Evaluation Report for the NOAA Real Time Ocean Forecast System Atlantic (RT_OFS_ATL)

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Abstract

The Real Time Ocean Forecast System Atlantic (RT_OFS_ATL) was evaluated by the NOAA Ocean Prediction Center for potential use as a forecasting tool. The evaluation focused on sea surface temperature (SST), surface features, and location of current features, as these are the most applicable fields to marine forecasting and would be the first fields introduced to forecasters. RT_OFS_ATL was compared to the daily 0.25° Optimum Interpolation SST analysis (OI SST) produced by the NOAA National Climatic Center (NCDC), in situ SST and NOAA National Data Buoy Center (NDBC) buoys over a 13 month period from June 2007 through July 2008. Across the entire domain, RT_OFS_ATL compared well with the OI SST analysis and in situ and buoy SSTs. RT_OFS_ATL was slightly cooler than the OI SST analysis (-0.09º C), cooler than the in situ SSTs (-0.11º C) and slightly warmer than the NDBC buoys along the East Coast and in the Gulf of Mexico (+0.17º C).

RT_OFS_ATL was evaluated in 3 sub-regions across the western North Atlantic from the Canadian Maritimes to the subtropics and the Gulf of Mexico. These sub-regional comparisons highlighted a warm bias in the Northwest Atlantic and premature separation of the Gulf Stream from the shelf waters by RT_OFS_ATL from east of South Carolina northward. The Gulf Stream position reflected in RT_OFS_ATL currents and in SST comparisons has shown significant differences with the Navy Gulf Stream analysis. The early separation and resulting misplacement of the Gulf Stream prohibits the OPC from using RT_OFS_ATL now to aid forecasters with Gulf Stream related forecast problems such as wind-current interaction and the resulting enhancement of waves. It is assumed that the data assimilation using various sources of in situ and remotely sensed thermal and Sea Surface Height Anomaly requires fine tuning to improve the placement of the main body of the Gulf Stream. Once the placement of the Gulf Stream is improved, the OPC encourages the coupling of RT_OFS_ATL with the NOAA Wavewatch III model in a parallel mode. RT_OFS_ATL compared well with SST analyses and the NCOM model in the southern Mid-Atlantic latitudes and in the tropics, and should provide improvement in the forecasting of tropical cyclones.

Introduction

The Real Time Ocean Forecast System Atlantic (RT_OFS_ATL) is a high resolution ocean circulation model developed by the Marine Modeling and Analysis Branch (MMAB) of NOAA National Centers for Environmental Prediction (NCEP) Environmental Modeling Center (EMC) and based on the Hybrid Coordinate Ocean Model, HYCOM (Bleck and Boudra, 1981). HYCOM was developed by the HYCOM Consortium for Data Assimilative Modeling of which MMAB is an active participant. Information regarding the HYCOM Consortium can be found at the following web site http://hycom.rsmas.miami.edu/index.shtml. The NOAA version of HYCOM uses a curvilinear grid favoring the western Atlantic, with the highest resolution of 5 km along the US coastline to 9-17 km resolution along the European and African coastlines. HYCOM uses isopycnal coordinates in the stratified open ocean, z coordinates in both the mixed layer (surface down to as deep as 200 meters in very high winds) and the unstratified open ocean, and terrain-following (sigma) coordinates in the shallow coastal ocean. HYCOM, through the use of hybrid coordinate systems, extends the coverage of traditional models by best representing the stratified open-ocean, unstratified seas, and the coastal ocean.

The operational RT_OFS_ATL presently covers the Atlantic Ocean from 25° S to 70° N (Fig. 1) with plans of expanding to a global model in the future. Model files are produced once daily and are available about 1400 UTC. Each daily model run starts with a 24 hour assimilation hindcast and creates hourly surface forecasts and full volume forecasts every 24 hours starting with 0000 UTC through 120 hours. The forecast was extended to 144 hours after the evaluation period in this report. Fields for sea surface temperature, sea surface currents, sea surface height, salinity and mixed layer depth are available in the hourly files. In order to display the model fields in the N-AWIPS (National centers - Advanced Weather Interactive Processing System) operational workstations used by the Ocean Prediction Center, latitude / longitude grid files in GRIB format are generated by MMAB from the native curvilinear grid files. Files are provided for the entire model region in the Atlantic (Figure 1) and two smaller domains; the Gulf Stream region (Figure 2) and the Gulf of Mexico (Figure 3). The Atlantic region has a resolution of 0.255 degrees in latitude and longitude. The RT_OFS_ATL grid for the Gulf Stream has a resolution of 0.046 degrees and the Gulf of Mexico grid has a resolution of 0.034 degrees.

The data assimilation occurs over a simulated 24 hour spin-up period prior to 0000 UTC for each day's model run. The assimilation includes satellite sea surface temperature (SST) from GOES (bias corrected with AVHRR data), and AVHRR SST. In-situ SST from ships and buoys are not assimilated at this time but will be added in the future. Sea Surface Height (SSH) is assimilated from the Jason and GFO altimeters with plans to add Jason-2 and ENVISAT SSH sources in the very near future. There are also plans to assimilate temperature and salinity profiles from Argos floats, XBTs of opportunity and data from Conductivity, Temperature, and Density casts (CTDs). The open boundaries are defined from climatology (NCEP version 6). River inflow data for U.S. rivers are from the USGS and from the RivDIS climatology (http://www.rivdis.sr.unh.edu/) for foreign rivers. Surface forcing is provided by the NCEP Global Forecast System (GFS) 3 hourly model output. For more in depth information about the RT_OFS_ATL model including monitoring and evaluation by MMAB (see http://polar.ncep.noaa.gov/ofs).

N-AWIPS Description for Users

The RT_OFS_ATL model is available in N-AWIPS under Grid/rtofs_watl, Grid/rtofs_gstr, and Grid/rtofs_gmex. The rtofs_watl selection is the entire model region that covers the Atlantic Ocean from 26.5° S to 75.25° N including the Gulf of Mexico (Figure 1). The resolution of the rtofs_watl grid is 0.255 degrees in latitude and longitude and the grids are available in hourly time steps. The rtofs_gstr option is for the Gulf Stream region (Figure 2) of the Atlantic (25° N to 48° N and 83° W to 52° W), has a resolution of 0.046 degrees and is available in 24 hourly time steps. The Gulf of Mexico region (Figure 3; 15° N to 32° N and 98° W to 70° W) is the rtofs_gmex option, has a resolution of 0.034 degrees and is available in 24 hourly time steps.

Parameters available to OPC forecasters in N-AWIPS from RT_OFS_ATL are: sea surface temperature (SST), surface currents, and sea surface height (SSH). Each region has a specific SST contour map tailored to best highlight the range of surface temperature across specific waters. The following examples in nmap can all be viewed by loading the Rtofs_Intro restore file. The Gulf of Mexico region's SST is best viewed by selecting:
GRID/rtofs_gmex/YYMMDD_0000/oceanic/SST_CONTOURS_GMEX.

In order to view the currents in the Gulf Stream region, select:
GRID/rtofs_gstr/YYMMDD_0000/oceanic/CURRENT_CONTOURS_DIR.
The arrows illustrate the direction and the color scale shows the magnitude of current in knots.

The sea surface height (SSH) for the Gulf Stream region can be found under:
GRID/rtofs_gstr/YYMMDD_0000/oceanic/SURFHGT_CONTOURS.
The sea surface height is measured in meters above and below the geoid, a standardized zero reference height for the earth. When displaying a loop of SSH across the entire model domain (watl option) using an hourly time step, the tides can be seen nicely rotating in a counter-clockwise motion around the North Atlantic basin.

An additional GEMPAK calculated field from RT_OFS_ATL is the magnitude of the SST gradient. This option for SST gradient in the Gulf Stream region is:
GRID/rtofs_gstr/YYMMDD_0000/oceanic/MAG_SST_GRADIENT.
The higher magnitude contours highlight frontal zones in RT_OFS_ATL. The north wall of the model based Gulf Stream shows up fairly well using the magnitude of SST gradient. Meanders of the Gulf Stream and eddies are also quite evident. Comparing the magnitude of SST gradient with the RT_OFS_ATL currents is helpful to identify features in the model. OPC forecasters, through their experience with remotely sensed near

surface winds, often look for areas of wind flow across gradients of SST as regions of changes of stratification of the Marine Atmospheric Boundary Layer and wind speed.

Regions for Evaluation

To evaluate the performance of the model, the RT_OFS_ATL grid was divided into regions with unique ocean characteristics (Figures 1 - 3). Comparisons were made over the entire RT_OFS_ATL region to estimate the overall performance of the model (Figure 1). Comparisons were also made in four sub-regions of interest to OPC forecast operations. These sub-regions include the Gulf of Maine (Figure 2a), the Mid-Atlantic Coast (Figure 2b), the Southeast Atlantic Coast (Figure 2c) and the Gulf of Mexico (Figure 3). The three Atlantic sub-regions are derived from the higher resolution output grid of the RT_OFS Gulf Stream region file that is provided by the MMAB. The Atlantic regions extend from the East Coast to 52° W. The Gulf of Maine region and the Mid-Atlantic Coast regions are divided at 40° N just south of Georges Bank. The Mid-Atlantic and the Southeast Atlantic regions are divided at 35.25° N, the parallel that passes through Cape Hatteras. The Southeast Atlantic Coast region extends to 25° N, the southern extent of the RT_OFS Gulf Stream region file. The Gulf of Mexico region includes the entire Gulf of Mexico and corresponds to the RT_OFS Gulf of Mexico region file that has a higher resolution than the entire region file.

Comparison with Buoy SST

RT_OFS_ATL SST was compared to observations from approximately 45 meteorological buoys, depending on availability for the period from June 6, 2007 through July 30, 2008. The buoys are distributed throughout the Western Atlantic and the Gulf of Mexico and are shown in Figure 4. Quality controlled data from the National Data Buoy Center (NDBC) (http://seaboard.ndbc.noaa.gov/) was used to compare to the RT_OFS_ATL SST's. The monthly mean bias (Figure 5) and monthly mean RMS (Figure 6) were calculated for the nearly 13 month period. RT_OFS_ATL was slightly warmer than the buoys with an average bias for this period of +0.17° C and a standard deviation of 0.80° C. With a larger standard deviation than the positive bias it is difficult to say whether the model SST was significantly different from the buoy SST. The average RMS difference is 1.03° C.

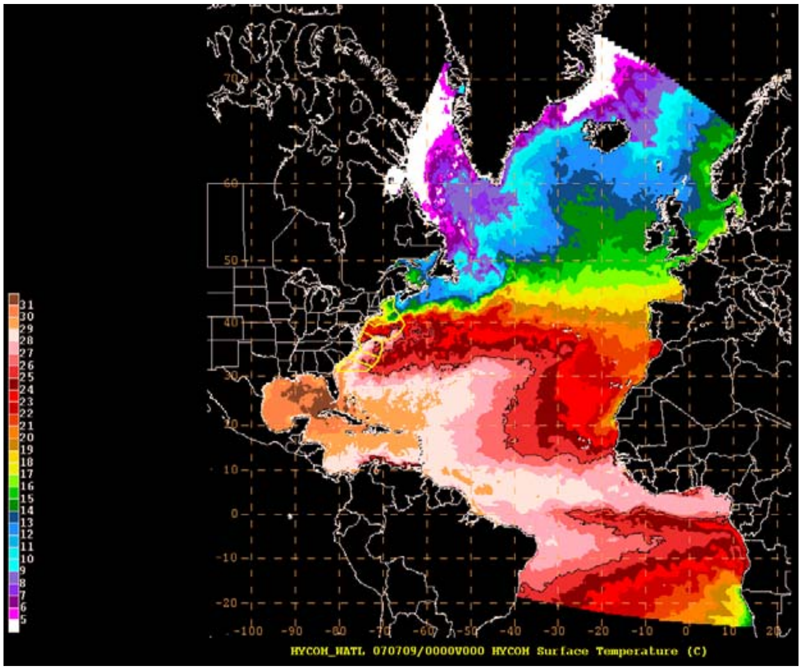


Figure 1. Real Time Ocean Forecast System Atlantic (RT_OFS_ATL) domain as displayed in the operational N-AWIPS workstation.

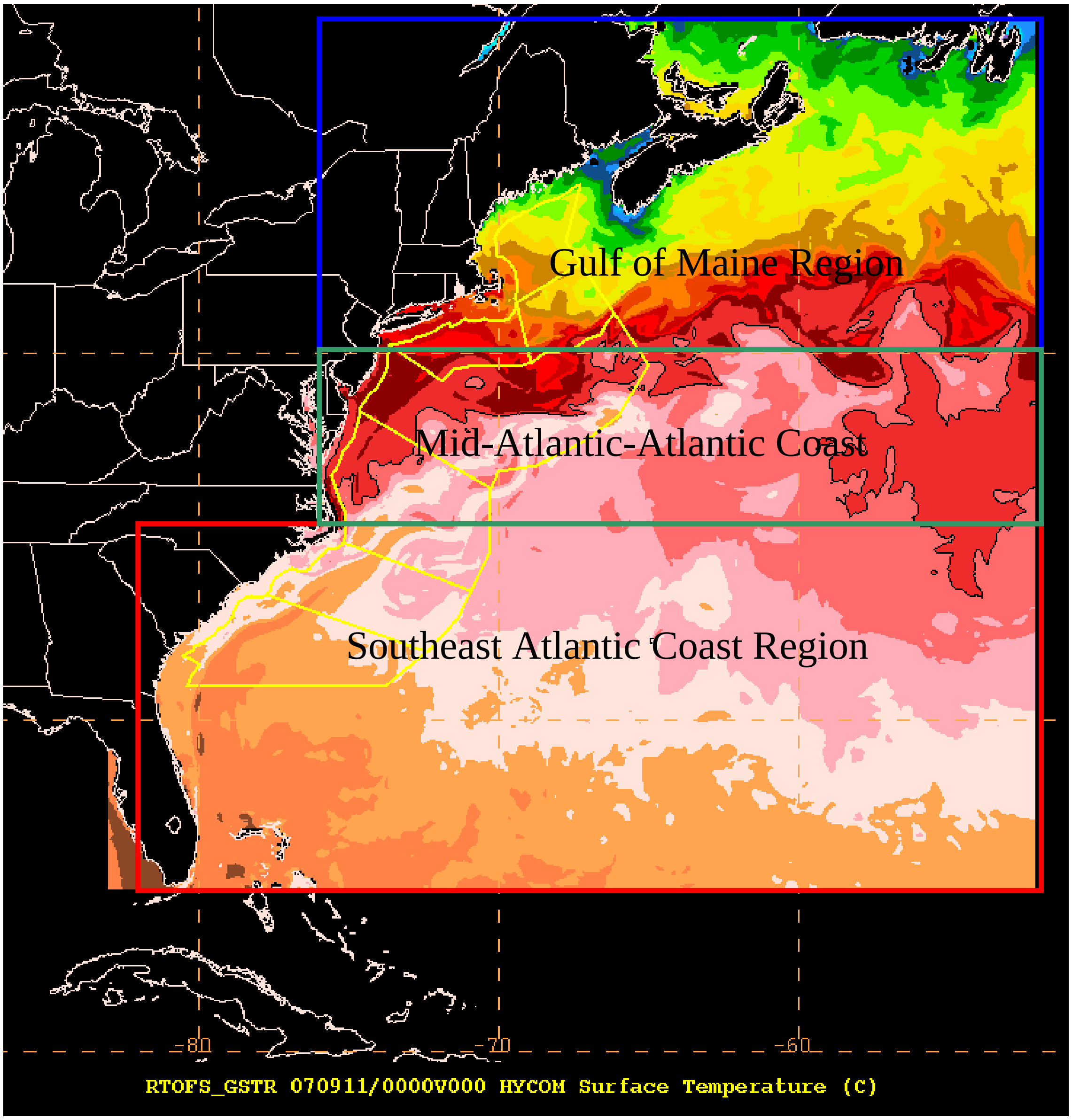


Figure 2. Atlantic Sub Regions of RT_OFS_ATL for evaluation, a) Gulf of Maine, b) Mid-Atlantic Coast, and c) Southeast Atlantic Coast Region.

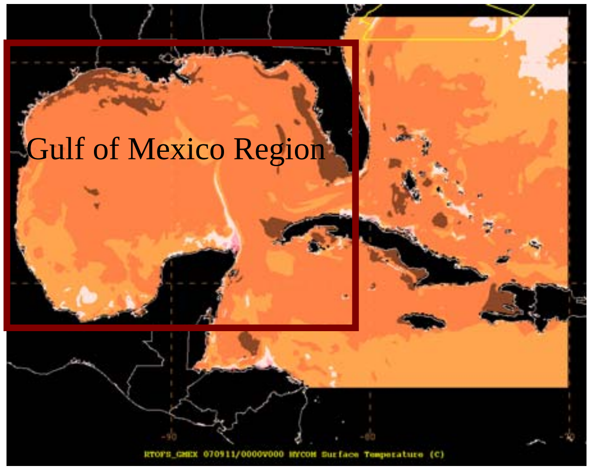


Figure 3. Gulf of Mexico sub region of RT_OFS_ATL for evaluation.

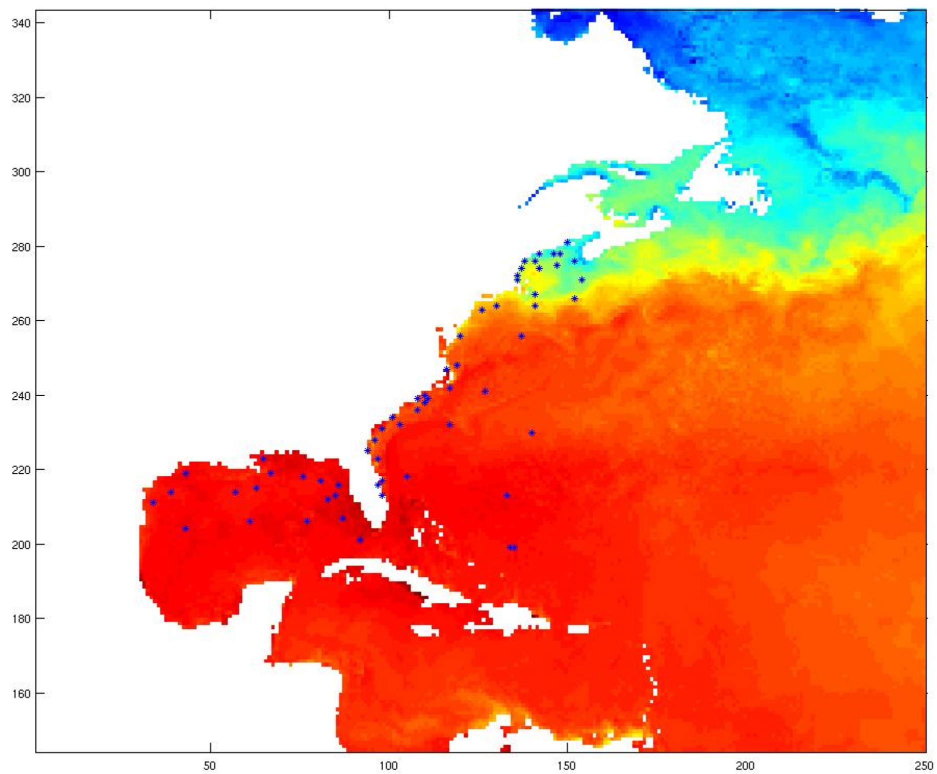


Figure 4. Locations of buoys (blue dots) used in RT_OFS_ATL SST verification.

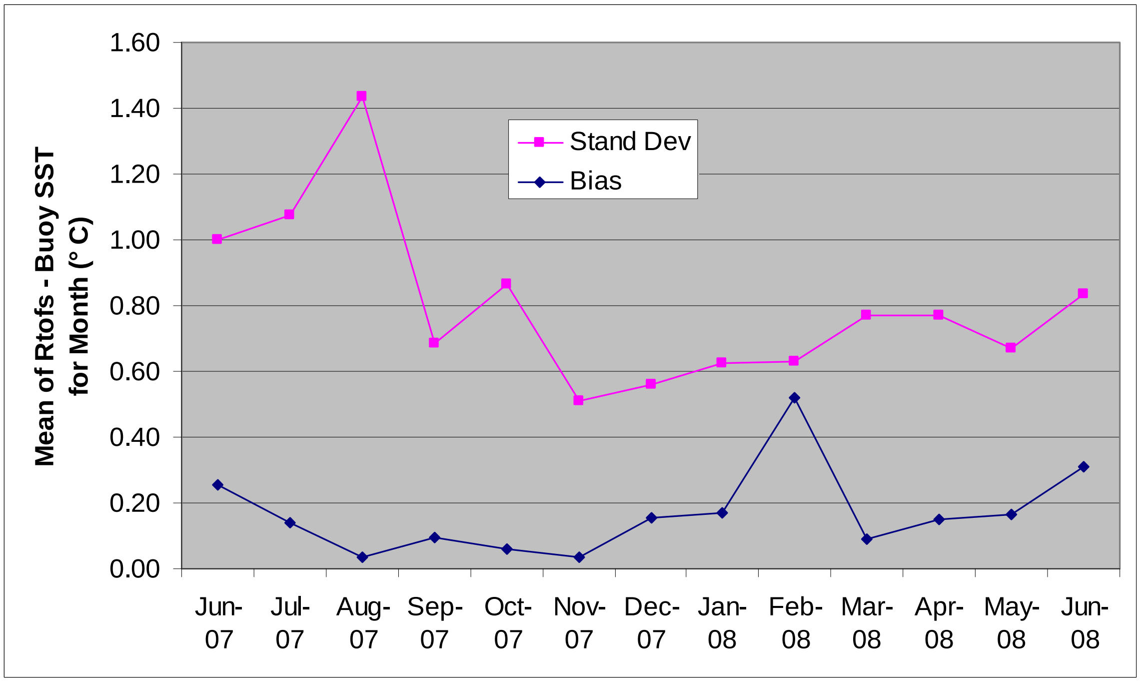


Figure 5. Monthly Mean Bias of RT_OFS_ATL versus Buoy SST from offshore and open ocean buoys shown in Figure 4.

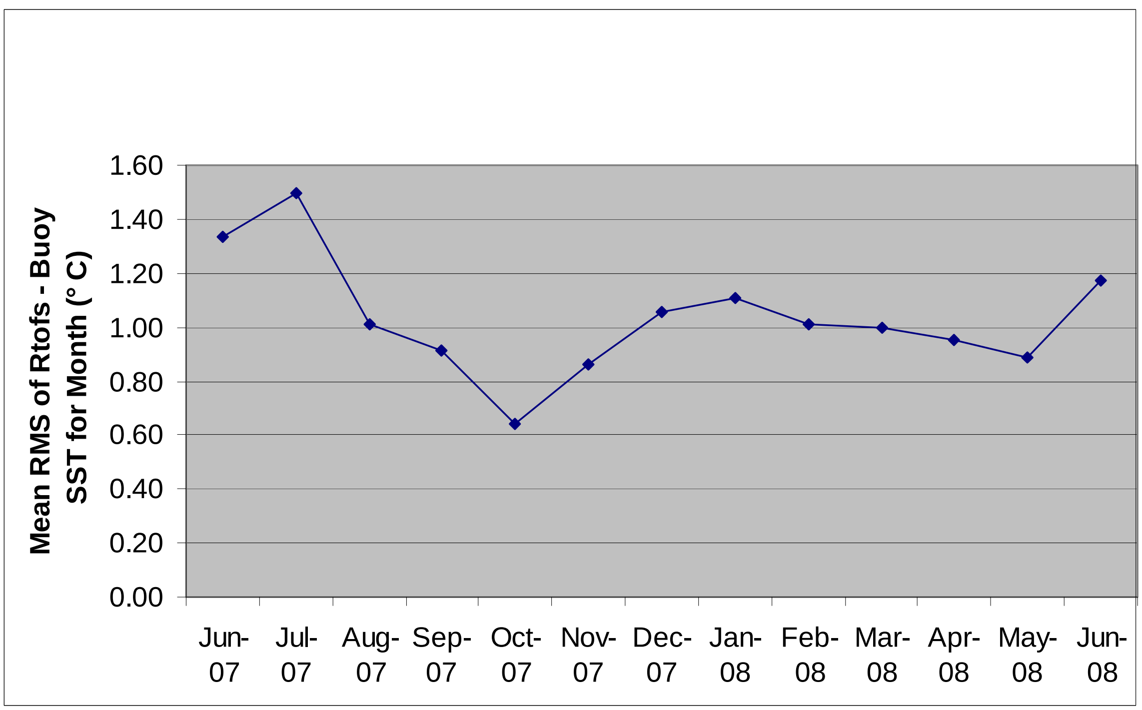


Figure 6. Monthly Mean RMS of RT_OFS_ATL versus Buoy SST

Comparison with OI SST

The 0.25° Optimum Interpolation SST (OI SST; Reynolds et al. 2007) produced by the National Climatic Data Center (NCDC) was also compared to the daily nowcasts of RT_OFS_ATL. OI SST is a daily analysis product that uses both infrared and microwave satellite SST data that is impervious to clouds. The infrared satellite data is taken from the Advanced Very High Resolution Radiometers (AVHRR) on the NOAA polar-orbiting satellites. The microwave data come from the Advanced Microwave Scanning Radiometer (AMSR) on the NASA Earth Observing System AQUA satellite. The OI SST analysis also includes in situ data from ships and buoys (Reynolds et al. 2007). The standard latitude/longitude grids from RT_OFS_ATL were used for the comparison with OI SST from June 6, 2007 through June 30, 2008. The monthly comparisons can be found on the website:
http://www.opc.ncep.noaa.gov/Regions_compareweb.shtml.
Statistics for the comparison are shown in Table 1.

Overall Atlantic Region

Overall RT_OFS_ATL was just slightly cooler than the OI SST (Table 1). The RT_OFS_ATL and OI SST as shown in Figure 7 for March 2008 compared quite well across the tropical and subtropical waters of both the south and north Atlantic oceans with a slight cold bias across the equatorial waters extending west from the African coast. These results are quite encouraging for potential use of RT-OFS_ATL for tropical applications such as coupling with tropical cyclone models such as the Hurricane Weather Research Forecast (WRF) Model (http://www.emc.ncep.noaa.gov/HWRF/index.html). However, monthly comparisons for periods of increased tropical cyclone activity such as September are needed.

Outside of the tropics there are persistent regions of significant differences between the OI SST analyses and RT_OFS_ATL 00 hour forecasts. The most striking difference can be seen in the difference fields from December, 2007. A relatively warm region in RT_OFS_ATL extended eastward from south of Nova Scotia at around 40° N to the Mid-Atlantic at approximately 40° W. This area is especially evident from December 2007 through June 2008, where temperatures on average are around 6° C warmer in RT_OFS_ATL than in the OI SST. Figure 7 from March, 2007 is a typical example of these persistent differences in the North Atlantic. A second area of difference occurred in the Labrador Sea and along the south coast of Greenland. In both cases the RT_OFS_ATL showed a persistent warm bias. The spring months of April and May showed better agreement in the Labrador Sea with the disappearance of the warmer RT_OFS_ATL area. Along the equator, there is a large region where RT_OFS_ATL was typically cooler than the OI SST by about 1-2° C in the monthly comparisons.

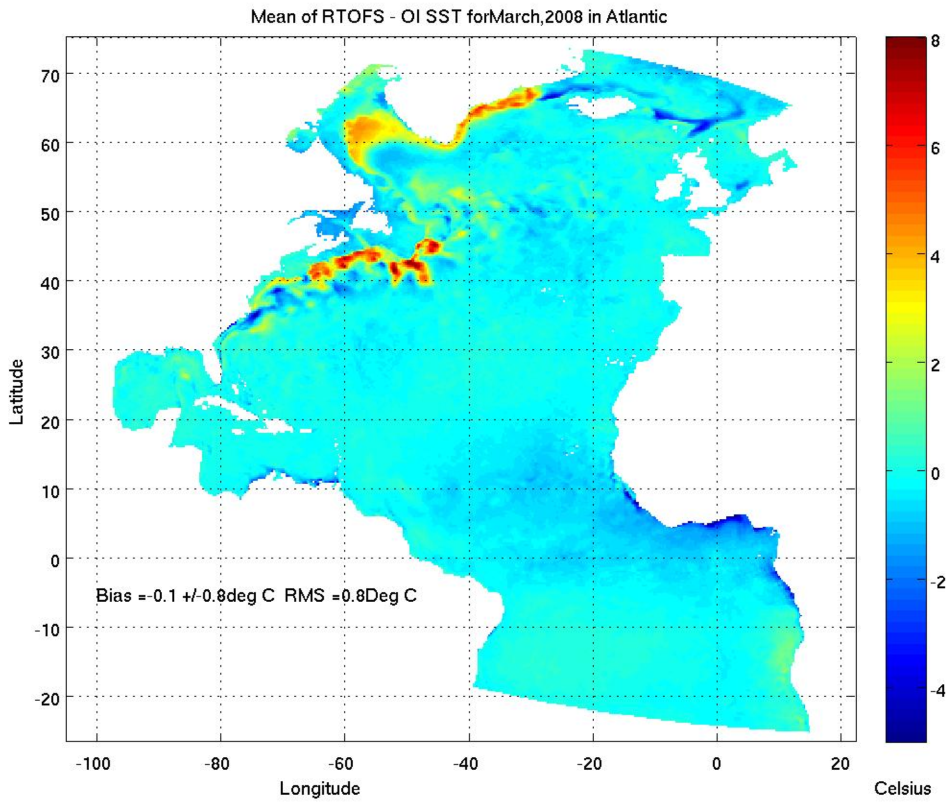


Figure 7. Mean of RT_OFS – OI SST for March, 2008 for the Atlantic Region

Gulf of Maine Region

In the Gulf of Maine Region, RT_OFS_ATL was warmer than OI SST by about 1.5° C (Table 1). Within the Gulf of Maine itself temperatures compared quite well over the study period. Starting with the December 2007 comparisons and continuing through June 2008, RT_OFS_ATL was significantly warmer over a southwest to northeast oriented area offshore of Nova Scotia. The May 2008 comparison in Figure 8 clearly shows this area in which maximum differences in excess of 6° C can be seen south of Cabot Strait. This area of RT_OFS_ATL warm bias is the eastern extension of a larger area described in the Mid-Atlantic and Atlantic comparisons. The area of warm bias reached its maximum extent and magnitude during the winter months of December through February with RT_OFS_ATL temperatures over 7° C warmer than the OI SST. Southeast of the most intense area of the warm region, centered at 43.5° N and 58° W is a large cool region with temperatures about 2° C cooler than OI SST.

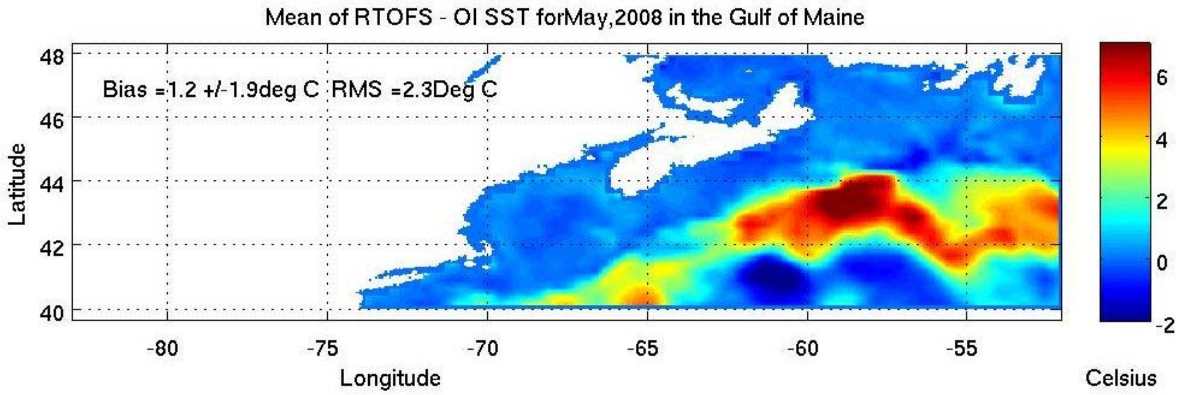


Figure 8. Mean of RT_OFS_ATL – OI SST for May, 2008 in the Gulf of Maine Region

Mid-Atlantic Coast Region

In the Mid-Atlantic Coast Region, RT_OFS_ATL was warmer than OI SST by about 0.4° (Table 1). September and October show the best agreement between RT_OFS_ATL and OI SST in the Mid-Atlantic region. Starting in November there is a large area where RT_OFS_ATL is warmer along the coast by at least 2° C. The comparison for May 2008 is a typical example of this area (Figure 9). The relatively warm area began along the coast at 35.5° N at Cape Hatteras and extended north northeastward and was about 2° in longitude off the coast in the northern part of the area. In November and December, to the south of the warm area there is a smaller cool region of between 1 and 2° C extending to the northeast. This relatively cool area becomes more exaggerated in January and February with RT_OFS_ATL temperatures about 3 to 4° C cooler than the OI SST. We have observed that the RT_OFS_ATL representation of the Gulf Stream departs eastward from the continental shelf break east of the South Carolina coast and well south of the climatological mean Gulf Stream. The cooler RT_OFS_ATL temperatures described here (north of Cape Hatteras across the slope waters) appear to be a result of the early departure from the shelf break of the main body of the Gulf Stream. The warm and cool regions were much less obvious in May and June 2008 (Figure 9). However, the RT_OFS_ATL representation of the Gulf Stream is still turning seaward much too far to the south. The premature departure of the RT_OFS_ATL representation of the Gulf Stream from the shelf waters will be discussed later.

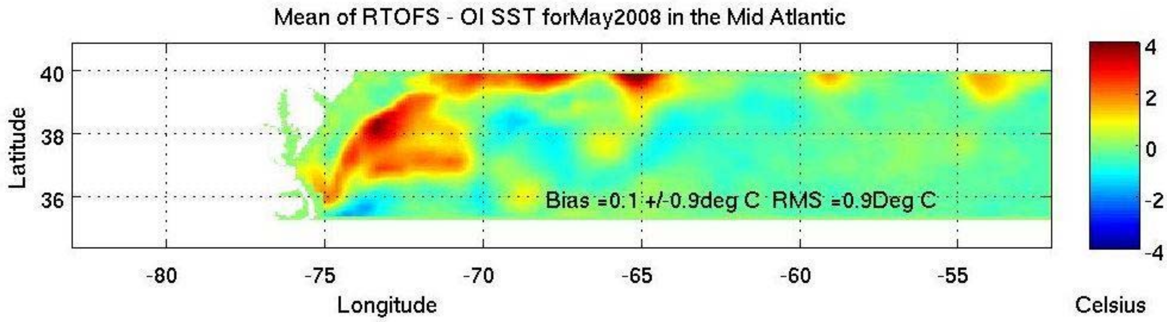
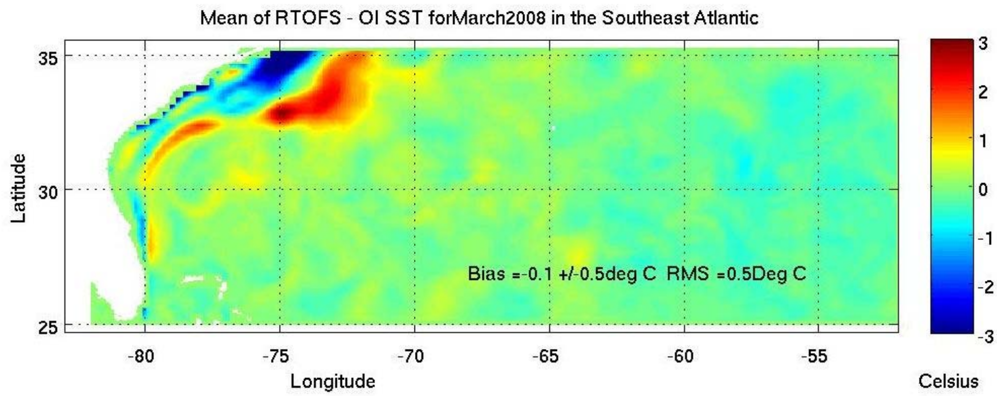


Figure 9. Mean of RT_OFS_ATL versus OI SST for May 2008 in the Mid-Atlantic Coast Region

Southeast Atlantic Coast Region

In the Southeast Atlantic Coast region, RT_OFS_ATL was slightly cooler than OI SST (Table 1). The persistent misplacement of the Gulf Stream to the south in RT_OFS_ATL is obvious in the comparisons in the Southeast Atlantic Coast region. The RT_OFS_ATL Gulf Stream shows up as the continuous warm region curving away from the coast well south of Cape Hatteras. In the earlier months, there is a large relatively cooler region close to the coast as seen in the March 2008 comparison (Figure 10a). The June 2008 comparison (Figure 10b) shows a less exaggerated warm region and a very small cool region. Despite the Gulf Stream position being too far south in the model, the overall agreement of surface temperatures in the Southeast Atlantic Coast region suggests the magnitude of the Gulf Stream is similar between RT_OFS and OI SST. The warm region where the Gulf Stream is displaced is balanced by the cooler region along the coast where the Gulf Stream usually has more of a warming influence.



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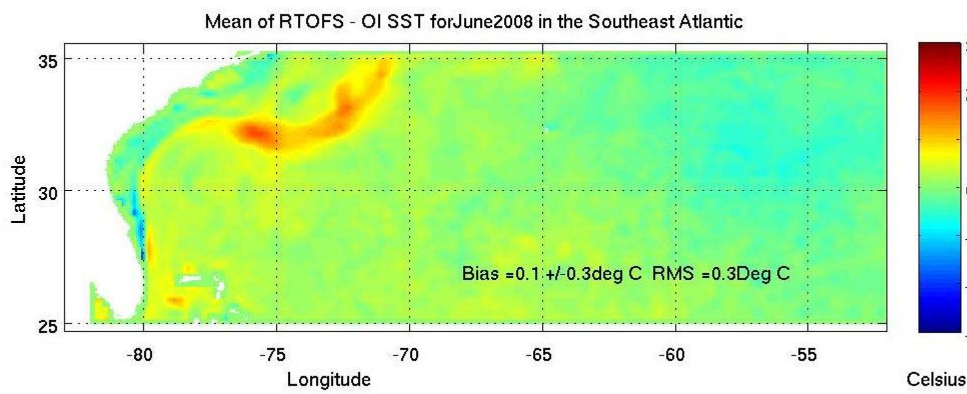
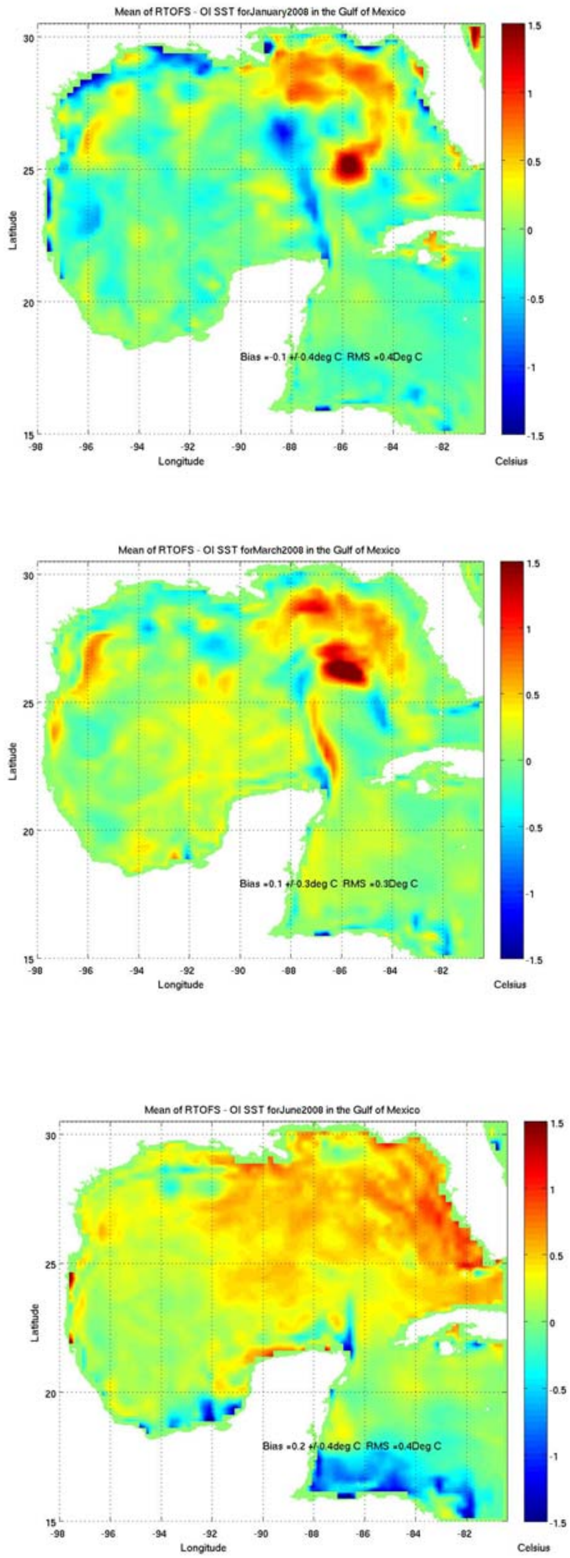


b.

Figure 10. Mean of RT_OFS_ATL – OI SST for a. March 2008 and b. June 2008 in the Southeast Atlantic Coast Region

Gulf of Mexico Region

RT_OFS_ATL was slightly cooler than OI SST in the Gulf of Mexico Region (Table 1). Differences in the Gulf of Mexico are smaller than those seen in the Atlantic. Maximum differences in the Gulf are usually less than 2° C (Figure 11), where maximum differences in the Atlantic can be greater than 6° C. The biggest differences in the Gulf of Mexico are related to the positioning of the Loop Current. RT_OFS_ATL is usually warmer than OI SST in the northern extent of the Loop Current with focused warm areas to the northeast or northwest of the Loop. The largest differences on the warm side are about 1° C. The largest warm difference is in January with RT_OFS warmer by 1.8° C in a focused region in the northern extent of the Loop Current at 25.5° N and –86° W



a.

b.

c.

Figure11. Mean of RT_OFS_ATL – OI SST for a. January 2008, b. March 2008 and c. June 2008 in the Gulf of Mexico Region

(Figure 11a). Most of the months show cooler RT_OFS_ATL temperatures very close to the east coast of the Yucatan Peninsula (Figure 11). There are also cool spots very close to the coast throughout the Gulf especially in November through February.

Comparison with OI SST, NCOM, and RTG_SST_HR for July, 2008

RT_OFS_ATL was compared to the 1/8º Global U.S. Navy Coastal Ocean Model (NCOM) SST and the 1/12º NOAA Real Time Global (RTG_SST_HR) SST analysis for the month of July, 2008 in order to broaden the basis for comparisons and further substantiate the OI SST comparisons. The NCOM model (Barron et al. 2007) is the Navy's operational global nowcast/ forecast system and is based mainly on the Princeton Ocean Model (POM; Blumberg and Mellor, 1987). The surface boundary conditions for the NCOM model, including wind stress, heat flux, and salt flux are driven by the Navy Operational Global Atmospheric Prediction System (NOGAPS; Rosmond et al., 2002). The Navy Modular Ocean Data Assimilation System (MODAS; Fox et al. 2002) provides the data assimilation for NCOM including SSH and SST. MODAS uses SSH from the Navy Layered Global Ocean Model (NLOM; Walcraft et al. 2003). NLOM is a 1/32º resolution purely isopycnal model. Rivers in NCOM are represented from a global database of monthly mean river discharge (Barron and Smedstad, 2002) that was enhanced from a database provided by Perry et al.(1996).

The 1/12º NOAA Real Time Global SST analysis (RTG_SST_HR; Gemmil et al., 2007) is produced by the Marine Modeling and Analysis Branch (MMAB) of NOAA/NCEP. The RTG_SST_HR daily analysis uses AVHRR data from the NOAA-17 and NOAA-18 polar orbiting satellites and in situ data from fixed and drifting buoys and ships. The RTG_SST_HR is the highest resolution SST analysis that we use in our comparisons but has the limitation of not using satellite data from cloud penetrating microwave sensors. More information and downloads of the RTG_SST_HR analysis can be found online at: http://polar.ncep.noaa.gov/sst/.

RT_OFS_ATL was slightly warmer than OI SST with a mean bias of 0.138° C for July, 2008 (Table 2). The comparison of RT_OFS_ATL with NCOM SST was similar to the comparison with OI SST (Figure 12). RT_OFS_ATL was slightly warmer than NCOM with a mean bias of 0.159° C (Table 2). RT_OFS_ATL was also slightly warmer than RTG_SST_HR but this comparison showed larger regional differences, especially in the Labrador Sea and along the coast of Greenland (Figure 12) that are reflected in the standard deviation and rms, each about 1° C (Table 2).

The comparison of RT_OFS_ATL and OI SST for July, 2008 showed better agreement along 40° N than earlier months but RT_OFS_ATL still has areas of much warmer SST(Figure 12). The comparison for the month of July between RT_OFS_ATL and NCOM is similar to the RT_OFS_ATL comparison with OI SST. The large warm region seen in the earlier comparisons around 40° N is present in the NCOM comparison and the OI SST comparison. To the northeast of the warm region is a cool "S" shaped region visible in both comparisons. The Labrador Sea looks similar and there are also warm areas along the coast of Greenland in both comparisons. The comparison of

RT_OFS_ATL with RTG_SST_HR SST also shows warm spots along 40° N, the cool "S" shaped region east of Newfoundland and the cool region along the northeast coast of South America. RTG_SST_HR is much cooler than RT_OFS_ATL in the Labrador Sea. RTG has had some issues in the North Atlantic recently, which most likely account for the large differences with RT_OFS_ATL in the Labrador Sea and along the coast of Greenland. Also, RT_OFS_ATL does not assimilate ice data, so we would expect warmer SSTs in these areas especially close to the Greenland coast, as seen in all three July comparisons (Figure 13).

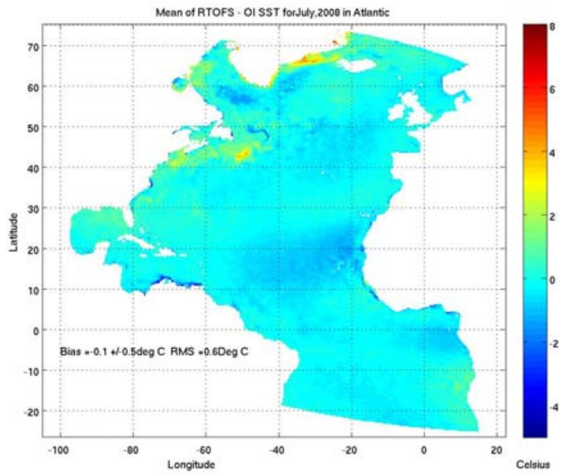
In the Southeast Atlantic region, all three comparisons look similar. The Gulf Stream in RT_OFS_ATL, turning seaward prematurely at 32.5° N is obvious in all 3 comparisons (Figure 13). Also, there is a small region of relatively warm RT_OFS_ATL SST of about 2° C at 29° N and 63° W. In the Gulf of Mexico region, the comparisons with OI SST and RTG_SST_HR SST look similar (Figure 14). RT_OFS_ATL is warmer in the northern and especially northeastern Gulf. There is a large eddy to the northwest of the loop current that is obvious in the comparison with RTG_SST_HR. There is a less obvious large eddy to the east of the first eddy in the comparison with RTG_SST_HR. The presence of these warm eddies contributes to the warmer RT_OFS waters also seen in the OI SST comparison. RT_OFS_ATL agrees much better with NCOM for July. The large warm area across the northern Gulf is not present in the comparison. The main difference is the region of warmer RT_OFS_ATL SST just north of the Yucatan Peninsula and west of the loop current. All three comparisons show cooler RT_OFS_ATL temperature in coastal waters near to the coast of northeastern South America and along the southeast Gulf of Mexico.

Table 1. Statistics for the comparisons between RT_OFS_ATL and OI SST, NDBC Buoys, and MMAB In Situ Temperatures. The bias is the average of RT_OFS_ATL – the comparison SST with a positive bias meaning RT_OFS_ATL is warmer.

RT_OFS vs OI SST (June 6, 2007 – June 30, 2008)	Bias (° C)	Standard Deviation (° C)	RMS (° C)
Atlantic (Entire Model Region)	-0.09	1.03	1.04
Gulf of Maine	1.45	0.47	1.53
Mid-Atlantic	0.43	0.28	0.51
Southeast	-0.03	0.20	0.12
Gulf of Mexico	-0.07	0.69	0.73
RT_OFS vs. NDBC Buoys (June 6, 2007 – June 30, 2008)	0.17	0.8	1.03
RT_OFS vs. MMAB In Situ T (July 1, 2008 – September 15, 2008)	-0.11	0.80	0.80

Table 2. Statistics for the comparisons between RT_OFS_ATL and OI SST, NCOM, and RTG_SST_HR for July, 2008 over the Atlantic Ocean (Entire RT_OFS_ATL region). The bias is the average of RT_OFS_ATL – the comparison SST with a positive bias meaning RT_OFS_ATL is warmer.

Comparison over Atlantic Region	Bias (° C)	Standard Deviation (° C)	RMS (° C)
RT_OFS vs OI SST (July 2008)	0.14	0.77	0.78
RT_OFS vs. NCOM (July 2008)	0.16	0.61	0.63
RT_OFS vs. RTG_SST_HR (July 2008)	0.05	1.05	1.05



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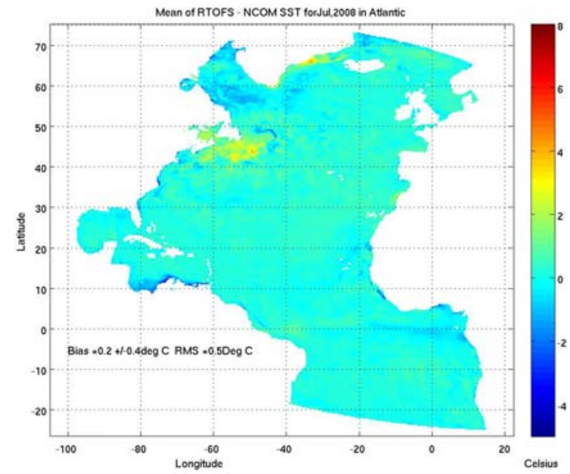

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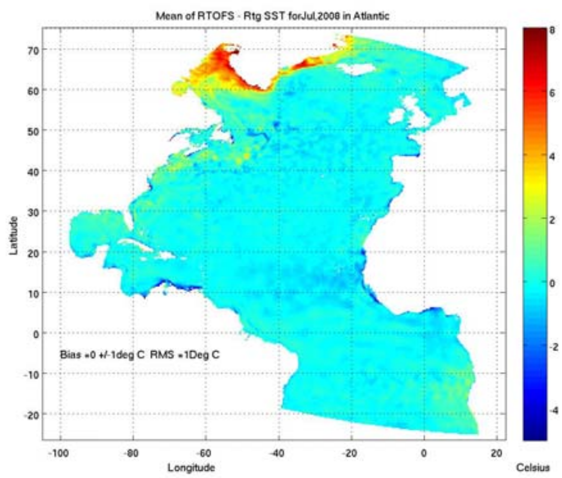
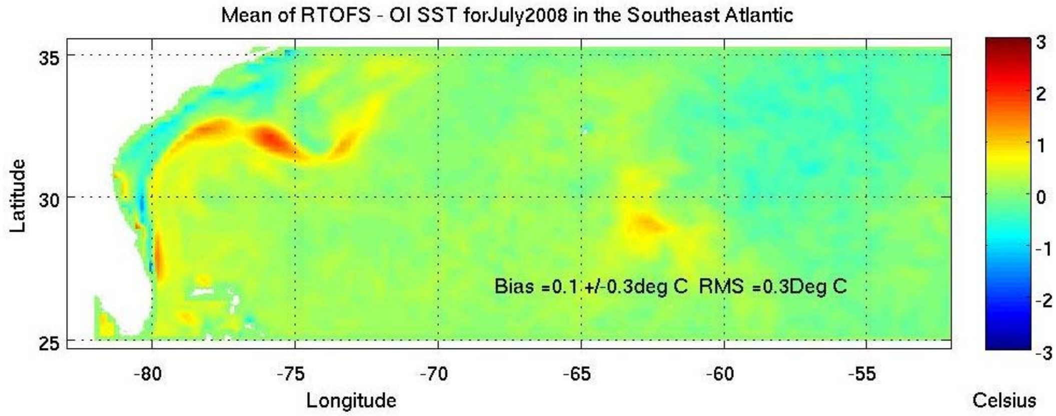
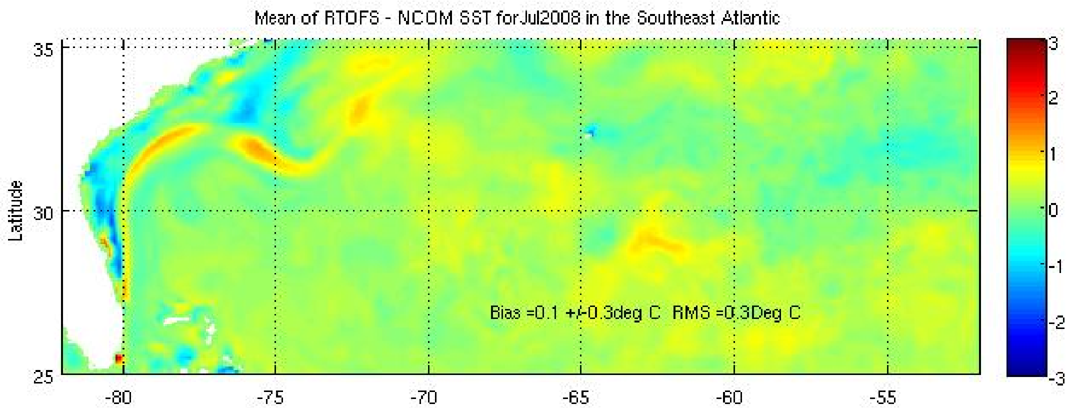


c.

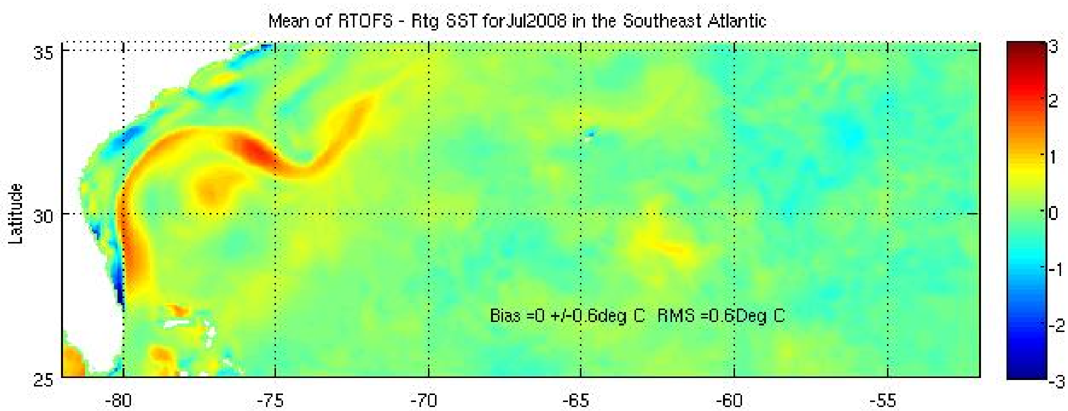
Figure 12. Comparisons of RTOFS_ATL SST for July, 2008 with a. OI SST, b. NCOM SST, and c. RTG_SST_HR SST.



a.

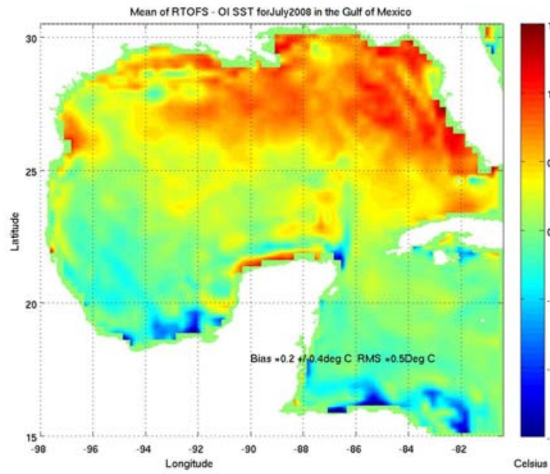


b.

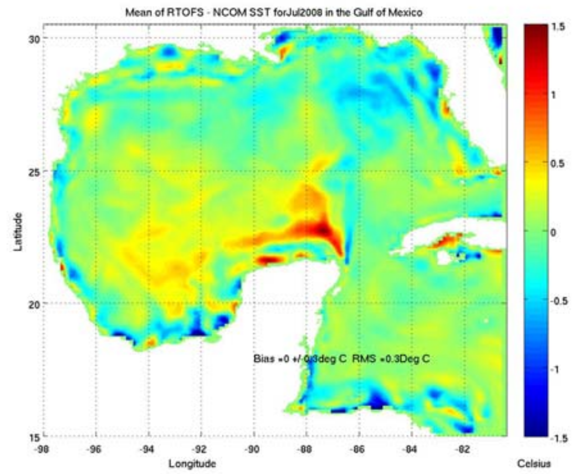


c.

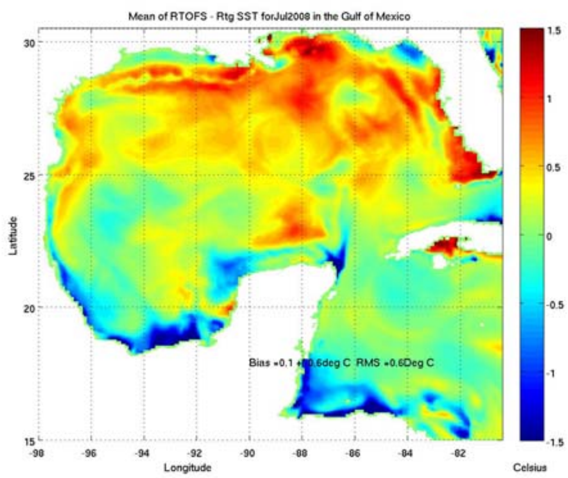
Figure 13. Comparisons of RT_OFS_ATL SST in the Southeast Atlantic Region for July 2008 with a. OI, b. NCOM, and c. RTG_SST_HR SST.



a.



b.



c.

Figure 14. Comparisons of RT_OFS_ATL SST in the Gulf of Mexico Region for July 2008 with a. OI, b. NCOM, and c. RTG_SST_HR

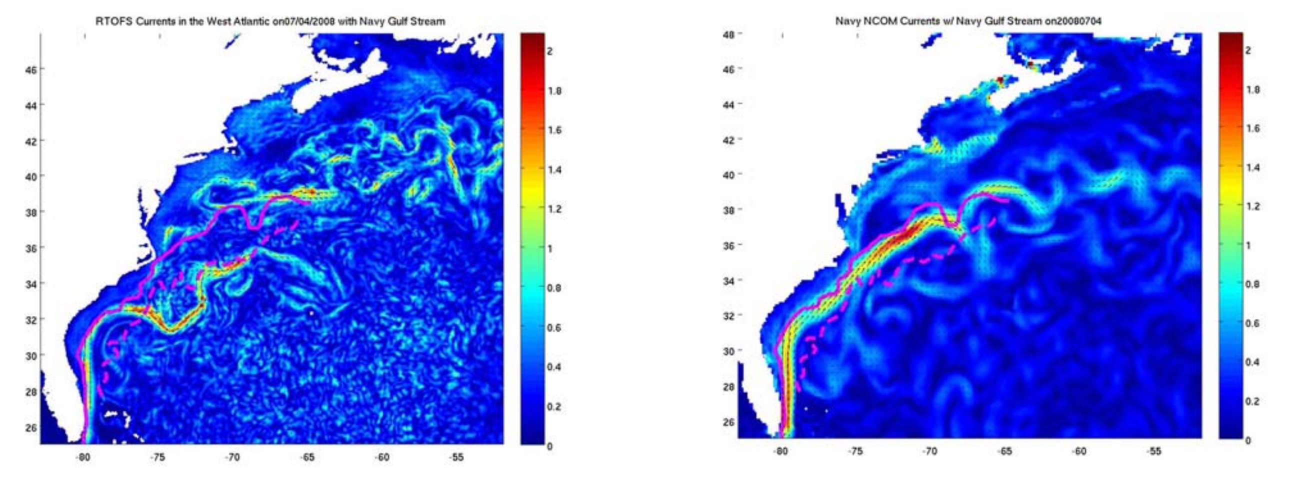
Comparison with In Situ Temperatures

In situ temperature from buoys, drifting buoys, and ships are collected daily by the MMAB. The in situ temperatures are not assimilated into RT_OFS_ATL, so they provide an excellent independent validation data set. We compared in situ sea surface temperatures and RT_OFS_ATL SST starting in July, 2008 though the middle of September, 2008. The in situ temperatures were filtered to remove any observations greater than 2 standard deviations away from the climatological mean provided by MMAB. The temperatures were averaged when more than one temperature was available for a corresponding model grid point. There was an average of 3,274 in situ temperatures per day that were compared to the RT_OFS_ATL SST, representing 0.4 % of the model grid. RT_OFS_ATL was slightly cooler than the in situ temperatures (Table 1) with a mean bias of -0.107° C.

Gulf Stream

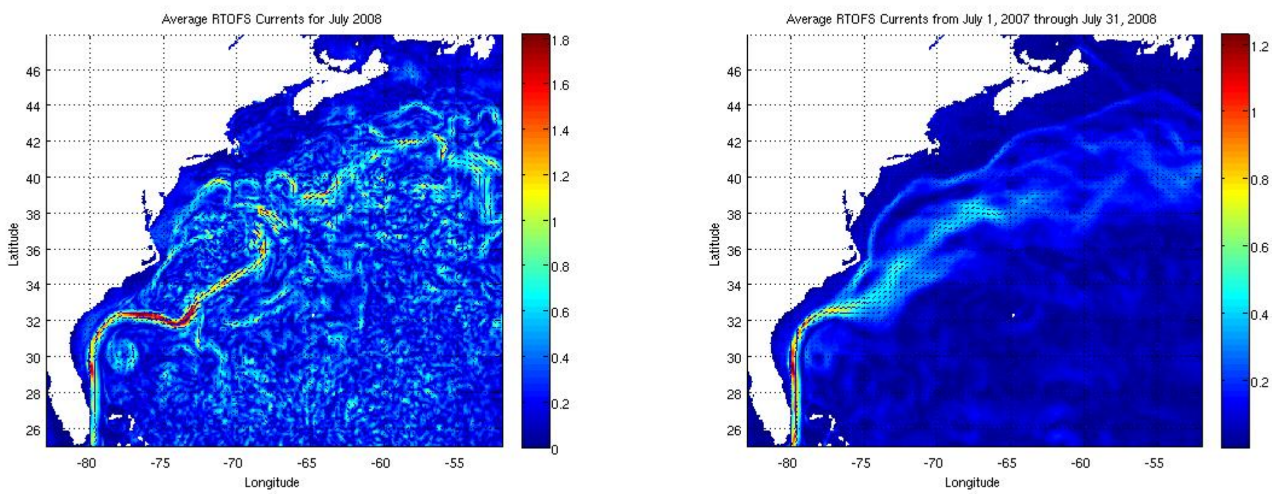
The Gulf Stream in RT_OFS_ATL has been consistently turning eastward about 150 miles south of Cape Hatteras as seen in the RT_OFS currents for July 4, 2008 (Figure 15a). The Gulf Stream usually begins to break away from the coast at Cape Hatteras similar to the Navy operational manual Gulf Stream analysis that is based on AVHRR SST and in situ observations (Figure 15). The Navy Gulf Stream analysis is available online at: https://oceanography.navy.mil/legacy/web/cgi-bin/search.pl/0-usjfcom/metoc//110+223//19. The NCOM model as shown in Figure 15b has a more accurate placement of the Gulf Stream, although the currents in NCOM are at a lower resolution than RT_OFS_ATL, tending to smooth over features like the many meanders in the Gulf Stream north of 38° N. The RT_OFS_ATL representation of the Gulf Stream has a bifurcation in the flow with the majority of the flow turning eastward off of South Carolina and a smaller flow proceeding northward close to the Navy analyzed Gulf Stream north wall. The northern section of the Gulf Stream above 38° N, along the shelf break compares relatively well with the many meanders and eddies associated with the Gulf Stream. Averaging the currents over the month of July, 2008 and over a little more than 1 year shows similar results for the Gulf Stream position (Figure 16). The long term average (Figure 16b) shows the undershoot or eastward turn of the Gulf Stream and a well defined northern current flowing along the shelf break.

As shown in Figure 17, the ocean fronts and Gulf Stream can be estimated using an SST gradient finder. The fronts show the southward misplacement of the RT_OFS Gulf Stream in relation to the Navy Gulf Stream analysis, as well as the complexity of the RT_OFS_ATL modeled ocean. The strongest fronts are found in the area of the Gulf Stream and along the shelf break off of the northeast coast.



a. b.

Figure 15. a. RT_OFS Currents with Navy Gulf Stream Analysis in the West Atlantic for July 4, 2008 and b. NCOM Currents with Navy Gulf Stream Analysis in the West Atlantic for July 4, 2008. The Magenta Line is the Navy Gulf Stream Analysis (Solid line = North Wall, Dashed Line = South Wall).



a. b.

Figure 16. Average of RT_OFS_ATL Currents for a. July 2008 and b. July 1, 2007 through July 31, 2008

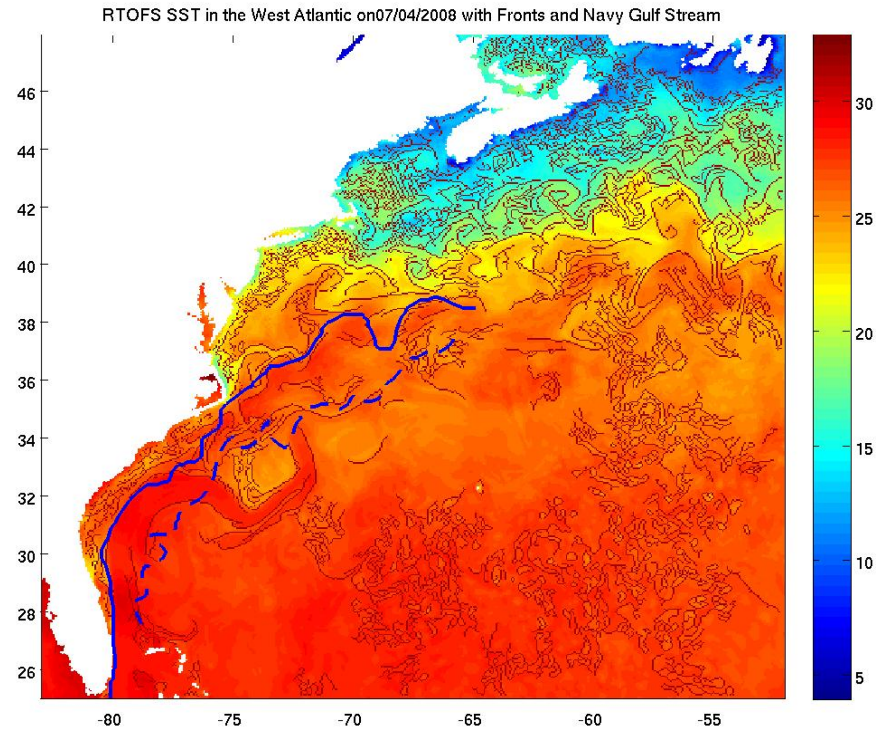


Figure 17. RT_OFS_ATL SST with Fronts and Navy Gulf Stream Analysis in the West Atlantic for July 4, 2008. The Navy Blue Line is the Navy Gulf Stream Analysis (Solid line = North Wall, Dashed Line = South Wall). The Fronts are the dark red lines and were found by an SST gradient front finder developed by Tim Mavor of IMSG @ NOAA/NESDIS/OAR.

Forecast Capability and Applications

In our evaluation of RT_OFS_ATL we have typically observed the realistic depiction of the evolution of SST over the Atlantic Ocean out to the 120 hour forecast hour. RT_OFS_ATL in most cases forecasts trends in SST well, as seen in the Gulf of Mexico at the Mid-Gulf buoy, 42001 starting on June 6, 2008 (Figure 18). The diurnal warming and cooling at buoy 42001 is reflected well, as is the decrease in SST from 0000 UTC to about 60 hours and the increasing trend over the remainder of the forecast period. The stability of the model is exemplified by comparing the nowcast to the 120 hour forecast valid 0000 UTC July 22, 2008 (Figure 19). Subtle differences in SST can be observed but in general the overall placement of thermal features compares exceptionally well. The Gulf Stream position, although misplaced at 0000 UTC and in the 120 hour forecast, remains stable and features such as the meanders in the vicinity of the shelf break near 40° N evolve naturally. Through this evaluation we have been impressed with the consistency of the evolution of RT_OFS_ATL features over the forecast period of the model. In essence the HYCOM based RT_OFS_ATL has proven to be an excellent model. The differences that we have observed in the placement and intensity of ocean surface features such as the Gulf Stream and associated meanders appear to be associated with the data used to define the initial state of the ocean and perhaps the data assimilation process itself. We realize that Sea Surface Height Anomaly data is used to help define the state of the ocean but contemplate whether the use of this data is fully optimized for RT_OFS_ATL.

Comparisons of the OI SST and RT_OFS_ATL have shown that over the open ocean in the deep tropics and southern Mid-Atlantic-latitudes small differences exist between the model and satellite based SST analyses. For operational applications such as tropical cyclone genesis and prediction, RT_OFS_ATL may indeed be ready to be fully coupled with atmospheric and wave models.

In the northern latitudes, along the Greenland coast, Davis Strait and along the Labrador coast, RT_OFS_ATL showed a significant warm bias as compared to the OI SST. This warm bias, in these frequently ice covered regions, is most likely a result of the lack of a sea-ice sub-model in RT_OFS_ATL. Freezing spray (the build up of ice on exposed metal surfaces) on vessels has been found to be a function of air temperature, wind speed, and sea surface temperature. It has been found that accretion rates are highly dependant on SST. Freezing spray guidance used by OPC forecasters uses the 1/12 degree RTG_SST_HR SST analysis as the basis for estimating ice accretion rates. The warm bias observed in RT_OFS_ATL occurs over waters frequented by freezing spray conditions. Before RT_OFS_ATL forecast SST can be used as a basis for freezing spray guidance, the warm bias in the near Arctic needs to be addressed. MMAB does plan to include a sea-ice sub-model in their implementation of the global version of RT_OFS.

The persistent and inaccurate placement of the Gulf Stream current system from off of the South Carolina coast northward certainly limits daily marine weather forecast applications such as wind wave interaction and forecasting winds and waves in the vicinity of ocean thermal features. The direct applications of forecasts of ocean features such as thermal gradients or fronts, surface currents, or sub-surface features are certainly limited in the Gulf Stream region with the present state of the Real Time Ocean Forecast System. Further development is certainly needed to fully optimize the use of all available ocean data but especially altimeter based Sea Surface Height Anomaly data. It is hoped that the recent addition of the Jason-2 altimeter and complimentary orbits of Jason and Jason-2 altimeters along with ENVISAT SSHA data will significantly improve the initial state of the RT_OFS_ATL over the western portion of the Atlantic basin. Once the placement of the Gulf Stream and associated meanders improves, the OPC encourages the application of RT_OFS_ATL currents to be coupled with the NOAA Wavewatch III Model in an experimental mode to begin to address wind wave and current interaction. This issue is one of the major forecast challenges for OPC Offshore forecasters.

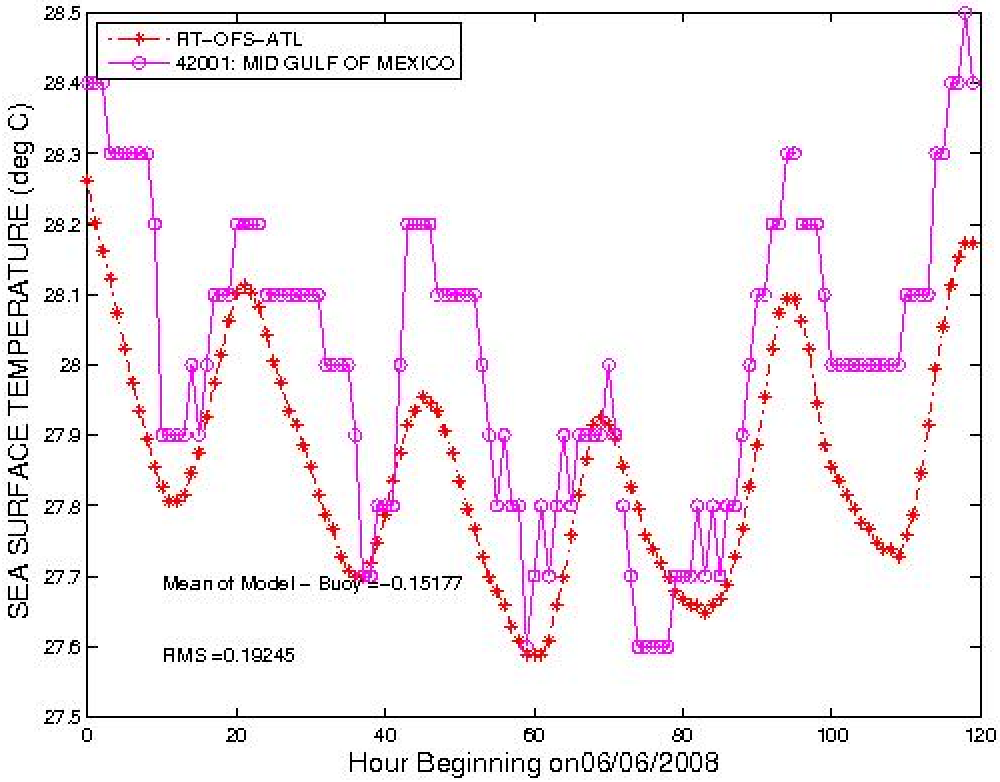
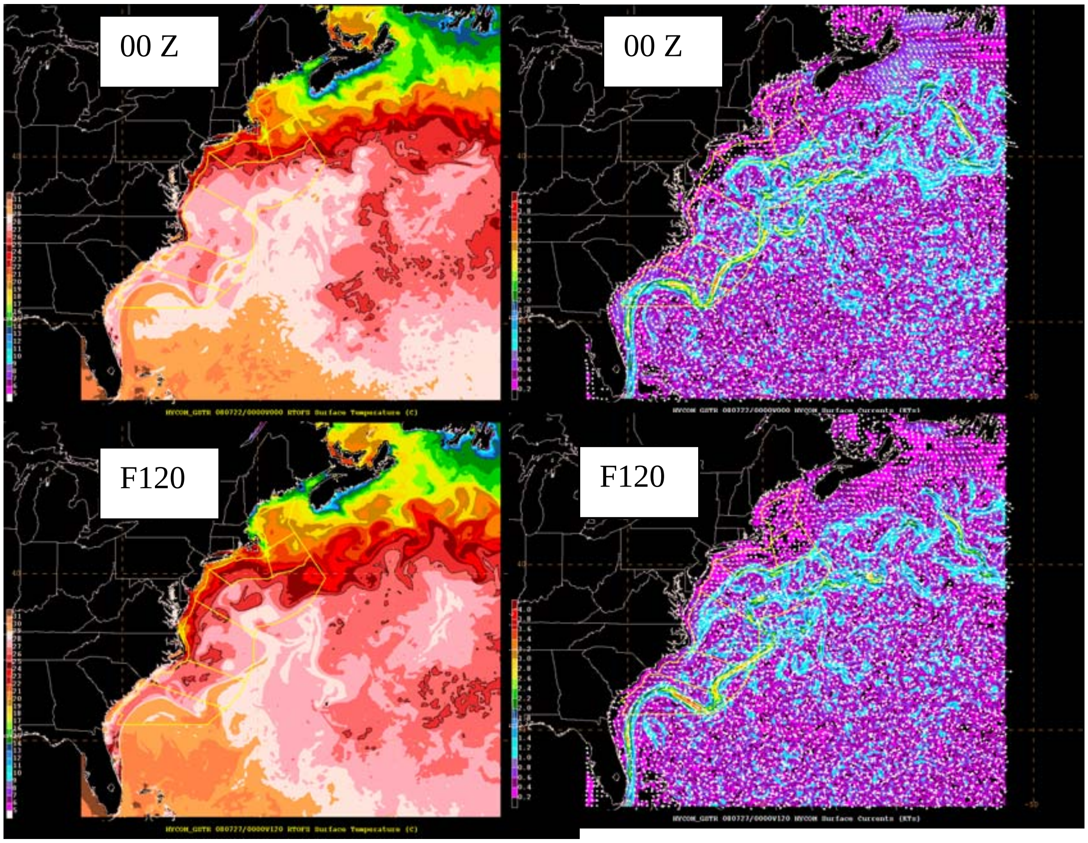


Figure18. Model and in situ SST at Buoy 42001 (Mid-Atlantic Gulf) starting on June 6, 2008



a. SST b. Current

Figure 19. RT_OFS_ATL SST (a.) and Current (b.) on 7/22/2008 at the nowcast (00 Z) and 120 hour forecast (F120).

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