OCEAN PREDICTION CAPABILITIES (PRESENT & FUTURE) AT THE NAVAL RESEARCH LABORATORY

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***Abstract*-The Oceanography Division of the Naval Research Laboratory (NRL) conducts a coordinated program of research and development (R&D) that results in Navy operational ocean nowcast and prediction capabilities. This R&D covers domains from global scales down to local surf zone scales with both military and civilian applications. It includes sophisticated primitive-equation ocean circulation models on global and nested regional and local domains designed for high performance computing platforms at the Naval Oceanographic Office (NAVOCEANO) and Fleet Numerical Meteorology and Oceanography Center (FNMOC). It also includes less sophisticated, but operationally-relevant, models designed to run on workstations and personal computers at the Navy's regional Meteorology and Oceanography Centers (METOCCEN) and on-scene. These latter capabilities, while capable of stand-alone operations, are specifically designed to accept initial and boundary conditions available from the central site products.**

This paper presents first, an overview of NRL R&D efforts in global and regional nowcast and prediction capabilities that provide these initial and boundary conditions. These efforts combine primitive equation models with optimal interpolation assimilation techniques using both in situ and remotely-sensed temperature and altimetry data. Assimilation of altimetry data via statistical models that relate surface height to subsurface density structure is key to mesoscale, nowcast and prediction skill, especially for deeper water. Second, this paper presents an overview of the current, rapidly-relocateable, local-area nowcast and forecast capabilities for temperature, salinity, currents, and surface waves for NAVOCEANO as well as the METOCCEN and on-scene applications.

1. INTRODUCTION

In the early 1990s, the deep ocean naval threat associated with the Cold War faded while Desert Storm demonstrated the necessity for enhanced U.S. capabilities in littoral warfare. This shift in warfare priorities, recognized by the U.S. Navy [1,2,3], resulted in a major shift in the naval oceanography community with greater emphasis placed on ocean science and prediction expected to affect mine warfare, amphibious warfare and special operations [4,5,6]. Burnett et al. [7], provides the most recent description of the Navy's changing mission and requirements as well as the corresponding changes in oceanographic support. The events of September 2001 have further strengthened the need for coastal and estuarine prediction capabilities as the potential threats have come yet closer to include those that might affect U.S. coastal waters.

Responding to the shift toward littoral requirements, the NRL has maintained a strategy since the early 1990s of addressing the near-shore, coastal threat while maintaining deep-water capabilities. This strategy recognizes that the local scale oceanographic environment responds to both locally and remotely-forced events. Present day computer power does not allow a single global prediction system at high enough horizontal and vertical resolution to use a single global model application. Therefore a nested approach is taken with increasing resolution in the smaller nests. Fig. 1 illustrates this concept and also demonstrates the range of domain sizes NRL has investigated. The nested approach allows remote effects to propagate into the local coastal domains of interest while retaining the large-scale deep-water ocean prediction capability relevant for anti-submarine warfare applications and civilian applications including the laying of telecommunication cables and drilling for oil and gas beyond the continental shelf break.

The NRL Ocean Science Division focuses on basic research through the advanced development of both open-ocean and high-resolution coastal prediction capabilities. Working collaboratively with both university researchers in R&D and with operational commands on system transitions provides NRL a unique perspective. This blend of research

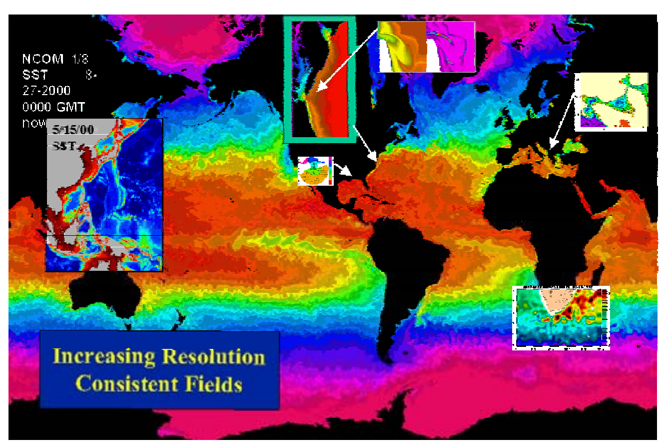

Fig.1. Pictorial description of NRL's global to littoral nested strategy including the range of domain scales that have been addressed.

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and development and transition allows NRL to focus on delivering near-term capabilities given today's computers and modeling and assimilation technology while concurrently investigating and developing the next generation.

II. GLOBAL PREDICTION

Given the sparsity of *in situ* global data, global ocean dynamic forecasting relies primarily on the assimilation of satellite altimetry [8], remotely-sensed sea surface temperature and heat and momentum fluxes from global atmospheric prediction systems [9] to maintain the global ocean prediction models on track. By the end of the decade, computer power and forecast model technology should yield the capability to allow high enough horizontal and vertical resolution for the Navy to use a single dynamic ocean model for eddy-resolving global prediction. Given present-day community model efforts including NRL involvement, the likely candidate for this single ocean model is the hybrid vertical coordinate model HYCOM [10]. However for the near future, computer resource limitations require a two-model solution. This near-term approach combines the deep water, $1/16^0$ horizontal resolution NRL Layered Ocean Model (NLOM) and the $1/8^0$ high vertical resolution NRL Coastal Ocean Model (NCOM), both running at the Major Shared Resource Center (MSRC) at NAVOCEANO. Rhodes et al. [11] describes this system that combines the long-term (~15-30 days) mesoscale forecast skill of NLOM, the "dynamic climatology" of the Modular Ocean Data Assimilation System (MODAS) [12] with the upper-ocean and shallow water strengths of NCOM.

Fig. 2 provides an example of the NLOM analysis and the NCOM analysis after assimilating the NLOM mesoscale information, both compared to independent ocean color imagery for the same day. Note especially the offshore filament in the NCOM temperature and currents as compared to the ocean color. Note also the ocean color coastal "hot spots" associated with the coastal upwelling appearing in NCOM.

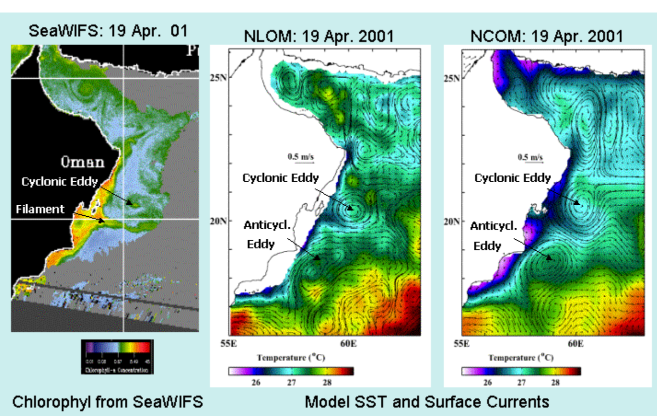

Fig.2. Oman coastal filaments during the spring inter-monsoon as seen in chlorophyll, derived from SeaWIFS ocean color imagery, and in sea surface temperature and currents from NLOM and the combined NLOM/NCOM prediction system.

The mean surface kinetic energy for 2001 in the left-most panels of Fig. 3 illustrates the skill of this NLOM/NCOM system in positioning western boundary currents. The model-derived mean path and variability of the Kuroshio and Gulf Stream compare well relative to the mean path positions independently derived by ocean analysts at NAVOCEANO. The right-most panels show surface eddy kinetic energy for this same period showing the envelope of positions for the mesoscale eddies shed during this period. While Fig. 2 and 3 provide examples of the mesoscale variability available from the global models, Fig. 4 provides an example of coastal effects due to remotely-generated coastally-trapped waves propagating into an area. The topmost panels show surface currents over current speed and surface currents over sea surface height for October 10, 2001.

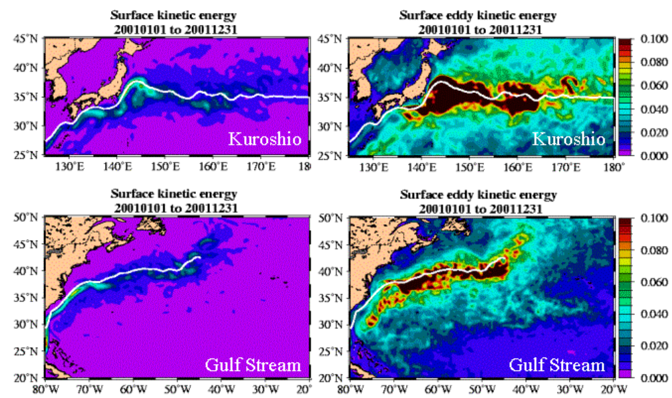

Fig.3. Global NLOM/NCOM prediction system mean surface kinetic energy and mean surface eddy kinetic energy for 2001 for both the Kuroshio and Gulf Stream regions. Mean position for the Kuroshio and Gulf Stream for the same period, independently derived by analysts at NAVOCEANO using remotely-sensed infrared imagery, are overlaid (white line).

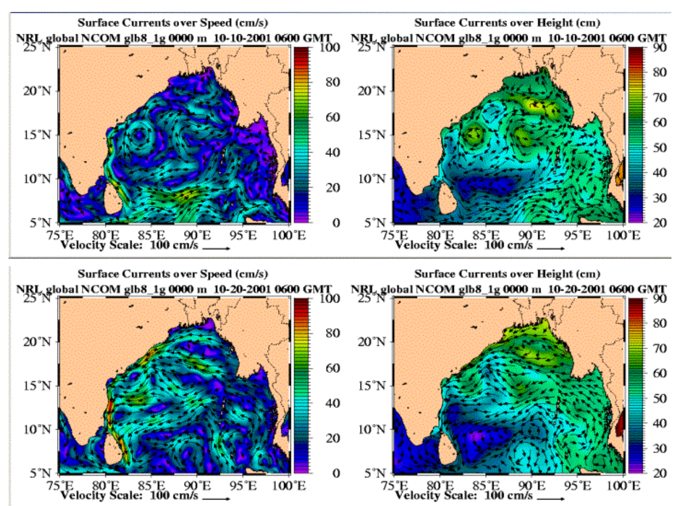

Fig.4. NLOM/NCOM prediction system surface current vectors over color-contoured speed (left panels) and surface current vectors over color-contoured sea surface height (right panels). Comparison of results from October 10, 2001 (top) and October 20, 2001 (bottom) illustrates the effect of a remotely-forced, coastally-trapped wave in the NW Bay of Bengal.

The bottom panel shows the same variables ten days later. Considering sea surface height from the 10th to the 20th, one observes a deepening cyclonic eddy impinging on the Sri Lankan and southern Indian coast with the resultant development of a coastal jet in this region. Further north along the NW Bay of Bengal, the lower left panel shows the development of a coastal jet greater than 1 m/s. This can be traced back to an equatorial Kelvin wave that, upon impinging the Indonesian coast, propagated cyclonically around the Bay of Bengal reaching the Indian coastal region 10 days later. Further examples of nowcasts and forecasts as well as real-time validation comparisons are available on the NRL web page at www.oceans.nrlssc.navy.mil.

Future data inputs to these and future global systems will include ARGO floats [13] especially supporting thermal analysis products such as MODAS. However, altimetry will likely remain the primary source necessary to resolve the mesoscale dynamics for ocean prediction. Ice cover within NCOM, currently parameterized making use of the ice analysis available from FNMOC, will be upgraded in the near future with the addition of a prognostic ice model. To better simulate ice-covered ocean processes NRL plans to couple an ice model, comparable to that described by Preller et al. [14], to the global NCOM. The primary difference is that the ice model will be coupled directly to the global NCOM as opposed to being coupled to an Arctic regional ocean model.

Global ocean wave forecasting, primarily dependent on accurate wind forcing has had a much longer history relative to dynamic ocean prediction. Jensen, et al. [15] describes these capabilities running operationally at both FNMOC and at NAVOCEANO. Given the relative maturity of the global wave systems, NRL's involvement in global wave forecasting has been mainly related to improved forcing and swell forecasting with the primary focus on regional and especially near-shore capabilities described later.

III. COASTAL/ RELOCATEABLE PREDICTION

With the change of Navy priorities in the early 1990s, the NRL Oceanography Division expanded its capabilities and areas of research. Coastal ocean scientists were hired to address the new littoral emphasis with special focus on currents, waves, surf, and surface elevation that are all key environmental parameters in littoral warfare. At the same time, the need for high-resolution local-area analyses and predictions became a goal with the requirement to relocate domains as rapidly as possible in response to operational demands at both NAVOCEANO and the METOCCEN. The Modular Ocean Data Assimilation System (MODAS) was the earliest of these relocateable systems and is currently applied operationally for thermal analysis as described by Fox et al. [12]. MODAS requires a trained user to relocate but this user can relocate and run the MODAS analysis in a matter of minutes on a workstation.

Allard et al. [16] describes an operational wave/surf relocation capability developed jointly with NAVOCEANO. The Rapid Ocean Assimilation, Modeling, Evaluation, Relocation (ROAMER) system, was specifically designed for the mixed workstation & supercomputer environment at NAVOCEANO. It allows a skilled technical user to rapidly set-up, run and monitor a surf model embedded within a near-shore wave model using boundary conditions supplied by regional and global deep water wave models (Fig. 5). The components of this system can be run together as an end-to-end system or as individual components. Fig. 6 illustrates an example surf model and near-shore wave model output generated during the NAVOCEANO AUV Fest in October of 2001 in the Mississippi Bight.

Tidal elevations necessary to support the wave/surf predictions, are derived from specific finite element ADCIRC areas run daily at NAVOCEANO or from a globally relocateable tide model (PC-Tides) run as a component of the ROAMER system. Blain et al. [17] describe these tide forecast capabilities in more detail. Fig. 7 illustrates coastal scales being resolved by the ADCIRC tidal current prediction also run during the NAVOCEANO AUV Fest last year. Fig. 8 provides an example of the tidal validation for PC-Tides.

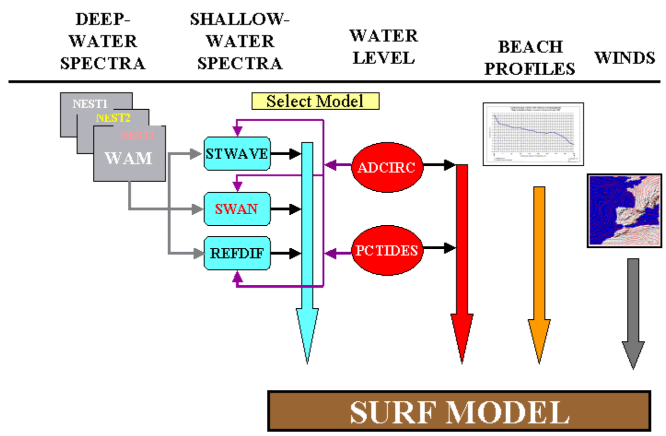

Fig. 5. Schematic of coupled wave/tide/surf capability

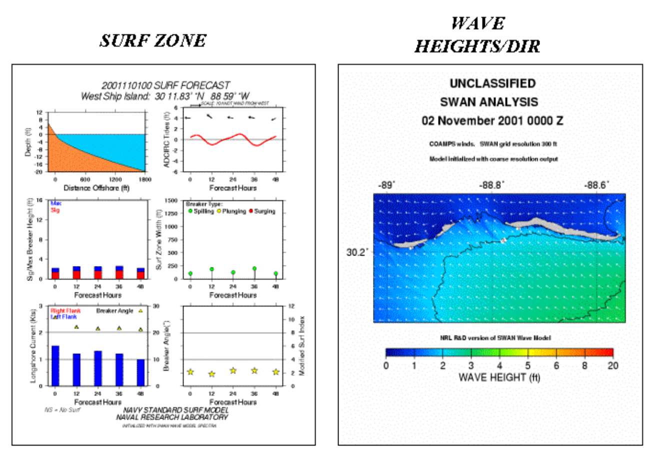

Fig. 6. Examples of near-real-time wave and surf products provided by NRL during the NAVOCEANO AUV Fest 2001.

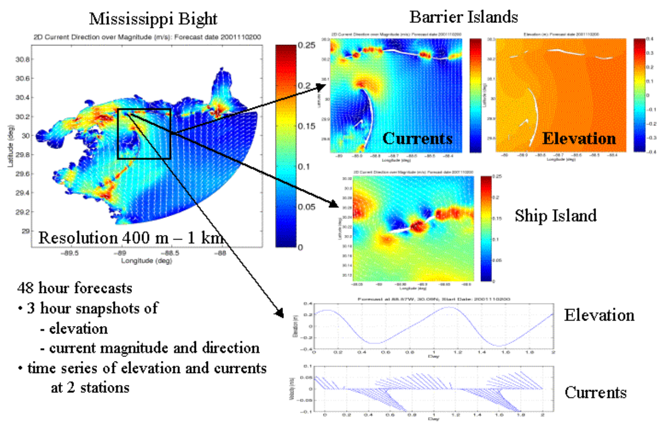

Fig. 7. Examples of near-real-time current and elevation products provided by NRL during the NAVOCEANO AUV Fest 2001.

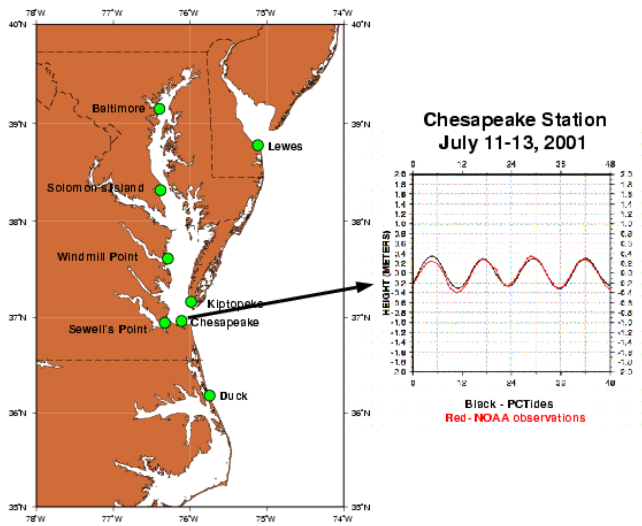

Fig. 8. PC-Tides rapidly-relocateable, tidal height prediction compared to independent NOAA tide data at Chesapeake Station for July 11-13, 2001.

A ROAMER analogue is under development for use, again by a skilled user, for the METOCCEN. The Distributed Integrated Ocean Prediction System (DIOPS) [16] will allow a skilled center user in a workstation environment, to run local near-shore wave and surf predictions using deep-water wave and area tide input from a central production site such as NAVOCEANO.

Adding the complexity of baroclinic coastal ocean models and/or near-shore wave circulation to the prediction equation to better describe the full spectrum of near-shore dynamics increases the skill level required of the potential operational user. Rapid (within hours) relocation can still be accomplished. However, the user must understand the limitations of the system with respect to boundary locations and nesting, potential blending of bathymetries and the general oceanography of an area so as to not misinterpret the results. Confidence in the results for a given area will grow with time as results are compared qualitatively and quantitatively with available independent data sets.

Both nested regional and local area versions of NCOM with boundaries constrained by the global system described earlier in this paper, are being run in R&D to evaluate nested boundary conditions and compare their potential for both regional and near-shore applications. Fig. 9 shows a nested NCOM regional application being used in evaluation of various boundary conditions of the west coast of the U.S. (John Kindle, 2002, personal communication). A real-time $1/16^0$ regional East Asian Seas NCOM prediction system is currently running in real time in preparation for transition to NAVOCEANO. This system will provide the initial scripts required for general relocateability of future nested regional and smaller domain NCOM systems. Fig. 10 demonstrates some of the complementary R&D for the higher resolution NCOM systems, comparing the freshwater-induced baroclinic flow exiting the Chesapeake Bay with various *in situ* and remotely sensed measurements (Pat Gallacher, 2002, personal communication).

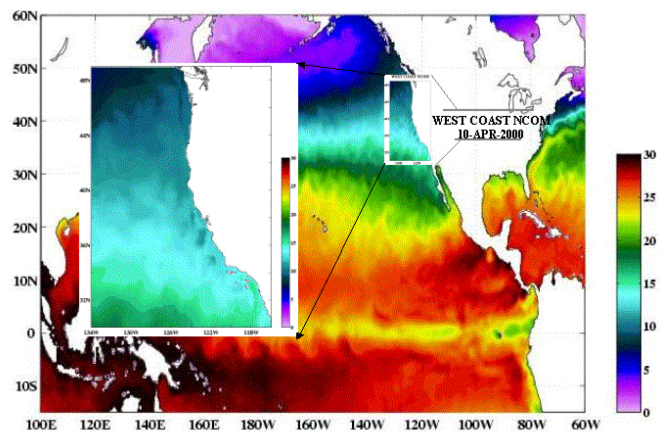

Fig. 9. Sea surface temperature for April 10, 2000 for a nested $1/12^0$ west coast NCOM within a $1/8^0$ global NLOM/NCOM prediction system.

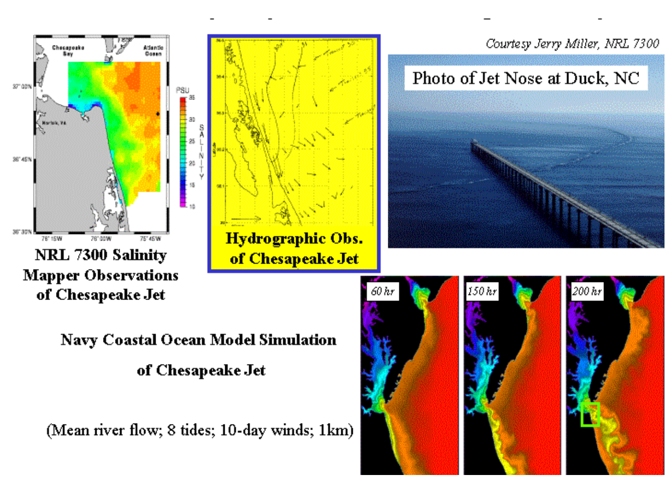

Fig. 10. Coastal buoyancy jet seen in remotely-sensed salinity data, from hydrographic data and from photography. These are seen in comparison to a NCOM simulation demonstrating the variability of the Chesapeake outflow as it transforms from jet to plume structure depending if the winds are downwelling or upwelling favorable.

Finally, Fig. 11 and 12 illustrate the use of NCOM as part of the COAMPS air/sea coupled model [18] being applied and evaluated in the Adriatic (Pullen, 2002, personal communication).

While finite difference models such as NCOM have been successfully applied for many years in near-shore and estuarine situations for engineering applications, e.g., [19], NRL is also actively engaged with the academic and engineering community investigating the potential for Navy applications of baroclinic finite element approaches nested within the larger domain ocean prediction systems (Cheryl Ann Blain, 2002, personal communication).

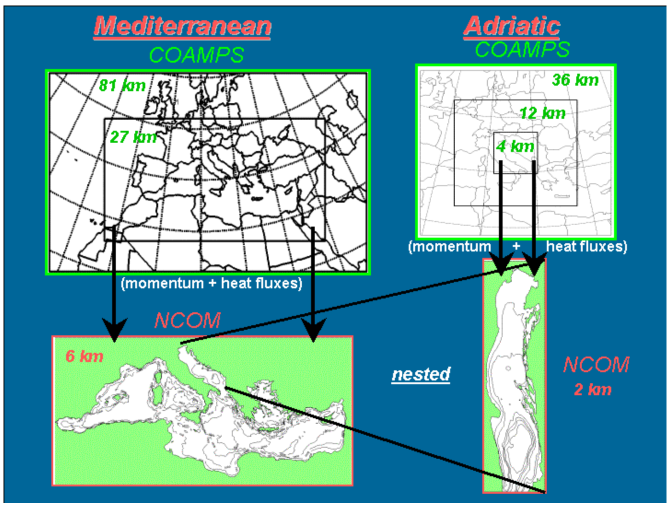

Fig. 11. Diagram of coupled air/sea nesting experiments in the Mediterranean Sea/ Adriatic Sea using COAMPS for atmospheric forcing to drive NCOM as the COAMPS ocean component.

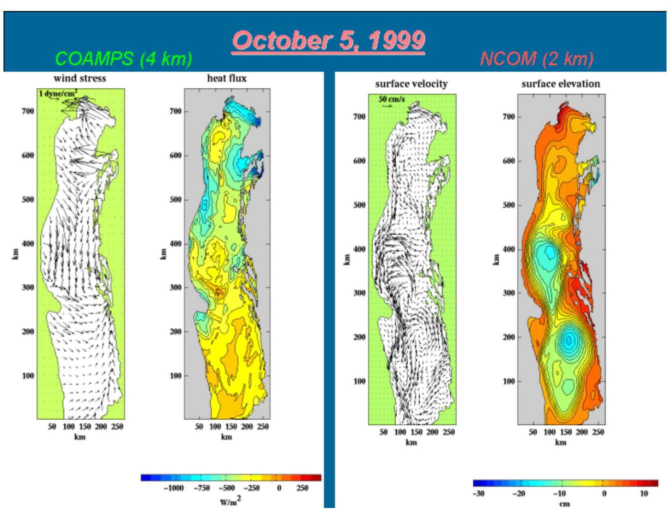

Fig. 12. Examples of wind stress and heat flux on October 5, 1999 from the inner nest of COAMPS as shown in Fig. 11. At right are the corresponding sea surface height and currents from the Adriatic NCOM.

IV. CONCLUSIONS

Long-term ocean prediction possibilities cover a broader scope than what is reflected in the brief summary provided above. The NRL Oceanography Division's R&D program includes bio-physical, sediment and optical measurements and modeling, non-hydrostatic and soliton modeling as well as extensive investigations in advanced data assimilation for both dynamic ocean model and near-shore wave applications. Many if not all of these will eventually appear in future transitioned naval capabilities.

Through its collaborative and coordinated R&D program of basic research through advanced development, the Oceanography Division of the NRL provides the U.S. Navy with near-term, state-of-the-art, ocean prediction capabilities while also developing next generation systems. Maintaining a global capability while actively developing and transitioning near-shore nested finite difference and finite element approaches provides the Navy a flexible and multi-purpose prediction tool set able to address the high-resolution, near-shore Navy requirements of both today and tomorrow.

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