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15. SUBJECT TERMS
numerical modeling, coastal dynamics, loop current, Florida current, data assimilation

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Evaluation of Global Ocean Data Assimilation Experiment products on South Florida nested simulations with the Hybrid Coordinate Ocean Model

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Abstract The South Florida Hybrid Coordinate Ocean Model (SoFLA-HYCOM) encompasses a variety of coastal regions (the broad Southwest Florida shelf, the narrow Atlantic Keys shelf, the shallow Florida Bay, and Biscayne Bay) and deep regions (the Straits of Florida), including Marine Protected Areas (the Florida Keys Marine Sanctuary and the Dry Tortugas Ecological Reserve). The presence of the strong Loop Current/Florida Current system and associated eddies connects the local and basin-wide dynamics. A multi-nested approach has been developed to ensure resolution of coastal-scale processes and proper interaction with the large scale flows. The simulations are free running and effects of data assimilation are introduced through boundary conditions derived from Global Ocean Data Assimilation Experiment products. The study evaluates the effects of boundary conditions on the successful hindcasting of circulation patterns by a nested model, applied on a dynamically and topographically complex shelf area. Independent (not assimilated) observations are employed for a quantitative validation of the numerical results. The discussion of the prevailing dynamics that are revealed in both modeled and observed patterns suggests the importance of topography resolution and local forcing on the inner shelf to middle shelf areas, while large scale processes are found to dominate the outer shelf flows. The results indicate that the successful hindcasting of circulation patterns in a coastal area that is characterized by complex topography and proximity to a large scale current system requires a dynamical downscaling approach, with simulations that are nested in a hierarchy of data assimilative outer models.

Keywords Numerical modeling · Coastal dynamics · Loop Current · Florida Current · Data assimilation

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1 Background

The seas that surround the southern part of the Florida peninsula form a unique oceanographic environment that includes ecologically sensitive shallow areas (Florida Bay, Biscayne Bay, the Dry Tortugas, and the Florida Keys Reef Tract), shelf areas (the relatively broad Southwest Florida shelf and the narrow Southeast Florida shelf extending to the Atlantic side of the Florida Keys), and deep areas (Straits of Florida); see Fig. 1. These regions are strongly connected through their circulation systems and exchange processes on local and regional scales as well as with

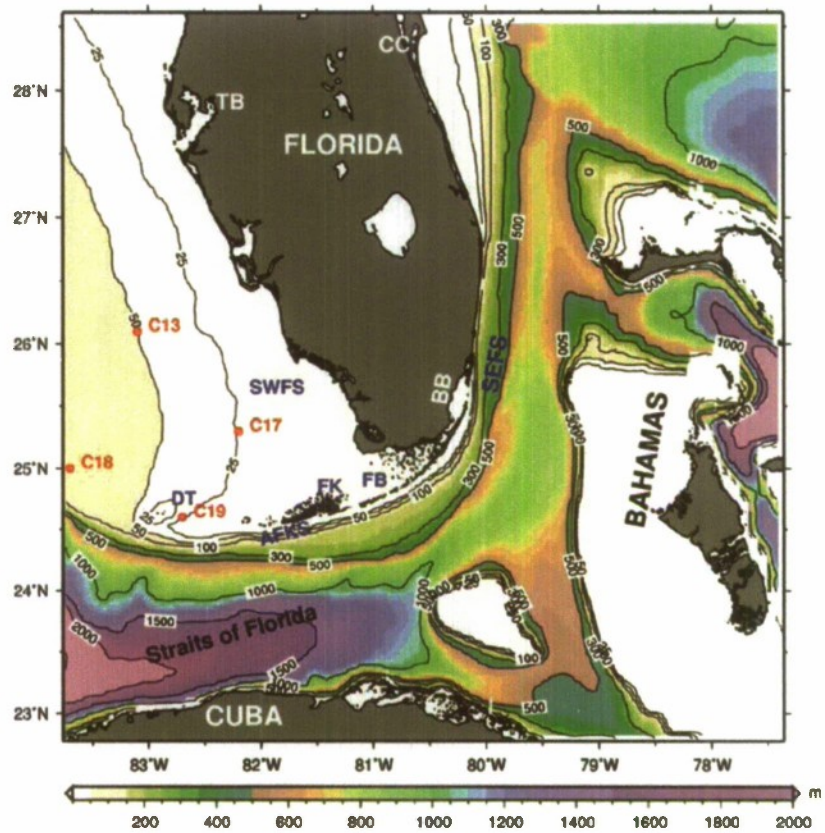


Fig. 1 The South Florida (SoFLA) model domain and bathymetry (*contours* in m). *Red dots* mark the ADCP mooring sites (see Table 1). *TB* Tampa Bay area, *SWFS* Southwest Florida Shelf, *DT* Dry Tortugas, *FK* Florida Keys, *FB* Florida Bay, *AFKS* Atlantic Florida Keys Shelf, *BB* Biscayne Bay, *SEFS* Southeast Florida Shelf, *CC* Cape Canaveral

remote upstream regions of the Gulf of Mexico and the Caribbean (Lee et al. 2002; Hamilton et al. 2005; Sponaugle et al. 2005; Kourafalou et al. 2007). These linkages are a unique characteristic of the South Florida coastal seas, directly connected to their proximity to a large scale current system, namely the Gulf Stream, that starts as the Loop Current in the Gulf, extends through the Straits of Florida as the Florida Current, and continues in the Atlantic Ocean as the main branch of this complex current system.

The narrow Southeast Florida Shelf (SEFS) and its southward extension, the Atlantic Florida Keys Shelf (AFKS), receive direct influence from the Florida Current front and associated transient passage of meanders and eddies, especially near the shelf break, while subtidal transport in the shoreward shelf areas is wind driven (Lee and Williams 1999). In addition, the SEFS is directly connected to the shallow Biscayne Bay, while the AFKS interacts with flows on the Southwest Florida Shelf (SWFS), through the narrow passages along the Florida Keys island chain and along the western boundary of the shallow, mudbank-dominated Florida Bay. The broad SWFS represents the southern extreme of the West Florida Shelf (WFS) as it merges with the Florida Keys. The SWFS has more distinct inner (~0–30 m), middle (~30–60 m), and outer (~60–100 m) domains that are influenced by different circulation forcing mechanisms. Wind stress and buoyancy due to freshwater input from rivers dominate circulation everywhere but in the outer shelf region, where the Loop Current influence is important. Observational and modeling studies on the WFS (see Weisberg et al. 2005 for a review) have shown the strong variability in the WFS current regime on several time scales and for different circulation governing dynamics. The inner shelf has top and bottom Ekman layers that interact with each other, with nearshore currents accelerated downwind, due to the coastal constrain (no cross-shore flow near the coastal wall) that eliminates the Coriolis term in the along-shore momentum balance. The mid-shelf is generally in Ekman balance, while the outer shelf is often dominated by flows associated with basin-wide circulation.

A numerical model of the South Florida coastal seas and surrounding deep sea areas has been developed to allow the study of the regional coastal processes and to serve as a tool for the support of limited area, high resolution interdisciplinary models around Florida Bay and the Florida Keys, in connection with the Comprehensive Everglades Restoration Project (http://www.evergladesplan.org/). Observational and modeling studies around the ecologically fragile CERP areas have suggested that management decisions must rely on limited area models that include the proper representation of the regional South Florida circulation. Detailed coastal dynamics and local forcing (such as local rivers) are of outmost importance for restoration-related simulations and are not present in the available large scale models. Furthermore, operational large scale models are not suitable for process-oriented studies, scenario-based simulations, and coupling with local biogeochemical models. The South Florida Hybrid Coordinate Ocean Model (SoFLA-HYCOM, Kourafalou et al. 2005) has been developed to fulfill these needs. The publicly available HYCOM code (http://www.hycom.org) has been selected for the flexibility on vertical discretization that offers transition from deep to coastal flows.

Modeling in the SoFLA domain poses the challenge of resolving both coastal and deep sea processes. Important circulation forcing mechanisms governing coastal transport processes are winds, river runoff and exchange through narrow channels and around the multi-island chains, and shallow mudbanks. The degree of linkage between the various coastal areas depends on the strength of their transports and the volume of water exchanged between SoFLA subregions as well as over the whole domain. The Loop Current/Florida Current front and associated eddies dominate the oceanic influence and effectively connect the coastal and shelf SoFLA areas to the overall Atlantic Ocean circulation. This suggests that numerical models around the South Florida coastal seas require a nested approach, with boundary conditions that demonstrate an adequate representation of the dominant large scale flows and their synoptic variability.

The main objective of the current study is to improve our understanding of the dynamics of the South Florida coastal seas, with an emphasis on the effects of large scale forcing on the shelf areas. Our methodology focuses on the evaluation of boundary condition effects on the circulation patterns simulated by the South Florida Hybrid Coordinate Ocean Model. We employ independent (not assimilated) observations and seek to examine if free-running simulations within a topographically and dynamically complex nested domain are adequate to simulate reliable flows, when aided by boundary forcing that is extracted from data assimilative larger scale products. This is an important step toward a future goal of achieving forecasting capabilities with the SoFLA-HYCOM model.

The Global Ocean Data Assimilation Experiment (GODAE; http://www.godae.org) has been selected as the source of suitable products for boundary conditions. Ongoing simulations and prediction with GODAE global and basin-scale models have fulfilled the main GODAE objectives of developing state-of-the-art models and assimilation methods to produce boundary conditions to extend predictability of coastal and regional subsystems (International GODAE Steering Team 2000). Around South Florida, two data assimilative models are directly affiliated with GODAE: the basin-scale North Atlantic (ATL) HYCOM, which provides archives of real-time simulations; and the regional Gulf of Mexico HYCOM with the Navy Coupled Ocean Data Assimilation (GoM-NCODA), which employs cyclic boundary conditions derived from a multi-year North Atlantic simulation and thus is capable to perform hindcasts beyond the available ATL-HYCOM years. A free-running simulation with the same Gulf of Mexico model (GoM-Free) is used to better highlight data assimilation effects prescribed to the SoFLA-HYCOM simulations through boundary conditions.

2 Model description

2.1 The HYCOM model

The hydrodynamic model chosen for this study is the Hybrid Coordinate Ocean Model (HYCOM; http://www.hycom.org), named after a unique vertical layer configuration that is dynamically transformable from isopycnal in the open stratified ocean to terrain-following (sigma) in shallow coastal regions and to fixed pressure-level coordinates in the surface mixed layer and unstratified seas. HYCOM is a comprehensive, three-dimensional hydrodynamic model with data assimilative capabilities and advanced mixing schemes (Bleck 2002; Chassignet et al. 2003; Halliwell 2004).

An addition to previously released standard HYCOM code employed in the SoFLA experiments involves the ability to add sigma and/or *z*-layers near the surface to better resolve shallow areas (Halliwell et al. 2008, this issue). The main task was to overcome the restriction of preserving a thin upper isopycnic layer in the mostly stratified subtropical areas that surround the study domains and smoothly transition from the deep to the shelf areas that require the resolution of surface and bottom Ekman layers. Another application of non-standard HYCOM code employed herein is the ability to simulate synthetic floats (either in the Lagrangian or Eulerian frame) that allow the tracking of particles through the model domain and optionally sample water properties at the location of each float (Halliwell et al. 2003). Stationary floats (synthetic mooring instruments) were launched in SoFLA simulations to compare simulated currents with ADCP mooring data.

2.2 The outer North Atlantic and Gulf of Mexico HYCOM models

One of the challenging tasks for nested models of coastal and shelf seas is the choice of appropriate boundary conditions. Nested models have to rely on available simulations from larger scale models, which often lack the resolution and topographic and forcing details that are necessary for the representation of coastal dynamics. It is often necessary to develop an intermediate model, nested within a global or basin-scale model, which, in turn, will provide boundary conditions for the coastal model. Such a multi-nested, downscaling approach has been followed herein, from the Atlantic to the Gulf of Mexico and then to the South Florida model (SoFLA-HYCOM, described in Section 2.3). Below, we give a brief description of three outer models employed in SoFLA-HYCOM simulations and we examine if the boundary conditions provided by the intermediate GoM model are an improvement over the coarser ATL model and if the data assimilative GoM-NCODA run is a better choice as outer model than the twin free-running GoM-Free model. The SoFLA-HYCOM model is being developed as a future regional model itself, to further support the boundary needs of higher resolution, limited area interdisciplinary local models.

The ATL-HYCOM model (see description in Chassignet et al. 2007) is the US contribution to the international GODAE project. The ATL-HYCOM model simulation that has been directly employed in this study will be referred to as ATL-OI, as the data assimilation scheme is using the Optimal Interpolation based Modular Ocean Data Assimilation System (MODAS). This system consists of daily operational 1/4° Sea Surface Height (SSH) analysis (gridded data) of available real-time satellite altimeter observations (Fox et al. 2002). The Cooper and Haines (1996) technique is used to project the surface information from altimetry SSH to the interior of the ocean. Relaxation to the MODAS 1/8° Sea Surface Temperature (SST) analysis derived from the five-channel Advanced Very High Resolution Radiometer (AVHRR) is also included. The vertical mixing is represented through the K-Profile Parameterization (KPP scheme, Large et al. 1994, 1997). As this model focuses on large scale processes and for computational efficiency, the coastline has been moved to 20 m, which effectively makes it unsuitable for representing circulation in coastal areas.

The GOM-HYCOM model has resolution of 1/25° (~3.5 to 4 km) and set-up similar to Prasad and Hogan (2007). It extends from 77.36°W to 98.0°W and from 18.09°N to 30.71°N and has 20 hybrid layers in the vertical. The model has used actual coastline with the minimum depth of 2 m, an improvement over the ATL-HYCOM in the Gulf of Mexico region. The NASA–GISS (Goddard Institute for Space Studies) Level 2 turbulence closure (Canuto et al. 2001, 2002) is employed for vertical mixing parameterization.

The intermediate GoM-HYCOM model employs a GODAE product at the open boundaries. A cyclic boundary condition has been developed from a synoptically forced simulation (1999–2002) of the ATL-HYCOM, to represent "climatology" in the Loop Current inflow through the Yucatan peninsula and the Florida Current outflow through the Straits of Florida and adjacent passages between Cuba and the Bahamas. The goal was to develop an intermediate model product closely related to GODAE objectives that would allow GoM-HYCOM simulations over any time frame, without having to rely on the availability of large scale model archives. The daily ATL-HYCOM boundary forcing fields were binned into monthly values to create perpetual year forcing archives. The cyclic boundary conditions have been successfully used to force GoM simulations forward in time, during the 2004–2005 simulation and beyond.

Two GoM-HYCOM simulations have been carried out: a free-running one (GOM-Free) and a data assimilative one, employing the Navy Coupled Ocean Data Assimilation (NCODA, Cummings 2005) system (GoM-NCODA). The NCODA is an oceanographic version of the multivariate optimum interpolation (MVOI) technique widely used in operational atmospheric forecasting systems. A description of the MVOI technique can be found in Daley (1991).

Figure 2 shows an evaluation of the two GODAE products that are used for boundary conditions in this study, namely the ATL-OI and the GoM-NCODA. Snapshots of Sea Surface Height on the same day (February 15, 2005) are plotted with superimposed tracking of the Loop Current, based on the operational IR (infrared) frontal analyses performed by the Naval Oceanographic Office. This is a routine model validation procedure performed at NRL, employing independent (not assimilated) satellite-derived high resolution SST observations. The cyclic boundary conditions used for GoM-NCODA perform well and maintain a robust Loop Current that is actually closer to the observed track, as compared to the ATL-OI. Both simulations agree very well with the satellite-derived frontal position, while the cyclonic eddy east of the front is absent in the course resolution (1/12°) ATL-OI and well resolved in the 1/25° GoM-NCODA.

Both outer models use atmospheric forcing from the coupled ocean–atmosphere FNMOC (Fleet Numerical Meteorology and Oceanography Center) Navy Operational Global Atmospheric Prediction System (NOGAPS, Hogan and Rosemond 1991; Rosemond 1992; Hogan and Brody 1993), which provides three-hourly wind and daily thermal forcing (interpolated to three-hourly values).

2.3 The nested South Florida HYCOM model

The SoFLA-HYCOM is the regional model of the South Florida seas (Kourafalou et al. 2005), extending from 22.78°N to 28.61°N and from 77.36°W to 83.76°W and with a horizontal resolution of 1/25°, i.e., about 3.5 to 4 km. It includes the full extent of the Straits of Florida (to Cuba in the South and to the Bahamas in the East), the inner, middle, and part of the outer Southwest Florida Shelf (south of ~28.5°N, from the Florida Keys to the Tampa Bay area) and the full Southeast Florida Shelf from Biscayne Bay to Cape Canaveral (Fig. 1).

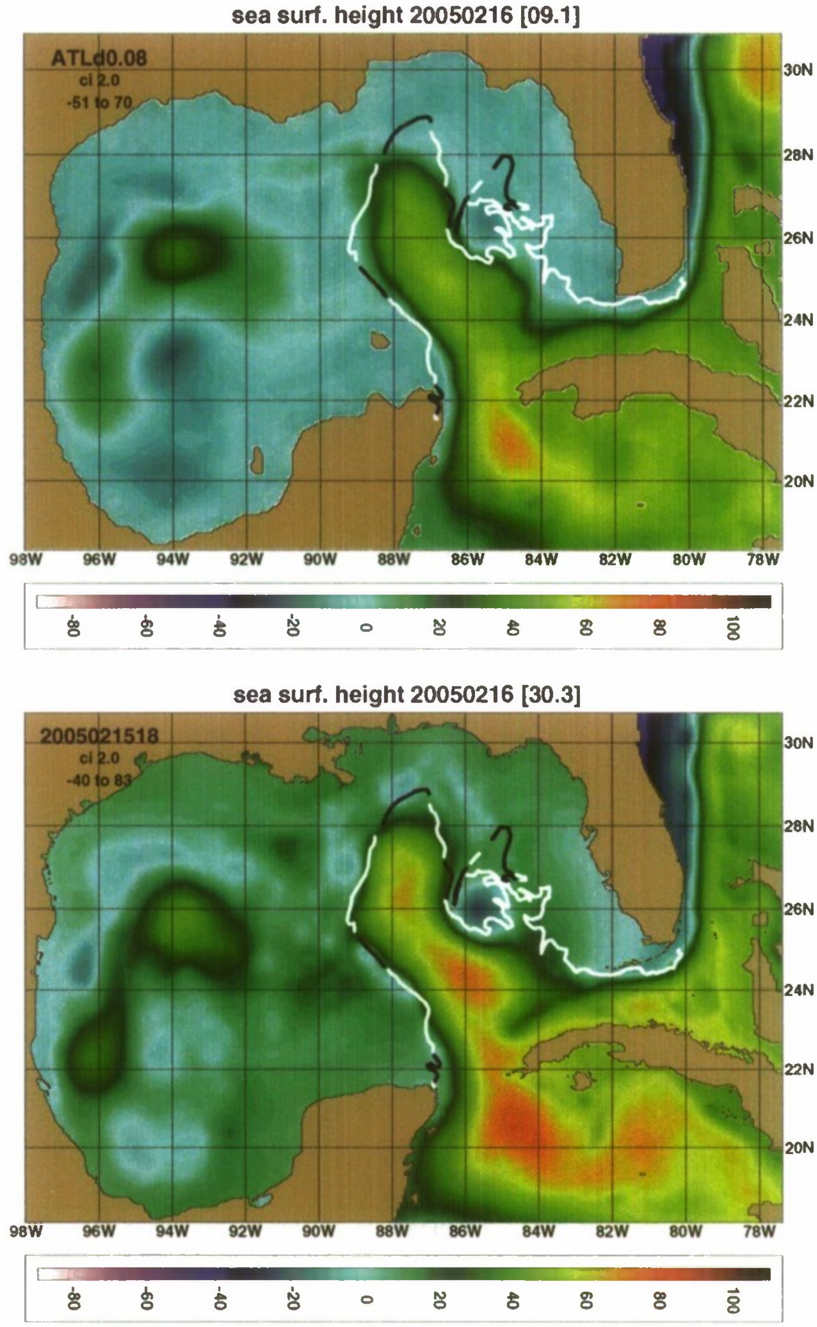


Fig. 2 Evaluation of GoM-HYCOM boundary conditions derived from ATL-HYCOM-based climatology. Sea Surface Height on February 15, 2005 computed by the ATL-OI (*upper*) and the GoM-NCODA (*lower*). The *continuous white/black line* marks the boundaries of the Loop Current and a cyclonic eddy, based on independent frontal analysis of high resolution SST data; *black lines* are segments based on data more than 4 days old

The topography is derived from the 2-min NAVO/NRL DBDB2 global data set with true coastline and a minimum depth of 2 m. As is the case for coastal and regional nested simulations, outer models are typically "large scale", basin-wide or global models that have coarser resolution and large minimum coastal depths. To address discrepancies between desired topographic details in shallow South Florida areas and larger scale models with deeper coastal minimum depths, a capability was developed to modify topography in the nested model to include shallower water regions and extrapolate initial and boundary conditions provided by the outer model into the SoFLA water grid points.

The model is driven by fields of wind stress, air temperature, atmospheric humidity, heat fluxes (surface shortwave and long wave), and salt flux (precipitation only). Surface latent heat and sensible heat fluxes, along with evaporation, are calculated using bulk formulae during the model run time using the model Sea Surface Temperature (Kara et al. 2005). All sources of land-based freshwater runoff have been included, both as point sources for the major rivers and as a line source for neighboring small rivers.

The vertical mixing is represented through the K-Profile Parameterization (KPP scheme, Large et al. 1994, 1997). No data assimilation has been applied within the SoFLA domain.

The nesting technique follows the standard and robust capability for nesting HYCOM within a larger HYCOM run, by employing boundary conditions that implement archived variables (off-line) from the coarse outer grid to the fine inner grid. The barotropic boundary conditions along the nested interface use the method of characteristics (Browning and Kreiss 1982, 1986). The baroclinic fields for temperature, salinity, pressure, and velocity in the nested model are relaxed toward the outer model solution within buffer zones and over e-folding times that were dictated by the archive frequency.

3 The data

Early studies on continental shelf dynamics have established that the primary subtidal current response to wind forcing on wide, shallow continental shelves, such as the West Florida Shelf, is a strong along-shore current directly forced by coherent, synoptic-scale along-shore winds and opposing cross-shelf currents in upper and lower Ekman layers (Csanady 1978; Beardsley and Butman 1974; Mitchum and Sturges 1982; Lee et al. 1985). The WFS exhibits the typical shelf dynamics with the additional complexity of flows associated with a north to south pressure gradient imposed on the Gulf of Mexico by the Loop Current, as well as shelf break processes associated with direct Loop Current influence (Huh et al. 1981; Paluszkiewicz et al. 1983; Weisberg et al. 1996, 2001; Weisberg and He 2003). Therefore, middle to outer shelf observations on the WFS are essential for the evaluation of SoFLA-HYCOM model simulations under different boundary conditions.

The Coastal Ocean Monitoring and Prediction System (COMPS; http://comps.marine.usf.edu) of the University of South Florida (USF) has four relevant mooring sites on the Southwest Florida Shelf: C13, C17, C18, and C19; see Fig. 1 and also Halliwell et al. (2008, this issue). Data from Acoustic Doppler Current Profilers (ADCP) will be used for comparison to modeled currents and will be employed in the evaluation of different boundary conditions for the SoFLA-HYCOM simulations. Mooring C18 is very close to the model boundary, so it will not be used for quantitative evaluation, but it will be employed in the discussion of certain processes. The mooring locations and the observing periods for each data record used in this study are given in Table 1. The longest record is for mooring C19 (full 2004–2005 period), followed by C17 that spans 15 months from May 2004 to August 2005.

4 Numerical simulations during 2004–2005

4.1 Model set-up and forcing

The objective of evaluating nested simulations in this study is to develop a regional model around the South Florida coastal seas that will properly account for coastal to offshore interactions, while being capable to simulate coastal flows. Although the focus is on the effect of the boundary conditions, certain improvements that are expected to be important for future simulations of wind-driven and buoyancy-driven coastal circulation and connectivity among shallow environments (such as Florida Bay and the Florida Keys) are also explored. These include the following.

- Certain topographic details in the SoFLA-HYCOM model are absent in the outer models: corrections in shallow depths around Florida Bay and the Florida Keys passages and the model minimum depth (2 m for SoFLA, same as in GoM, but much smaller than the ATL 20 m minimum depth which excludes the inner shelf and hence coastal currents).
- SoFLA-HYCOM has higher vertical resolution in the shelf areas, which is important for the proper representation of near surface buoyant plumes that are critical for inner shelf circulation, CERP restoration scenarios, and biophysical applications, to be explored in ancillary studies. The bottom 20 SoFLA layers are identical to the GoM layers (total number of GoM layers is 20) and to the top 20 layers of the 26-layer ATL-O1, whose bottom five layers were discarded because their densities do not exist in the regional SoFLA-HYCOM

Table 1 West Florida Shelf buoy and model buoy attributes

Data buoy ID	Lat	Lon	Water depth (m)	Missing data during 2004-2005	Model buoy sampling depth range starting:interval:ending
C13	26.07	83.07	50	02/08/05–09/14/05	3:1:45
C17	25.25	82.22	25	03/10/04–05/06/04; 09/13/05–10/12/05	4:1:21
C18	25.00	83.71	82	07/14/04–12/07/04	10:5:74
C19	24.62	82.72	25	none	3:1:24

Table 2 SoFLA-HYCOM simulations attributes

Exp #	Boundary conditions	Forcing	Vertical layers
1	GoM-Free	COAMPS	26
2	GoM-NCODA	COAMPS	26
3	ATL	COAMPS	26
1.1	GoM-Free	NOGAPS	20
2.1	GoM-NCODA	NOGAPS	20
3.1	ATL	NOGAPS	20

model. SoFLA has a total of 26 hybrid vertical layers ranging from sigma or z-coordinate in shelf regions to isopycnic coordinate in deep waters. The number and thickness of the upper model layers have been chosen to adequately resolve the entire water column in the shelf areas, especially where stratification due to riverine freshwater inputs prevails.

- The nested simulations employ the best available forcing, namely three-hourly archives of the 27 km horizontal resolution Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS, Hodur 1997; Hodur et al. 2002), as compared to the 1° NOGAPS forcing of the outer models (see Section 2.2).

4.2 Numerical experiments

In order to evaluate the effect of boundary conditions in South Florida nested simulations, three experiments were performed for a 2-year simulation (2004–2005): exp1 is nested in the GoM-Free, exp2 is nested in the GoM-NCODA, and exp3 is nested in the ATL-OI. All three experiments have the attributes described in Section 4.1 and were initialized from outer model fields on January 1, 2004. In order to evaluate the effect of atmospheric forcing in the numerical simulations, identical experiments were performed, but with NOGAPS atmospheric forcing employed in the SoFLA runs, similar to the forcing of the outer model simulations. These are: exp1.1, exp2.1, exp3.1, nested on GoM-Free, GoM-NCODA, and ATL-OI, respectively. To further highlight the effects of boundary conditions, experiments 1.1 and 2.1 have also the same vertical structure as the outer Gulf of Mexico simulations and exp3.1 has the same number of layers as the outer ATL model within the SoFLA domain. The attributes of all model simulations are given in Table 2.

At the open boundaries, 13 grid point-wide "buffer" (or boundary relaxation) zones with e-folding time of 0.1 to 24 days (outer to inner grid) are used to relax the baroclinic mode temperature, salinity, pressure, and velocity components.

4.3 Simulation of the circulation in the South Florida region

The synoptic variability in the South Florida flow field is characterized by periods of wind-driven versus buoyancy-driven and eddy-driven currents. Frequent eddy passages dominate the current field in the Straits of Florida, with substantial influence on the hydrodynamics around the

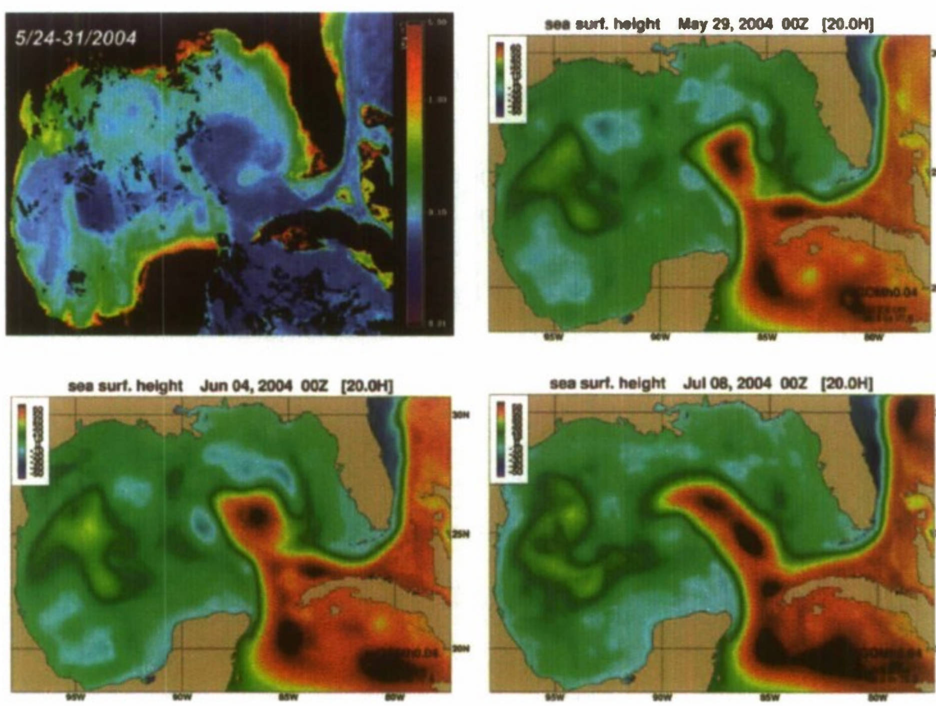


Fig. 3 Seven-day composite (May 24 to 31, 2004) from the Aqua-satellite chl-*a* data (*upper left*); Sea Surface Height fields from GoM-NCODA on May 29, 2004 (*upper right*); June 4, 2004 (*lower left*); and July 8, 2004 (*lower right*)

narrow Southeast Florida shelf and the Florida Keys Reef Tract. The broad Southwest Florida Shelf is mostly influenced by the passage of weather systems and by the freshwater inputs from local rivers.

Variability in the Loop Current has also been shown to impact circulation on the West Florida Shelf (Paluszkiewicz et al. 1983; Weisberg and He 2003; Weisberg et al. 2005). Based on several years of measurements, a mean southward flow has been found in the Southwest Florida Shelf (Lee et al. 2002) and has been attributed to a north to south pressure gradient imposed by the LC in the Gulf. An example of LC variability is shown in Fig. 3. A weekly Aequa-satellite chl-*a* image composite for May 24–31, 2004 shows the Loop Current under the tendency to shed a large ring, while anticyclonic eddy activity at the eastward periphery of the ring (near the WFS) was quite strong. The GoM-NCODA SSH fields around the same period (May 29 and July 4) are in very good agreement, as this simulation assimilates satellite-derived SSH fields. The ocean color data are not assimilated in the model. Also shown in Fig. 3

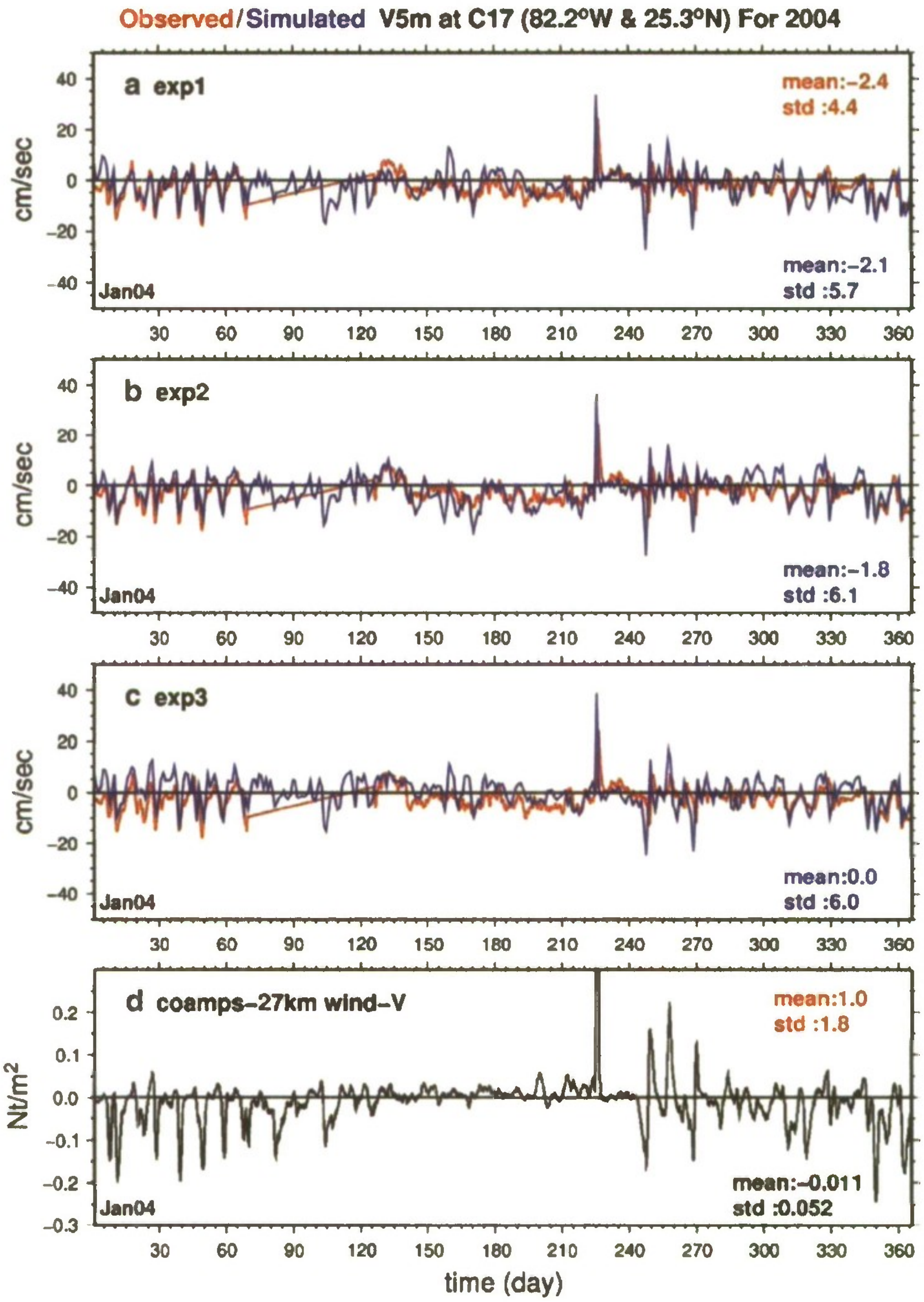


Fig. 4 Observed and simulated hourly values of near-surface (at 5-m depth) along-shore velocity (in cm s^{-1}) at the mooring station C17 (position marked on Fig. 1) for year 2004 (see Table 1 for data attributes), computed from COMPS data (*red lines*) and SoFLA model simulations (*blue lines*): **a** exp1; **b** exp2; **c** exp3. The along-shore wind stress component (in N m^{-2}) from the three-hourly COAMPS–27 km forcing is given in (**d**). Time series mean and standard deviations (*std*) are also given. Maximum winds in the summer–fall are associated with hurricanes Charlie (day 226, August 13, 2004) and Ivan (day 259, September 15, 2004). The *straight red line* marks a data gap

is the SSH field from the GoM-NCODA for July 8. The LC stayed in a relatively "young" (limited northward extension) position through the beginning of June, bending eastward and approaching the shelf break. This was associated with a southward flow event that spanned across the WFS (see Section 5.1). As the ring reattached itself, the LC changed to an extended configuration by the beginning of July and a westward bending, while the southward flow gradually became confined in the outer shelf. This agrees with the findings of Weisberg and He (2003) and adds support in the hypothesis by Hetland et al. (1999) that a mature Loop Current (which is fully extended into the Gulf of Mexico) can cause trapping of the cross-shelf pressure gradient and a southward flow confined over the shelf break region, while a young Loop Current (following a recent eddy shedding) located near the southwest portion of the shelf will cause a larger along-isobath sea level slope and the onshore penetration of the southward flow.

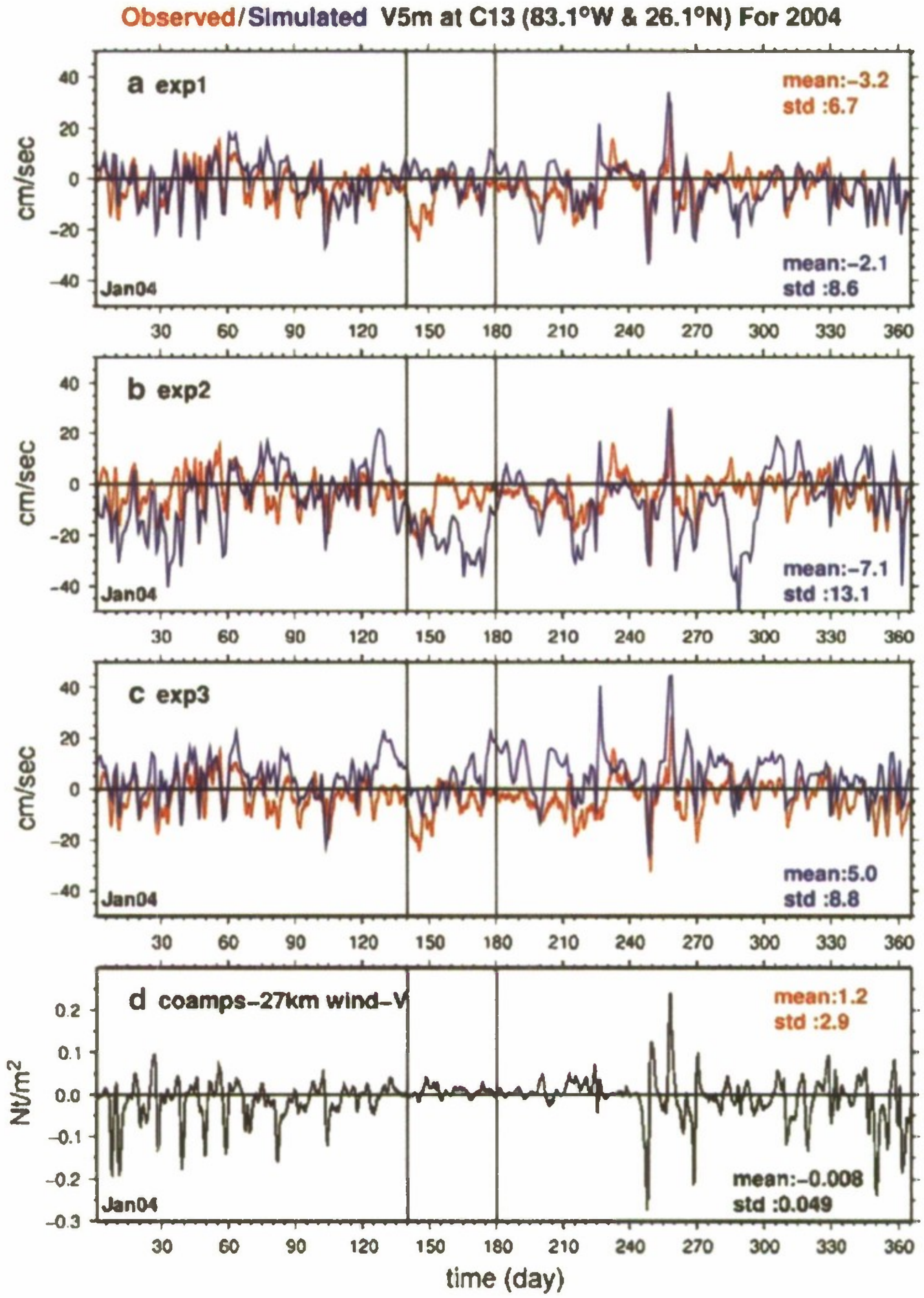


Fig. 5 Same as in Fig. 4, but for mooring station C13. The *vertical lines* mark a shelf flow event associated with oceanic influence (days 140–180, May 19–June 28, 2004)

5 Discussion of results

5.1 Evaluation of simulated currents

The SoFLA experiments are evaluated against measured currents at the COMPS moorings marked in Fig. 1. We first concentrate on experiments 1, 2, and 3; a comparison with experiments 1.1, 2.1, and 3.1 will follow. Synthetic moorings have been placed in the model at the grid point closest to the mooring locations, so that they extract three-dimensional current fields (see Table 1 for the starting/ending and interval depths of the float sampling). A daily Boxcar filtering has been applied on the hourly observed mooring data for direct comparison with daily archived model fields. Currents are rotated according to the local isobaths orientation.

Time series for near-surface along-shore velocity components during 2004 are presented in Figs. 4, 5, and 6 from the three model experiments and the observations, to illustrate certain circulation characteristics and the ability

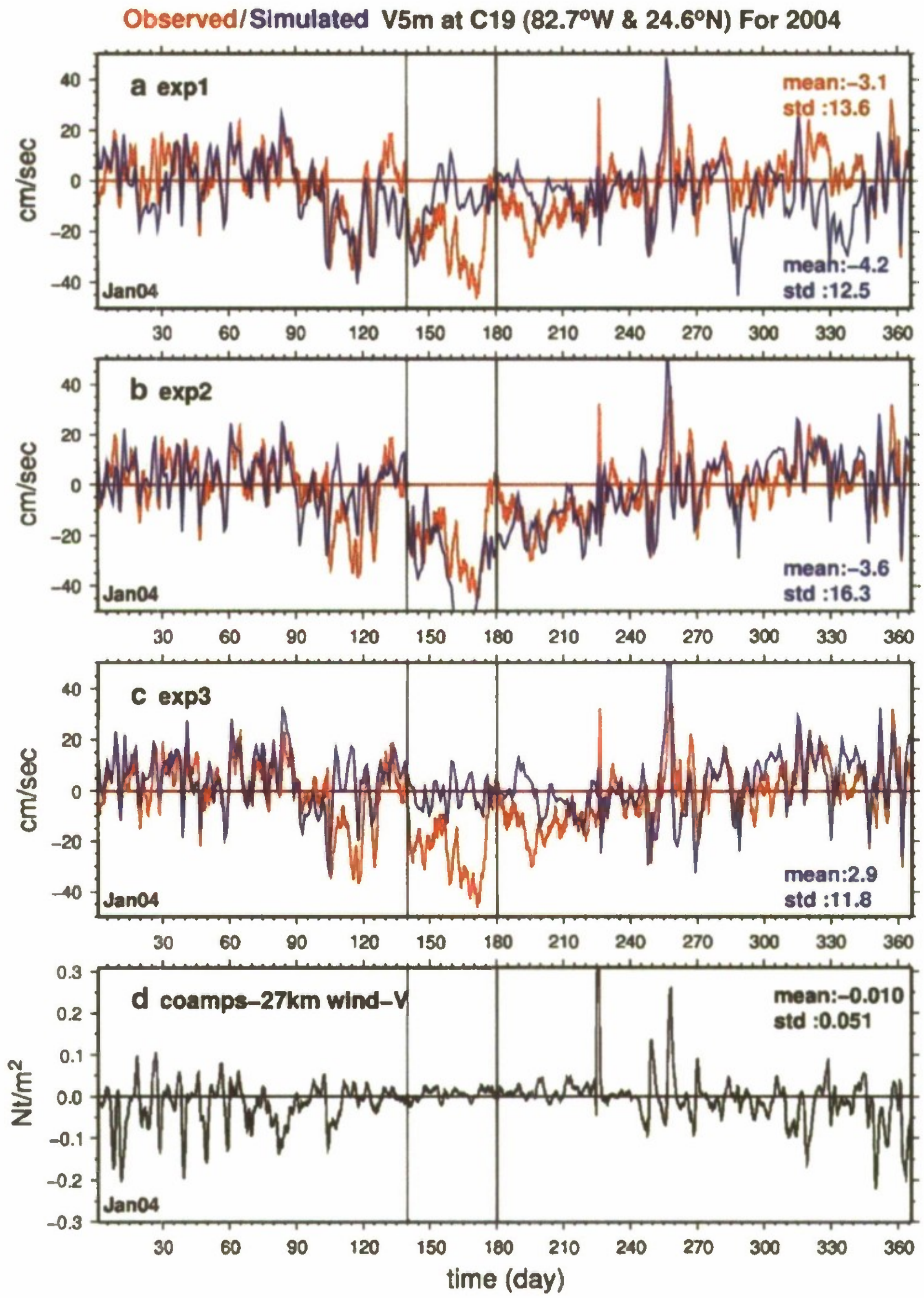


Fig. 6 Same as in Fig. 4, but for mooring station C19. The *vertical lines* mark a shelf flow event associated with oceanic influence (days 140–180, May 19–June 28, 2004)

of the SoFLA-HYCOM model to capture them under different boundary conditions. We concentrate on middle and outer shelf flows; inner shelf flows were largely buoyancy driven and will be discussed in a separate paper.

Currents have the smallest overall magnitude in the middle shelf mooring C17 (Fig. 4), considerably increasing in the outer shelf moorings C13 (Fig. 5) and C19 (Fig. 6). The rapid succession of northward and southward currents is generally evident in the winter months, following reversals in wind direction that are associated with cold front passages. Strong currents during the summer months are obviously not wind driven, as supported by the seasonal pattern in the wind field. With the exception of very strong wind events associated with tropical storm activity (especially hurricanes Charlie in August and Ivan in September), currents are strongly influenced by large scale flows during the summer months, especially on the outer shelf. Exp3 (BCs from the ATL-OI) has the poorest comparison with data in all locations, both in the mean/std values and in comparing individual events. Exp1 (BCs from GoM-Free) has generally good comparison everywhere, but at C19, where exp2 (BCs from GoM-NCODA) decisively outperforms all experiments not only in the mean, but (most importantly) over the individual events associated with eddy passages during summer.

The free-running exp1 has a mean value of -2.1 cm s^{-1} at C17, which is in excellent agreement with the mean value of -2.4 cm s^{-1} derived from the observations (Fig. 4). The same mean value of -2.1 cm s^{-1} is calculated by exp1 for C13, still in relatively good agreement with the data-derived

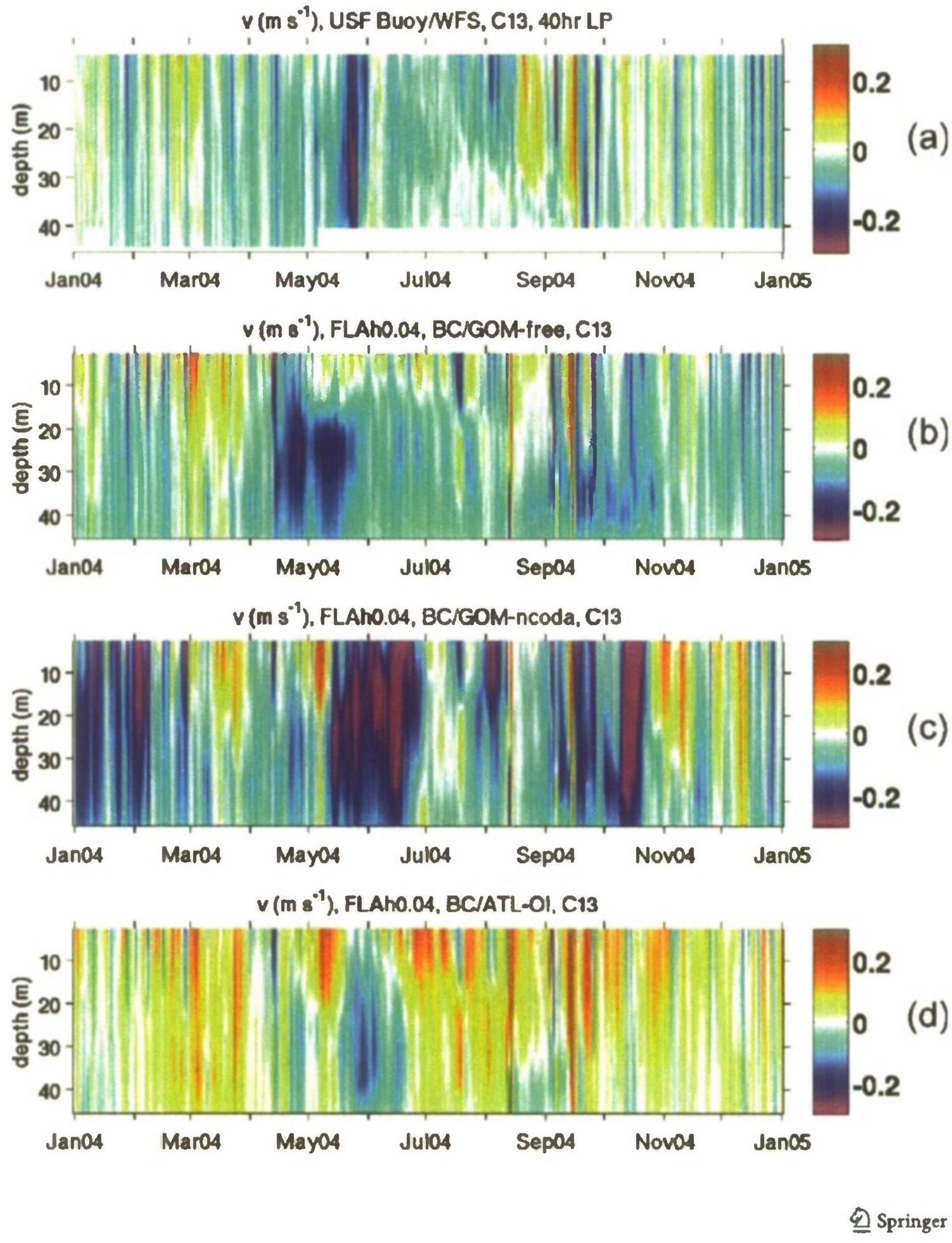


Fig. 7 Vertical-time section of along-shore current velocity (in cm s^{-1}) at the position of mooring C13 (see Fig. 1) for 2004 (see Table 1 for data attributes). Currents are from **a** data, **b** exp1, **c** exp2, and **d** exp3. *Time ticks* mark the first day of each month

value of −3.2 cm s^{-1} (Fig. 5). This suggests a dominance of vertical (atmospheric inputs) over lateral (boundary conditions) forcing fields in areas that are governed by shelf processes. However, episodic influence of large scale flows (and hence boundary conditions) is expected on shelf areas, as is the case for the strong southward event from May 19 to June 28 (days 140–180); see the time series in Fig. 5 and Fig. 6. This event is associated with the interaction of the Loop Current with the West Florida Shelf depicted in Fig. 3. The southward flow was best represented in exp2 and marginally in exp3 (both with data assimilative boundary conditions), while missing in exp1. At the outer shelf mooring C19, which is located at the west of the Dry Tortugas, exp2 produces a mean meridional velocity of −3.6 cm s^{-1} which has the closest agreement to the −3.1 cm s^{-1} mean value from the observations (Fig. 6). The large scale effects are strongest at C19, as marked for the May 24–June 28 southward flow event. In general, all three simulations capture the big signals from the tropical storm activity in the intense hurricane season during August and September 2004. Similar results are seen in the comparison for 2005 (not shown).

The southward flow event that was discussed above is depicted more clearly in the time slices of vertical distribution for the along-shore velocity (Figs. 7 and 8). The onset of the southward flow is reproduced by the model, with exp2 performing best at the beginning of the event (velocities of about 20–40 cm s^{-1}, in agreement with observations), but predicting a longer event at C13, while in very good agreement at C19. Exp3 produced weaker southward flows. The fact that boundary conditions from the GoM-NCODA data assimilative run helped the SoFLA

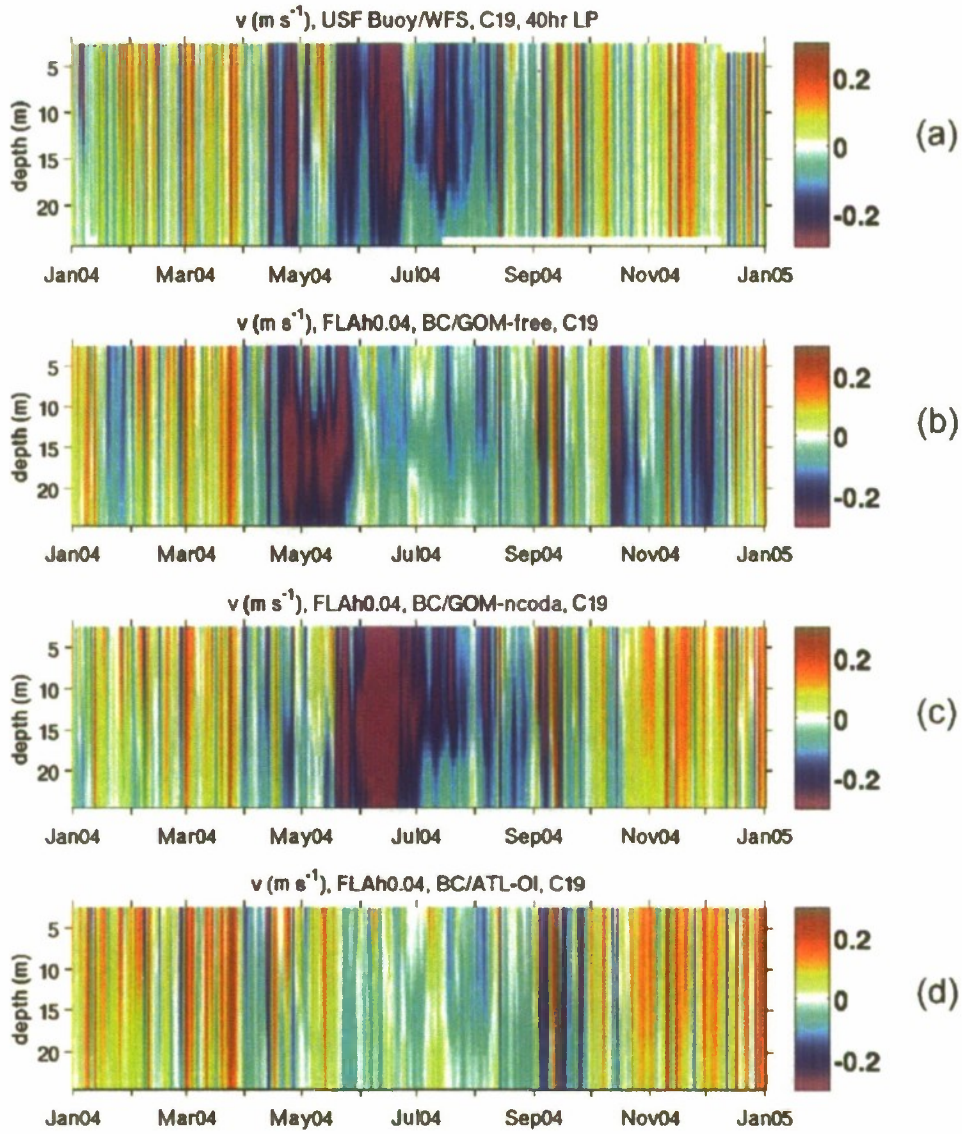


Fig. 8 Same as in Fig. 7, but for 2004 along-shore current velocity in mooring C19

simulation capture a strong southward event during a period of weak winds clearly suggests that the cause was larger scale lateral forcing, as discussed above. The data in C18 (not shown) also indicate that the outer shelf experienced a sustainable southward flow over several weeks in June. During the same period, C19 showed the strongest cross-shore velocities on record over all moorings (Fig. 9). Following the isobath turn near the Southwest Florida escarpment, the southward flow coming from the northern part of the WFS turns southwestward there. C19 is the only mooring that has noticeable cross-shore flows year round, as it is subject to direct influence from eddy passages.

Periods of vertical stratification and rapid changes from northward to southward flows in Figs. 7 and 8 are associated with wind influence. This is even more evident for the middle shelf mooring C17, where along-shore flows in 2005 (Fig. 10) are generally less than 20 cm s^{-1}, with the exception of three strong short-term northward flow events in the summer season, that are associated with tropical storm activity and are depicted in all SoFLA experiments and the data. Similar patterns were present in 2004 (not shown). The similarity among the three SoFLA experiments at C17 suggests that middle shelf currents experience substantially less influence from LC variability as compared to outer shelf flows.

5.2 Correlation estimates

The correlation of velocity vectors is computed, first between modeled and measured currents and then among different nested and outer model simulations. The two components of the velocity vectors are assigned to form a

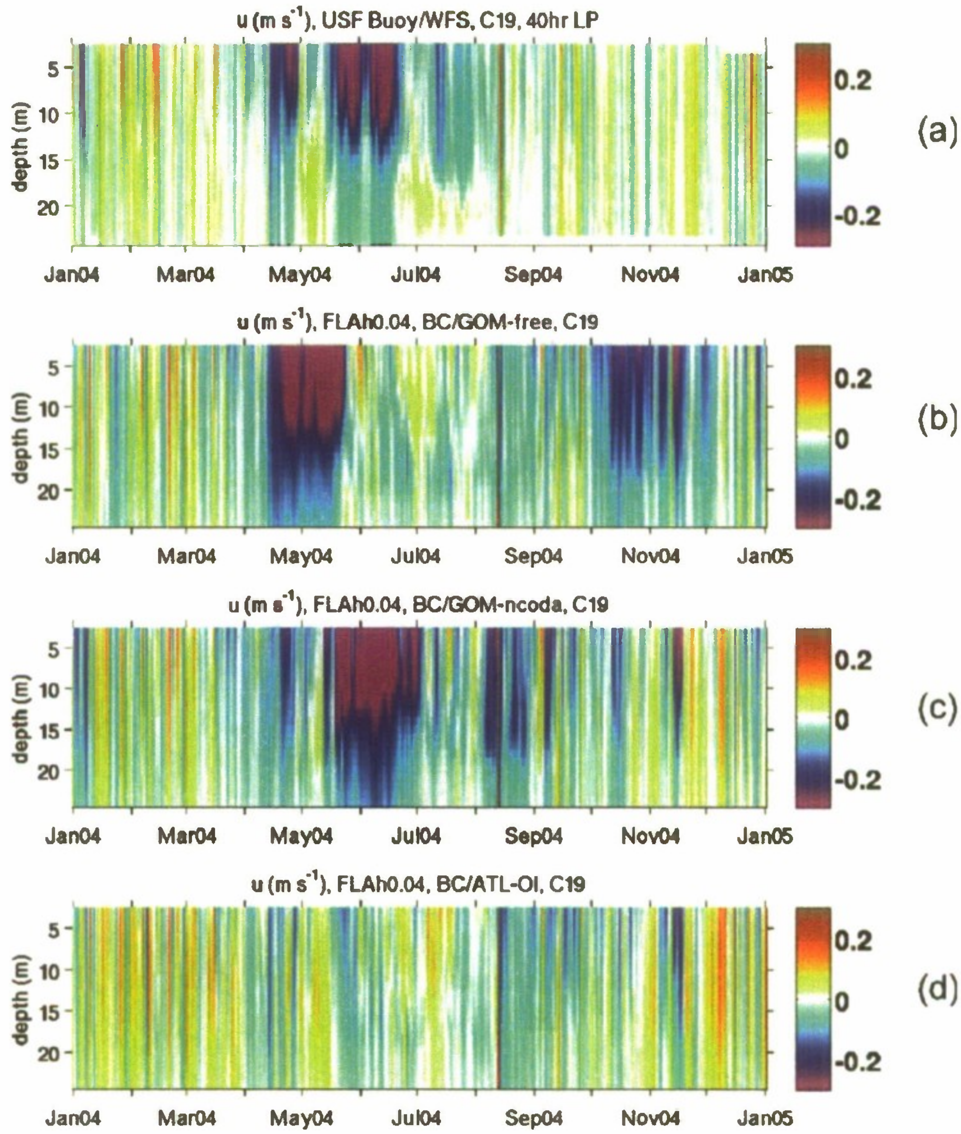


Fig. 9 Same as in Fig. 7, but for 2004 across-shore current velocity in mooring C19

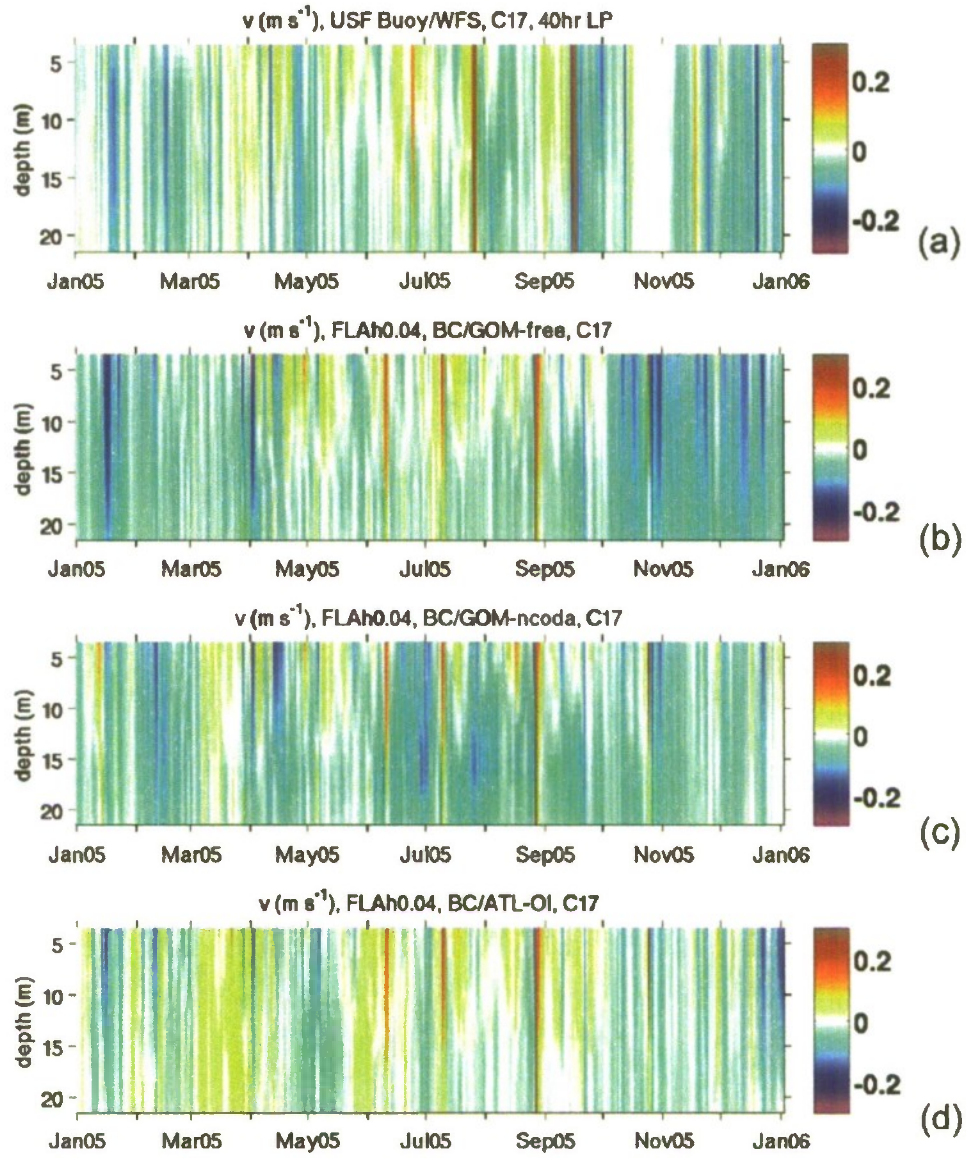


Fig. 10 Same as in Fig. 7, but for 2005 along-shore current velocity in mooring C17

complex number ($n = a + bi$). Then, the correlation between (a_1+b_1i) and (a_2+b_2i) is performed through the "corrcoef" Matlab function.

The vertical correlation estimates of along-shore model computed currents magnitude and phase (angle) from exp1, exp2, and exp3 with measured currents during 2004 at the position of buoys C17 and C19 are shown in Fig. 11. All three experiments are very close in C17, which supports the previous discussion that the boundary condition effects are secondary in the middle shelf areas, where atmospheric and land inputs dominate as circulation forcing mechanisms. Correlation is highest near surface, decreasing with depth in magnitude, where a slight offset in angle is also present. At C19, exp2 outperforms both exp1 and exp3. As was discussed above, the GoM-NCODA boundary conditions used in exp2 greatly improved the representation of the Florida Current and associated eddies entering the SoFLA domain, which have a direct impact near the Tortugas area and, therefore, on C19. Although exp3 has also boundary conditions from a data assimilative outer model (ATL-OI), the results suggest that either the NCODA data assimilation scheme is superior to the MODAS-OI or the elimination of coastal depths under 20 m in the ATL-OI seriously degrade the outer model solution (and hence the boundary conditions) near shallow areas. Not surprisingly, exp1 performs worst at C19, as the GoM-Free has no correction on the Florida Current mean flow and the eddy field. Both exp2 and exp3 are in phase with the data near the surface, with small angle deviations between 10-m and 20-m depth.

The correlation of horizontal currents between the nested and outer model simulations for the entire 2004–2005 period is shown in Fig. 12. The near surface currents

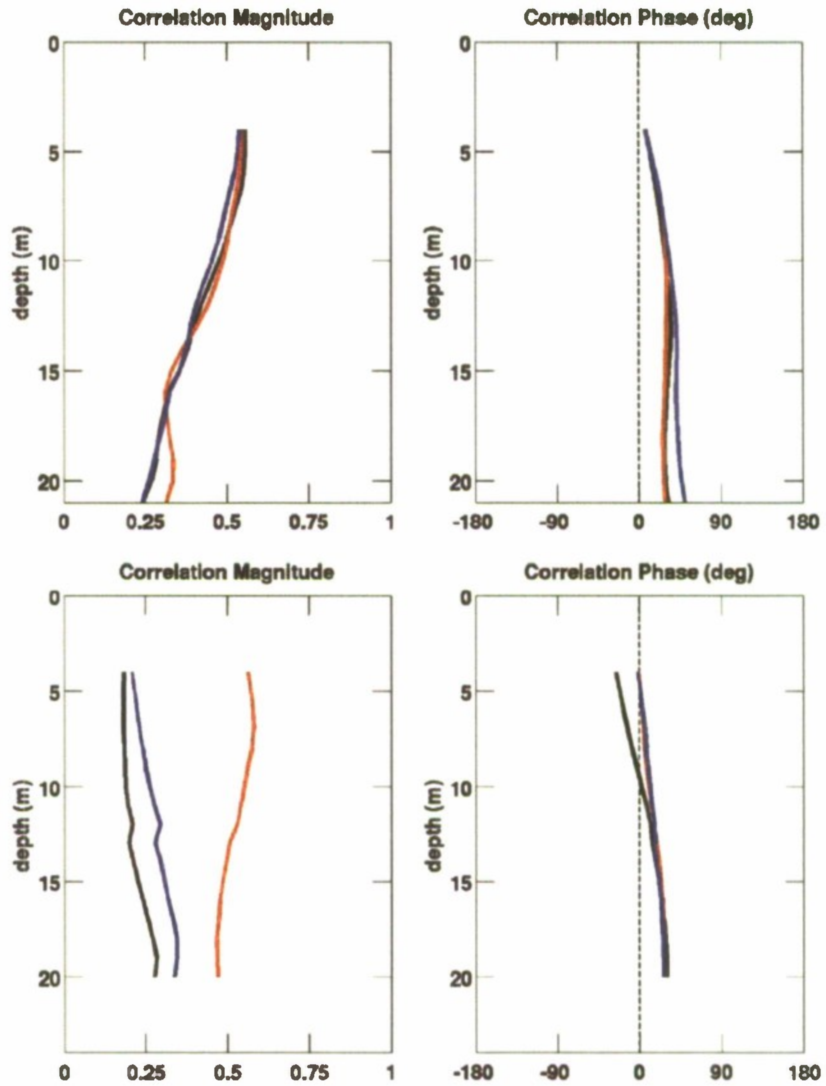


Fig. 11 Vertical correlation of along-shore model computed currents magnitude (*left*) and angle phase (*right*) from exp1 (*black line*), exp2 (*red line*), and exp3 (*blue line*) with measured currents at the position of buoy C17 (*upper*) and C19 (*lower*) for year 2004

between the nested SoFLA exp1 and the outer GoM-Free simulation are generally very highly correlated, with correlation values approaching unity in many areas, especially in the southern (extending east to west) part of the Straits of Florida. This is not surprising as these are two free-running models with the same resolution. The correlation is not as strong in the northward (extending north to south) part of the Straits. The patterns are similar for the correlation between the nested exp2 and outer GoM-NCODA velocities, but the correlation values are overall lower, as exp2 is free running and the GoM-NCODA is data assimilative. As expected, all areas near the nested boundaries have values near unity. All models seem to be well correlated in phase with lags in direction generally less than 10°.

We sought to examine if factors different than the nesting influence the correlation between nested and outer model current vectors. One important difference between the nested and outer simulations is the forcing (27 km COAMPS and 1° NOGAPS, respectively, see Section 2). The high resolution forcing was employed as part of the strategy to utilize the best available forcing in the nested domain. Examination of the COAMPS and NOGAPS time series of winds at various points in the domain (not shown) revealed that the two data sets are well correlated, with differences in magnitude that generally range from 0% to 10%, but can occasionally reach 30%, especially during high winds and near channels or narrow passages. The NOGAPS values are generally higher, presumably due to differences in resolving the land–sea interface. The two atmospheric data sets are in phase, with the exception of a slight phase difference (a few hours) during brief periods of high activity in the 2004 hurricane season, namely during the passages of hurricanes Charlie and Ivan (August 13 and

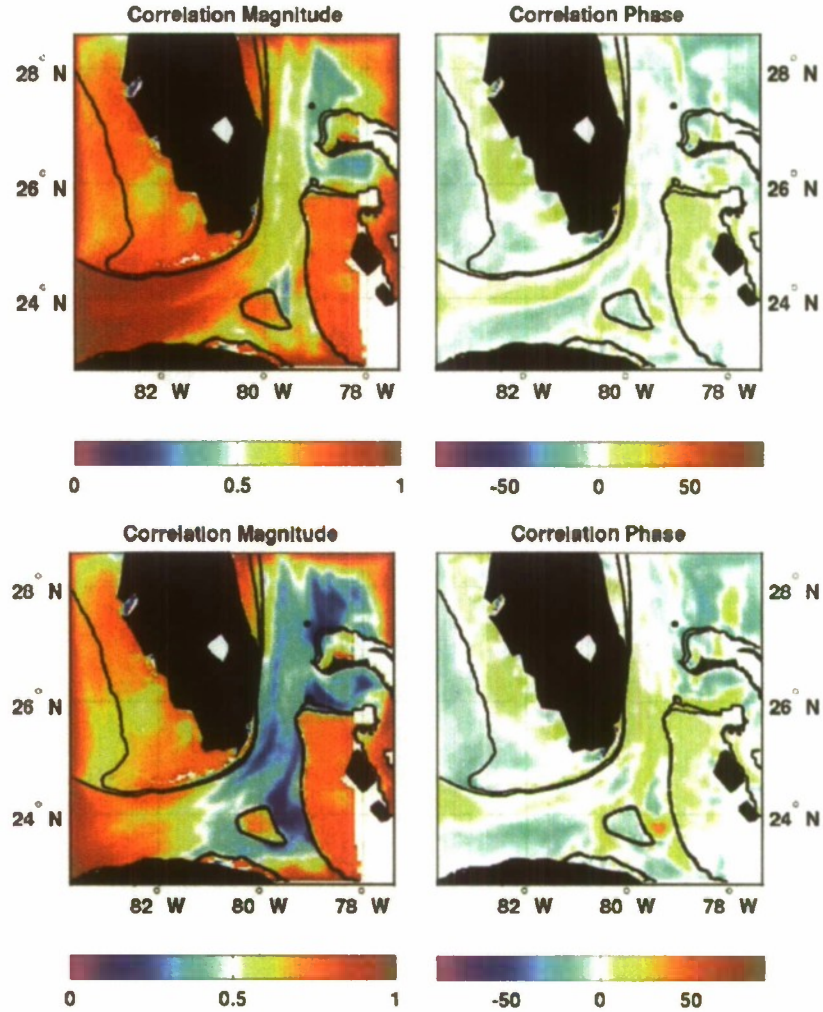


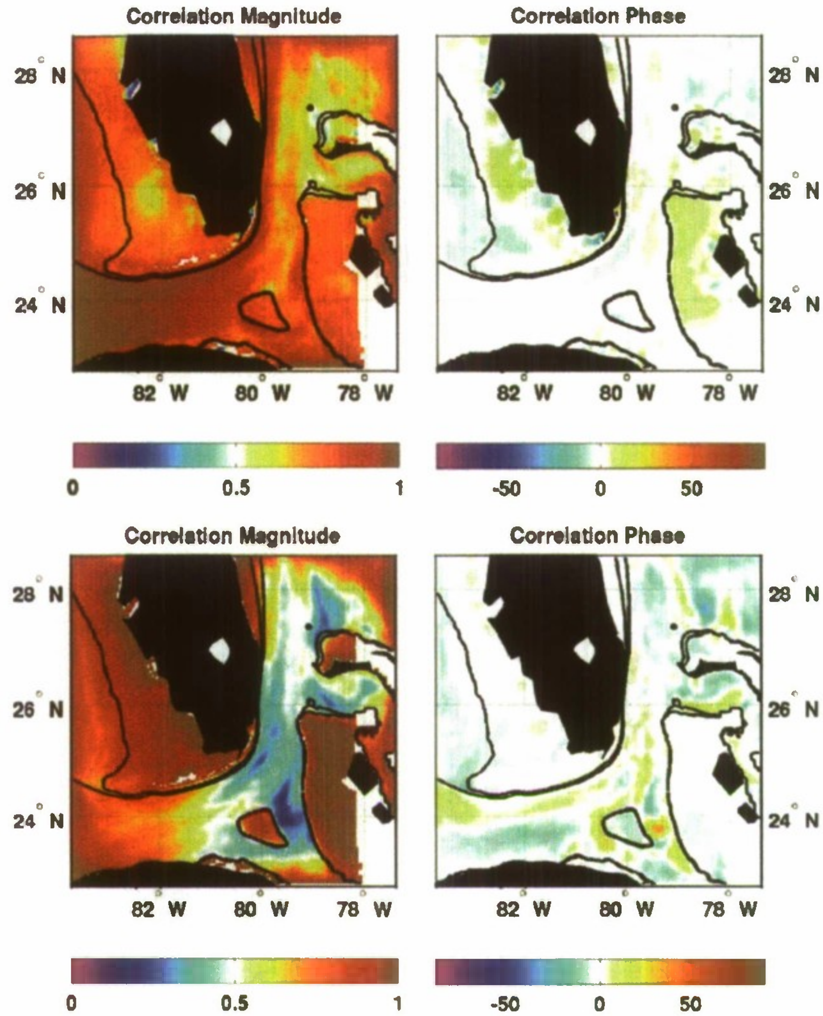
Fig. 12 Horizontal vector correlation magnitude (*left*) and phase (*right*) of near surface currents over the 2-year simulation period (2004–2005) between SoFLA exp1 and the GOM-Free simulation (*upper*) and between SoFLA exp2 and the GOM-NCODA simulation (*lower*). *Black lines* mark the 40-m and 100-m isobaths

September 15, 2004), which had a direct impact in the vicinity of moorings 17 and 19.

To address the impact of forcing, we employ experiments 1.1, 2.1, and 3.1 that have the same boundary conditions as experiments 1, 2, and 3, respectively, but with the same forcing as the outer models (see Table 2). We also revert to lower vertical resolution in these experiments to resemble the outer models set-up. It should be noted that a sensitivity experiment where only the vertical resolution was altered did not have any impacts beyond the nearshore river plume areas and will not be discussed here.

The horizontal vector correlation of magnitude and phase for the simulated near surface current between the two nested simulations SoFLA exp2.1 and exp2 are shown in Fig. 13 for the 2004–2005 simulation period. The same calculation is carried out for the correlation between the nested exp2.1 and the outer GoM-NCODA model. The vector correlation between experiments 2 and 2.1 clearly shows the strong similarities between the two SoFLA simulations, with small differences in passages around the Bahamas. Areas where the hurricane passages were important exhibited brief periods of small differences due to the phase lag between the two atmospheric data sets during the 2004 hurricane season, as mentioned above; this bared a small influence on the correlation average. Similar results were obtained comparing exp1.1 to exp1 and exp3.1 to exp3 (not shown). As expected, we observe an increase in the correlation between the nested exp2.1 and the outer model, when comparing to the correlation between exp2 and GoM-NCODA (see Figs. 12 and 13). This is evident on the shelf areas and it is obviously attributed to the wind forcing being identical to the outer model for the nested exp2.1, as compared to different forcing fields for exp2. However, the influence of the boundary conditions in the Straits of Florida is still evident in exp2.1, as the correlation starts strong near the open boundary in the southeastern Straits and diminishes downstream, a result similar to what was obtained with exp2.

Fig. 13 Same as in Fig. 12, but for correlation between SoFLA exp2.1 and exp2 (*upper*); the nested SoFLA exp2.1 and the outer GOM-NCODA simulation (*lower*)



5.3 Error estimates

The Root Mean Square Error (RMSE) has been computed as an estimate of the agreement between modeled and measured currents and as a tool for the comparative evaluation of the various simulations discussed above:

$$RMSE = \sqrt{\frac{1}{n}\sum_{j=1}^{n}\left(M_{i,j} - D_j\right)^2}$$

where $M_{i,j}$ is the model computed value at the (*i, j*) grid point corresponding to the (*j*) buoy location that provides the D_j observed value and *n* is the number of samples in the chosen time series interval.

The RMSE values for the six SoFLA experiments described above are presented in Fig. 14 for mooring 17 and at seasonal intervals; the values for the three outer models are also given. The differences between models and data are strongest in the spring–summer months and smallest in the fall season. The nested experiments outperform the outer models, with the large scale ATL-O1 simulation giving the poorest coastal results. The experiments that had the high resolution wind forcing (exps. 1, 2, and 3) outperform the ones with the coarser atmospheric fields (exps. 1.1, 2.1, and 3.1). Highest errors were found for the experiments that were nested in the coarser ATL-O1 model (exps. 3 and 3.1). Interestingly, experiments nested in the regional, data assimilative GoM-NCODA (exps. 2 and 2.1) did not have smaller errors compared to the ones nested in the non-assimilative GoM-Free (exps. 1 and 1.1). However, this was not the case in the RMSE calculations for the outer shelf mooring C19 (not shown), where the data assimilative boundary conditions had a positive effect, especially during the summer season.

6 Summary and conclusions

Simulations with the regional South Florida Hybrid Coordinate Ocean Model (SoFLA-HYCOM) have been performed

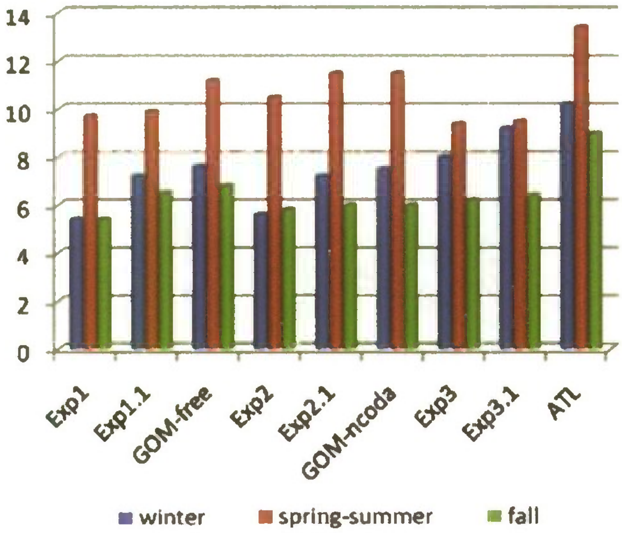


Fig. 14 Seasonal variability of the Root Mean Square Error (RMSE) between modeled and measured values of the along-shore velocity component at the location of mooring 17 and for the six SoFLA experiments and three outer models. South Florida seasons are defined as: winter (January, February, March); spring–summer (April, May, June, July, August, September); fall (October, November, December)

with different boundary conditions from GODAE products that also employ the HYCOM code. The Atlantic Ocean basin-wide implementation of HYCOM (ATL-HYCOM) and an intermediate Gulf of Mexico model (GoM-HYCOM) have been employed as outer models. The ATL-HYCOM is a coarser resolution basin-wide model and uses the Optimal Interpolation based Modular Ocean Data Assimilation System (MODAS). The GoM-HYCOM is a higher resolution regional model and has been run both without (GoM-Free) and with data assimilation (GoM-NCODA, based on the Navy Coupled Ocean Data Assimilation code). All SoFLA simulations are free running and the study has evaluated if boundary conditions from data assimilative models can improve the nested model results, in the context of other differences, such as grid resolution, coastal topography, and atmospheric forcing.

The South Florida study domain is a unique environment for such an evaluation, as it contains both shelf and deep areas that are linked through a strong boundary current and associated eddy field. It was found that the effects of boundary conditions depended on the dynamics that governed circulation in these regimes. Based on model results that were validated against observations on the Southwest Florida Shelf (SWFS), it was found that shelf areas away from the shelf break (so called inner and middle shelf domains) were dominated by atmospheric and land inputs and were thus generally shielded from the influence of offshore flows. Consequently, boundary conditions from outer models with or without data assimilation appeared to have a diminishing impact toward the shallower regions. On the contrary, outer shelf flows were largely influenced by the Loop Current/Florida Current front and eddies, especially near the entrance to the Straits of Florida, where the oceanic flows were closest to the shelf. This result was particularly evident in the summer period, when strong currents and flow reversals could not be explained with the seasonally light winds. A characteristic event of southward flow on the SWFS associated with Loop Current variability was elucidated by employing SoFLA and GoM simulations and observations. The proximity of the Loop Current to the SWFS shelf break and the ring shedding process were connected to the shelf flows. Our results suggest that a nested approach is important for limited area modeling in the South Florida domain, as the large scale flows influence shelf circulation, either directly (outer shelf) or indirectly (middle and inner shelf).

Although a one to one comparison between models and observations at single buoy locations are quite challenging, SoFLA-HYCOM has exhibited satisfactory performance over synoptic and seasonal time scales. The evaluation of data assimilative GODAE products showed that the nested, free-running SoFLA simulation performed best on the middle to outer shelf areas when boundary conditions were supplied from the intermediate GoM-NCODA model. This was largely attributed to the lack of coastal circulation in the ATL-OI model, which has a 20-m coastline. The NCODA assimilation scheme is possibly superior to the MODAS scheme, but this evaluation is beyond the scope of this study. All nested model experiments had smaller errors than the outer models, when simulated currents were compared to a coastal ADCP buoy.

The successful nested simulations of the South Florida Hybrid Coordinate Model relied on outer data assimilative models for realistic representation of coastal to offshore interactions. In return, the SoFLA simulations added value to the GODAE products, by dynamically downscaling the outer fields and improving the simulation of the shelf flows and their interaction with the regional ocean current system. Certain discrepancies in the correlation of modeled and observed currents suggest that data assimilation in the nested domain should be explored. However, this would require the proper design of a suitable observing system that satisfies the dominant scales with sufficient spatial and temporal data resolution. Future plans include the performance of Ocean System Simulation Experiments and biophysical applications with the South Florida Hybrid Coordinate Ocean Model that will further address observational and modeling needs toward an integrated, interdisciplinary forecast system for the South Florida coastal seas.

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