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An air-ocean-wave modeling system has been developed by the Naval Research Laboratory to provide improved predictive capabilities to the warfighter in regions that include an oceanic component. Each of the three operational models, run in a standalone mode, have provided 48 to 96 hour forecast guidance for the past several years. Utilizing the Earth System Modeling Framework, a model coupler exchanges needed information between the model components and interpolates between the model grids. This paper will discuss the model coupling and provide a brief overview of validation studies that have been performed in the Adriatic Sea, Ligurian Sea and Kuroshio extension, with a particular emphasis on air-sea interactions. Model studies presented here focus on the upper ocean (mixed layer) heat fluxes, near surface winds, temperature, moisture, the air-sea interaction, and the marine boundary layer characteristics. Validation studies presented here show the most improvements in ocean heat fluxes, due to a more realistic sea surface temperature. The coupled system is scheduled for operational implementation at Navy production centers beginning in 2011.

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The Navy's Coupled Atmosphere-Ocean-Wave Prediction System

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Abstract- An air-ocean-wave modeling system has been developed by the Naval Research Laboratory to provide improved predictive capabilities to the warfighter in regions that include an oceanic component. Each of the three operational models, run in a standalone mode, have provided 48 to 96 hour forecast guidance for the past several years. Utilizing the Earth System Modeling Framework, a model coupler exchanges needed information between the model components and interpolates between the model grids. This paper will discuss the model coupling and provide a brief overview of validation studies that have been performed in the Adriatic Sea, Ligurian Sea and Kuroshio extension, with a particular emphasis on air-sea interactions. Model studies presented here focus on the upper ocean (mixed layer) heat fluxes, near surface winds, temperature, moisture, the air-sea interaction, and the marine boundary layer characteristics. Validation studies presented here show the most improvements in ocean heat fluxes, due to a more realistic sea surface temperature. The coupled system is scheduled for operational implementation at Navy production centers beginning in 2011.

I. INTRODUCTION

The Naval Research Laboratory has developed a coupled atmosphere-ocean-wave modeling system comprised of three primary components: 1) the Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS), 2) the Navy Coastal Ocean Model (NCOM), and 3) wave components consisting of the Simulating Waves Nearshore (SWAN) and WaveWatch-III models. The coupled modeling system is referred to as COAMPS5. The atmospheric elements of COAMPS [1 ,2] are used operationally by the U.S. Navy for numerical weather prediction in various regions around the world. NCOM [3] is run operationally at the Naval Oceanographic Office as both a global model and relocatable regional model. The wave components of the system are run operationally at production centers at both NAVOCEANO and the Fleet Numerical Meteorology and Oceanography Center (FNMOC). The integrated system provides a more realistic depiction of the physical processes at the air-ocean-wave interface.

II. MODEL COUPLING

The exchange of information between the individual model components is shown in Fig. 1. The atmospheric component exchanges wind stress and surface heat and moisture fluxes to the ocean model which in turn provides an updated sea surface temperature to the atmospheric model. The wave model exchanges wave-induced stress, Stokes drift current (effect of ocean waves on ocean current) and bottom drag to the ocean model which provides updated water levels and surface currents to the wave model to represent wave-current interaction.

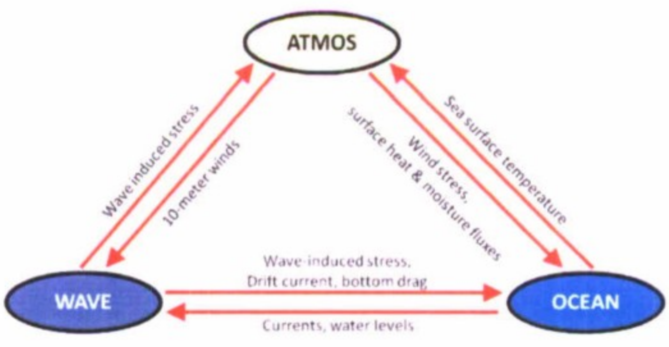

Fig. 1 Data exchange between atmospheric, ocean circulation and ocean wave models in COAMPS5.

The coupled driver that controls the time-stepping and coordinates the exchange of fields between model components is enabled utilizing the Earth System Modeling Framework (ESMF, www.earthsystemmodeling.org). For each of the component pairs, the eoupler eomputes a sparse matrix that eombines the weights for interpolating between grids and extrapolation weights for treatment of mismatch in the land-sea boundaries. The grid transformations at eaeh coupling interval are effieiently handled by the ESMF parallel sparse matrix multiply. On contrast to loosely eoupled systems, the sealability and effieieney of the eoupling allows for tight integration of models. The coupling interval can be as small as the least eommon multiple of the time steps of the coupled components. Baekground oeean and wave eomponents are ineluded in support of flexible model setup and improved relocation capability. Optional sequential or coneurrent exeeution of eomponents allows for improved load balancing on parallel computers.

The system can run in a one-way (atmosphere "forees" oecan) or two-way (atmosphere "forces" oeean and ocean "forces" atmosphere ete.) eoupling. COAMPS [1] utilizes meteorologieal observations including radiosondes, satellite data, ship reports, and oeean observations with time-dependent global atmospheric lateral boundary conditions from the Navy Operational Global Predietion System (NOGAPS) whieh has a 1.0° horizontal resolution. Ocean lateral boundary eonditions are obtained from the global (1/8°) NCOM. Atmospheric and oceanographie foreeast model output ineludes surfaee and upper air fields, sea surfaee temperature (SST), three-dimensional (3D) ocean temperature, salinity, two-dimensional (2-D) sea surface height, mixed layer depth and ocean acoustic products. Fig. 2 illustrates the data flow for a two-way coupled simulation. Additional information about COAMPS, NCOM and the eoupled system deseribed in this paper ean be found in [1, 2, 3, 4].

Data Assimilation

Atmospheric data assimilation ean be performed using either three-dimensional multi-variate optimum interpolation (MVOI) or three-dimensional variational assimilation (3DVAR) using the NRL Atmospherie Variational Data Assimilation System (NAVDAS) [5]. For the purpose of this study, only MVOI was used for the atmospherie data assimilation. Oeean data assimilation is facilitated through the Navy Coastal Oeean Data Assimilation (NCODA) 3D system). The NCODA is a fully three-dimensional MVOI routine that produces simultaneous analyses of temperature, salinity, geopotential, and vector veloeity [6]. However, for the validation studies presented here, only oeean data assimilation at the oeean surfaee was performed.

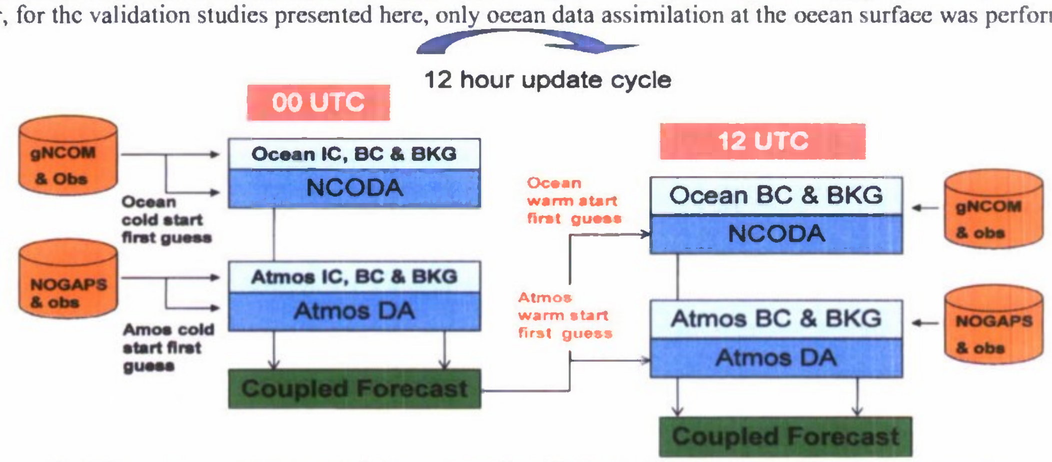

Fig. 2 Two-way coupled data assimilation system, where IC denotes initial conditions, BC represents boundary Conditions, and BKG denotes background fields.

III. RESULTS AND ANALYSIS

The coupled model has been tested and validated in several geographieal loeations ineluding the Gulf of Mexieo, Monterey Bay, CA, eoastal Peru, Kuroshio Extension, Ligurian Sea and Adriatie Sea. The following seetion provides a brief summary of some recent validation studies. A eomplete summary of all validation studies performed with COAMPS5 can be found in Ref. [7].

Adriatic Circulation Experiment (ACE)

The Adriatie Sea has recently been the subjeet of numerous atmospherie and oeeanic modeling and observational studies (see Ref. [8, 9, 10, 11, 12, 13]. Many of these studies foeus on the downslope windstorms, or "bora", that occur in the topographic mountain gaps of the Dinaric Alps of Croatia during the late fall and winter months. The eireulation patterns of the northern Adriatic Sea are heavily influenced by bora jet flows. Due to the nature of the bora events and the fact that these winds traverse the Adriatie Sea in the form of mesoseale jet flows, this region is of partieular interest to air/sea interaction studies at the mesoseale level. This test ease eompared the effects of one-way and two-way coupling on atmospherie and oeean foreeasting during bora events. In this study, we reproduce and extend the results of Ref. [9] and Ref. [13] by using COAMPS, incorporating ESMF-based (rather than file-based) two-way coupled simulations.

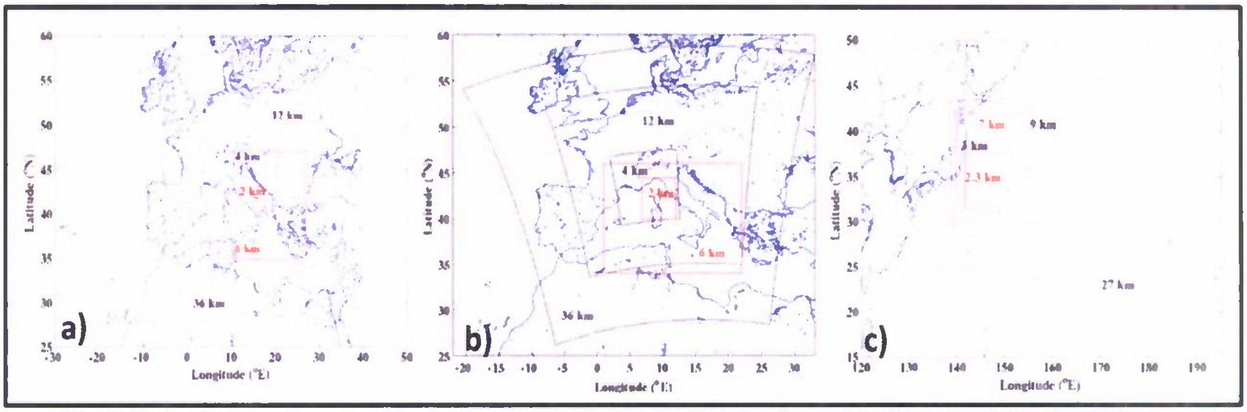

Fig. 3 Atmospheric and ocean grid setup for a) Adriatic Sea, b) Ligurian Sea and c) Kuroshio Extension System Study. The resolutions of the atmospheric nests (black) and ocean nests (red) are indicated.

The COAMPS Adriatic Sea configuration shown in Fig. 3a, employed a triple-nested (36, 12, 4 km horizontal resolution) domain where nest 3 extended from 39.6°N to 47.3°N and 10.4°E to 20.6°E.. There were 40 vertical terrain-following levels. At 00 UTC and 12 UTC of each day, a data assimilation cycle was initiated using the prior 12 hr forecast as background, incorporating quality-controlled observations from aircraft, radiosondes, satellite, ship, and surface stations. An MVOI analysis was used for both *in situ* and satellite measurements. The length of the model run extended from 25 January to 21 February 2003, a period of 28 days. The ocean model NCOM [10] configuration consisted of two nests (6 and 2 km horizontal resolution) where nest 2 covered approximately the same area as nest 3 in the atmospheric model (Fig. 3a). There were a total of 50 vertical levels, of which 36 were sigma coordinates in the upper 190 m of the water column. NCOM was initialized using global NCOM hindcast data, while the atmospheric and ocean models were coupled every 12 minutes through exchange grid processes.

In all of the coupled runs, the winds, wind stresses, and heat fluxes were interchanged between the atmosphere and ocean (i.e., the ocean feeds back to the atmosphere and the atmosphere feeds back to the ocean). In the uncoupled runs, the ocean *did not* feedback to the atmosphere, i.e., the heat fluxes calculated by the atmospheric model were computed using NCODA SSTs rather than the NCOM SSTs used in the coupled runs. Though wind forcing from the atmospheric model was still passed to NCOM in the uncoupled run, there was no feedback from the ocean to the atmosphere.

There were two bora events during the study period. Bora 1 was a cyclonic bora occurring for 41 hours from 31 January through 2 February of 2003. The second bora was a 70-hour anticyclonic event from 11-14 February 2003. A complete description of the test area is found in Ref. [9]. Data from ACE included latent, sensible, and total heat fluxes, wind stress, and SSTs gathered from meteorological gauges on gas platforms at Acqua Alta (Venice), Azalea, Ancona, and Veli Rat.

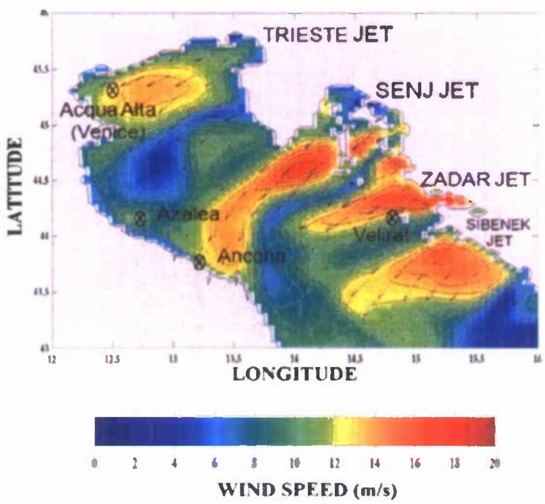

Fig. 4 Average 10-m wind speed and direction from bora study during the period of 31 January to 21 February, 2003. Major jet features resolved and gas platform observation locations are shown.

Fig. 4 depicts the study area in the northern Adriatic Sea with the locations of four coastal oil platforms where observational data was available for this validation study [8,9,14]. Also shown are the major jet features resolved in these bora studies including the Trieste and Senj jets. Table 1 presents summary statistics for the validation studies at Acqua Alta (Venice), Azalea, Ancona and Veli Rat. Comparisons are made between coupled and uncoupled test cases. While there is very little statistical difference in the correlation coefficients for all four platforms, we observe an overall reduction in mean bias and root mean square error, particularly at Acqua Alta and Azalea. Fig. 5 depicts a time-series comparison of the coupled and uncoupled simulations versus observations at Acqua Alta. There is a noticeable improvement with the coupled model for both latent and sensible heat flux.

Table 1 COAMPS atmospheric parameter comparisons to observations at four gas platforms. CC refers to correlation coefficient, [u] denotes uncoupled run, [c] coupled run, MB represents mean bias and RMSE root mean square error.

Variable	Obs mean/STD	COAMPS mean/STD [c]	COAMPS mean/STD [u]	CC [c]	CC [u]	MB [c]	MB [u]	RMSE [c]	RMSE [u]
			ACQUA ALTA						
Net Heat Flux (W/m²)	62/190	49/167	131/179	0.83	0.82	12	-69	108	130
Wind Stress (N/m²)	0.151/0.168	0.118/0.101	0.135/0.111	0.79	0.78	0.03	0.02	0.112	0.108
Latent Ht. Flux (W/m²)	71/41	88/38	135/47	0.78	0.76	-17	-64	31	71
Sensible Ht. Flux (W/m²)	13/15	59/34	93/44	0.55	0.53	-46	-79	54	88
			VELI RAT						
Net Heat Flux (W/m²)	280/296	197/208	228/207	0.95	0.91	83	51	144	145
Wind Stress (N/m²)	0.092/0.070	0.147/0.077	0.154/0.079	0.74	0.74	-0.05	-0.06	0.076	0.082
Latent Ht. Flux (W/m²)	242/74	188/48	206/50	074	0.74	54	37	74	62
Sensible Ht. Flux (W/m²)	88/32	130/42	142/44	0.81	0.80	-42	-54	49	60
			ANCONA						
Net Heat Flux (W/m²)	101/112	-19/125	151/134	0.57	0.55	120	-50	163	129
Wind Stress (N/m²)	0.085/0.075	0.057/0.063	0.088/0.079	0.52	0.50	0.03	0.00	0.074	0.077
Latent Ht. Flux (W/m²)	71/33	40/24	138/43	0.45	0.42	31	-66	44	79
Sensible Ht. Flux (W/m²)	27/21	16/21	86/37	0.40	0.37	11	-59	25	68
			AZALEA						
Net Heat Flux (W/m²)	15/164	41/117	152/134	0.82	0.77	-25	-137	99	172
Wind Stress (N/m²)	0.063/0.057	0.106/0.061	0.120/0.071	0.51	0.53	-0.04	-0.06	0.072	0.085
Latent Hle t. Flux (W/m²)	47/30	76/28	141/41	0.62	0.62	-29	-95	38	99
Sensible Ht. Flux (W/m²)	-1/7	40/29	87/38	0.34	0.36	-42	-88	50	95

Overall, the fully coupled COAMPS5 model run for the Adriatic Sea showed improvements over the uncoupled run, especially with regard to heat fluxes produced by the NCOM SSTs in the fully coupled run versus the NCODA SSTs in the uncoupled run. The correlation coefficients for the winds, wind stresses, and heat fluxes showed no appreciable differences between the coupled and uncoupled runs. Refer to Ref. [7] for a more in-depth discussion of this study, including comparisons (with depth) at several acoustic doppler current profilers (ADCP) locations.

Ligurian Air Sea Interaction Experiment

The goal of this investigation was to validate COAMPS5 against a detailed dataset of atmospheric and oceanic measurements data from the Ligurian Sea Air-Sea Interaction Experiment of June/July 2007 (LASIE07). LASIE07 focused on the coincident measurement of oceanic and atmospheric boundary layer properties through the gathering of concurrent atmospheric and oceanic soundings. The atmosphere provides strong forcing (buoyancy and stress) on the ocean in this region, in winter and to a slightly lesser extent in summer. The model simulations were designed to resolve strong summer Mistral winds due to steep land topography, specifically demonstrating their effect on the ocean (mixed layer cooling and eddy response) and feedback to the atmosphere (impacts on clouds, heat fluxes and wind stress). A comprehensive report has been written that details the LASIE07 test area, observations, model configuration and results [15]. Please refer to this document for an in depth discussion of LASIE07. A very brief summary is provided below.

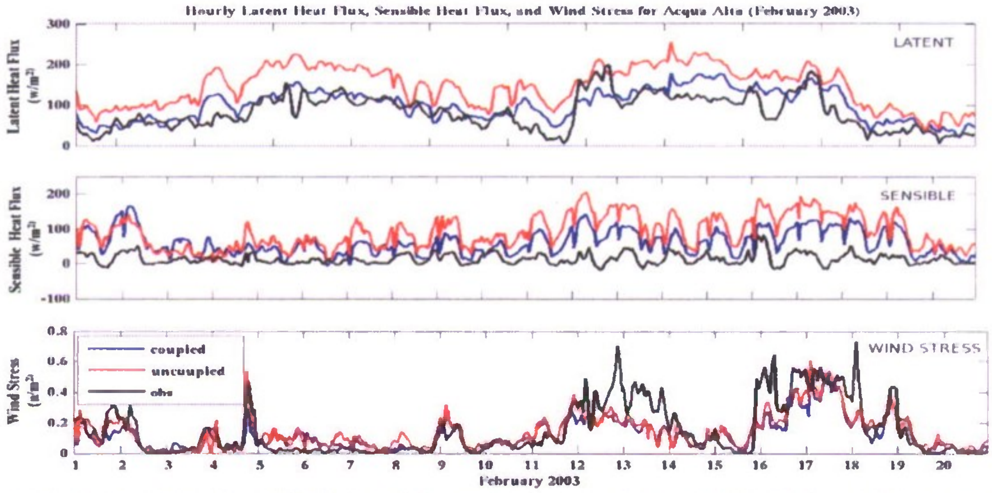

Fig. 5 Hourly latent and sensible heat fluxes (W/m²), and wind stress (N/m²) for the fully-coupled COAMPS run (blue) versus uncoupled (red) and observations (black) at the Acqua Alta gas platform.

COAMPS5 has been validated against *in situ* and satellite data from the LASIE07 experiment in the Ligurian Sea (western Mediterranean) during the summer of 2007. A month long simulation was performed with atmospheric data assimilation for both a fully coupled case and an uncoupled case using an analysis SST to compute bulk fluxes.The COAMPS Ligurian Sea configuration consisted of three nests of horizontal spacing 36 km, 12 km and 4 km, respectively (see Fig. 3b for the nest locations), with each nest having 40 vertical layers (with 14 layers in the lowest 1000 m and four in the lowest 100 m). Explicit microphysics were switched on in the inner nest to model cumulus convection, which was parameterized in the outer nests using the Kain and Fritsch [16] scheme. Lateral boundary conditions for the atmospheric model came from the operational NOGAPS 1° model with 6-hourly output.

The NCOM had a 6 km horizontal resolution course mesh grid and a 2 km inner nest with 50 vertical levels, 35 sigma layers in the top 550 m, and 15 z levels below that. Initial and boundary conditions came from a data-assimilating run of the global NCOM (1/8°). The model was initialized on 10 June, five days before the main observation-model comparison began. The reason for this short spin-up was that the ocean model had no data assimilation, and a longer spin-up would have possibly allowed a large drift away from observed conditions. A 12-minute coupling interval was used in the simulations. At every coupling interval, SST from the ocean model was passed to the atmospheric model, formulating the bulk fluxes from the near-surface atmospheric variables (temperature, humidity, and wind velocity) with the modified Louis [16] scheme. The fluxes were then passed back to the ocean. In COAMPS5, the atmospheric model and then the ocean model were run in sequence. Time steps for the outer ocean and atmospheric grids were both 90 seconds. .

The monthly average near-surface winds over the Ligurian Sea from the coupled model, during the study period (June – July 2007) is shown in Fig. 6a. The time-mean structure of the near-surface wind field matched up to non-assimilated QuikSCAT satellite data and added enhanced detail to that seen by satellite (Fig. 6b). The fully coupled model also performed well in the month-long simulation when compared against independent buoy data (Table 2).The wind speed correlation coefficient was 0.68 at a deep ocean station (offshore location marked in Fig. 6a) and 0.43 at a coastal station (also shown in Fig. 6a). The model slightly under-predicted wind speeds at the deep station and overestimated wind speeds at a coastal station, due to an overly strong land breeze in the model. At the deep water site there was no statistically significant change in the model-buoy comparison when coupling was introduced. However, the coupled model performed significantly better at the coastal location for sea surface temperature (see Fig. 7a for a timeseries comparison of the observed SEPTR SST, the coupled model SST, NCODA SST used in the uncoupled simulation, and an independent satellite analysis), air temperature and latent heat flux.

Table 2 Buoy versus COAMPS 4 km grid statistics for the period June10 to July 9, 2007.

ODAS Buoy	CC [c]	CC [u]	MB [c]	MB [u]	RMSE [c]	RMSE [u]
Wind Stress (N/m^2)	0.74	0.72	0.0057	0.0068	0.0460	0.0480
Wind Speed (m/s)	0.68	0.63	0.54	0.62	2.36	2.54
Downwelling solar flux (W/m^2)	0.93	0.94	-17	-21	122	121
Long-wave radiation (W/m^2)	0.59	0.59	-1.90	-1.00	24.41	24.28
Near surf. Air Temp (°C)	0.63	0.61	-0.23	0.14	1.04	1.01
Near surf. rel. humidity (%)	0.62	0.64	2.16	0.83	8.62	8.52
Sensible Heat Flux (W/m^2)	0.53	0.44	-3.81	-3.34	7.01	6.97
Latent Heat Flux (W/m^2)	0.61	0.64	-23.87	-18.72	46.93	46.00
METEO Buoy	**CC [c]**	**CC [u]**	**MB [c]**	**MB [u]**	**RMSE [c]**	**RMSE [u]**
Wind Speed (m/s)	0.43	0.42	-0.74	-0.63	2.40	2.40
Wind Stress (N/m^2)	0.34	0.29	-0.007	-0.004	0.02	0.05
Near surf. Air Temp (°C)	0.50	0.09	1.13	2.05	3.12	2.76
Near surf. rel. humidity (%)	0.54	0.50	-6.79	-6.69	11.80	11.92
Sensible Heat Flux (W/m^2)	0.60	0.57	-4.27	2.79	6.49	9.05
Latent Heat Flux (W/m^2)	0.72	0.76	-4.29	25.55	39.90	47.24

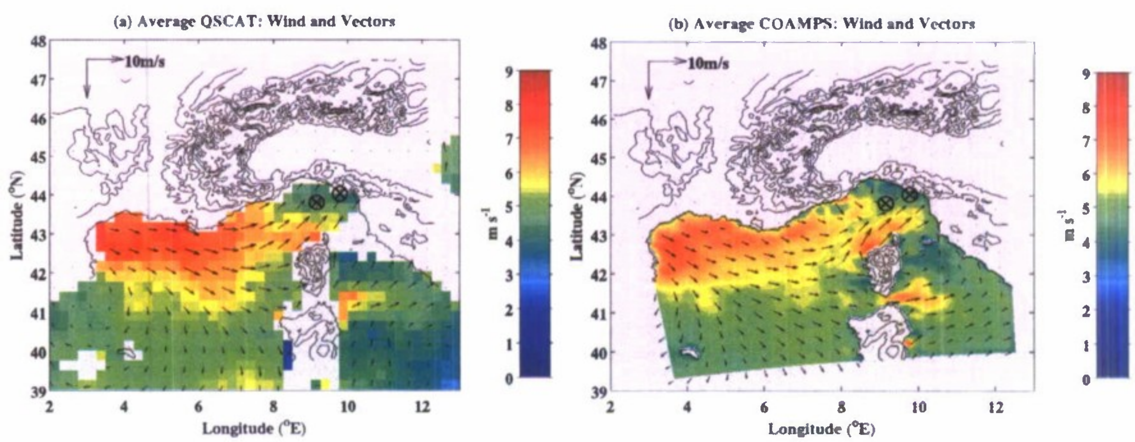

Fig. 6 Near-surface winds over the Ligurian Sea. (left): Monthly average of neutral equivalent of 10 m winds from QuickSCAT. (right): monthly average of 10 m winds from COAMPS for the period 10 June to 9 July 2007.

In order to see what effects changes in surface fluxes have on oceanic and atmospheric fields, the flux analysis of METEO station data was expanded to a wider area in the model. As a starting point, a warm coastal band of SST was identified as a dominant feature throughout the month long simulation, as seen in the time-average of SST from the coupled model (Fig. 7b) for the period 15 June to 12 July, 2007 (referred heretofore as a "month-average"). The warm band occurred in the northeast Ligurian and Tyrrhenian Seas, including off the La Spezia coast and further south towards Pisa (Fig. 7b, area circled). The corresponding time average from NCODA (Fig. 7c) showed a much weaker feature near the coast. The difference between the time-averaged coupled model SST and NCODA SST increased up to 2°C in the narrow coastal band. As discussed above, the LASIE07 *in situ* data shows that the coupled model SST was more accurate than NCODA in this coastal region (Fig. 7a).

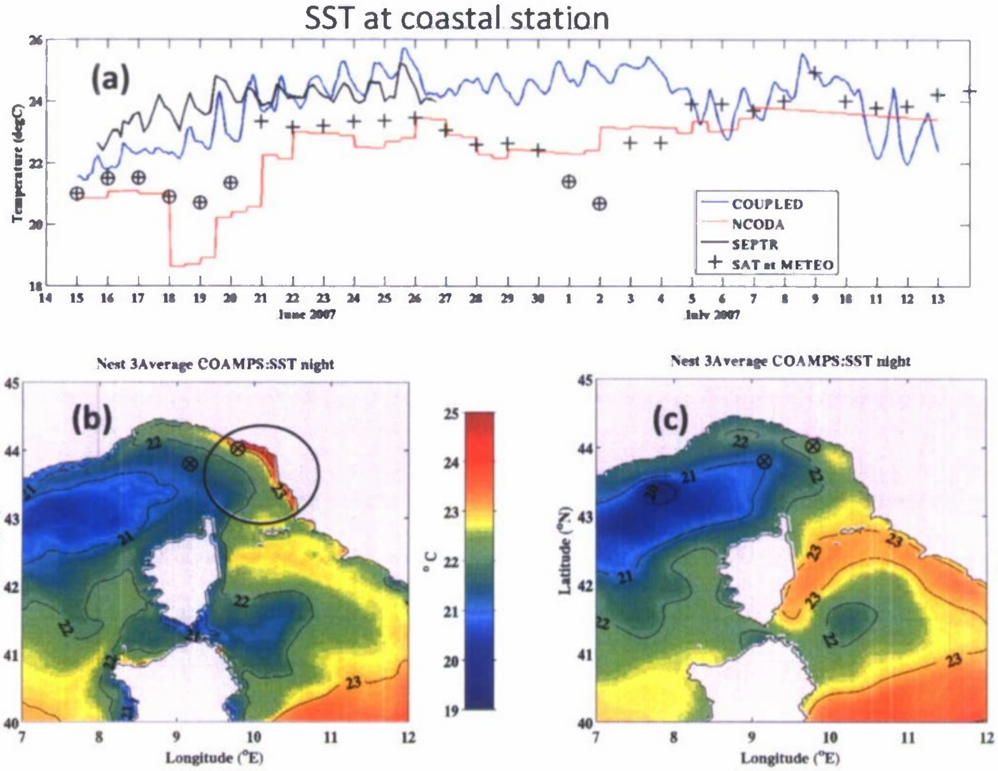

Fig.7 a) Timeseries of sea surface temperature at the coastal METEO location from observations (SEPTR), coupled model, NCODA, and an independent satellite product. (Satellite analysis records marked by a circled cross were obtained on days of cloud cover and are likely bad records.) Model and SEPTR temp. at 0.25m b), c) Month-long (15 June to 12 July) averages of nighttime SST, (b): from the coupled COAMPS model, (c): from the NCODA analysis. The coastal area of interest is circled in Fig. 7b.

Kuroshio Extension System Study

The Kuroshio Extension is the region of the North Pacific Ocean occupied by the Kuroshio Current after it separates from the coast of Japan near 35°N and becomes a warm, eastward-flowing, free inertial jet. Joining this region from the north, the cold waters of the Oyashio Current flow south along the east coast of Japan and depart the coast to flow as another eastward jet near 40°N. The Kuroshio Extension is the major crossroads for the exchange of heat and fresh water between the subtropical and subpolar gyres in the North Pacific and is one of the most intense air–sea heat exchange areas on the globe.

The Kuroshio Extension system is an opportune area to test hypotheses formulated from previous observational and modeling studies because of its distinct stratification, bathymetry, strong fronts and thermohaline circulation. A primary goal of this study was to examine air-sea fluxes at a strong SST front, focusing more closely on boundary layer processes and air-sea interaction in synoptic storms, particularly on weekly to intra-seasonal time scales.

The study [18] area shown in Fig. 3c covers the KESS region over an area of about 5400 km x 2700 km using a Lambert conformal projection centered on 142°E, 35°N, extending from the Asian continent to the date line and from about 25°N to 45°N. The model uses three nested grids: a 27 km coarse grid (199 x 100), a 9 km resolution grid spanning from about 140°E to 155°E and 30°N to 42°N (199 x 169) with a resolution of 9 km covering the NCOM grid area, and a 3 km resolution grid (283 x 277) extending from about 142°E to 151°E and 32°N to 38.5°N. The atmospheric model uses 40 vertical levels. The time step is 80 sec in the coarse grid model. Initial and boundary conditions were provided by NOGAPS.

The first NCOM nest covers the area from 140°E to 155°E and 30°N to 42°N with a horizontal resolution of 1/16° (5.7 km (at 35°N) x 7 km) and 50 vertical levels (15 *z*-levels and 35 sigma levels). It has a 241 x 193 x 50 grid. The second nest is a 1/48° grid (1.89 km (at 35°N) x 2.3 km) covering a region from 142°E to 150°E and 32°N to 38°N with the same vertical levels. It has a 389 x 293 x 50 grid. Tidal potential for the first eight diurnal and semi-diurnal tidal constituents (K1, O1, P1, Q1, K2, M2, N2 and S2) are included in the forcing. The COAMPS model is initialized and its boundaries forced by output from the East Asian Seas NCOM Nowcast/Forecast System [19]. The EAS NCOM has the same vertical and horizontal resolution, covering the Western Pacific from 17°S to 52°N from the Asian continent to 158°E and includes the same tidal components. The boundary conditions for the EAS NCOM come from the 1/8° Global NCOM and the surface forcing is from NOGAPS. Both surface forcing and boundary conditions are provided every three hours.

Cold Air Outbreak

During the wintertime extreme cold air outbreak over the warm pool region, COAMPS produced remarkably good surface winds as shown in Table 3. Both the uncoupled and coupled runs showed very similar results. The very deep ocean mixed layer (200 m) limited feedback from the ocean to the atmosphere during the short simulation. The coupled run had a smaller negative bias in relative humidity and a slightly smaller positive bias in wind speed, with better correlation than the uncoupled run, but not significantly.

During the cold air outbreak, the sum of the model latent and sensible heat fluxes exceeded 1000 W/m^2 in the warm pool region that encompasses the KEO buoy location (Fig. 8, left). This is similar to observations of the Gulf Stream region [20], where air-sea temperature differences exceeding 20°C have been observed [21]. SST contours on the atmospheric grid are shown in Fig. 8 (left) and also in the bottom figure in the color shading of the ocean model grid (Fig.8, right). It is clearly evident that high heat fluxes were confined to the warm subtropical waters south of the Kuroshio front. Also note the cyclonic cold core eddy visible at the KEO buoy location (Fig. 8, right). This recirculation gyre was present during the entire model simulation.

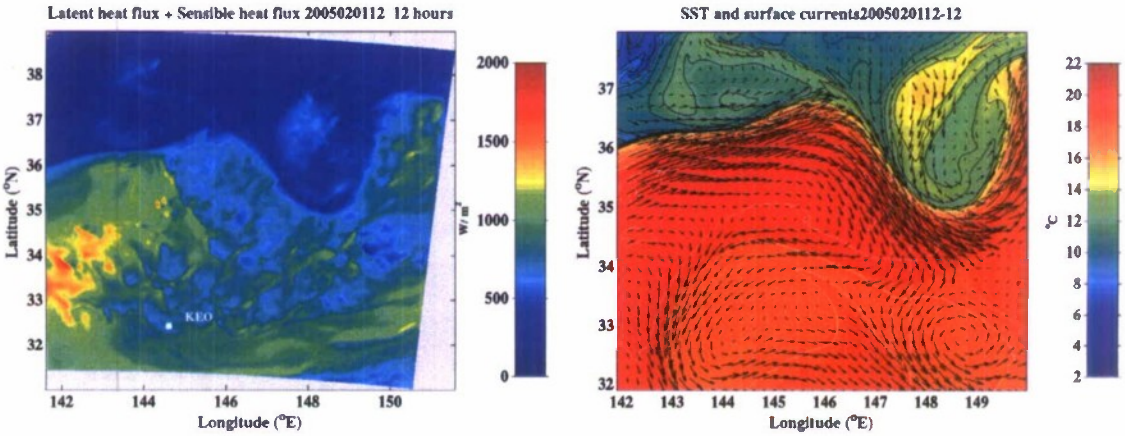

Fig. 8 (Left): The sum of latent and sensible heat flux (W/m^2) from COAMPS atmospheric 3 km grid on 2 February, 2005 00UT. (Right): SST and current vectors from the 1/48° grid NCOM model.

Table 3 Statistics for atmospheric quantities from the 3km nest COAMPS uncoupled [u] and coupled [u] runs for 30 January through 6 February, 2005 compared to the KEO buoy.

	Mean [u]	Mean [c]	CC [u]	CC [c]	MB [u]	MB [c]	RMSE [u]	RMSE [c]	KEO RMSE
Air Temp °C	12.50	12.33	0.87	0.83	-0.11	-0.27	1.16	1.28	1.34
Rel. Hum. %	71.73	55.86	56.97	-0.03	0.21	-16.09	-14.76	17.75	16.38
Zonal Wind m/s	12.26	12.03	0.70	0.75	3.31	3.07	4.87	4.56	5.29
Merid. Wind m/s	-3.78	-3.43	0.73	0.77	1.97	2.33	3.79	3.84	3.84
Wind Spd m/s	13.77	13.59	0.64	0.71	1.84	1.66	3.45	3.25	3.54

Summertime Studies

During the summer, the ocean mixed layer in the northern portion of the Kuroshio Extension is much shallower, allowing for a stronger ocean feedback to the atmosphere. A summer COAMPS simulation was conducted from 15 June through 17 July, 2005. During the month-long summer simulation the air temperature was increasing at a near constant rate from 23°C to 27°C. The bias was just over 1°C for the coupled run and 0.5°C or less for the uncoupled run, but the correlation was slightly better for the coupled run (0.86 – 0.89) than the uncoupled run (0.82 – 0.84). With relative humidity, the correlations were much smaller, but higher than during winter. The bias was small, about -2.5% for the uncoupled run and about -1% for the coupled run. The summer winds were in excellent agreement with the KEO buoy observations. For the total wind speed, the bias was only about 0.1 m/s for the coupled run and about 0.3 m/s for the uncoupled run. Correlations were about 0.8 (Fig. 8; Table 4).

During the summer simulation month the SST increased from about 24°C to above 27 °C (Fig. 9). However, both the uncoupled and the coupled model had significant cold biases of more than 1°C. As seen during the winter, the deeper water was too cold, which may have influenced the upper ocean temperatures as well. The near surface temperature in the coupled run showed a smaller bias than the uncoupled run towards the end of the simulation. The large heat capacity of the ocean mixed layer, even during the summer when it is shallow, required a large difference in heat flux to respond to differences in atmospheric heat flux. Statistics are shown in Table 5.

Table 4 Statistics for atmospheric quantities from the 3 km nest COAMPS uncoupled [u] and coupled [c] run from

Jun 15 through July 16, 2005.

	KEO Buoy Mean	Mean [u]	Mean [c]	CC [u]	CC [c]	MB [u]	MB [c]	RMSE [u]	RMSE [c]
Air Temp. (°C)	24.74	24.33	23.68	0.82	0.86	-0.41	-1.06	0.69	1.16
Relative Hum. (%)	94.71	92.26	93.63	0.46	0.47	-2.45	-1.08	4.35	3.56
Zonal Wind (m/s)	4.75	4.65	4.22	0.79	0.78	-0.10	-0.53	2.51	2.58
Merid. Wind (m/s)	3.96	4.50	4.51	0.78	0.78	0.53	0.55	2.24	2.18
Wind Spd (m/s)	7.31	7.54	7.27	0.87	0.88	0.23	-0.04	1.65	1.56

Table 5 Mean ocean temperatures and CC, MB and RMSE for the 27 km (Nest 1) and 9 km (Nest 2) grids from Jun 15 through Jul 16, 2005.

	KEO Buoy	Nest 1 [u]	Nest 1 [c]	Nest 2 [u]	Nest 2 [c]
1 m Temp (°C)	24.60	23.08	23.27	23.05	23.27
CC		0.91	0.93	0.90	0.92
MB				-1.55	-1.33
RMSE				1.62	1.40
10 m Temp (°C)	24.37	22.94	23.14	22.92	23.14
CC		0.88	0.90	0.87	0.89
MB				-1.45	-1.23
RMSE				1.52	1.31

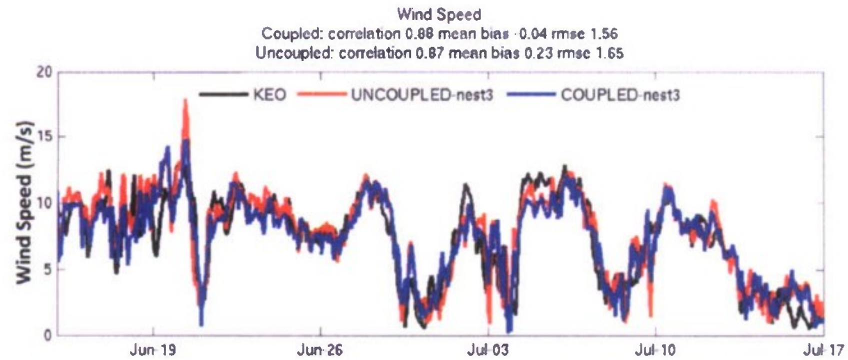

Fig. 6 Wind speed for atmospheric nest 3 (3 km grid) for 15 June to 17 July, 2005 at the KEO buoy. Observations are depicted in black, uncoupled in red, and the fully coupled model is shown in blue.

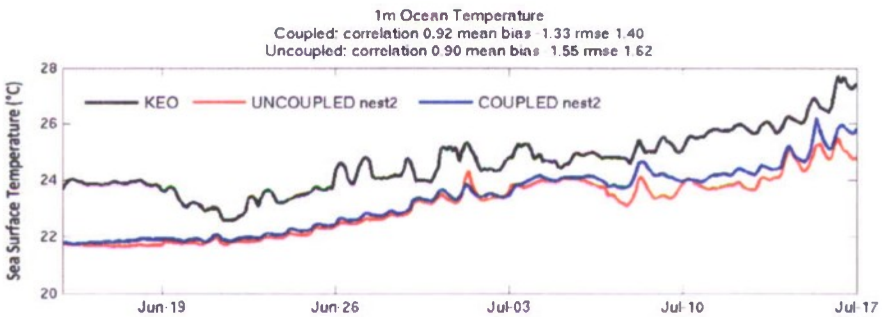

Fig. 7 Ocean temperature at 1m depth comparisons of 9 km coupled (blue) and uncoupled (red) COAMPS5 to KEO (black) observations.

IV. CONCLUSIONS and FUTURE PLANS

The fully-coupled COAMPS system performed well in a wide range of conditions and areas, comparing favorably against observational datasets. Most importantly, we found that using high-resolution NCOM sea surface temperatures (SSTs) in the coupled model generally improves upon the use of NCODA SSTs in the uncoupled model to accurately predict surface heat fluxes. This is especially true in regions with a complex SST field (such as mesoscale eddies and fronts) and/or intense atmospheric events (e.g., the Adriatic Sea mesoscale bora and cold air outbreaks over the Kuroshio Extension), where turbulent heat fluxes have high spatial homogeneity and large gradients. The additional processing time and cost to couple both the ocean and atmosphere models is very small, furthering the advantages of using coupled COAMPS.

Work is underway to validate the two-way coupled ocean-wave component. Additional validation data sets will include drifter and surface current data to examine the feedback mechanisms between ocean and wave fields. The final component of these validation studies will investigate the air-ocean-wave system as shown in Fig. 1. COAMPS5 will be transitioned to operations at FNMOC and NAVOCEANO beginning in FY11. The coupled modeling system can run under a script-based system or as part of a Graphical User Interface system called COAMPS-On Scene.

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