can influence Florida Current transport over time scales of a few days to a few weeks. This suggests the importance of variability of the remote internal ocean dynamics, since the atmospheric forcing is the same in both ATLd091 and GOMh200. Coastally-trapped wave variability forced to the north of the Florida Straits was also suggested as a possible mechanism in influencing the transport variability (Mooers et al. 2005), which implies the effect of local internal ocean dynamics rather than an impact of local and remote atmospheric forcing.

The FLA simulated transport fluctuations are not always in phase with observations, so improvements in the model and assimilation of observations may be necessary to improve the accuracy of simulated synoptic and seasonal Florida Current transport variability.

## (iii) Decadal Variability

In this section, the decadal variability of Florida Current transport is examined using the model output from a 1/3-degree North Atlantic HYCOM simulation (ATLn303, Table II). The impact of the remote atmospheric forcing variability related to the NAO is investigated. The model is initialized from a 20-year spin-up run using climatologic atmospheric forcing and is integrated from 1948 to 2003, forced by six-hourly surface fields obtained from the NCEP atmospheric reanalysis. Only the results from 1950-2003 will be used here to allow the model to adjust to time-varying atmospheric forcing.

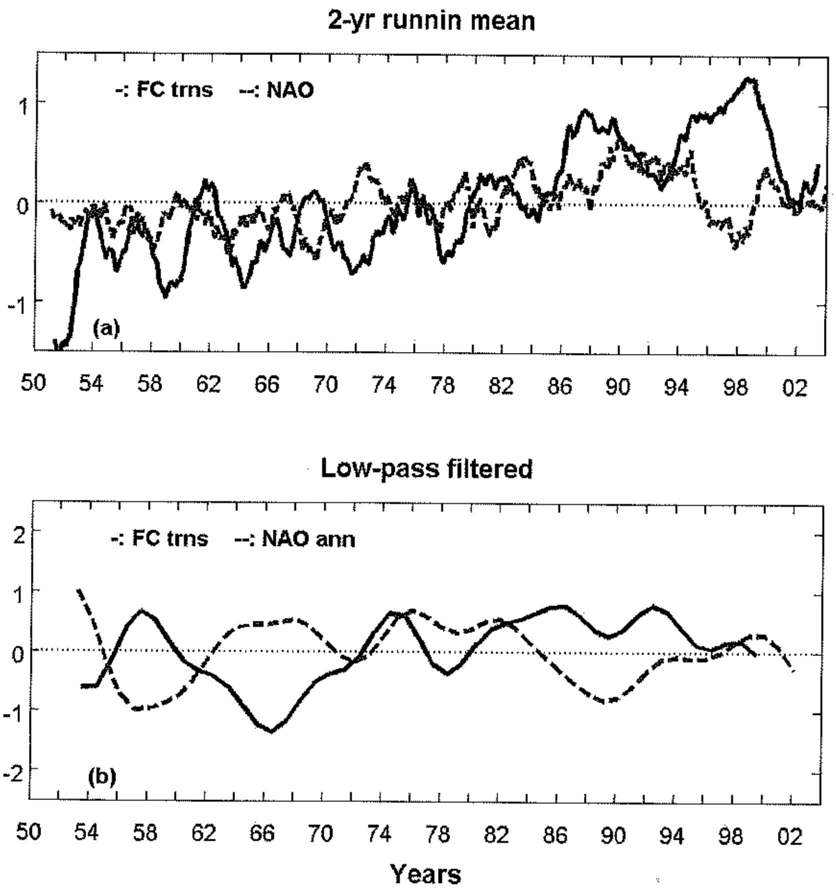


Figure 5. Time series of normalized anomalies of model Florida Current transport (solid) and NAO (dashed). The anomalies in (a) are from the two-year running means and normalized by their respective standard deviations. The anomalies in (b) are from the total record means and normalized by their perspective standard derivations. A 7-years low-pass filter with the weight values of (0.0417 0.1250 0.2083 0.2500 0.2083 0.1250 0.0417) is applied to the times series in (b).

Figure 5a shows the time series of normalized anomalies of the model Florida Current transport and the NAO from their two-year running means based on the monthly values. The two time series are visually negatively correlated but there are periods of in-phase or in transition, similar to the results from the cable observations shown in section (i).

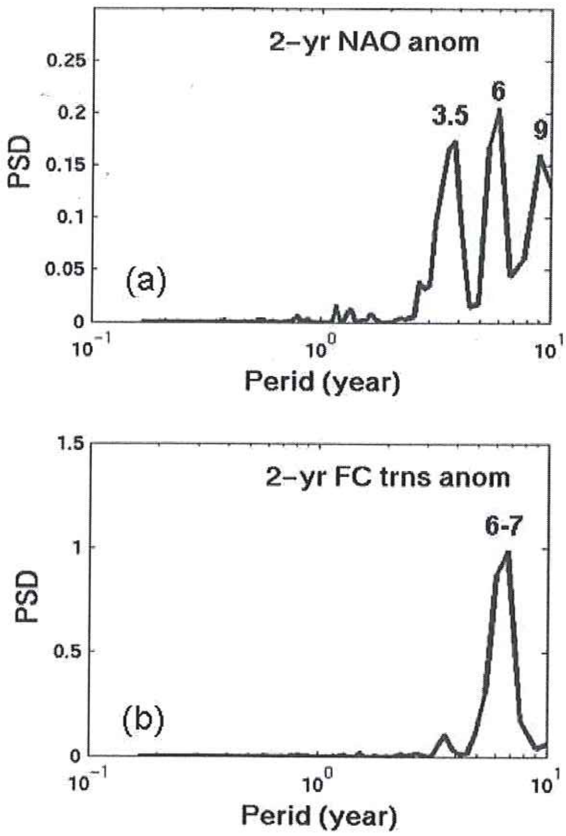


Figure 6. The power spectrum density diagram of time series of two-year running mean anomalies of (a) NAO and (b) the Florida Current transport.

One possible explanation for this behavior is the fact that the NAO cycle ranges from 2 to 7 years and is generally irregular. The power spectrum density diagram of the NAO anomaly from the two-year running mean reveals multiple peaks, ranging from 3.5 to 9 years, while that of the Florida Current transport anomaly has a distinct peak at 6-7 years (Figure 6).

On decadal time scales, the time series of normalized low-pass filtered Florida Current transport anomaly from the 1950-2003 mean based on the annual values, is out of phase with that of the NAO anomaly from 1953 to 1972, but largely in phase for the rest of the period (Figure 5b). A weak negative correlation at zero lag (-0.45) exists between the Florida Current transport and the NAO anomalies. A stronger positive correlation between the two is found at a lag of 7 years (0.59). However, both peaks are just below the 95% confidence level.

The NAO index denotes the fluctuations in the difference of sea-level pressure between the winter Icelandic low and the Azores high pressure systems. The NAO values can be affected by the intensity changes of either one of those two systems as well as by their spatial shift due to seasonal regime changes.

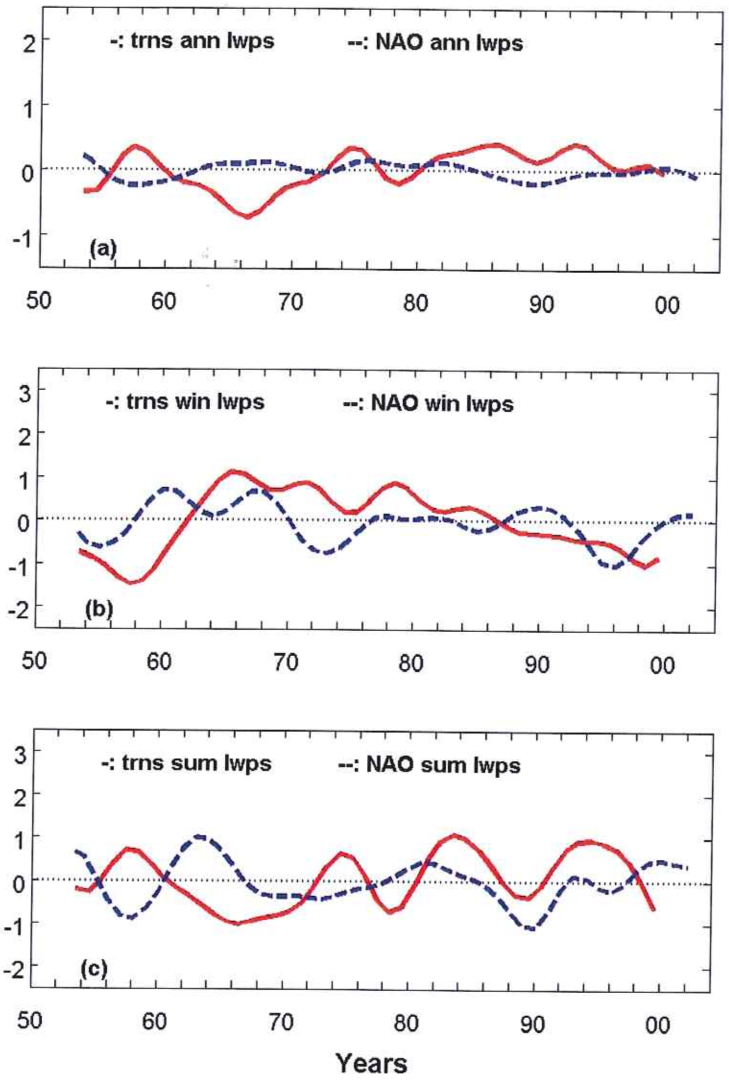


Figure 7. Time series of (a) low-passed filtered annual Florida Current transport and NAO; (b) winter Florida Current transport and NAO; and (c) summer Florida Current transport and NAO. The winter average is done from December to March and summer average is done from June to September from their monthly values.

To examine if winter or summer regime dominates the correlation between the NAO and the Florida Current transport and therefore can be used as a better indicator to predict decadal variability of the Florida Current transport, we have decomposed both the NAO and the Florida Current transport into winter mean (from December to March) and summer mean (from June to September), from their monthly values. The time series of the normalized low-pass filtered NAO and Florida Current transport anomalies are shown in Figure 7. Overall, the time series of the winter Florida Current transport is in phase with that of the winter NAO anomaly (Figure 7b).

For the time series of the summer Florida Current transport, it is generally out of phase with that of the summer NAO before the middle of the 1970s, in transition during the next decade, then in phase for the following decade - from the mid-1980s to the mid-1990s), and then out of phase again during the last decade of the integration (Figure 7c). It is not clear to us at this time what promotes these phase relationship shifts. They may be associated with the spatial variation of atmospheric wind stress fields in the North Atlantic basin, which will be investigated in Garraffo et al. (2008). Compared to the time series of the annual NAO and Florida Current transport anomalies (Figure 7a), it is clear that the summer NAO and Florida Current transport correlation dominates the annual NAO and Florida Current transport correlation. Unfortunately, none of those two correlations is good enough to be a reliable indicator for predicting decadal variability of the Florida Current transport due to its irregular nature.

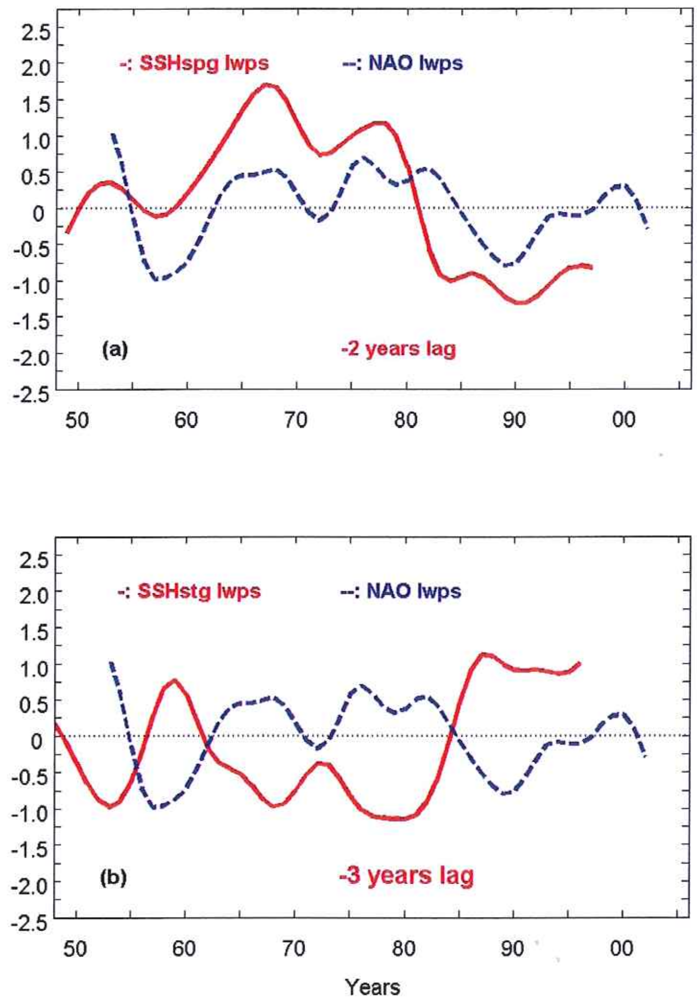


Figure 8. Time series of (a) low-pass filtered subpolar sea surface height (sshspg, solid) anomaly and (b) subtropical sea surface height (sshstg, solid) anomaly. The time series of low-pass filtered NAO anomaly is also plotted (dashed). The time series of sshspg and sshstg are shifted to better depict the correlations between the sea surface height anomalies and the NAO anomaly.

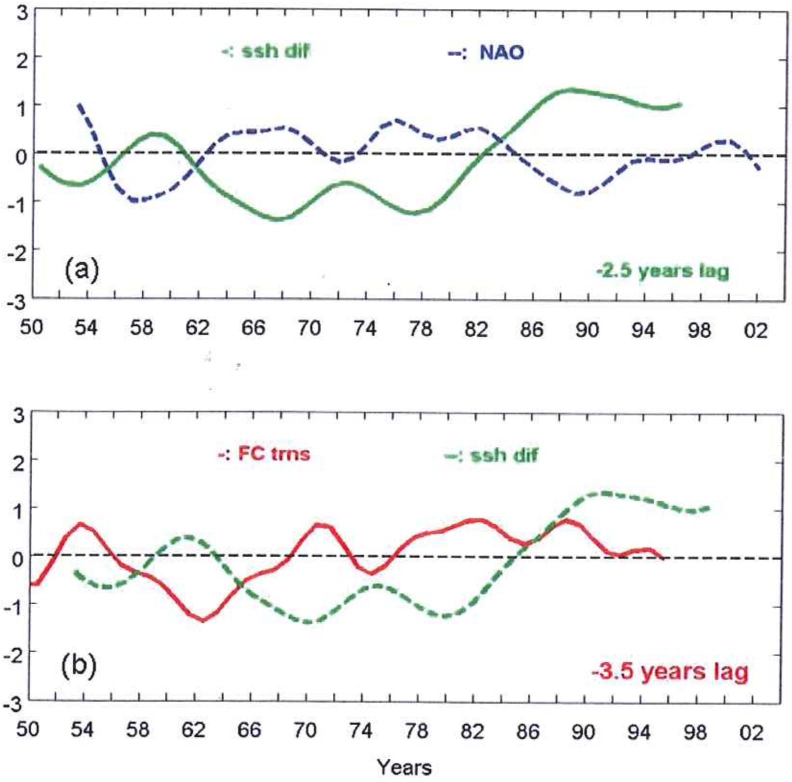


Figure 9. (a) Time series of low-pass filtered sea surface height difference between the subpolar and subtropical gyres (sshdif, solid) and the NAO (dashed) anomalies. (b) Time series of low-pass filtered Florida Current transport (solid) and sshdif (dashed) anomalies. The time series are shifted to better depict the correlation between each pair of the time series.

Curry and McCartney (2002) indicated that the basin states of the subtropical and subpolar gyres are fairly stable. The fluctuations are not large enough to alter the basic characteristics of the gyres. However, it could be the fluctuations in those gyres that influence the Florida Current transport. From their modeling study, Paiva and Chassignet (2001) have shown that there is a strong correlation between the NAO and potential vorticity anomaly (PV') of the subtropical and subpolar gyres, and that PV' of these two gyres are negatively correlated on decadal time scales.

Figure 8 shows the time series of normalized low-pass filtered sea surface height for the subpolar (sshspg) and subtropical (sshstg) gyres, respectively. The time series of sshspg is overall in phase with that of the NAO, with NAO leading by about 2 years (Figure 8a). The time series of sshstg is generally out of the phase with that of the NAO, with NAO leading by about 3 years (Figure 8b). Thus, in this section the effect of fluctuations in those two gyres will be considered in the form of the difference in their sea surface heights (sshdif=sshspg-sshstg). The sshdif time series is found to be negatively correlated with the NAO, with NAO leading by about 2.5 years (Figure 9a). The maximum correlation coefficient is 0.81, which is significant above the 95% confidence level. Equally significant negative correlation is found between Florida Current transport and sshdif, with sshdif leading by about 3.5 years (Figure 9b). The maximum correlation coefficient is 0.71. Since the variability of sshdif represents the variability of the ocean gyres forced by NAO variability, our results suggest that the

Florida Current transport variability is more controlled by variability of the internal ocean dynamics forced by the NAO variability than by the NAO variability itself.

Since the decadal variability of sshdif is better correlated with both the NAO and the Florida Current transport, with sshdif leading the Florida Current transport, it might be used as an indicator to predict the decadal trend of the Florida Current transport.

## CONCLUSION

Twenty-four years of daily Florida Current transport values inferred from the submarine cable voltage measurements from 1982 to 2005 are utilized to examine the impact of strong positive and negative NAOs on the annual cycle of the Florida Current transport. Although, as shown in the previous study (Baringer and Larson, 2001), a transport minimum is found in January and a maximum in July for all records, a negative correlation between those two NAO regimes is found in March with a minimum (maximum) for the strong positive (negative) NAOs.

As to the summer peak, the difference lies in the onset timing: in May for the strong positive NAOs while in July for the strong negative NAOs. In the later case, a maximum is found in May instead. There is a 5% fluctuation in the mean Florida Current transport values between those two strong NAO regimes.

There is a 17-month gap in the time series that runs from late October 1998 to March 2000 (Figure 2a). The number of available data points for computing monthly and two-year running means, shown in Figures 2b-c, will be reduced, especially in the middle of the gap. Fortunately, this period largely falls in the normal NAO years. Thus, the impact to the characteristics of the annual cycle for the extreme NAO years is minimal. The impact is further reduced by using the transport values derived from the in-situ cruise observations when computing monthly and two-year running means.

Using the time series of daily Florida Current transport from various model experiments for the year 2004, we found that the Florida Current transport is not sensitive to the resolution of local atmospheric forcing or to the vertical resolution of the model. However, the major influence on the fluctuations on time scales of a few days to several weeks is found to be associated with the variability of circulation in the North Atlantic basin. Thus, our results imply that although the Gulf of Mexico could maintain the overall magnitude of the Florida Current transport, it is the high frequency fluctuations associated with the North Atlantic subtropical-subpolar gyres that play an important role in inducing fluctuations in the Florida Current transport on time periods of a few days to several weeks.

The impact from the North Atlantic basin is also important for the decadal variability of the Florida Current transport. On the decadal time scales, the variability of sshdif, representing the fluctuations of both Atlantic subpolar and subtropical gyres, correlates well with the variability of the NAO and of the Florida Current transport while the variability of the NAO is only loosely correlated with that of the Florida Current transport. This implies that the Florida Current transport variability is controlled largely by the variability of the internal ocean dynamics forced by the NAO variability rather than by the NAO variability itself.

As the decadal variability of sshdif correlates well with both the decadal variability of the NAO and of the Florida Current transport and leads the variability of the Florida Current transport, it could potentially be a good indicator for predicting decadal Florida Current transport variability.

## ACKNOWLEDGMENTS

G. Peng, G.R. Halliwell, and V. Kourafalou were supported by grants ONR N000140510892 and NOAA NA17RJ1226. Z. Garraffo was funded by Grant ONR N000140410676 and O.M. Smedstad was supported by the projects: National Ocean Partnership Program (NOPP): HYCOM Consortium for Data-Assimilative Ocean Modeling: U.S. GODAE: Global Ocean Prediction with the Hybrid Coordinate Ocean Model (HYCOM): HYCOM Coastal Ocean Hindcast and Predictions: Impact of Nesting in HYCOM GODAE Assimilative Hindcasts. T.F. Hogan was sponsored by the Office of Naval Research under program element 601153N.

The ATL and GOM nowcasts were performed on an IBM Power5+ computer at the Naval Oceanographic Office under a grant of computer time from the DoD High Performance Computer Modernization Office (HPCMO).

The Florida Current cable and section data are made freely available on the Atlantic Oceanographic and Meteorological Laboratory web page (www.aoml.noaa.gov/phod/floridacurrent/) and are funded by the NOAA Office of Climate Observations. We thank M. Baringer for introducing us to the cable data.

The monthly NAO index is downloaded from www.cpc.ncep.noaa.gov/teledoc/nao.shtml.

The discussion with Z. Li on NAO spectral analysis is beneficial to Peng. We thank A. Wallcraft for helping in HYCOM related issues and Linda Smith for reading the manuscript, which has improved the clarity of this chapter.

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