Improving Ocean Model Initialization for Coupled Tropical Cyclone Forecast Models Using GODAE Nowcasts

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ABSTRACT

To simulate tropical cyclone (TC) intensification, coupled ocean-atmosphere prediction models must realistically reproduce the magnitude and pattern of storm-forced sea surface temperature (SST) cooling. The potential for the ocean to support intensification depends on the thermal energy available to the storm, which in turn depends on both the temperature and thickness of the upper-ocean warm layer. The ocean heat content (OHC) is used as an index of this potential. Large differences in available thermal energy associated with energetic boundary currents and ocean eddies require their accurate initialization in ocean models. Two generations of the experimental U.S. Navy ocean nowcast-forecast system based on the Hybrid Coordinate Ocean Model (HYCOM) are evaluated for this purpose in the NW Caribbean Sea and Gulf of Mexico prior to Hurricanes Isidore and Lili (2002), Ivan (2004), and Katrina (2005). Evaluations are conducted by comparison to in situ measurements, the navy's three-dimensional Modular Ocean Data Assimilation System (MODAS) temperature and salinity analyses, microwave satellite SST, and fields of OHC and 26°C isotherm depth derived from satellite altimetry. Both nowcast-forecast systems represent the position of important oceanographic features with reasonable accuracy. Initial fields provided by the first-generation product had a large upper-ocean cold bias because the nowcast was initialized from a biased older-model run. SST response in a free-running Isidore simulation is improved by using initial and boundary fields with reduced cold bias generated from a HYCOM nowcast that relaxed model fields to MODAS analyses. A new climatological initialization procedure used for the second-generation nowcast system tended to reduce the cold bias, but the nowcast still could not adequately reproduce anomalously warm conditions present before all storms within the first few months following nowcast initialization. The initial cold biases in both nowcast products tended to decrease with time. A realistic free-running HYCOM simulation of the ocean response to Ivan illustrates the critical importance of correctly initializing both warm-core rings and cold-core eddies to correctly simulate the magnitude and pattern of SST cooling.

1. Introduction

The ocean is the primary energy source for tropical cyclones (TCs) through latent heat released by the condensation of water evaporated from the sea surface.

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Tropical cyclone intensification is often associated with warm ocean features such as western boundary currents and warm-core rings (WCRs) as documented in recent studies of Hurricane Opal in the Gulf of Mexico (GOM) during 1995 (Hong et al. 2000; Shay et al. 2000), Typhoon Maemi in the western Pacific during 2003 (Lin et al. 2005), and Hurricanes Katrina and Rita in the GOM during 2005 (Scharroo et al. 2005; Sun et al. 2006; Shay 2008). Numerical model studies have documented the influence of large upper-ocean heat content on in-

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tensification (Hong et al. 2000; Emanuel et al. 2004; Lin et al. 2005). The oceanic influence can work both ways, with weakening of both Ivan (Walker et al. 2005) and Rita (Sun et al. 2006; Shay 2008) occurring as they passed over cold-core eddies (CCEs) in the GOM.

Nearly all TCs form over oceanic regions where SST exceeds 26°C (Palmen 1948). Observational (Miller 1958; DeMaria and Kaplan 1994), theoretical (Emanuel 1988; Holland 1997), and numerical model (Ooyama 1969; Chang 1979; Tuleya and Kurihara 1982) studies have demonstrated the sensitivity of TC intensity to SST in the directly forced area of the storm. However, SST alone is a poor predictor of the oceanic influence on TC intensity. If SST remains constant, a positive feedback exists where the increasing wind speed of an intensifying storm increases the evaporation rate to supply the storm with the additional thermal energy required for intensification. However, a negative feedback mechanism also exists where increasing wind speed increases the rate of SST cooling beneath the storm, thus reducing the evaporation rate and the energy available to the storm. It is the strength of this negative feedback (the rate of SST cooling) relative to the positive feedback between the wind speed (intensity) and the evaporation rate that determines whether the ocean promotes intensification or weakening. Additional complexities exist, such as the potential contribution of the structure of the SST cooling pattern relative to the center of the storm. Wu et al. (2005) demonstrate that the symmetric component of SST cooling relative to the TC center produces a larger negative feedback on intensity than does the asymmetric component.

The SST cooling rate depends on factors such as upper-ocean warm-layer thickness, upper-ocean stratification, and storm propagation speed. Typically 60%-80% of TC-forced SST cooling results from the entrainment of deeper cold water into the ocean mixed layer (OML) due to shear-driven turbulence at the OML base resulting from the strong baroclinic near-inertial currents forced by the storms (Elsberry et al. 1976; Chang and Anthes 1978; Price 1981; Shay et al. 1992; Jacob et al. 2000). Consequently, both the initial temperature and the thickness of the upper-ocean warm layer are important factors in determining the oceanic contribution to TC intensity. Ocean heat content (OHC) relative to the 26°C isotherm (Leipper and Volgenau 1972; Shay et al. 2000) is an index that takes both factors into account:

OHC =
$$c_p \int_0^{D_{26}} \rho[T(z) - 26] dz,$$
 (1)

where c_p is the specific heat at constant pressure and D_{26} is the 26°C isotherm depth. OHC derived from satellite altimetry is used in the Statistical Hurricane Intensity Prediction Scheme (SHIPS) to forecast intensity at the Tropical Prediction Center (DeMaria et al. 2005, Mainelli et al. 2008). SST will cool slowly within the Loop Current (LC) in the eastern GOM where OHC is large and horizontal heat advection by the flow quickly replaces thermal energy loss within the OML. WCRs that detach from the LC, along with CCEs that form on the periphery of the LC and WCRs, produce large upper-ocean temperature differences across the eastern GOM that influence the OML response to storm forcing (Jacob et al. 2000; Jacob and Shay 2003) and potentially impact storm intensity.

For a coupled TC prediction model to accurately forecast intensity evolution, these oceanographic features must be properly initialized in the ocean model with respect to both location and the properties of the water contained within them. Inaccurate initialization of vertical T and S profiles within these features degrades the OML evolution and SST cooling in the ocean model. Data-assimilative ocean nowcast products developed for the Global Ocean Data Assimilation Experiment (GODAE) are an attractive source of initial fields because they use satellite and in situ observations in conjunction with an ocean general circulation model (OGCM) to provide optimum real-time ocean nowcasts. Given that these products are in various stages of development and evaluation, there is a critical need to begin evaluating them now, specifically for the purpose of initializing coupled hurricane prediction models in order to provide feedback that will guide the improvement of the nowcast products. Herein, experimental GODAE nowcast products are evaluated in the NW Caribbean and Gulf of Mexico prior to Hurricanes Isidore and Lili (2002), Ivan (2004), and Katrina (2005). These products are based on the Hybrid Coordinate Ocean Model (HYCOM) and are produced at the Naval Research Laboratory (NRL) in preparation for transition of a 0.08° global version of HYCOM to operational use by the U.S. Navy in 2008.

It is not possible at this time to perform the definitive evaluation of these ocean analysis products. They are continually evolving, with next-generation products becoming available every 1–2 yr. Moreover, high quality observations must still be collected for additional storms to provide a database sufficiently large to perform definitive evaluations over a broad range of atmospheric and oceanic conditions. The present analysis is designed to demonstrate the strengths and weaknesses of the currently available HYCOM-based ocean nowcast products as a benchmark against which future evaluation efforts will be compared. It is also timely to evaluate these products since HYCOM is being considered as the ocean component of the next-generation coupled hurricane forecast model (the Hurricane Weather Research and Forecast model, HWRF).

The storms analyzed here are chosen based on available high quality in situ ocean observations (Isidore and Lili) and to permit evaluation of ocean model initialization for three scenarios within the GOM: 1) low-amplitude LC penetration into the GOM without WCRs or CCEs present (Isidore and Lili), 2) medium-amplitude LC penetration with both WCRs and CCEs present (Ivan) and 3) large-amplitude LC penetration with a detaching WCR (Katrina). Two generations of the experimental HYCOM nowcast-forecast system are evaluated herein. The first system (H-OI) uses optimum interpolation to assimilate satellite altimetry with Cooper and Haines's (1996) downward projection of the surface observations. The second system (H-NCODA) uses multivariate optimum interpolation, specifically the Navy Coupled Ocean Data Assimilation system, to assimilate all available observations. The nowcast product evaluation prior to the storms is supplemented by results from free-running simulations of the ocean response to Isidore (2002) and Ivan (2004) nested in different nowcast products to demonstrate the impact of initial temperature-salinity biases and to correct the ocean feature initialization. Collectively, these analyses demonstrate the critical importance of ocean observations for initializing and evaluating ocean models with the goal of improving coupled TC prediction models.

The paper is organized as follows. Section 2 describes the observations, ocean model, and nowcast systems used in this study. Section 3 presents the pre-Isidore evaluation while section 4 presents the pre-Ivan and pre-Katrina evaluations. This is followed by a discussion in section 5.

2. Data and models

a. Ocean observations and analyses

Multiple ocean snapshots were acquired by aircraft prior to, during, and after the passage of Hurricane Isidore in the Caribbean Sea and Gulf of Mexico as part of the U.S. Weather Research Program with National Science Foundation (NSF) and National Oceanic and Atmospheric Administration (NOAA) support. Airborne expendable bathythermographs (AXBTs), airborne expendable conductivity–temperature–depth profilers (AXCTDs), and airborne expendable current profilers (AXCPs) obtained temperature, conductivity (salinity), and current measurements prior to Isidore on 18–19 September 2002 (Shay and Uhlhorn 2008). Two regions are sampled: one in the NW Caribbean Sea and the other in the southeastern GOM. Three-dimensional temperature and salinity fields were gridded in each region using objective analysis, with OHC maps then calculated from the temperature field using (1).

OHC maps derived from climatological hydrographic data and surface height anomaly (SHA) fields measured by satellite altimetry were calculated prior to all storms. These maps are especially important prior to Ivan and Katrina due to the unavailability of in situ aircraft measurements. To derive the OHC, satellite altimetry fields are first used to estimate upper-layer thickness (defined as D_{20} , the 20°C isotherm depth) based on a two-layer approximation where SHA perturbation is compensated by upper-layer thickness perturbation plus a barotropic component (Goni et al. 1996). Here, D_{20} represents the depth at which the temperature-salinity curves converge between the Gulf Common Water (GCW) of the interior GOM and the subtropical Atlantic water present in the NW Caribbean and the LC (Shay et al. 1998). It is estimated using

$$D_{20}(x, y, t) = \overline{D}_{20}(x, y) + \frac{g}{g'(x, y, t)} \eta'(x, y, t), \quad (2)$$

where \overline{D}_{20} is mean upper-layer thickness determined from climatological hydrographic data, g' is the reduced gravity obtained from climatological hydrographic data, and η' is SHA obtained from altimetry. To derive OHC relative to D_{26} , the latter depth is first estimated based on its relationship to D_{20} established from historical hydrographic data:

$$D_{26}(x, y, t) \cong 0.5 D_{20}(x, y, t).$$
 (3)

OHC is then estimated as

$$OHC = \rho c_p \nabla_z T(x, y, t) D_{26}^2(x, y, t), \qquad (4)$$

where the difference between SST and 26°C [$\nabla_z T(x, y, t)$] is obtained from satellite observations and historical hydrographic data.

Three-dimensional temperature and salinity analyses for several months during 2002 were obtained from the Modular Ocean Data Assimilation System (MODAS; Fox et al. 2002) for the pre-Isidore evaluation and also to provide improved initial and boundary conditions for nested, free-running simulations of the ocean response to Isidore and Lili (section 3d). MODAS fields were also obtained just prior to Ivan and Katrina. MODAS is a set of tools to grid and analyze global ocean temperature and salinity structure using optimum interpolation (OI) in two or three dimensions. Fields are relaxed



FIG. 1. Maps of OHC calculated from (a) the GDEM3 and (b) the 0.25° WOA01 September climatologies.

slowly toward climatological values in regions where observations are not available. The MODAS fields are available at 0.125° horizontal resolution at 35 discrete depths. Finally, microwave satellite measurements of SST were obtained from the blended product derived from the Tropical Rainfall Measuring Mission's (TRMM) Microwave Imager (TMI) and the Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E) instruments produced by Remote Sensing Systems (information online at http:// www.ssmi.com) to document the SST response pattern forced by Hurricane Ivan.

b. Ocean climatologies

The observed ocean state in the western Caribbean and GOM prior to the storms analyzed herein is compared to climatology to document the anomalously warm conditions that were present. The September OHC index is calculated from two climatologies: the navy's Generalized Digital Environmental Model (GDEM; Teague et al. 1990) and the 0.25° version of the NOAA World Ocean Analysis 2001 (WOA01; T. Boyer et al. 2004, unpublished manuscript; available online at http://www.nodc.noaa.gov/OC5/WOA01/ qd_ts01.html). The largest climatological OHC values (100-120 kJ cm⁻²) are present in the NW Caribbean Sea. OHC values in this region are about $\sim 10\%$ larger in the WOA01 climatology, demonstrating sensitivity to the choice of observations and time interval used in the different climatologies (Fig. 1).

c. The HYCOM nowcast-forecast system

HYCOM is a primitive equation ocean model that uses a hybrid vertical coordinate designed to be quasioptimal throughout the ocean. This coordinate is isopycnic in the stratified ocean interior, but dynamically transitions to level coordinates near the surface to resolve the surface mixed layer and to terrain-following (σ) coordinates in the coastal ocean. This strategy enables HYCOM to use advanced turbulence closures for vertical mixing while retaining the advantages of isopycnic coordinates in the stratified ocean interior. A detailed discussion of the HYCOM equations and initial evaluation of the hybrid vertical grid generator is presented in Bleck (2002). Subsequent evolution and further evaluation of the model are presented in Chassignet et al. (2003) and Halliwell (2004), with the latter study emphasizing the various vertical mixing schemes.

Two generations of the experimental HYCOM nowcast-forecast system, H-OI and H-NCODA, are evaluated herein. The H-OI system (Chassignet et al. 2007) is configured in a 0.08° Atlantic Ocean domain, using an optimum interpolation (OI) scheme to assimilate SHA from satellite altimetry and the Cooper and Haines (1996) technique for the downward projection of the surface observations. Real-time satellite altimeter data [Geosat-Follow-On (GFO), the Environmental Satellite (ENVISAT), and Jason-1] are provided via the Altimeter Data Fusion Center (ADFC) at the Naval Oceanographic Office (NAVOCEANO) to first generate the two-dimensional MODAS 0.25° SHA analysis (Jacobs et al. 2001; Fox et al. 2002) that is assimilated daily into the ocean model. In addition, HYCOM SST is relaxed to the daily MODAS 0.125° SST analysis, which uses Multichannel Sea Surface Temperature data derived from the five-channel Advanced Very High Resolution Radiometer. Sea surface salinity is relaxed toward climatology. The 3-hourly surface forcing fields are provided by the 1.0° NOGAPS atmospheric model.

The next-generation H-NCODA nowcast-forecast system is based on the U.S. Navy's Coupled Ocean Data Assimilation analysis (NCODA; Cummings 2005), which is a fully three-dimensional multivariate optimum interpolation system. The three-dimensional ocean analysis simultaneously analyzes temperature, salinity, geopotential, and velocity components. For coupling to HYCOM, a new analysis variable was added to NCODA that corrects the model layer pressure of the hybrid vertical coordinates. The NCODA horizontal correlations are multivariate in geopotential and velocity, with velocity adjustments in geostrophic balance with the corresponding geopotential increments and geopotential increments in hydrostatic agreement with temperature-salinity (density) increments. NCODA makes full use of all sources of operational ocean observations, and new ocean observing systems are added as they become available, such as microwave SST from AMSR-E. All observations assimilated by NCODA are passed through quality control procedures, which include sensibility checks, gross error checks, and consistency checks with nearby observations and analysis-forecast background fields. An incremental updating scheme has been implemented so that the model variables are gradually updated over a specified number of time steps. The NCODA analysis is performed every 24 h, assimilating all available observations within 12 h of the analysis time except for the satellite altimeter data where a 72-h window is used. The model is cycled with the NCODA system, so that the model 24-h forecast is used as the first guess for the analysis, and then the analysis is used to incrementally update the model over a 12-h interval. A 1/12° global version of HYCOM with NCODA as the assimilation component is planned to become operational at the Naval Oceanographic Office in 2008.

Evaluation of these nowcast systems is complicated by the fact that we had little control over the available experimental ocean nowcast products produced by the navy. We therefore encountered unavoidable differences in product characteristics between the two nowcast systems, and also for each individual system among the individual storms. The two nowcast products are generated on two different grids. H-OI is run on a 0.08° Atlantic Ocean grid with climatological buffer zones present at the northern $(70^{\circ}N)$ and southern $(28^{\circ}S)$ boundaries. The initial H-NCODA experiment performed by the navy is run on a regional 0.04° GOM grid (which also includes the NW Caribbean west of 77.4°W and north of 18.1°N) nested within a model climatology calculated from a multiyear, free-running, high-resolution (0.08°) HYCOM Atlantic Ocean simulation forced by interannual air-sea fluxes. H-OI was initialized using fields extracted from an earlier climatologically forced, free-running, 0.08° Atlantic Ocean simulation performed using the Miami Isopycnic-Coordinate Ocean Model (MICOM), which was later found to contain large biases in temperature and salinity relative to climatology. H-NCODA was initialized from a freerunning interannual HYCOM run that did not display large biases relative to climatology. H-OI was initialized on 4 July 2003 while H-NCODA was initialized on 2 September 2003, and then both runs were continued into 2007. It was therefore necessary to perform special runs of both H-OI and H-NCODA for the 2002 pre-Isidore analysis. The identical nowcast systems and initialization procedures were used, with the special runs commencing on 4 July 2002 and running until early October. All of these factors are taken into account in interpreting the analyses performed herein.

HYCOM is also used to perform free-running ocean response simulations nested within different nowcast products to document the impact of biases and of ocean feature initialization on the forced upper-ocean temperature response. These experiments are outlined in section 3d (Isidore) and section 4b (Ivan).

3. Pre-Isidore evaluation

a. Observed upper-ocean state

The pre-Isidore ocean state constructed from aircraft observations and derived from satellite altimetry using (2)-(4) both demonstrate that the upper ocean contained much more thermal energy than normal prior to Isidore. Mean OHC and D_{26} values from several sources are presented in Table 1 for both the NW Caribbean and the interior of the LC, with these two domains outlined by the boxes in Fig. 2. The measured OHC value of 170 kJ cm⁻² in the NW Caribbean exceeds the GDEM3 and WOA01 climatological values of 110 and 97 kJ cm⁻² by >50% (Table 1). The measured D_{26} value of 164 m exceeds the GDEM3 and WOA01 climatological values of 142 and 130 m by ~15%–25%. The smaller percentage difference for D_{26} demonstrates that increased surface warm-layer thickness and increased water temperature above D_{26} both contribute to the above normal OHC. The measured LC OHC value of 140 kJ cm⁻² exceeds the GDEM3 and WOA01 climatological values of 57 and 53 kJ cm^{-2} . The measured D_{26} value of 147 m exceeds the GDEM3 and WOA01 climatological values of 86 and 68 m. The low climatological values in the LC result from excessive smoothing associated with the temporally variable LC. Values of OHC and D₂₆ derived from satellite altimetry are close to the measured values in both the NW Caribbean and the LC, confirming the realism of altimetry-derived estimates that was demonstrated by Shay (2008).

The anomalously warm conditions are evident in the observed temperature profile over the upper 300 m at a

TABLE 1. Comparison of SST, OHC, and D_{26} among several sources in two regions: the NWC and the interior of LC, with the two regions delineated by the black rectangles in Fig. 2. The sources are the GDEM3 and WOA01 climatologies (Fig. 1); gridded aircraft measurements (Fig. 2a), derived from satellite altimetry (Fig. 2b); the H-OI nowcast (Fig. 2d); the H-MODAS nowcast (Fig. 2e); and the H-NCODA nowcast (Fig. 2f). The sample sizes *n* reflect the resolutions of the respective grids; the GDEM3 climatology was interpolated to the 0.08° HYCOM Atlantic basin grid before averaging.

		CCT.	OHC	ת	
D	0	(00)	$(1 \text{ L} \text{ m}^{-2})$	D_{26}	
Region	Source	(°C)	(KJ cm ⁻²)	(m)	n
NWC	GDEM3	29.1	110	142	620
	WOA01	29.1	97	130	61
	Measured	29.8	170	164	273
	Derived	29.5	160	158	24
	H-OI	29.7	100	112	620
	H-MODAS	30.2	142	157	620
	H-NCODA	29.8	113	127	2520
LC	GDEM3	28.8	57	86	84
	WOA01	28.7	53	68	9
	Measured	29.5	140	147	45
	Derived	29.4	127	152	6
	H-OI	29.7	89	94	84
	H-MODAS	30.0	134	146	84
	H-NCODA	29.5	112	116	350

point within the warm water of the NW Caribbean (point NWC, 19.7°N, 85.0°W; Fig. 3). Anomalously warm conditions also extended into the interior of the GOM within the Gulf Common Water, as revealed by the observed temperature profile at point GCW located north of the LC (26.2° N, 85.2° W; Fig. 3). At point NWC, the observed temperature exceeds climatology by 2°–4°C over the upper 300 m (Fig. 3) and extending to 500 m (not shown). At point GCW, observed and climatological temperatures are similar in the warm layer above 50 m, but the observed temperature decreases faster than climatology between 50 and 100 m and remains colder down to 300 m.

Accurate initialization of salinity cannot be neglected due to its influence on water column stability, but the paucity of observations makes this difficult. Poor observational coverage contributes to differences of up to 0.2 psu between the vertical salinity profiles extracted from the two climatologies at both NWC and GCW (Fig. 3). A salinity maximum exists at both locations, which increases stability above and decreases it below. Observed salinities at both NWC and GCW differ by as much as 0.5 psu from the two climatologies, with the largest differences present at the depths of the salinity maximum. The observed salinity maximum is about 70 m deeper than the climatological maximum at NWC while it is about 25 m shallower than climatology at GCW.

b. Initial upper-ocean state from H-OI and H-NCODA

The H-OI and H-NCODA LC paths correspond closely to the path delineated by both the observed and satellite-derived OHC maps (Fig. 2). The good path correspondence between nowcast and derived OHC maps is expected since both nowcasts rely primarily on satellite altimetry for feature location. However, the path derived from in situ observations does confirm that these paths are all correct. In the H-OI nowcast, a large cold bias exists nearly everywhere in the domain, leading to low OHC values (Fig. 2). In the H-NCODA nowcast, the cold bias tends to be smaller over the NW Caribbean and LC regions while a small warm bias is present over the Gulf Common Water. Also, there is no continuity between the warm water slightly present in a warm feature centered at the NW corner of the averaging box and another warm feature covering only part of the LC region (Fig. 2). In the NW Caribbean, the nowcast OHC and D_{26} values of 100 kJ cm⁻² and 112 m (H-OI), and of 113 kJ cm⁻² and 127 m (H-NCODA), are much smaller than the observed values of 170 kJ cm^{-2} and 164 m (Table 1). In the LC, the nowcast OHC and D_{26} values of 89 kJ cm⁻² and 94 m (H-OI), and of 112 kJ cm⁻² and 116 m (H-NCODA), are much smaller than the observed values of 140 kJ cm⁻² and 147 m. The H-NCODA values are low because the two warm spots do not cover the entire NW Caribbean and LC averaging boxes (Fig. 2).

At point NWC, the H-OI vertical temperature profile completely misses the abnormally warm pre-Isidore conditions in the upper 300 m (Fig. 3). The H-NCODA profile is much closer to reality because point NWC is located within the warm eddy feature centered in the NW part of the averaging box (Fig. 2). At point GCW, the H-OI nowcast temperature is colder than observed throughout the upper 300 m, resulting in an OHC that is a small fraction of the observed value. Again, the H-NCODA profiles are closer to reality. For salinity, large fresh biases are present in the H-OI nowcast at both locations. The fresh bias present in the H-NCODA nowcast is slightly reduced at NWC and substantially reduced at GCW (Fig. 3).

c. Initial upper-ocean state from H-MODAS

The temperature biases in H-OI and H-NCODA were judged to be too large to provide initial and boundary conditions to free-running simulations of the ocean response to Isidore and Lili. Inspection of the three-dimensional MODAS temperature and salinity fields prior to Isidore determined that they more closely resembled observed fields than did either now-



FIG. 2. Maps of OHC in the NW Caribbean and southeast Gulf of Mexico (a) calculated from objective analysis of in situ aircraft observations, (b) derived from satellite altimetry, (c) calculated from the MODAS temperature analysis, (d) calculated from the H-OI nowcast, (e) calculated from the H-MODAS nowcast, and (f) calculated from the H-NCODA nowcast. The boxes illustrate the two domains within which mean OHC and D_{26} values are compared in Table 1.

cast (Figs. 2 and 3). To produce ocean fields with reduced bias, the 0.08°North Atlantic HYCOM was modified to relax model fields with a 10-day *e*-folding time scale to MODAS fields that had been vertically remapped to hybrid vertical coordinates. This system was then initialized from climatology and run from June through September 2002 to spin up and provide nowcast initial and boundary conditions to the Isidore– Lili ocean response simulations (section 3d). The surface atmospheric forcing used for H-OI was also used for H-MODAS.

The resulting OHC field closely resembles the OHC calculated directly from the MODAS analysis (Fig. 2), with only a small cold bias remaining. In the NW Caribbean, the H-MODAS nowcast OHC and D_{26} values

of 142 kJ cm⁻² and 157 m compare favorably to the observed values of 170 kJ cm⁻² and 164 m (Table 1). In the LC, the nowcast OHC and D_{26} values of 134 kJ cm⁻² and 146 m are close to the observed values of 140 kJ cm⁻² and 147 m. The H-MODAS temperature and salinity profiles at points NWC and GCW tend to follow the observed profiles throughout the upper 300 m, with the improvement being especially large for salinity (Fig. 3).

d. Impact of initial bias reduction on the simulated ocean response to Isidore

This impact is assessed using free-running simulations at 0.08° resolution within the domain spanning 9°–31°N and 65°–98°W. These simulations were run for



FIG. 3. Vertical profiles of (a) temperature at a location in the NW Caribbean (point NWC), (b) salinity at NWC, (c) temperature at a location north of the LC within the Gulf Common Water (point GCW), and (d) salinity at GCW. In all panels, red lines are climatological profiles (GDEM3, dashed; WOA01, solid), blue lines are from observations (MODAS analyses, dashed; in situ measurements, solid), and black lines are from model nowcasts (H-OI, short dashed; H-NCODA, long dashed; H-MODAS, solid).

a project designed to evaluate HYCOM vertical mixing schemes under TC forcing (Jacob et al. 2006). The simulations presented here used the K-profile parameterization (KPP; Large et al. 1994) vertical mixing scheme. The forcing used for these simulations is derived from the 3-hourly H*WIND Project analyses of surface winds (Powell et al. 1998; Houston et al. 1999; Houston and Powell 2003) generated from wind observations made by the NOAA aircraft stepped-frequency microwave radiometer (SFMR; Uhlhorn and Black 2003; Uhlhorn et al. 2007) by reducing flight-level winds to 10-m standard height and combining them with in situ measurements using objective analysis. The final product is a wind component analysis on a $\sim 8^\circ \times 8^\circ$ moving grid with ~ 6 km resolution centered on the storm. These maps are generated every 3 h using all available aircraft and in situ data within a specified time window. The H*WIND analyses were blended with forcing fields obtained from the National Centers for Environmental Prediction (NCEP) atmospheric model using a cubic B-spline analysis. The large-scale model flow field was removed wherever analyzed data were available to preserve the H*WIND inner-core storm structure. The simulations analyzed here were integrated beginning 0000 UTC 14 September 2002 and lasting until 0000 UTC 5 October 2002, with the NCEP surface wind forcing being smoothly transitioned in time to the analyzed hurricane forcing. Additionally, due to the size of Isidore and Lili, the 3-hourly winds were subsampled to every hour to avoid smearing of the hurricane-core winds.

When the free-running model was initialized with H-OI, SST cooling was larger than observed nearly everywhere. In particular, simulated cooling exceeded 2° C within the LC flow whereas observed cooling was $0.5^{\circ}-1^{\circ}$ C (Shay and Uhlhorn 2008; Fig. 4). When the model was initialized with H-MODAS, simulated SST cooling was reduced by more than 0.5° C over the southeastern GOM and NW Caribbean Sea, and by at least 1.5° C within the LC flow and within the upwelling region just north of the Yucatan Peninsula.

The mixed layer temperature for H-OI and H-MODAS initial conditions are quantitatively compared by examining simulated vertical profiles extracted at the loca-



FIG. 4. Mixed layer temperature maps during Hurricane Isidore (1200 UTC 21 Sep 2002) from free-running simulations initialized by (a) H-MODAS and (b) H-OI.

tion of observations corresponding to the time of deployment with respect to the storm center positions (Fig. 5). The mean initial mixed layer temperatures prior to Isidore on 18 September (NW Caribbean) and prior to Isidore on 19 September (SE GOM) at the profile locations in H-MODAS are 1°C higher than in H-OI. The mixed layer temperature is 1.4°C higher in the directly forced region on 22 September (SE GOM). While the OHC values in the H-OI initial conditions are also less than in the H-MODAS conditions, in the NW Caribbean on 18 September, the mean difference



FIG. 5. Comparison between profiles extracted from the two free-running simulations of the ocean response to Hurricane Isidore, H-OI, and H-MODAS. Shown are mixed layer temperature and OHC (a), (b) from the NW Caribbean prior to the storm on 18 Sep, (c), (d) from the southeastern GOM prior to the storm on 19 Sep, and (e), (f) from the eastern GOM within the directly forced region of the storm on 22 Sep.

exceeded 55 KJ cm⁻². The mean difference in the SE GOM is 30 KJ cm⁻² on 19 September, and, in the directly forced region on 22 September, this difference remains large at 45 KJ cm⁻². Regression statistics comparing these two initial conditions are shown in Table 2. Overall, the analyses demonstrate that the H-MODAS upper-ocean response on 22 September 2002 is closer to the observations.

4. Pre-Ivan and pre-Katrina evaluations

a. Initial ocean state from H-OI and H-NCODA

With no in situ aircraft surveys available prior to Ivan and Katrina, H-OI and H-NCODA are evaluated by comparing the nowcast OHC to satellite-derived maps (Fig. 6). The comparison for Ivan demonstrates that the large upper-ocean cold bias present in H-OI is consid-

TABLE 2. Comparison of the ocean response to Hurricane Isidore between two free-running simulations that used initial and boundary conditions from the H-OI and H-MODAS nowcast products. Mixed layer temperature (MLT) and OHC are used for the comparison.

Date (data points)	18 Sep 2002 (46)		19 Sep 2002 (42)		22 Sep 2002 (41)	
	MLT	OHC	MLT	OHC	MLT	OHC
Slope	0.58	0.39	1.12	0.62	0.83	0.46
Bias	11.69	16.54	-4.61	-7.67	3.52	-6.10
μ	0.83	56.95	1.04	31.02	1.37	44.72
σ	0.31	15.25	0.34	17.51	0.42	22.17
RMS	0.89	58.91	1.09	35.52	1.43	49.79

erably reduced in H-NCODA, particularly in the NW Caribbean Sea and within the Gulf Common Water. Some discrepancies do exist, however. Prior to Ivan, large OHC associated with the LC extends farther north in both H-NCODA and H-OI than in the derived map. Also, the region of large OHC associated with the detached WCR in the north-central GOM is larger in size in the H-NCODA nowcast than in the derived map while the H-OI nowcast underestimates the large OHC within this ring. Mean OHC values prior to Ivan from the three sources (derived, H-NCODA, and H-OI) are presented in Table 3 within four regions: the NW Caribbean Sea, the LC, the WCR, and the CCE located southeast of the WCR, with these regions outlined by the rectangles in Figs. 6a-c. The derived OHC value of 125 kJ cm⁻² in the NW Caribbean Sea compares favorably to the H-NCODA value of 118 kJ cm⁻² and is larger than the H-OI value of 101 kJ cm^{-2} (Table 3). The cold bias in the H-OI nowcast is substantially smaller in the NW Caribbean prior to Ivan than it was prior to Isidore. The derived OHC value of 83 kJ cm⁻² in the LC is smaller than the H-NCODA value of 92 kJ cm^{-2} and is larger than the H-OI value of 59 kJ cm^{-2} . The derived OHC value of 118 kJ cm⁻² in the WCR equals the H-NCODA value and exceeds the H-OI value of 49 kJ cm⁻². The derived OHC value of 39 kJ cm^{-2} in the CCE exceeds the H-NCODA value of 26 kJ cm⁻² and the H-OI value of 16 kJ cm⁻². The H-OI cold bias is much larger in the LC, WCR, and CCE than in the NWC while the H-NCODA bias is small everywhere.

Mean OHC values prior to Katrina from the three sources (derived, H-NCODA, and H-OI) are presented in Table 3 within three regions: the NW Caribbean Sea, the LC, and the detaching WCR, with these regions outlined by the rectangles in Figs. 6d–f. The derived OHC value of 134 kJ cm⁻² in the NW Caribbean exceeds both the H-NCODA value of 117 kJ cm⁻² and the H-OI value of 113 kJ cm⁻² (Table 3). The derived

OHC value of 107 kJ cm⁻² in the LC exceeds the H-NCODA value of 72 kJ cm⁻² and the H-OI value of 78 kJ cm⁻². The derived OHC value of 146 kJ cm⁻² in the WCR again exceeds the H-NCODA value of 104 kJ cm⁻² and the H-OI value of 117 kJ cm⁻². Prior to Katrina, the H-NCODA nowcast underestimates the OHC in all three regions and did not perform as well as it did prior to Ivan. The H-OI nowcast still underestimates OHC, but not by as much as for the earlier storms, perhaps demonstrating that the effects of the biased initialization slowly diminish with time. The H-OI OHC estimates are closer to the derived estimate than H-NCODA in both the LC and WCR.

Although these results are encouraging, the significant errors and biases documented in both nowcast products demonstrate that further improvements to nowcast–forecast systems and improved observational coverage are still necessary. The continuing evaluation effort must involve a larger number of storms spanning a wide range of atmospheric and oceanic conditions where high quality in situ measurements of currents, temperature, and salinity deployed from aircraft are available (Shay 2008).

b. Impact of initial ocean state on the simulated SST response to Ivan

A free-running HYCOM simulation of the ocean response to Hurricane Ivan was performed to demonstrate that the reduced temperature bias in H-NCODA, and in particular accurate initialization of ocean features, is critically important to simulating the magnitude and pattern of SST cooling. This simulation could not be run on the larger domain used for the Isidore analysis (section 3d) since H-NCODA was only available within the GOM domain. The Ivan simulation is therefore run within the GOM domain. The coastline follows the actual land-sea boundary with a minimum water depth of 2 m. The model uses the Goddard Institute for Space Studies (GISS; Canuto et al. 2001, 2002) level-2 turbulence closure to provide vertical mixing. Monthly river inflow from 12 rivers is included. To improve model representation of the OML, six additional layers were added at the top to the original 20 vertical layers used for H-NCODA to increase the resolution in the upper ~ 100 m. No attempt was made to use H-MODAS to provide initial conditions because the large horizontal smoothing in the MODAS analysis resulted in poor resolution of the relatively small CCEs that were critically important to the SST response pattern (not shown). This was not an issue prior to Isidore.

Substantial effort was directed toward generating surface atmospheric forcing fields that continuously resolve the eye and surrounding eyewall as accurately as



FIG. 6. Maps of OHC in the Gulf of Mexico domain prior to Hurricane Ivan (10 Sep 2004): (a) derived from satellite altimetry, (b) calculated from the H-NCODA nowcast, and (c) calculated from the H-OI nowcast. Maps of OHC from the same sources prior to Hurricane Katrina (26 Aug 2005) are presented in (d)–(f). The boxes illustrate the domains within which mean OHC, OHC, and D_{26} values are compared in Table 3.

possible. The basic surface forcing fields were obtained from the U.S. Navy's 0.5° NOGAPS atmospheric model and spatially interpolated to the GOM model grid. Since this forcing product is too coarse to resolve the inner core of the storm, a special effort was required to improve the resolution, at least for the wind speed and wind stress forcing fields. Specifically, NOGAPS wind velocity fields were blended with high-resolution wind velocity fields derived from the H*WIND analysis, then the blended fields were used to calculate the final wind speed and wind stress forcing fields. A major limitation of the H*WIND product is that it is only generated every 1–2 days when aircraft surveys are available. Intermediate 3-hourly H*WIND maps, which rely on measurements made by U.S. Air Force reconnaissance aircraft, were not used because these measurements have larger errors and biases than do the NOAA measurements. The 3-hourly H*WIND surface wind analyses of Powell et al. (1998), Houston et al. (1999), and Houston and Powell (2003) produced for the 2002 storms substantially correct this problem, but they were not available during Ivan.

TABLE 3. A comparison of prestorm OHC from three sources (derived, H-OI, and H-NCODA). For Hurricane Ivan, comparisons are made in four regions delineated by black rectangles in Figs. 6a–c: the NWC, the interior of the LC, the WCR, and the CCE located SE of the WCR. For Hurricane Katrina, comparisons are made in three regions (NWC, LC, WCR) delineated by the black rectangles in Figs. 6d–f. The sample sizes n reflect the resolutions of the respective grids.

Storm	Region	Derived		H-OI		H-NCODA	
		OHC	n	OHC	n	OHC	n
Ivan	NWC	125	45	101	5450	118	5450
	LC	83	9	59	700	92	700
	WCR	118	12	49	1064	118	1064
	CCE	39	12	16	1025	26	1025
Katrina	NWC	134	45	113	5450	117	5450
	LC	107	25	78	2754	72	2754
	WCR	146	15	117	1428	104	1428

The wind velocity maps for Ivan generated from NOAA aircraft observations were available at four times that impact the GOM domain: 1330 UTC 12 September, 2200 UTC 13 September, 0030 UTC 15 September, and 0230 UTC 16 September. To insure that the final forcing fields reproduced the inner-core structure, a Lagrangian interpolation procedure was devised to generate H*WIND wind velocity fields on the moving grid box every 30 min. First, the center of the box was constrained to follow the 6-hourly best-track positions produced by the NOAA National Hurricane Center. For each 30-min map, field values on each individual grid point were linearly interpolated between the previous and following H*WIND maps generated from aircraft observations. This temporal interpolation to 30 min is important because HYCOM linearly interpolates between two forcing fields adjacent in time, and maps separated by 1 h or more may have the inner-core structure degraded, especially if the storm has a small eye or moves rapidly.

The 30-min H*WIND wind velocity maps were spatially interpolated to the GOM grid while the 3-hourly NOGAPS wind velocity maps previously interpolated to the GOM grid were temporally interpolated to 30 min. The resulting NOGAPS and H*WIND fields were then blended so that they represented 100% H*WIND in the inner core of the storm and 100% NOGAPS over the outer reaches of the H*WIND box where the analysis is relatively poor. The transition region is radially symmetric, with the blended variable *B* given by

$$B = w_H H + w_N N, \tag{5}$$

where *H* is the H*WIND variable, *N* is the NOGAPS variable, and w_H and w_N are the respective weights for H*WIND and NOGAPS given by

$$w_{N} = 1 - w_{H}$$

$$= \begin{cases} 0 & r < r_{1} \\ 0.5 \left[1 - \cos \pi \left(\frac{r - r_{1}}{r_{2} - r_{1}} \right) \right] & r_{1} \le r \le r_{2} \\ 1 & r > r_{2} \end{cases},$$
(6)

where *r* is radial distance from the storm center and r_1 , r_2 are chosen to be 120, 360 km to ensure a broad smooth transition. After blending these data products, wind speed and vector wind stress are calculated, the latter using the Powell et al. (2003) representation of the bulk aerodynamic drag coefficient that decreases with wind speed above 33 m s⁻¹ so that stress remains approximately constant with increasing wind speed. Other forcing fields from the 0.5° NOGAPS model (shortwave and longwave radiation, atmospheric temperature and mixing ratios, and precipitation) are spatially interpolated to the GOM grid and temporally interpolated to 30 min without further modification.

The wind speed map from 1330 UTC 15 September 2004, a time that is halfway between two H*WIND maps generated from aircraft observations (Fig. 7), demonstrates that the Lagrangian interpolation procedure maintained the storm structure and intensity reasonably well. Although the detailed banded structure of hurricanes is not present in H*WIND images, the eye is resolved and the expected asymmetry of maximum winds in the evewall, being higher to the right of the direction of motion, is reproduced. Ideally, atmospheric forcing should be obtained from a very-high-resolution atmospheric model, either stand alone or coupled to an ocean model that accurately resolves the detailed structure, track, and intensity of the storm. However, the H*WIND-based product used here remains an optimal choice for driving ocean response studies pending further improvement in atmospheric models.

The free-running simulation commenced on 10 September 2004. The oceanographic features present during Ivan are illustrated in the simulated surface height field at the time of maximum coastal storm surge (Fig. 8). The LC followed a medium-amplitude intrusion into the eastern GOM while a strong, previously detached WCR was located to the northwest. Two smaller CCEs were also present: one located to the northeast and the other to the southeast of the WCR. Within the CCEs, the largest cooling during the simulation exceeded 6°C and occurred within the two CCEs. This result is confirmed by the SST cooling pattern observed in daily SST images derived from microwave satellite sensors, specifically the TMI–AMSR-E fusion product (Fig. 8). The 18 September image was chosen to represent post-



FIG. 7. Wind speed forcing field from the blended 0.5° NOGAPS and H*WIND product for 1330 UTC 15 Sep 2004. This time is halfway between the 0030 UTC 15 Sep and 0230 UTC 16 Sep 2004 H*WIND maps, illustrating that the Lagrangian interpolation scheme successfully preserved the eye and eyewall structure present in the original H*WIND maps.

Ivan conditions because the largest cooling in the northern GOM was observed on this date. Overall, there is good pattern agreement between the satellite measurements and simulations in both the structure and magnitude of the large-scale cooling pattern. The large cooling that occurred within the two CCEs was also documented in an analysis of AVHRR satellite imagery by Walker et al. (2005), who discuss the possible contribution of this cooling on the weakening of Ivan before landfall.

The generally realistic cooling pattern reproduced here is partly a result of the improvements achieved by the H-NCODA nowcast product. However, close inspection of Fig. 8 indicates that quantitative discrepancies still exist, in particular the insufficient simulated cooling that occurred within the WCR. While these results are encouraging, additional model evaluation and improvement efforts involving a larger ensemble of storms sampled by high quality in situ observations are still necessary to guide further improvement in ocean nowcast products. This will help determine if additional targeted observations are required to improve the nowcast fields prior to individual storms.

5. Discussion

For a coupled TC prediction model to correctly forecast intensity evolution, the ocean model must accurately respond to the storm forcing, particularly in regard to the magnitude and pattern of the SST cooling relative to the storm center. This necessitates accurate initialization of oceanographic features associated with horizontal temperature differences and with strong thermal advection. Data-assimilative ocean nowcast– forecast systems can be used to initialize the ocean model, but these systems are in various states of development and heretofore have not been evaluated for this purpose.

An initial benchmark evaluation of two generations of the experimental navy ocean nowcast-forecast system was therefore performed to document the present quality of these systems with respect to ocean model initialization. Since both generations assimilate satellite altimetry, the nowcasts reproduced the prestorm locations of important ocean features with reasonable accuracy. However, the first-generation product (H-OI) produced large temperature and salinity biases in the upper ocean prior to Hurricane Isidore (2002) while the second-generation H-NCODA nowcast generally produced somewhat smaller but significant cold bias over the NW Caribbean. The biases prior to Isidore were so large that an interim nowcast (H-MODAS) that relaxed HYCOM to MODAS temperature and salinity analyses had to be performed to provide realistic initial and boundary conditions to free-running simulations of the ocean response to Hurricane Isidore. The smaller cold bias in the initial fields decreased the tendency for the simulated ocean to overcool in response to the storm.

Evaluation of the two nowcast systems prior to Hur-



FIG. 8. Sea surface height (a) from the free-running simulation of the ocean response to Hurricane Ivan at the time of maximum simulated coastal storm surge (0300 UTC 16 Sep 2005). SST maps prior to Ivan (10 Sep 2004): (b) estimated from blended microwave satellite measurements from the TMI and AMSR-E instruments and (c) obtained from the initial fields used for the free-running Ivan simulation. SST maps following Ivan (17 Sep 2004): (d) from the microwave satellite measurements and (e) obtained from the free-running Ivan simulation.

ricanes Ivan (2004) and Katrina (2005) demonstrated that the H-NCODA biases were small prior to Ivan, due in part to the improved initialization procedure that was used. However, H-NCODA displayed a moderate cold bias prior to Katrina. Meanwhile, the cold bias present in the H-OI product during 2002 decreased with time so that by the time of Katrina, the bias was smaller than the H-NCODA bias. Accurate location of ocean features and relatively small bias were very important to the simulation of the ocean response to Hurricane Ivan initialized with H-NCODA, which produced a realistic SST cooling pattern in comparison to microwave SST measurements. Large SST cooling (>6°C) was confined to two cold cyclones in the northeastern GOM, which may have contributed to the weakening of Ivan before landfall. This result demonstrates the importance of accurately initializing both warm and cold ocean features.

The present study demonstrates the feasibility of eventually using a near-real-time ocean nowcast for initializing the ocean component of operational coupled TC prediction models. However, significant errors and biases are still present in these systems, so ongoing research and evaluation must continue. Although new assimilation procedures and ocean model parameterizations are expected to produce some additional improvement, the present study emphasizes the central importance of ocean observations. An increase in high quality observations provided by instruments such as expendable profilers or profiling floats may be necessarv to improve ocean model initialization to the point that significant improvement in intensity forecasts can be achieved (Shay and Ulhorn 2008; Shay 2008). High quality observations are required for assimilation into nowcast products that provide the initial conditions, for evaluating the initial conditions prior to storms, and for evaluating the ocean response simulated by freerunning ocean models or by coupled TC prediction models. As the navy HYCOM-based systems continue to evolve and as other nowcast-forecast systems become available, such as the HYCOM-based system that recently became operational at the National Centers for Environmental Prediction, they must be evaluated against the performance of previous systems. The issue of whether the acquisition of additional observations is necessary and cost effective, either at the beginning of the hurricane season or prior to individual storms, to constrain the nowcast system and provide more accurate initial conditions also needs to be addressed.

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