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Cold event in the South Atlantic Bight during summer of 2003: Model simulations and implications

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[1] A set of model simulations are used to determine the principal forcing mechanisms that resulted in anomalously cold water in the South Atlantic Bight (SAB) in the summer of 2003. Updated mass field and elevation boundary conditions from basin-scale Hybrid Coordinate Ocean Model (HYCOM) simulations are compared to climatological forcing to provide offshore and upstream influences in a one-way nesting sense. Model skill is evaluated by comparing model results with observations of velocity, water level, and surface and bottom temperature. Inclusion of realistic atmospheric forcing, river discharge, and improved model dynamics produced good skill on the inner shelf and midshelf. The intrusion of cold water onto the shelf occurred predominantly along the shelf-break associated with onshore flow in the southern part of the domain north of Cape Canaveral (29° to 31.5°). The atmospheric forcing (anomalously strong and persistent upwelling-favorable winds) was the principal mechanism driving the cold event. Elevated river discharge increased the level of stratification across the inner shelf and midshelf and contributed to additional input of cold water into the shelf. The resulting pool of anomalously cold water constituted more than 50% of the water on the shelf in late July and early August. The excess nutrient flux onto the shelf associated with the upwelling was approximated using published nitrate-temperature proxies, suggesting increased primary production during the summer over most of the SAB shelf.

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1. Introduction and Background

[2] During summer 2003 an intense upwelling event took place in the South Atlantic Bight (SAB). The event extended from Florida to New Jersey, and its effects have been described in the Mid-Atlantic Bight [*Sun et al.*, 2004] and the SAB [*Aretxabaleta et al.*, 2006]. *Aretxabaleta et al.* [2006] summarized observations of the anomalous conditions in the central SAB during spring and summer of 2003. Observed temperatures were as much as 8°C colder than normal in some areas of the mid-to-outer shelf in the SAB, and effects were felt even in nearshore areas. They concluded that a combination of factors was responsible for the anomalous cold water intrusion over the shelf: anomalously intense and persistent upwelling-favorable winds, increased river discharge that resulted in stronger than average stratification, and Gulf Stream dynamics. The cold water that upwelled onto the shelf during the event originated in the lower part of the water column of the Gulf Stream (depth > 200 m).

[3] The present study builds on the analysis of observations presented in the work of *Aretxabaleta et al.* [2006]. Here we evaluate the relative importance of the different forcing mechanisms at work during the 2003 cold event using model simulations. The purpose of the present study is twofold: to explain the forcing mechanisms during the 2003 event, and to improve the understanding of the baroclinic dynamics in the SAB shelf.

[4] The SAB extends from Cape Hatteras, North Carolina, to Cape Canaveral, Florida, along the eastern coast of the United States. The inner shelf of the SAB (coast to 20-m isobath) is controlled by wind, tides, and river discharge, and during spring and summer, a frontal system is established around the 10-m isobath [*Blanton and Atkinson*, 1983]. The midshelf (20- to 40-m isobath) is dominated by wind and tidal forcings. The outer shelf (40-m isobath to shelf-break) is controlled by the Gulf Stream and its instabilities [*Lee and Atkinson*, 1983]. This study focuses on the central part of the SAB from NE Florida to northern South Carolina (Figure 1).

[5] Modeling studies have explored intensively the barotropic processes on the SAB shelf. *Kourafalou et al.* [1984]

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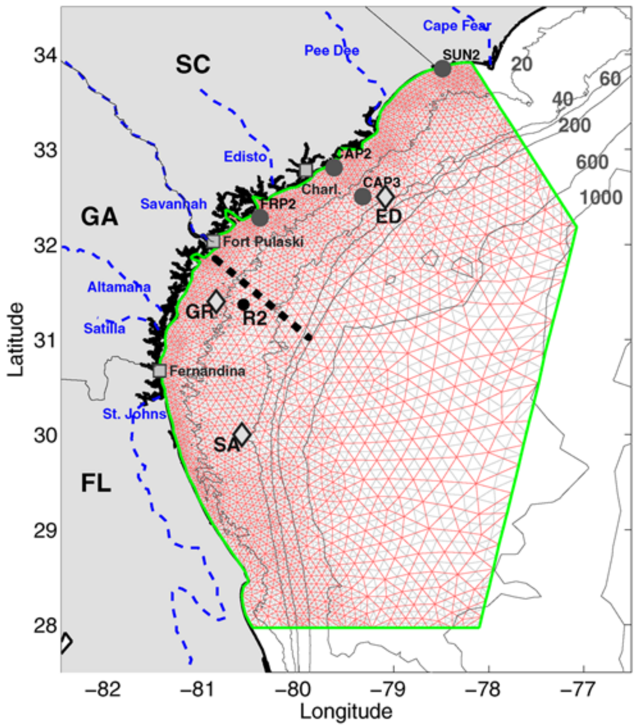

Figure 1. South Atlantic Bight region. The black dot corresponds to the R2 SABSOON-instrumented tower location. The gray squares are NOS water level stations used in this study. The gray diamonds correspond to NDBC buoys 41012 (St. Augustine, SA), 41008 (Gray's Reef, GR), and 41004 (Edisto, ED). The gray dots correspond to nearshore Caro-COOPS stations. The dashed thick black line represents one of the hydrographic cruises conducted from the R/V Savannah during the summer of 2003. The thin black dashed lines show rivers with USGS stream gauge stations. The thick gray line corresponds to the boundary of the model domain. The dark gray mesh corresponds to the coarser, quadratic elements. The light gray mesh represents the denser, lower-order mesh. One quadratic element covers exactly four of the linear elements. The 20-, 40-, 60-, 200-, 600-, and 1000-m isobaths are shown.

and *Wang et al.* [1984] developed a model to study the shelf response to wind-driven flow during winter. *Lorenzzetti et al.* [1987] presented model simulations of the SAB response to an upwelling event during summer of 1981. *Lorenzzetti et al.* [1988] extended their previous study using a simple two-layer model. *Werner et al.* [1993] studied the response of the shelf during autumn of 1987 using an early implementation of the model used in the present study. *Lynch et al.* [2004] presented barotropic model simulations with data assimilation to study forecasting feasibility in the SAB. *Blanton et al.* [2004] used a two-dimensional model to produce the best available estimate of the barotropic tides in the SAB. Baroclinic dynamics have been introduced in several other simulations of the SAB. *Oey* [1988] focused on the interaction of the Gulf Stream frontal instabilities with the continental slope. *Kourafalou et al.* [1996] studied the transport and fate of freshwater over the SAB shelf during spring of 1984. *Chen et al.* [1999] studied perturbations in the low-salinity fronts in the inner shelf. *He et al.* [2005] conducted a set of experiments in which the complexity of forcing mechanisms included in a simulation of the shelf response to the passage of two atmospheric systems was gradually increased.

[6] The focus of the previous SAB model studies has been mostly on the barotropic shelf response, while the baroclinic dynamics have been poorly characterized and remain a challenge. Key challenges for baroclinic models include the representation of stratification, the inclusion of realistic forcing and domains, and the achievement of adequate skill when compared to observed fields. The current model study represents progress in every aspect with respect to previous published model simulations in the SAB.

2. Data, Methods, and Simulations

2.1. Observations

[7] A description of the basic characteristics of the observations is provided in the study by *Aretxabaleta et al.* [2006]. The observations used for comparison and validation of the model results were obtained from hydrographic cruises in the central SAB, National Data Buoy Center (NDBC) stations, South Atlantic Bight Synoptic Offshore Observational Network (SABSOON) towers, Carolinas Coastal Ocean Observation and Prediction System (Caro-COOPS) stations, and National Ocean Service (NOS) water level stations (Figure 1). The cruises provided the best observational data for the evaluation of the hydrographic conditions across the shelf. Data from NDBC buoys 41008 (Gray's Reef), 41004 (Edisto), and 41012 (St. Augustine) provided time series of surface water temperature and wind speed and direction. Coastal water level data were obtained from several NOS stations in the domain: Charleston, SC; Fort Pulaski, GA; and Fernandina Beach, FL. River discharge data were obtained from US Geological Survey (USGS) stream gauge stations for the seven main rivers in the model domain: St. Johns, Satilla, Altamaha, Savannah, Edisto, PeeDee, and Cape Fear (Figure 1). The R2 SABSOON tower provided surface and bottom temperature and current velocity during the spring of 2003 (Figure 1). Unfortunately, during the summer of 2003, the instrumented towers were being refurbished by the US Navy, and data were not available from mid-June until September. A temporary replacement mooring deployed near the R2 tower provided current (acoustic Doppler current profiler, ADCP), bottom temperature, and bottom salinity from mid-June to the end of July. The use of observational products to force model simulations, such as heat flux observed at the towers, is therefore not possible. Additional bottom temperature data off South Carolina were obtained from moored instruments maintained by the Caro-COOPS program (http://www.carocoops.org). Data from three nearshore stations (CAP2, FRP2, and SUN2) and one midshelf (CAP3) station were used in this study. The data from the Caro-COOPS stations were available from mid-August 2003 on.

2.2. Model

[8] The model used in these simulations was Quoddy [*Lynch and Werner*, 1991; *Lynch et al.*, 1996], a three-dimensional, prognostic, tide-resolving, finite element

model with level 2.5 turbulence closure [*Mellor and Yamada*, 1982]. The model used a higher-order advection scheme developed by *Kliem* [2004]. That study showed that the use of the new advection scheme resulted in considerable improvement in the quality of the advection of temperature and salinity, and therefore in the baroclinic dynamics. The new advection scheme was especially necessary for simulations over periods longer than a week, helping to mitigate overshooting and undershooting and unrealistic smoothing effects. The advection scheme by *Kliem* [2004] used pointwise corrected transport advection with nodal quadrature (PCTNQ) to reduce the computational requirements.

[9] To produce long-period simulations (longer than a few days), appropriate mass field boundary conditions must be introduced. A modified mass field boundary condition was developed as part of this study and used to update temperature, salinity, and sea surface elevation fields whenever new information was available. The modified condition maintained the current model-time temperature and salinity (T-S) values at the boundary during outflow and updated them during inflow to the available time-dependent T-S values. Additionally, input of river discharge into the model domain was conducted at the nodes closest to the USGS river stations.

2.3. Domains

[10] The main requirement for the use of the PCTNQ advection scheme is the generation of two "concurrent" meshes: one fine mesh with linear basis functions and a second coarser mesh with quadratic basis functions (Figure 1). One quadratic element covers exactly four of the linear elements. The basic domain is a finite element mesh that includes the SAB continental shelf from NE Florida to the South Carolina-North Carolina border as well as the open ocean region west of 78°W longitude. The finest horizontal resolution is 3 km near the coast, and it increases to around 20 km in the open ocean. Additional simulations were conducted using a shelf-scale domain [*Aretxabaleta*, 2005], but the location of the open-ocean boundary over the time-varying edge of the Gulf Stream made the representation of shelf-open ocean exchanges impractical.

2.4. Inputs

[11] There are two sources of initial and open boundary conditions used in this study: one, climatological, and the other, extracted from a basin-scale model simulation. The climatological conditions were required for the simulations for spring 2003 because the basin-scale model solutions were not available until 1 June 2003. The climatological mass fields were developed by *Blanton et al.* [2003] using an optimal interpolation technique [*Bretherton et al.*, 1976] to project hydrographic observations onto the model grid. The observations used to develop the climatological fields included historical temperature and salinity observations from the National Ocean Data Center (NODC) database (1950–1999).

[12] The basin-scale model is a North Atlantic implementation of the Hybrid Coordinate Ocean Model (HYCOM [*Bleck*, 2002; *Chassignet et al.*, 2003; *Hamilton*, 2004]). The North Atlantic HYCOM is run operationally by the Naval Research Laboratory as part of the Global Ocean Data Assimilation Experiment (GODAE). The HYCOM products have a temporal resolution of 1 day and a spatial resolution of 1/16° and do not include forcing by tides. One goal of the HYCOM/GODAE initiative is to provide initialization products for regional and limited-area coastal models, such as that described in this study. The use of appropriate updated offshore boundary conditions is believed to be critical to the development of adequate representations of the open-ocean effects associated with the Gulf Stream and its instabilities.

[13] In addition to the initial mass field, inclusion of river discharge is required to obtain realistic salinity structures for simulations over seasonal timescales, especially for the inner shelf of the SAB. River inputs in the present operational HYCOM integrations do not include rivers in the SAB. Discharge from SAB rivers is incorporated in the Quoddy simulations assuming constant salinity values (salinity = 20) for the input into the shelf. A brackish salinity is prescribed because the model does not have the appropriate resolution in the estuaries to allow for the proper description of the estuarine mixing processes. The inflow of water is proportionally increased so that the buoyancy flux remains consistent.

[14] The atmospheric forcing (wind stress and heat flux) used in the present study to drive the regional ocean model was specified from NCEP's ETA Data Assimilation System (EDAS), which computes meteorological analyses for the USA at the synoptic times 0, 6, 12, and 18 hours UTC. The 12-km midlatitude resolution product was used. The model heat flux was computed from the net latent, sensible, shortwave and long-wave radiation heat flux fields. Wind stress was computed from the EDAS 10-m wind fields using the study by *Large and Pond* [1981]. For comparison to observations, observed heat flux during spring 2003 was calculated from the atmospheric sensors on R2 using the work of *Beardsley et al.* [2003]. As noted above, R2 observations were not available during summer.

[15] During the summer of 2003, the EDAS products recovered the intense pressure signal for the Bermuda-Azores High and the strong persistent upwelling-favorable winds in the SAB [*Aretxabaleta et al.*, 2006]. On the basis of a spring comparison (not shown), the temporal resolution of the EDAS product was not sufficient to accurately represent the daily heat flux cycle and resulted in root mean square (RMS) differences between EDAS values and those calculated from observations around 150 W/m^2. The comparison between monthly mean heat flux for 2002 and 2003 (Figure 2) suggests substantially greater (20–60 W/m^2) modeled mean net heat flux values than observed from May until August 2003. The observed values for 2003 were in fact lower (20–40 W/m^2) than for 2002. Therefore EDAS seems to have underpredicted the heat flux during 2002 and overpredicted it during 2003 (Figure 2).

[16] The tidal boundary conditions for eight constituents (M_2, S_2, N_2, K_2, O_1, P_1, K_1, and Q_1) were obtained from the latest Advanced Circulation (ADCIRC) model tidal database (TDB [*Blanton et al.*, 2004]). The TDB provides a significant improvement from previous tidal estimates in the SAB region because of the inclusion of the Estuaries and Tidal Inlet Complex (ETIC), which extends from the Florida-Georgia border to North Carolina in the SAB. Even using the TDB tides as boundary conditions, some inaccuracy was introduced because the model domain used in the

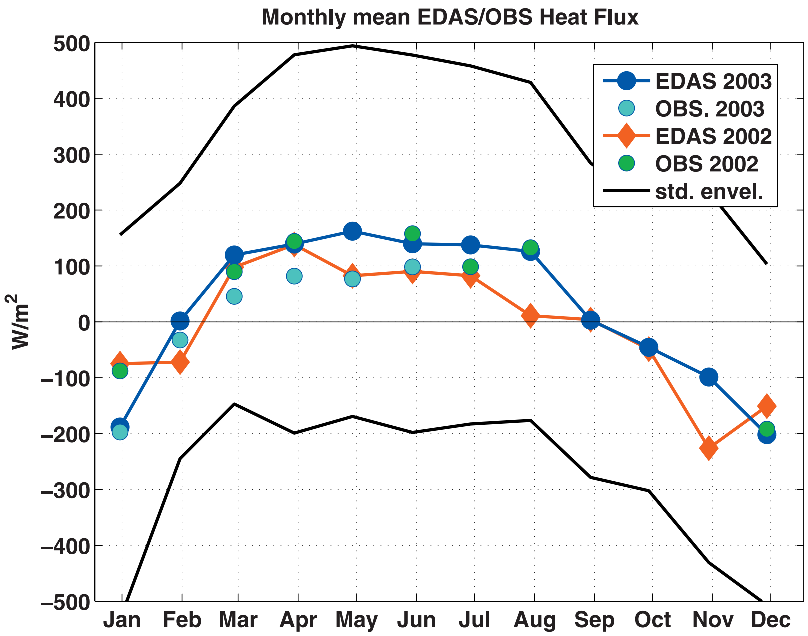

Figure 2. EDAS monthly mean heat flux for 2003 (black solid line with open circles) and 2002 (gray solid line with light gray circles) compared to net heat flux calculated from observations at the R2 tower. The available observations for 2003 (2002) are indicated with black (gray) diamonds. The dashed black lines correspond to the monthly standard deviation for 2003.

current study did not resolve the ETIC. Even with that limitation, the inclusion of tidal forcing is a major difference between the HYCOM and the present Quoddy simulations, considering the importance of tides to mixing on swallow continental shelves like the SAB.

2.5. Simulations

[17] A number of simulations were conducted to evaluate the different forcing products and the relative importance of the forcings for the 2003 event. The complete set of simulations presented in this study is listed in Table 1. The simulations used Quoddy with higher-order advection scheme (PCTNQ), river discharge from available USGS stations, and EDAS atmospheric forcings, with different combinations of initial and boundary conditions. The first simulation (case 1) was conducted to compare the available HYCOM fields over the shelf with Quoddy solutions that used HYCOM initial and boundary conditions, which was limited to the summer period starting 1 June 2003. The second and third simulations (cases 2 and 3) were conducted to explore the conditions during spring 2003 and its transition to summer conditions under different summer boundary condition forcing. Case 5 was conducted to study the effect of a different initial and boundary conditions (climatology) by comparison with case 1 (initialized from HYCOM). The last two simulations included in this study (case 9, no river discharge; and case 10, with 2002 atmospheric fields) using unrealistic forcing for the 2003 simulations were created in order to isolate the importance of specific mechanisms. Additional simulations (not presented in this study) were conducted to evaluate several other possible initial conditions, boundary conditions, and start times. Presented below are the results from the simulations 1, 2, 3, 5, 9, and 10, which were found to capture the variability in the entire set of cases run.

3. Results

3.1. Skill Evaluation

[18] Model skill for the different simulations was evaluated by comparing observations and model output for 13 different parameters (station locations in Figure 1): bottom temperature at the R2 SABSOON tower and four Caro-COOPS stations (CAP2, CAP3, FRP2, and SUN2), surface temperature at three NDBC buoys (Edisto, Gray's Reef, and St. Augustine), water level at three NOS stations (Charleston, Fort Pulaski, and Fernandina Beach), bottom velocity at R2, and surface velocity at R2.

[19] The first estimate of model skill considered is the RMS difference between observations and model (Table 2). The RMS difference for water level was similar for every simulation and was in a range between 0.08 and 0.16 m. The bottom velocity difference was on the order of 0.05 m/s, while the surface velocity difference was on the order of 0.15 m/s. The greatest variability in RMS differences occurred in surface and bottom temperatures. The regional-scale simulations (Quoddy, cases 1–10) showed the smallest temperature differences, especially for bottom temperature. Of the regional-scale simulations, case 5, which used climatology to specify the initial mass field and open boundary conditions, best reproduced observed bottom temperature variability and magnitude.

[20] An alternative measure of model skill has been proposed by *Hetland and Signell* [2005]. In order to elim-

Table 1. Model Simulations Conducted for Spring and Summer of 2003[a]

Case	Initial Condition Source and Date	Open Boundary Conditions	River Discharge	EDAS Forcing
Case 1	HYCOM (01 Jun 2003)	HYCOM (Jun-Sep)	2003	2003
Case 2	CLIMAT (Feb)	CLIM (Feb-Sep)	2003	2003
Case 3	CLIMAT (Feb)	CLIM (Feb-May), HYCOM (Jun-Sep)	2003	2003
Case 4	CLIMAT (Jun)	HYCOM (Jun-Sep)	2003	2003
Case 5	CLIMAT (Jun)	CLIM (Jun-Sep)	2003	2003
Case 6	HYCOM (01 Jun 2003)	CLIM (Jun-Sep)	2003	2003
Case 7	CLIMAT (May)	CLIM (May-Sep)	2003	2003
Case 8	CLIMAT (May)	CLIM (May-Jun), HYCOM (Jun-Sep)	2003	2003
Case 9	CLIMAT (Jun)	CLIM (Jun-Sep)	NO	2003
Case 10	CLIMAT (Jun)	CLIM (Jun-Sep)	2003	2002

[a]HYCOM means initial and/or boundary conditions extracted from the North Atlantic HYCOM simulations (only available from 1 June 2003 on). CLIMAT means initial and/or boundary conditions extracted from the monthly SAB climatology of *Blanton et al.* [2003].

inate magnitude biases, they proposed that the model skill be evaluated as:

$$\text{skill}_{\text{hs}} = 1 - \frac{\sum_{i=1}^{N} (d_i - m_i)^2}{\sum_{i=1}^{N} (d_i - c_i)^2} \quad (1)$$

where d_i are the available observations, m_i are the model results transformed to match the observations (for example, concurrent spatial and temporal locations), and c_i is a vector of climatological or background values. A perfect model has a skill of 1, while when the model returns climatological values, the skill is 0. A significant departure from the observations may result in negative values of skill. This estimate of skill varies depending on the parameter considered, length of records compared, and the extent to which the observed record differs from climatological values. While this definition of skill makes the comparison between different parameters problematic, it allows for comparisons between different model simulations for specific parameters.

[21] The model skill assessed using equation (1) is presented in Table 3. The skill of the regional simulations (cases 1–10) was higher than the basin-scale solutions (HYCOM) for bottom temperature at R2 and surface temperature at Gray's Reef (41008) and comparable for the rest of the parameters. The simulations with better skill (cases 5 and 7) used both climatological initial and boundary conditions. The use of initial conditions from HYCOM (cases 1 and 6) produced the worst agreement between observed and modeled temperature, but skill for the other parameters was comparable.

3.2. Comparison With in Situ Observations

[22] The first case study (case 1) used HYCOM (starting from 1 June 2003) to set the initial conditions as well as boundary conditions for temperature, salinity, and low-frequency elevation. Model bottom temperatures at R2 for case 1 were significantly colder than observed (Figure 3). During June, the difference was 6°C for Quoddy and 7°C for the basin-scale HYCOM simulation. The model bottom temperatures increased to levels in the vicinity of observed values at R2 around mid-July, when in fact the observed values showed a decreasing trend during that time. No further comparison with observations is possible at that station until 27 August when observed and model temperatures are similar. Surface temperatures showed a similar pattern (Figure 4) with model values ~3.5°C colder than observed during June and converging toward observed values by early August.

[23] Case 2 was initialized using the February climatological fields and used boundary conditions from climatology and was the only model estimate for the period from February until June because no other boundary and initial forcing was available at the time. This simulation showed better skill than case 1 both for surface and bottom temperature. The model surface temperature at Gray's Reef showed a good agreement with observations (Figure 4, RMS difference 1.2°C) during the period between mid-June and mid-September, reproducing both the observed magnitude and the variability. During the early period of the simulation (February-June), the model overpredicted the surface temperature, which is consistent with the systematic difference between observed and EDAS estimates of the heat flux (Figure 4). The simulated bottom temperature at R2 was persistently lower than observed between mid-May and early July (Figure 3).

[24] A compromise to reproduce both the surface and bottom temperature cycle was achieved with case 5, which was initialized from June climatological fields. Both the model bottom temperature at R2 (Figure 3, RMS difference 0.9°C) and model surface temperature at Gray's Reef (Figure 4, RMS difference 1.81°C) showed a good agreement with observations. Given the skill for this simulation, and since the focus of the current study is on the near-bottom intrusion of cold water, the case 5 simulation was chosen as the baseline for further comparisons.

[25] The observed bottom temperature from the cruise on 27 August 2003 was best reproduced by the HYCOM basin-scale simulation (Figure 3). The regional-scale simulations estimated 2–2.5°C warmer bottom temperatures. The lack of other observations to estimate the bottom temperature skill during the late summer period made the skill estimation only partially possible.

[26] The comparison between cases 1 and 5 emphasizes the importance of appropriate initial and boundary conditions in model simulations. With regard to the initial condition, by the use of appropriate forcing (heat flux and wind stress) during some time (45 days over the midshelf in our experiments), the model in case 1 was able to partially achieve more realistic values, at least over the midshelf (Figure 3).

Table 2. Skill of Model Simulations Estimated as RMS Difference Between Observations and Model Results

	Bottom Temp. R2, °C	Surface Temp. Edisto, °C	Surface Temp. Grays R., °C	Surface Temp. St. Aug., °C	Water Level Charlest, m	Water Level F. Pulaski, m	Water Level Fern. B., m	Bottom Veloc. R2, m/s	Surface Veloc. R2, m/s	Bottom Temp. CAP2, °C	Bottom Temp. FRP2, °C	Bottom Temp. CAP3, °C	Bottom Temp. SUN2, °C
HYC.	7.46	2.00	5.55	1.90	0.079	0.086	0.082	0.062	0.145	2.72	2.99	3.30	1.43
Case 1	5.73	4.22	3.28	3.68	0.089	0.077	0.083	0.052	0.153	2.16	1.20	3.09	3.58
Case 2	1.87	2.15	2.88	2.36	0.147	0.155	0.166	0.056	0.147	3.83	3.69	3.37	3.47
Case 3	2.78	3.67	2.85	3.48	0.090	0.084	0.088	0.052	0.160	2.20	1.70	3.03	3.38
Case 4	2.32	3.09	2.06	3.10	0.081	0.069	0.079	0.048	0.157	2.18	0.99	2.54	2.94
Case 5	0.90	1.81	1.81	1.87	0.099	0.102	0.128	0.052	0.142	2.52	1.89	1.64	2.69
Case 6	3.27	3.11	1.84	1.90	0.084	0.087	0.119	0.052	0.146	NO	NO	NO	NO
Case 7	1.53	1.75	1.31	1.86	0.090	0.099	0.118	0.056	0.140	2.88	2.28	1.80	2.89
Case 8	2.77	2.93	2.09	3.25	0.108	0.099	0.108	0.058	0.156	NO	NO	NO	NO
Case 9	0.94	1.87	1.96	1.87	0.103	0.108	0.130	0.052	0.140	3.87	3.74	1.45	5.17

Table 3. Skill of Model Simulations Estimated Using the Definition by *Hetland and Signell* [2005]

	Bottom Temp. R2, °C	Surface Temp. Edisto, °C	Surface Temp. Grays R., °C	Surface Temp. St. Aug., °C	Water Level Charlest, m	Water Level F. Pulaski, m	Water Level Fern. B., m	Bottom Veloc. R2, m/s	Surface Veloc. R2, m/s	Bottom Temp. CAP2, °C	Bottom Temp. FRP2, °C	Bottom Temp. CAP3, °C	Bottom Temp. SUN2, °C
HYC.	−4.47	−4.0	−10.0	−2.62	0.65	0.47	0.66	0.80	0.71	−0.66	−0.77	0.04	0.63
Case 1	−1.60	−21.4	−2.84	−12.3	0.55	0.56	0.64	0.50	0.57	−0.44	0.54	0.01	−2.15
Case 2	−2.16	−2.6	−2.50	−6.32	−0.04	0.01	0.23	0.55	0.44	−3.49	−3.34	0.10	−2.00
Case 3	−2.88	−16.0	−1.90	−11.0	0.53	0.47	0.60	0.52	0.51	−0.51	0.07	0.04	−1.82
Case 4	0.52	−10.4	−0.48	−8.36	0.65	0.67	0.70	0.77	0.62	−0.06	0.81	0.37	−0.53
Case 5	0.58	−3.1	−0.17	−2.44	0.43	0.22	0.16	0.48	0.71	−0.96	−0.15	0.72	−0.77
Case 6	0.04	−10.6	−0.18	−2.51	0.62	0.48	0.31	0.69	0.85	NO	NO	NO	NO
Case 7	0.68	−2.4	0.33	−2.39	0.55	0.36	0.27	0.42	0.65	−0.85	−0.01	0.69	−0.48
Case 8	−0.04	−8.6	−0.72	−9.28	0.35	0.36	0.40	0.42	0.39	NO	NO	NO	NO
Case 9	0.54	−3.4	−0.37	−2.43	0.39	0.13	0.12	0.47	0.70	−3.60	−3.51	0.78	−5.56

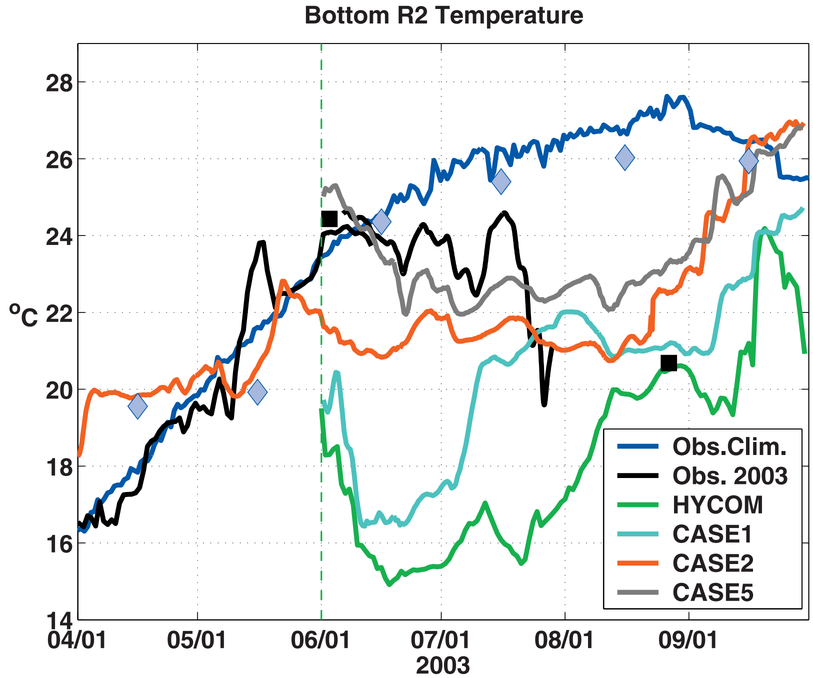

Figure 3. Time series of observed and model near-bottom temperature at the R2 tower location. The dashed gray line corresponds to the mean observed temperature for the period 1999–2004. The black line (open circle markers) is the observed bottom temperature at the R2 location during 2003 both from the tower package and the temporary mooring. The light gray line (triangle markers) is the HYCOM simulated bottom temperature at that location. The gray line (square markers) corresponds to the Quoddy model estimate for case 1, the gray line (open circle markers) corresponds to case 2, and the dark gray line (full circle markers) to case 5. The black squares correspond to bottom temperature observations taken from cruises at the R2 location on 3 June 2003 and 27 August 2003. The gray diamonds are climatological values for that location from the study by *Blanton et al.* [2003]. Note: HYCOM simulations only available from 1 June 2003.

[27] The comparison of model simulations with observations from the Caro-COOPS array off South Carolina showed better model skill for the southern (FRP2) and midshelf (CAP3) stations (Table 3). The simulation with no river discharge (case 9) did not reproduce the observed bottom temperatures at the nearshore stations (FRP2, CAP2, and SUN2). The comparison of model and observed time series (Figure 5) showed the ability of the model to reproduce the sharp transition from the anomalously cold conditions during summer of 2003 to normal conditions (climatological) during autumn that was observed at the CAP3 station, where a sudden 7°C change was appropriately captured by the different model simulations. The sharp temperature change was associated with the passage of an atmospheric front on 7–8 September 2003 that resulted in an overturning of the stratification, at least in the inner shelf and midshelf. Observations on the outer shelf during this period were not available, and the next cruise (3 October) observed well-mixed conditions. Model results showed that the transition from anomalously cold bottom temperatures to normal conditions was sharper in the northern midshelf station (CAP3) than in the southern one (R2). The impact of the atmospheric front on the nearshore stations was smaller (~1°C, not shown) because of weaker thermal stratification inshore. The breakdown of thermal stratification associated with the passage of the front was observed as well in the surface temperature signal (Figure 4) as a sudden 3°C decrease in temperature. The model captured the magnitude of the temperature decrease even if the absolute values were not reproduced.

[28] The comparison of model currents with bottom velocity observations at R2 showed good skill (RMS difference ~0.05 m/s, Table 2). The model near-bottom velocity compared well with observations in the cross-shelf direction (not shown), displaying fluctuations between onshore and offshore flow during spring and consistent onshore flow for most of the summer associated with upwelling dynamics. The along-shelf flow (not shown) was underestimated by the model (20–30% smaller than observed) and was the largest contribution to the RMS difference. This underestimate produced inaccuracies in the timing of the arrival of upwelled water from the south into the areas where it was observed. During summer, the along-shelf flow (both model and observed) was northward consistent with normal summer conditions from climatology [*Blanton et al.*, 2003]. The skill of the near-surface velocity (RMS difference ~0.15 m/s, Table 2) was lower than for the near-bottom currents. The model near-surface cross-shelf flow during spring (not shown) captured the variability of the observed flow but underpredicted its magnitude. During summer, the

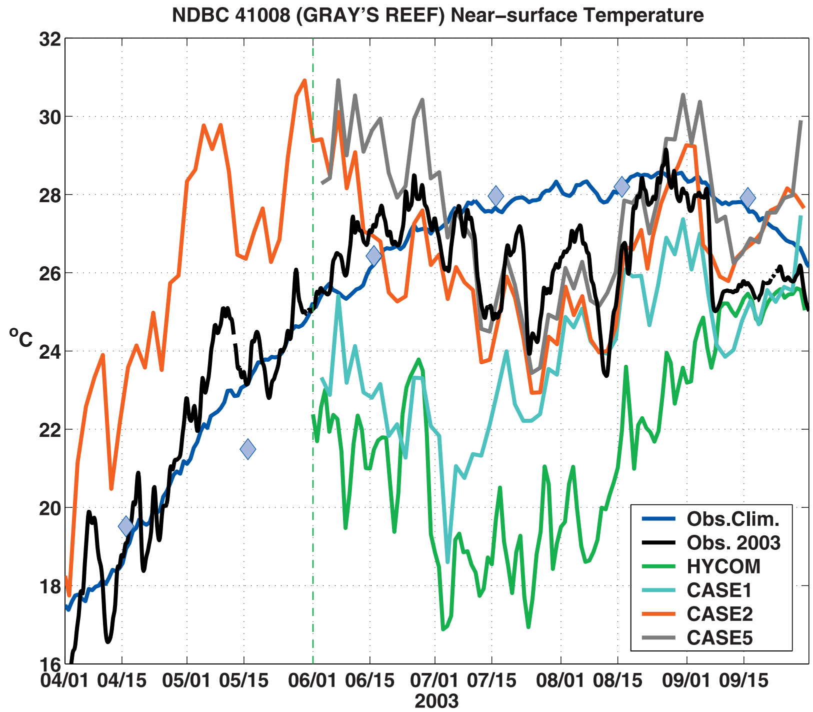

Figure 4. Time series of observed and model near-surface temperature at NDBC buoy 41008 (Gray's Reef). The gray dashed line corresponds to the mean observed temperature for the period 1988–1992 and 1996–2004. The black line (open circle markers) is the observed surface temperature at the buoy during 2003. The light gray line (triangle markers) is the HYCOM simulated surface temperature at that location. The gray line (square markers) corresponds to the Quoddy model estimate for the same location in case 1. The gray line (open circle markers) corresponds to case 2 and the dark gray line (full circle markers) to case 5. The gray diamonds are climatological values for that location from the study by *Blanton et al.* [2003].

model near-surface cross-shelf flow was consistently in the offshore direction as expected for upwelling-favorable winds.

[29] Comparison of observed and modeled water level at three coastal stations (Charleston, Fort Pulaski, and Fernandina Beach) showed adequate skill during summer (RMS difference ~0.08 m, Table 2). During spring, however, the difference between model and observations was considerable and resulted in poor skill for the case 2 simulation (Table 3). During summer, each simulation adequately captured both the phase and intensity of the water level fluctuations (not shown).

3.3. Comparison With Cruise Transects

[30] To evaluate the cross-shelf intensity and extent of the cold event, a comparison between model simulations and the complete set of cruises conducted during spring and summer 2003 was produced. In general, the model skill with respect to in situ time series was better than for cruise transect observations, since the latter requires reproducing not only point values but vertical and horizontal gradients.

[31] The model temperature in the lower part of water column along the cruise transects showed lower values than observed for both HYCOM and HYCOM-initialized simulations (for example, case 1) during June and July (not shown). The simulations initialized with climatological fields reproduced the lower part of the water column temperatures over the midshelf and outer shelf during June and July, but the surface temperatures are higher than observed (not shown). During August (Figure 6), the regional Quoddy simulations were able to reproduce the observed temperature signal for the inner shelf. HYCOM solutions for the inner shelf showed stronger stratification than observed, possibly associated with the lack of tidal mixing in the HYCOM simulation, resulting in colder than observed temperatures in the lower part of the water column. Observed temperatures in the lower part of the midshelf and outer shelf water column were colder than any of the model estimates, and the resulting observed thermal stratification was stronger than simulated. Model stratification for the 2003 simulations was higher than normal conditions (climatology), but maybe not strong enough to reproduce the dynamics associated with the cold intrusion. The mixed layer was poorly represented in several simulations because of two factors: (1) the lack of adequate meteorological forcing for this period (stronger than observed heat flux, relatively weaker than observed wind stress), and (2) the comparison between observed temperatures and daily averaged low-pass filtered model values that smoothed out some of the features from the model results. Similar vertical and horizontal gradients were estimated by every regional simulations (Figures 6d–6f). Case 1 temperatures were colder than the other simulations particularly over the outer shelf and shelf-break, but still 1.5°C warmer than observed.

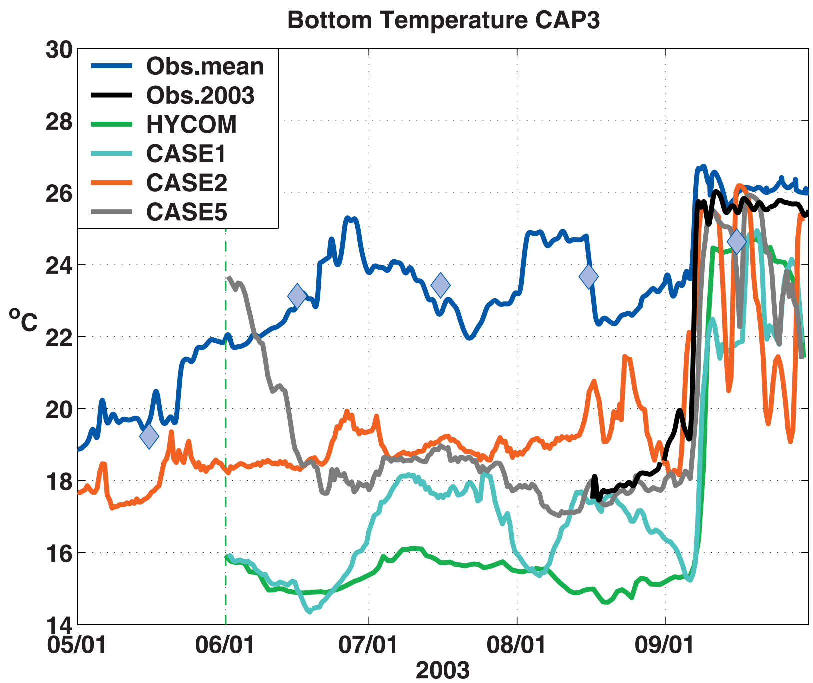

Figure 5. Time series of observed and model near-bottom temperature at the CAP3 Caro-COOPS station. The gray dashed line corresponds to the mean observed temperature for the period 2003–2005. The black line (open circle markers) is the observed bottom temperature at each station during 2003. The light gray line (triangle markers) is the HYCOM simulated bottom temperature at those locations. The gray line (square markers) corresponds to the Quoddy model estimate for case 1, the gray line (open circle markers) corresponds to case 2, and the dark gray line (full circle markers) to case 5. The light blue diamonds are climatological values for that location from the study by *Blanton et al.* [2003]. The observed Caro-COOPS time series at this station starts 15 August 2003.

[32] As a result of the anomalously high river discharge during spring 2003, the observed salinity was fresher than climatology over the inner shelf and midshelf (Figure 7). The additional buoyancy flux resulted in stronger than normal stratification during that period. Since local river discharge was not included in the HYCOM simulations, these showed higher salinity values than observed across the inner shelf. Lower salinities than climatology were estimated for the outer shelf and shelf-break caused by differences between initial salinity conditions between climatology and HYCOM. The model salinity for late June in case 1 was closer to the initialization values (HYCOM) than to the observations because the river discharge had only affected a small part of the inner shelf. In the case 5 simulation for late June, the salinity field was similar to the simulation initialized from the February climatology (Figure 7e, case 2) which included realistic river discharge throughout the spring. Case 2 was able to produce a salinity structure that closely resembled observations.

3.4. Comparison of Simulations With and Without River Discharge

[33] A model simulation was conducted without the inclusion of any river discharge (case 9). The purpose of the simulation was to isolate the effect of river discharge on thermal stratification and evaluate whether it played a role in enhancing the upwelling response and the cold water intrusion. The resulting salinity field (not shown) was substantially different because of a freshwater deficit over the shelf. By late June (Figure 8b), the temperature difference between models was small over the outer shelf, but had already produced an additional input of cold water in the simulation with river discharge over the inner shelf and midshelf, through the associated increased thermal stratification. By early August (Figure 8d), the inclusion of river discharge increased the thermal stratification in the midshelf, but remained weaker than observed (not shown). The additional stratification contributed to an increased upwelling strength via the reduction of the Ekman depth [*Aretxabaleta et al.*, 2006]. The average temperature in the lower part of the water column over the shelf was 0.3°C colder in the simulation that included river discharge (case 5). The upper part of the water column in the simulation with river discharge was warmer during the summer over the inner shelf and outer shelf. On the inner shelf, the simulation that included local river forcing (case 5) recovered the signature of the nearshore front (around the 10-m isobath, not shown), while in the simulation without river forcing, the front was not observed.

3.5. Simulation With 2002 Atmospheric Forcing (Case 10)

[34] Anomalously strong and persistent upwelling-favorable winds were observed in the SAB between May and August 2003 [*Aretxabaleta et al.*, 2006]. To evaluate the role of the atmospheric forcing on the development and

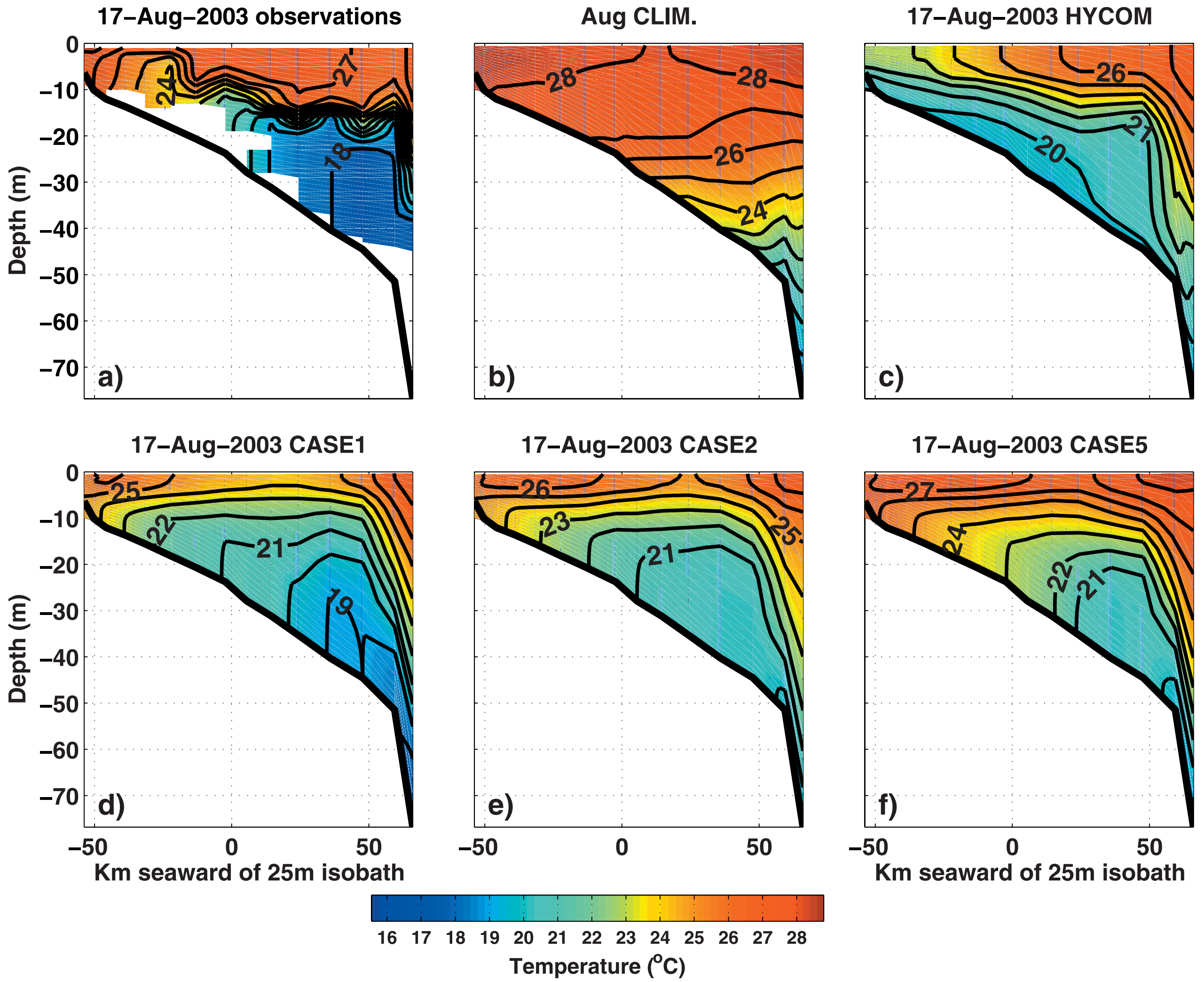

Figure 6. Observed and model temperature transect for 17 August 2003. (a) Observed temperature, (b) climatological, (c) HYCOM, (d) case 1, (e) case 2, and (f) case 5. The contour intervals are 1°C.

evolution of the 2003 event, a simulation was conducted (case 10) in which the EDAS atmospheric forcing for 2002 was imposed while maintaining the remaining 2003 forcings (river discharge, initial and boundary conditions). The atmospheric forcing for 2002 was chosen because it was considered a normal atmospheric year, based on a comparison between monthly mean wind stress and heat flux for 2002 and climatological values. The climatological atmospheric values were not used as forcing in this study because of the additional smoothing associated with the averaging.

[35] The resulting temperature fields for the simulation forced with 2002 atmospheric fields showed significantly less stratification than the normal 2003 solutions forced with 2003 winds and heat flux (case 5), and the cold intrusion in the lower part of the water column throughout the shelf was less intense (Figure 9). During late June, the surface temperature was 2°C warmer for the simulation forced with 2003 atmospheric fields than for case 10. This difference was mostly the result of the lower EDAS heat flux during 2002 (Figure 2). During June, the largest difference in water temperature associated with the atmospheric forcing occurred in the lower part of the water column over the midshelf where water temperatures were 1.5–2°C colder with the 2003 forcing. By early August (Figure 9b), the effects of the anomalous 2003 atmospheric forcing were evident in the lower part of the water column over the entire shelf, where the temperature was 0.5–1.5°C colder than resulted from the simulation forced with 2002 atmospheric fields. Over the inner shelf, the 2003 wind and heat flux forcing contributed to lower temperatures than normal in the entire water column as part of the effects of a fully developed upwelling system in midsummer. Separating the effects of wind and heat flux was not possible with this simulation.

4. Analysis

4.1. HYCOM Evaluation

[36] A fundamental concern for the development and assessment of shelf simulations is the quality of the initialization and boundary products. As part of the GODAE effort, a basin-scale ocean prediction system was developed using HYCOM and its performance is currently being

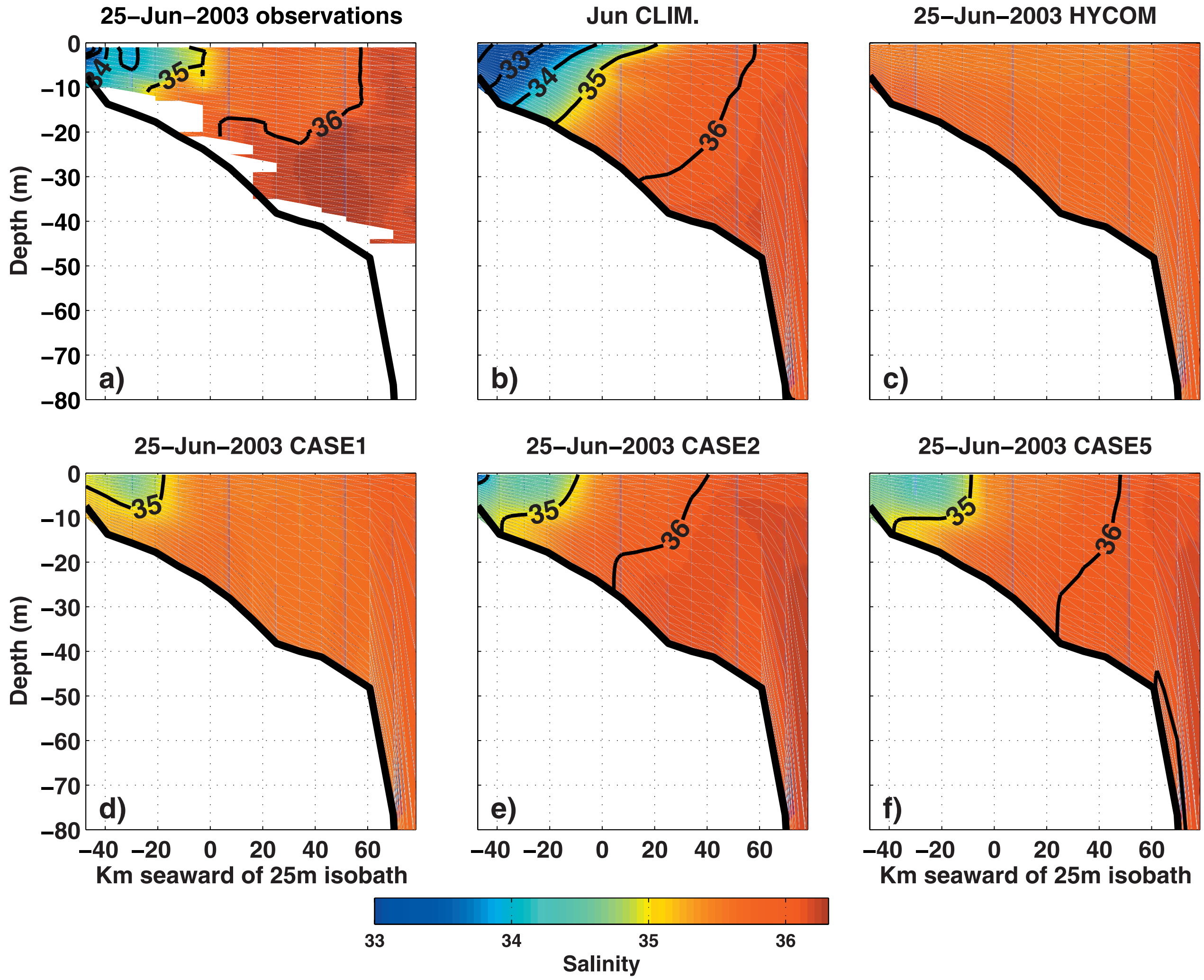

Figure 7. Observed and model salinity transect for 25 June 2003. (a) Observed salinity, (b) climatological, (c) HYCOM, (d) case 1, (e) case 2, and (f) case 5. The contour intervals are for every unit of salinity.

assessed. One of the objectives of this initiative was to provide boundary conditions to finer-resolution coastal models such as the present setup. In this study, we did not assess the quality of the entire basin-scale HYCOM solution, nor was the quality of the solution systematically evaluated over the SAB shelf. Rather, possible influences introduced by using HYCOM products as initialization and boundary forcing during the specific period of summer 2003 were considered. A rigorous evaluation of the character of the HYCOM solution in the SAB shelf is underway [*Blanton et al.*, 2005].

[37] When HYCOM solutions were compared to observed mass fields, several differences were evident. First, the absence of any river discharge along the SAB coast in the HYCOM system resulted in mostly uniform salinities over the shelf (Figure 7c). Second, the HYCOM temperature in the lower part of the water column in the midshelf and outer shelf during June was colder (up to 7°C) than observed (not shown). The HYCOM surface temperature in June was 2–3°C colder than observed across the entire shelf in the central SAB as well. Third, during August, the temperature in the lower part of the midshelf and outer shelf water column was 2–4°C warmer than observations (Figure 6c). However, the surface temperature in August remained 2–3°C colder than observed, resulting in weaker stratification in the model solution.

[38] The purpose of the HYCOM operational product is not to simulate the conditions over the relatively small region and short timescales that are the focus of the current study. The skill metrics of the basin-scale simulations focus on recovering the appropriate variability in large scales, but do not guarantee accuracy in shelf-scale specific events. Limiting factors include inconsistencies in bottom topography, limited resolution over the shelf, and the lack of certain dynamics (notably tidal forcing) that are fundamental for shelf processes. Still, the basin-scale solution captured, at least partially, the cold event in the SAB during summer 2003 (not shown), although the magnitude of the event was not consistent with observations during that period. Considering the limitations, the HYCOM solution buildup of water colder than climatology over the shelf during the summer of 2003 is encouraging and supports further appli-

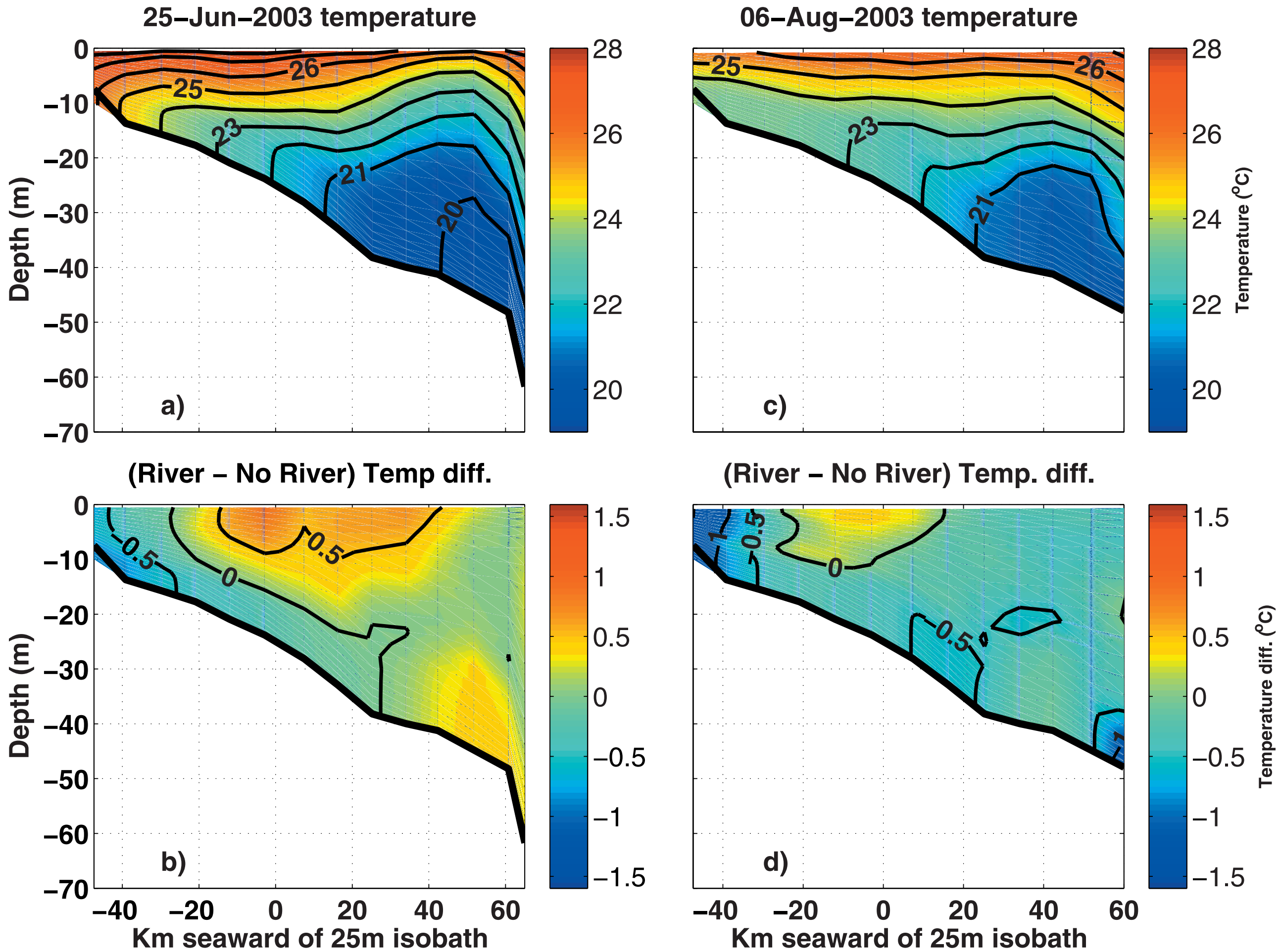

Figure 8. Temperature comparison for simulations with (case 5) and without (case 9) river discharge. (a) Model (case 5) temperature transect for 25 June 2003. (b) Temperature difference (case 5 minus case 9) for 25 June 2003. (c) Same as Figure 8a but for 6 August 2003. (d) Temperature difference for 6 August 2003. The contour intervals are 1°C (0.5°C) for the top (bottom) panels.

cation of basin-scale models, such as HYCOM, to provide open-ocean forcings for shelf-scale simulations.

4.2. Dynamics of the Cold Anomaly

[39] In this section, the model results are analyzed to describe the circulation over the SAB shelf and the dynamics of the intrusion and estimate the total volume of anomalously cold water upwelled onto the shelf. The model simulations used in this analysis are case 5 for the period of June-September and case 2 for any analysis that required solutions before June (before HYCOM was available).

[40] The model along-shelf flow was small over most of the shelf and was dominated by northward flow on the outer shelf over the spring and summer period (not shown). The along-shelf flow advected the already upwelled water from the south into the region in which it was observed, which was consistent with the mechanism proposed in previous studies [*Atkinson et al.*, 1987; *Aretxabaleta et al.*, 2006]. The cross-shelf velocity showed slow downwelling flow during February and March. In May, there was a transition to upwelling conditions with near-surface offshore flow and near-bottom onshore flow. Upwelling conditions persisted through the entire summer over most of the shelf, especially over the inner shelf and midshelf. Over most of the outer shelf, the model result showed near-bottom onshore flow between June and early September. As noted above, the upwelling flow was abruptly ended by the passage of the atmospheric front on 7–8 September 2003. After the passage of the front, predominantly downwelling flow was estimated for most of the inner shelf and midshelf. On the outer shelf, onshore flow was still present but was highly variable associated with the Gulf Stream and its frontal features (not shown).

[41] The model cross-shelf flow presented substantial temporal and spatial variability. To evaluate where the shelf flow was predominantly on-shelf or off-shelf, a set of along-isobath daily mean velocity transects (flow across the 40- and 75-m isobaths) were generated from the model solution (Figure 10). An onshore maximum in the flow across the 40-m isobath (transition between midshelf and outer shelf) was found between 29° and 30.5°N latitude (Figures 10c and 10e). This maximum extended through the entire water column and peaked during August (flow > 0.3 m/s onshore, Figure 10e). North of this maximum, during the entire summer period (June-August), upwelling conditions were evident with offshore flow predominating in the upper 10 m

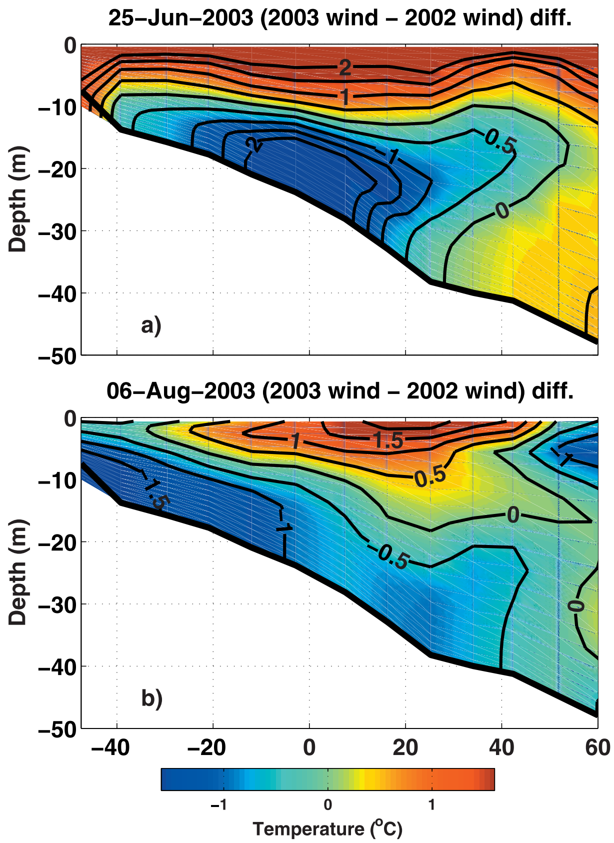

Figure 9. Temperature differences for simulations forced with 2003 EDAS atmospheric fields (case 5) and with 2002 fields (case 10). (a) Model temperature difference (cases 5–10) for 25 June 2003. (b) Same as Figure 9a but for 6 August 2003. The contour intervals are 0.5°C.

of the water column and weak onshore flow below the surface layer. The maximum offshore surface flow during summer (~0.2 m/s) occurred in the northern part of the domain (Figure 10e).

[42] The daily average model flow across the 75-m isobath showed high temporal variability during spring associated with changing wind direction and the passage of Gulf Stream meanders (not shown). By early June (Figure 10b), relatively weak onshore flow ($-0.2 <$ flow < 0 m/s) was simulated for the central SAB, between 30° and 31.5°N. By late June (Figure 10d), strong onshore flow was simulated for the entire water column from the southern boundary of the domain (28.5°N) to 32°N, with strongest flow (~1 m/s) around 29.5°N. The northernmost part of the model domain, around 32.5°N, was the only region with weak offshore flow, associated with the energetic Gulf Stream dynamics in the proximity of the Charleston Bump. These conditions persisted until the end of August (Figure 10f), with sporadic intensifications of the offshore flow near the Charleston Bump.

[43] The spatial distribution of the cross-shelf flow (Figure 10) suggests that most of the anomalously cold water came onto the shelf north of Cape Canaveral, FL, between 28.5°N and 30°N. This result is consistent with earlier studies that suggested the point of entrance of Gulf Stream water onto the SAB shelf is associated with Gulf Stream interaction with the divergent isobaths north of Cape Canaveral [*Blanton et al.*, 1981; *Atkinson et al.*, 1987; *Lorenzzetti et al.*, 1987]. The model flow across the 40-m isobath suggests that the cold water reached the midshelf in the southern part of the domain, then flowed predominantly along isobaths into the central and northern portions of the model domain (not shown) except for relatively weak near-bottom contributions (Figures 10c and 10e). The action of this locally forced upwelling modified slightly the advection of cold water into the observation region through near-bottom cross-shelf flows in the midshelf in the region north of 30.5°N (Figures 10a, 10c, and 10e).

[44] The distribution of anomalously cold water on the SAB shelf from spring through summer 2003 was calculated by estimating the areas of the model results that were more than 2°C colder than climatological values. The temperature anomaly magnitude (absolute value of model minus climatological temperatures) was vertically averaged over the entire water column. Case 2 is considered so that the comparison could be extended from May until September. The difference in the depth-averaged temperature anomaly magnitude between cases 2 and 5 is small (RMS difference ~0.4°C). The evolution of the anomalously cold water on the shelf is shown in Figure 11, where only the areas where the vertically averaged anomaly magnitude was more than 2°C are represented. The area impacted by the anomalously cold water increased from May until early August. During July and early August, the area affected by the pool of cold water remained fairly constant. The maximum cold water anomaly occurred in the northern part of the domain (north of 32°N) over the outer shelf (temperature anomaly ~5°C colder). The colder anomalies on the outer shelf in the northern part of the model domain (north of 32°N) are partly explained by considering that, during a normal summer, the southern region of the SAB is the area typically affected by subsurface intrusions [*Atkinson et al.*, 1987], and therefore the presence of cold water in the northern area is more anomalous. A related anomaly occurred in the region north of Cape Canaveral over the inner shelf and midshelf during July and appeared to propagate northward by early August. During September, the temperature anomaly disappeared first from the inner shelf in the north and central regions and then from the midshelf by mid-September. The cold anomaly persisted over the outer shelf in the northern region into mid-September.

[45] The volume of anomalously cold water on the shelf (defined as above, but for a full three-dimensional volume estimate) was estimated, and the resulting volumes are presented in Table 4. In mid-May, the pool of anomalously cold water represented around 5% of the entire shelf volume. This percentage rapidly increased from late May to early June, reaching a peak in mid-July and early August (61.6%, volume > 800 km^3). During August, the volume of the cold anomaly started decreasing, and by mid-September, the anomalous water occupied 5% of the shelf volume. As a reference value, the volume of water present in one of the cold water domes associated with Gulf Stream frontal eddies [*Bane et al.*, 1981; *Lee et al.*, 1981; *Lee and Atkinson*, 1983] is on the order of 600 km^3 (length ~ 50 km, width ~ 40 km, depth ~ 300 m). This suggests that in the hypothetical case in which a single frontal eddy

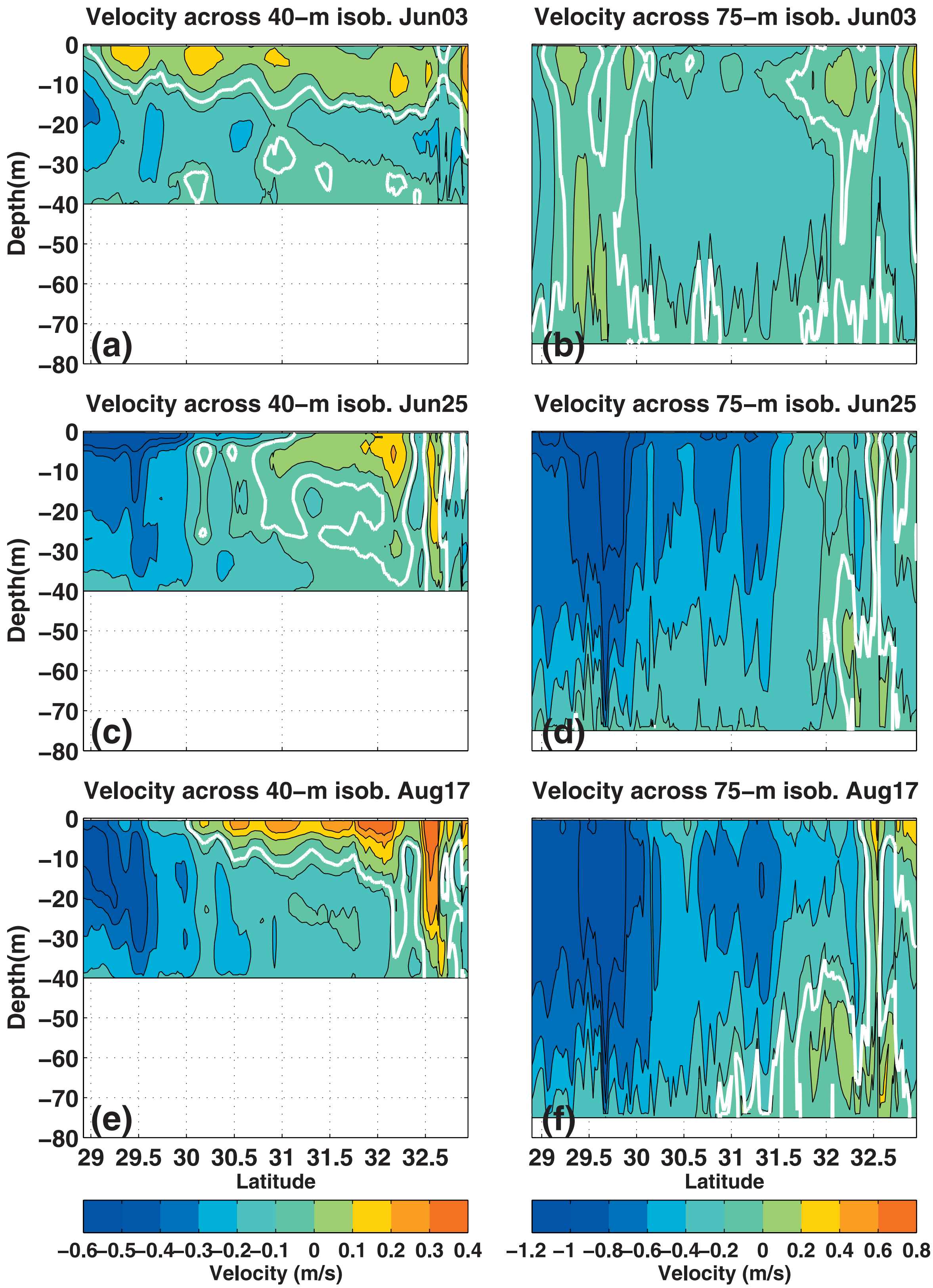

Figure 10. Daily average model velocity across the 40-m (left) and 75-m (right) isobaths. The top row (a, b) corresponds to the flow during 3 June 2003, the middle row (c, d) is for 25 June 2003, and the bottom row (e, f) is for flow during 17 August 2003. Negative values correspond to onshore flow, and the white contour corresponds to zero cross-shelf flow. The *x* axis is latitude in degrees. Note that the range of velocity values for the left panels is smaller than the range for the right panels.

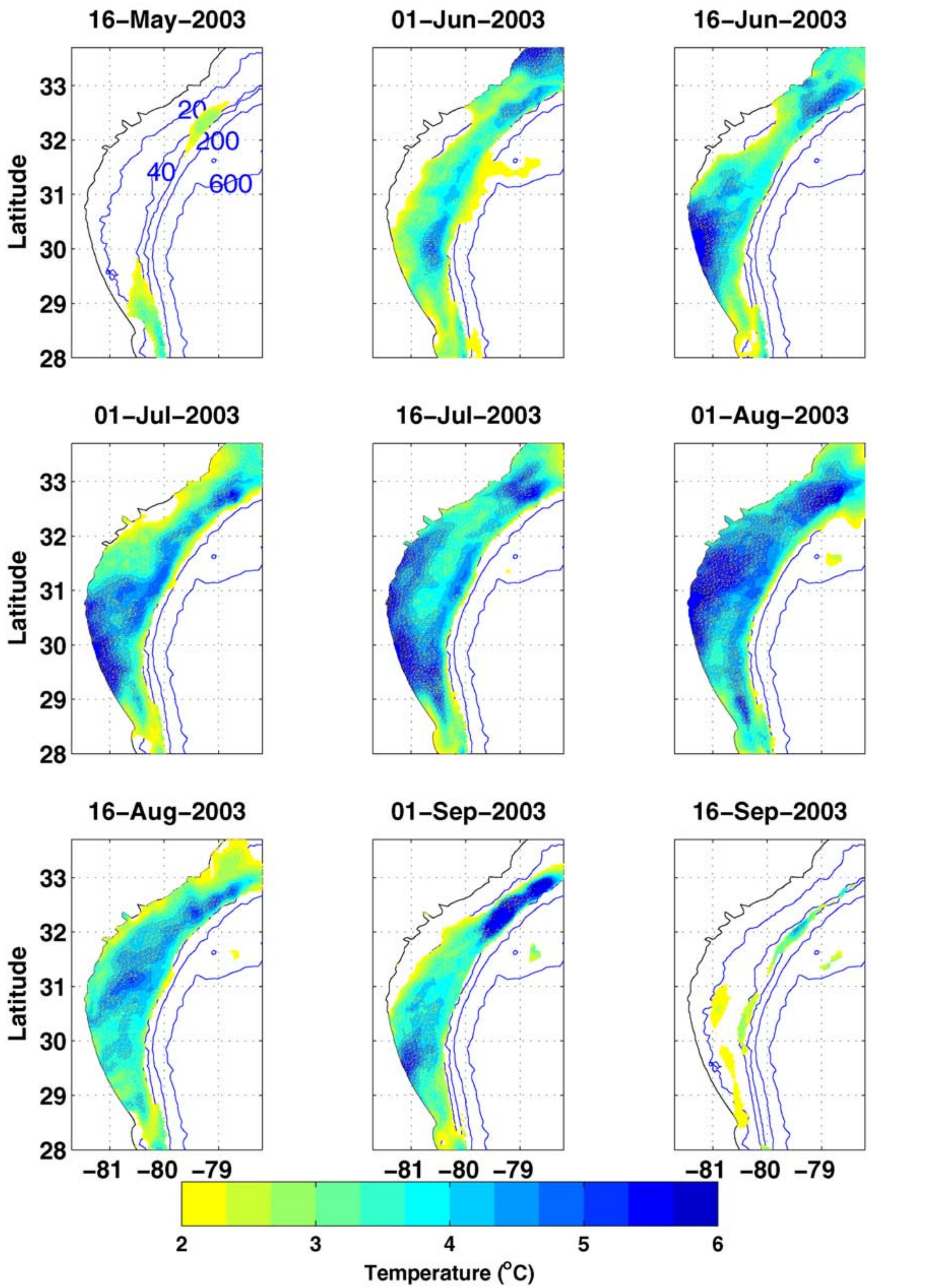

Figure 11. Vertically averaged temperature anomaly magnitude in the model domain. The anomalously cold water is defined as water more than 2°C colder than climatological values for that month ($T_{anol} = |T_{mod} - T_{clim}| > 2°C$). The white areas inside the model domain correspond to areas in which the model temperature difference with climatology is smaller than 2°C ($T_{anol} = |T_{mod} - T_{clim}| < 2°C$). The 20-, 40-, 60-, 200-, and 600-m isobaths are shown.

Table 4. Volume of Anomalously Cold Water (More Than 2°C Colder Than Climatological Values) on the Model Domain[a]

	Volume (km^3)	Percentage
16 May 2003	73	5.3
1 Jun 2003	602	43.8
16 Jun 2003	512	37.2
1 Jul 2003	687	50.0
16 Jul 2003	788	57.3
1 Aug 2003	846	61.6
16 Aug 2003	655	47.8
1 Sep 2003	477	34.9
15 Sep 2003	69	5.0

[a]The total volume of the shelf enclosed in the model domain is 1380 km^3.

dome were to be upwelled onto the shelf, it would essentially occupy the lower part of the water column over the entire shelf region.

4.3. Biological Implications

[46] The presence of anomalously cold water over much of the SAB shelf during the summer of 2003 had consequences beyond the dynamical aspects of the event. The cold water upwelled into the shelf is enriched in nutrients that can support new primary production on the shelf. Subsurface (bottom layer) phytoplankton blooms were observed during the summer of 2003. Chlorophyll concentrations in the warm surface mixed layer in the central SAB shelf region ranged from 0.2 to 0.3 mg m^{-3} in July and 0.3–0.8 mg m^{-3} in August, while concentrations in the colder bottom layer ranged from 1 to 4 mg m^{-3} in July and 3–6 mg m^{-3} in August [*Aretxabaleta et al.*, 2006]. Bottom chlorophyll concentrations were similar to those observed during the summer of 1981, another major upwelling event [*Yoder et al.*, 1985; *Paffenhöfer and Lee*, 1987].

[47] Several studies have considered the biological effects of the nutrient flux associated with Gulf Stream frontal eddies and bottom water intrusions on the SAB shelf [*Atkinson et al.*, 1982, 1984; *Lee et al.*, 1991]. Hypothetical nitrate concentrations for waters unexposed to biological activity can be calculated given the temperature using the relationship derived by *Atkinson et al.* [1984] for the SAB: $NO_3 = 38.21 - 1.67T$ (°C). This relationship has been used in several previous studies in the SAB [*Hofmann*, 1988; *Pribble et al.*, 1994] and was applied in this study to

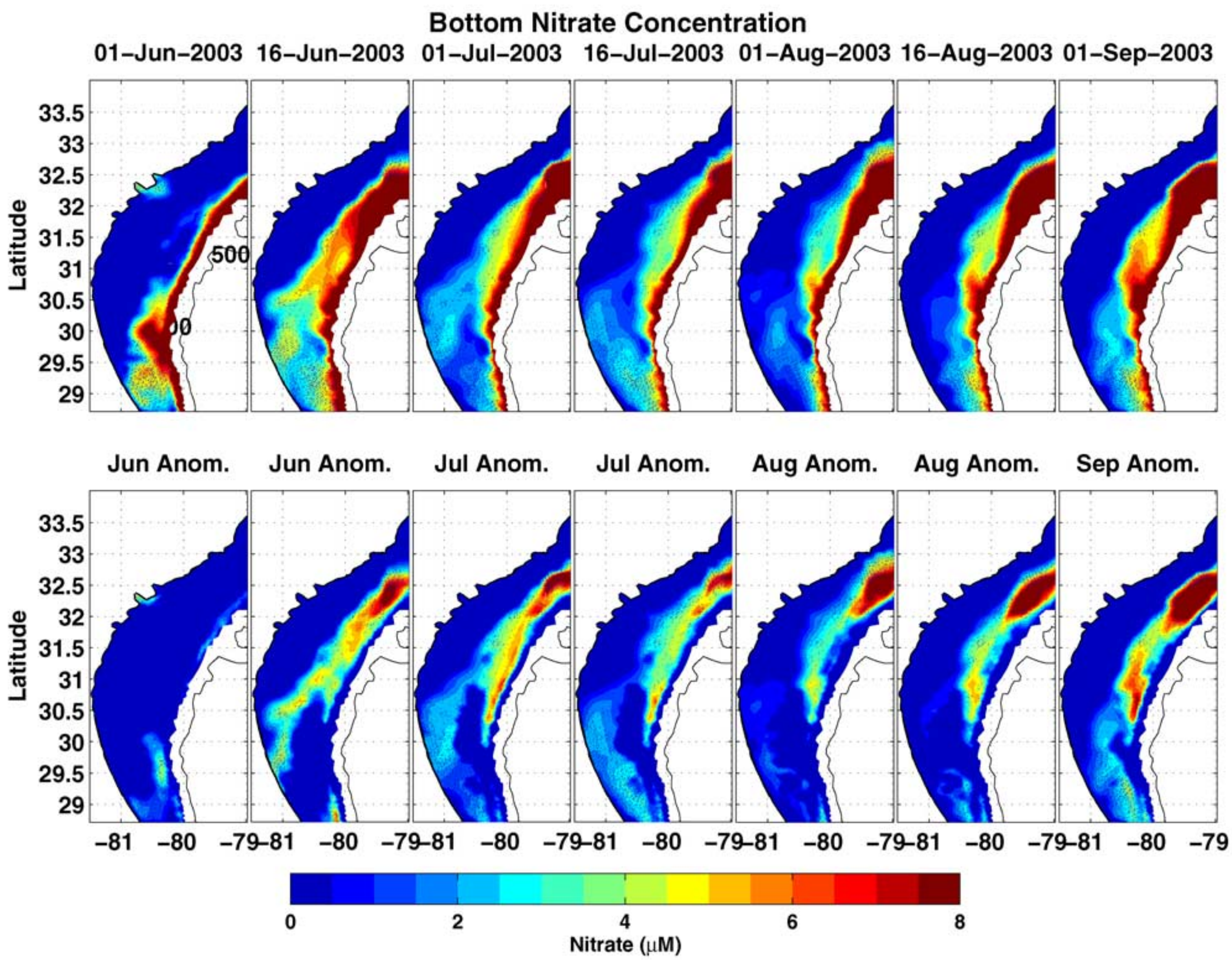

Figure 12. (Top) Bottom potential nitrate concentration (μM) assuming no biological uptake for the central SAB shelf during 2003 estimated from the empirical relationship developed by *Atkinson et al.* [1984]. $NO_3 = 38.21 - 1.67T$ (°C). (Bottom) Bottom potential nitrate concentration anomalies (departures from values estimated from climatology). The 20-, 40-, 100-, and 500-m isobaths are shown.

evaluate where on the shelf new production may have been significantly enhanced during the 2003 cold water event.

[48] The resulting potential nitrate concentration estimates were greater than climatological values for much of the shelf throughout the summer of 2003 (Figure 12). The highest potential concentrations during 2003 occurred along the shelf-break, but significantly higher values than estimated from climatology were predicted for most of the midshelf and outer shelf. The potential concentrations estimated for the outer shelf were greatest between mid-June and early August. The maximum anomalies in potential nitrate concentration were estimated for the inner shelf and midshelf in the central SAB during mid-July and early August. This is consistent with the fact that cold water and elevated nitrate concentrations are common over the shelf-break and outer shelf (associated with the passage of Gulf Stream frontal eddies). But in most years, the influence of the frontal eddies and associated upwelling does not reach the inner-shelf region, especially in the central SAB, where the shelf is wider.

[49] The spatial structure and magnitude of the bottom potential nitrate concentration estimated for 2003 in the southern part of the model domain (between 29° and 31°N) was similar to observed concentrations during 1981 [*Paffenhöfer and Lee*, 1987]. For the 2003 event, the maximum potential nitrate concentrations were estimated for the outer-shelf region north of 31.5°N; however, no observations were available for this area for either year. The distribution in the midshelf was similar in both years with peaks associated with specific intrusion events. In the inner shelf, the potential nitrate concentration during 2003 was greater than observed during 1981 [*Paffenhöfer and Lee*, 1987] and much greater than estimated from climatological bottom temperature. On the basis of this initial evaluation, the nutrient flux associated with the anomalously cold subsurface water may have stimulated increased primary production over much of the SAB shelf in the summer of 2003.

5. Discussion

[50] Comparisons of model simulations with in situ observations show the ability of the model to capture complex shelf processes, such as the 2003 cold water event. The model skill (Tables 2 and 3) shows encouraging progress toward the reproduction of temperature, salinity, velocity, and water level cycles and gradients. However, a rigorous study of the level of skill required for the different parameters in regional-scale model simulations needs to be conducted. Nonetheless, the present study has contributed to the understanding of baroclinic dynamics on the SAB shelf including the role of river discharge in the development of stratification and the importance of stratification in the intensification and extension of cold water intrusions.

[51] From the results of this study, we can characterize the relative importance of different forcing mechanisms to the development and intensity of the cold event of 2003. The main factor controlling the event, at least in the midshelf, was the presence of anomalously intense and persistent upwelling-favorable winds (Figure 9). The model simulations suggest that the atmospheric forcing not only influenced the upwelling process during the summer but contributed to the development of the stratification during spring as well, by the combined effects of wind and heat flux (not shown). Both the salinity stratification during spring and the subsequent thermal stratification during summer enhanced the upwelling process (via the reduction of the Ekman depth [*Aretxabaleta et al.*, 2006]) and the shoreward propagation of the intruded water on the shelf. Previous studies explained the cold water intrusions observed during the summer of 1981 as resulting from a combination of upwelling-favorable winds, proximity of Gulf Stream to the shelf-break, and Gulf Stream frontal eddy activity [*Lee and Pietrafesa*, 1987; *Hamilton*, 1987]. During 2003, the contribution of the stratification, which set up during spring and strengthened during summer, preconditioned the shelf for an extreme upwelling event. However, since the stratification in the model solutions was weaker than observed (Figure 6), a full evaluation of stratification effects on the development of the cold water intrusion was not achieved in the present study.

[52] The river discharge directly influenced the stratification over the inner shelf and midshelf (Figure 8) and contributed to the strengthening of the intrusion process. The inclusion of freshwater discharge is also fundamental to appropriately describe the dynamics of the inner shelf, the salinity balance, and the interaction between inner shelf and midshelf processes (Figure 7). The inclusion of realistic buoyancy fluxes was associated with a retention of relatively colder water over the inner shelf, representing an expression of the nearshore front (around the 10-m isobath). A rigorous evaluation of the sensitivity of the model solution to river discharge and the assumed salinity of the water input at the coastal boundary (salinity = 20, in this study) will be needed to achieve realistic salt balance for the SAB shelf.

[53] The Gulf Stream and its associated frontal eddies controlled the input of cold water into the shelf, predominantly in the southern part of the model domain, north of Cape Canaveral (Figures 10d and 10f). The intrusion process into the midshelf (onshore flow in the bottom layer) was more pronounced in the southern part of the domain (Figures 10a, 10c, and 10e), while offshore flow in the northern part compensated the onshore flow. A more complete evaluation of the importance of the Gulf Stream and other open-ocean effects in the generation and evolution of the intrusion of cold water onto the shelf requires additional model simulations and observations to confirm realistic Gulf Stream dynamics during the 2003 event. This constitutes a challenge, since the model simulations needed, both basin- and regional-scale, should realistically reproduce the Gulf Stream dynamics, not just statistically but also the magnitude, extent, and timing of specific meanders and frontal eddies associated with the stream.

[54] The evaluation of model results over the outer shelf was limited because of the reduced availability of observations in this part of the SAB. The outer-shelf dynamics are strongly influenced by open-ocean processes such as the passage of Gulf Stream frontal eddies and meanders [*Lee and Atkinson*, 1983]. Basin-scale models, like HYCOM, provide an important source of open-ocean forcing estimates for coastal ocean models. The comparison with short-time, limited-scale events like that presented in this study constitutes a challenging measure of skill for basin-scale models. Although the magnitude of the cold event of 2003

was not completely captured by HYCOM, we believe the results of these simulations constitute encouraging progress in our efforts to downscale from basin- to regional-scale domains. The use of climatological estimates of initial and boundary conditions remains a useful approach until more reliable products are fully developed. A possible alternative to either climatological or HYCOM fields is the development of fields for initial and boundary conditions using data assimilation (for example, optimal interpolation, weighted least squares, ensemble smoother) using both climatological estimates, basin-scale products, such as HYCOM, and in situ and remote observations.

[55] In addition to the factors discussed above, some of the differences between model fields and observations might be related to the atmospheric forcing product provided by EDAS (Figure 2). Inappropriate heat flux in the inner shelf and midshelf regions or underestimated wind stress might explain inconsistencies in surface temperature (Figure 4) and in the level of stratification (Figure 6). Another factor affecting the level of stratification may be the turbulence closure scheme (Mellor-Yamada 2.5 [*Mellor and Yamada*, 1982] in this study).

[56] Further analyses will also be required to better exploit the potential of the physical modeling system for biogeochemical applications. In order to appropriately characterize the new primary production associated with the nutrient flux during 2003, an evaluation of both 2003 and climatological nitrate fluxes should be conducted. A rigorous comparison of net eddy fluxes (nitrate, $\overline{u'NO_3'}$; heat, $\overline{u'T'}$; and momentum, $\overline{u'v'}$) with previous estimates from observations [*Lee et al.*, 1991] is planned. Future studies will include an evaluation of these fluxes from model results and model estimates of primary production to evaluate both climatological conditions (complementing the results from the study by *Blanton et al.* [2003]) and anomalous conditions such as those observed during 2003.

6. Conclusions

[57] Model characterization of baroclinic processes on the central SAB shelf during spring and summer of 2003 was achieved. Comparison of model results with observed velocity, water level, and surface and bottom temperature showed that the model was capable of adequately simulating baroclinic and barotropic processes on the shelf. The inclusion of atmospheric forcing from EDAS, river discharge from USGS, and a higher-order advection scheme for the model dynamics produced a good level of model skill over the inner shelf and midshelf especially during the summer (RMS difference $\sim$1°C in bottom temperature and RMS difference $\sim$0.05 m/s in near-bottom velocity).

[58] The results of the simulations indicate that atmospheric forcing (anomalously strong and persistent upwelling-favorable winds and heat flux) was the main mechanism controlling the magnitude of the cold water intrusion over the inner shelf and midshelf. The anomalous river discharge resulted in stronger than normal stratification in late spring and through the summer, and had a complementary effect by intensifying the magnitude of the cold water intrusion. The model estimated considerably less stratification than was observed, and therefore the evaluation of the stratification effects on the 2003 intrusion was only approximated. Some of the differences between model and observations might have been related to limitations of the atmospheric forcing product provided by EDAS (for example, heat flux magnitude and daily cycle, magnitude of wind stress) and/or the turbulence closure scheme used.

[59] Despite these limitations, the dynamics of the cold water intrusion event could be characterized. The intrusion of cold water onto the SAB shelf, initiated in late May, occurred predominantly along the shelf-break, especially in the southern part of the domain, north of Cape Canaveral (between 28.5°N and 30°N). By mid-July, the resulting pool of anomalously cold water constituted almost half of the water on the shelf. The maximum temperature anomalies occurred over the outer shelf in the northern part of the domain (north of 32°N) and in the region north of Cape Canaveral over the inner shelf and midshelf. The passage of an atmospheric front in early September resulted in the overturning of the stratification in the inner shelf and midshelf and abruptly transformed the anomalous temperature conditions into normal conditions for that period.

[60] The use of updated mass field boundary conditions from basin-scale HYCOM simulations and climatological fields represents an improved mechanism for providing offshore and upstream influences into regional and shelf-scale simulations. The nesting process described in this study requires further development in order to transfer basin-scale forcings all the way to the near shelf, but the current results constitute significant progress.

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