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14. ABSTRACT

We pursued understanding of regional upper ocean and lower atmospheric variability in large part by participation in fleet exercises and examination of the realism of oceanographic and meteorological models. The exercises were MIREM (Mine Warfare Readiness Effectiveness Measuring) Programs focusing on the performance of Navy systems in the upper ocean and/or atmospheric boundary layer in the littoral environment. We conducted enhanced environmental monitoring, placing small, non-intrusive instruments on ships operating in the exercise region to collect time series of the surface meteorological forcing and upper ocean structure and deploying easily deployable/recoverable buoys with meteorological sensors and upper ocean temperature, salinity, optical, surface wave, and current sensors. These provided accurate air-sea flux measurements and the moored observations documented the variability in the ocean. We carried out reconstructions and retrospective analyses of the exercises, focusing on quantifying the environmental variability, examining the predictability of this variability and exploring how the environment may have impacted performance of operational systems. In addition, we deployed an array of six such moorings in a regional array in a littoral setting to examine the ability of present ocean and atmosphere models to capture the spatial as well as temporal variability seen near the coast.

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Regional Variability and Predictability in the Upper Ocean

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LONG-TERM GOALS

Our long-term objectives are to understand the dynamics of upper ocean physical processes and air-sea exchange and to see that understanding integrated into operational Navy strategies. Of particular interest is understanding the variability of the upper ocean on vertical scales from tens of centimeters to hundreds of meters, and on horizontal scales of meters to tens of kilometers, and the role that spatial-temporal variability in the atmospheric forcing plays in setting those scales.

OBJECTIVES

Our objective for this project is to improve our understanding of variability in the upper ocean encountered by mine warfare forces and to determine if local observations will lead to improved predictions that can be used to the advantage of the Navy.

APPROACH

Our approach is to pursue our research objectives in large part by participation in fleet exercises and examination of the realism of oceanographic and meteorological models. The exercises have been MIREM (Mine Warfare Readiness Effectiveness Measuring) Programs focusing on the performance of Navy systems in the upper ocean and/or atmospheric boundary layer in the littoral environment. We conduct enhanced environmental monitoring during exercises. We place small, non-intrusive instruments on ships operating in the exercise region to collect time series of the surface meteorological forcing and upper ocean structure. We also deploy easily deployable/recoverable buoys equipped with meteorological sensors and upper ocean temperature, salinity, optical, surface wave, and current sensors. The marine boundary layer observations provide complete and highly accurate air-sea flux measurements; and the moored observations, together with Battlespace Profiler

(BSP) data we obtain from the minesweepers after the exercise, document the variability in the ocean. Using telemetry, we work to provide high quality *in-situ* measurements to the METOC (MEtorological and OCeanographic) support for the exercise for their combination with all other data collected in stride during the exercise. We later use the internally recorded data in an environmental reconstruction and retrospective analysis of the exercise, focusing on quantifying the environmental variability seen in the upper ocean, examining the predictability of this variability and exploring how the environment may have impacted performance of operational systems used in the exercise. In addition, we deployed an array of six such moorings in a regional array in a littoral setting to examine the ability of present ocean and atmosphere models to capture the spatial as well as temporal variability seen near the coast. This was done as part of the Coupled Boundary Layer Air-Sea Transfer (CBLAST) Low Wind experiment south of Martha's Vineyard.

WORK COMPLETED

A large part of our effort during the first year went towards becoming familiar with the ONR and Navy groups and activities that we would be working with. In the second year of the project we participated in GOMEX 99-2/MIREM-9. Our objective for this project was to assist the Surface Warfare Development Group and the Office of Naval Research in observing, documenting and improving our understanding of the marine environment encountered in the exercise area. We deployed an oceanographic buoy to monitor surface winds as well as the vertical temperature and salinity (and thus sound speed) profiles during the exercise.

In the third year of the project we developed a small, portable, moored coastal observatory that uses acoustic, inductive, satellite and radio telemetry to report surface meteorology (wind, radiation, barometric pressure, humidity, temperature, precipitation), wave, current, and full water column temperature, salinity, and diver visibility data in real-time. The incorporation of telemetry, wave data, optical (visibility) data, and full water column capability was motivated by feedback garnered from operators at post MIREM-9 briefings. This new system was deployed during Kernel Blitz 2001/MIREM-16 off Camp Pendleton, CA in March 2001, providing data in real time that was used for METOC support of the exercise as well as a high quality data set for post-exercise analyses. To provide additional operational testing of telemetry components the system was also deployed in support of the ONR sponsored CBLAST initiative off Martha's Vineyard, MA in August 2001. At the beginning of the third year, Joe LaCasce replaced Steve Anderson as the SECNAV/CNO Institution Scholar on the project. He is working on the on the predictability portion on of the project.
In the fourth year, we moved to examine the spatial as well as temporal variability in the coastal ocean and atmosphere. An array of six surface moorings was deployed for two months in the summer of 2002 south of Martha's Vineyard, covering of the region that includes the CBLAST site. This was done to obtain a unique data set to be used to quantify atmospheric and oceanic variability in this coastal setting and to examine the ability of the best regional ocean and atmosphere models to replicate that variability. Final work under this support was devoted to analysis of the CBLAST data.

RESULTS

Telemetered results from the moorings were published on web sites once per hour during the experiments. During Kernel Blitz, ONR and fleet participants could visit the site (http://flux.whoi.edu/kb01) to get near real time information about conditions. The results from the Kernel Blitz 2001 deployment are also reported in a WHOI Technical report that has been distributed to SWDG and COMINEWARCOM METOC staff. In contrast to MIREM-9 in the Gulf of Mexico, there was significant temporal variability on a range of timescales during Kernel Blitz. The dominant signal near the surface is due to diurnal heating. Semi-diurnal fluctuations near the bottom are tidally driven. The most striking feature of the dataset is an intrusion of cold, salty water along the bottom that continued throughout the experiment and produced the thickening of the dense bottom layer seen. The interface between warm surface water and cold bottom water supported internal waves. At the beginning of the experiment, high frequency (greater than 48 cycles per day) internal wave energy is present at 45 m depth. By the end of the experiment that energy was found shallower than 15 m depth. This high level of variability, on a range of time scales from weeks to minutes, presents a challenge to our ability to forecast environmental conditions. It illustrates the need for both continued enhancements to our observational efforts and the use of the consequently expanding datasets to improve modeling efforts.

In the littoral environment the atmospheric forcing, the geography, and the regional ocean variability add energetic variability in space to that we have noted in time. To examine this a six mooring array was deployed south of Martha's Vineyard in June 2002 (Figure 1) and was recovered in late August 2002. Data was being shared with atmospheric and ocean modelers in near-real time (http://uop.whoi.edu/cblast/cblast2argos.html). A succession of synoptic weather patterns marched across the site, and variability associated with the Gulf Stream and cooler inshore currents added to the complexity of the site.

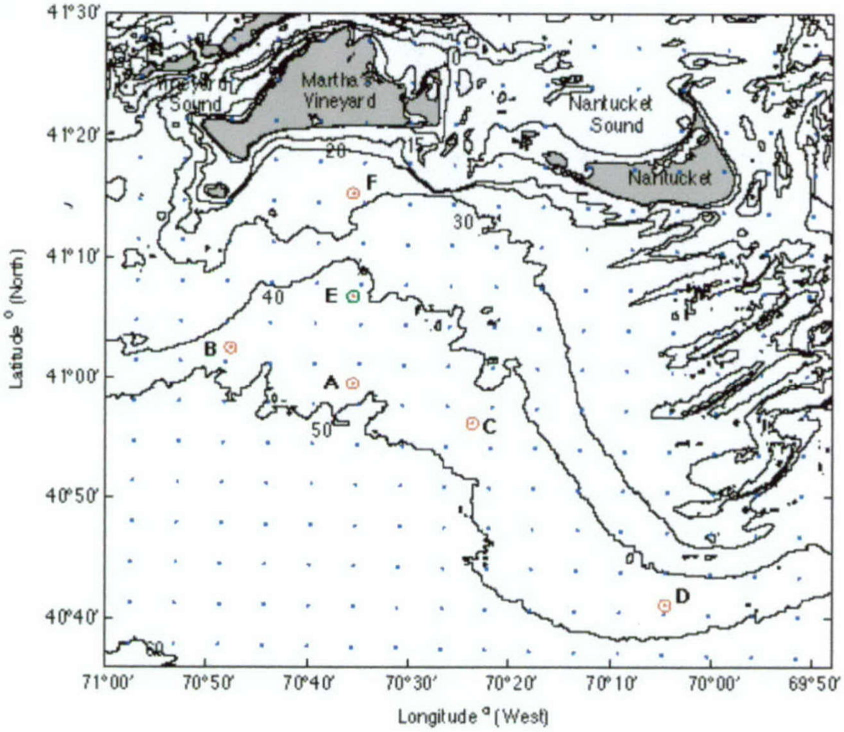

Figure 1. The locations of six surface moorings (labeled A through F) deployed during the summer of 2002 south of Martha's Vineyard.

Additional fieldwork continued in the summer of 2003 in the same site under support from the CBLAST program. Support from this effort helped finish a publication (Pritchard and Weller, 2005) documenting high frequency variability found in this region in association with shoaling internal waves that form solitons.

The primary focus of Lacasce's work has been Lagrangian and Eulerian predictability. One project in each area was pursued, and both are nearing completion with publications in preparation. The first project, also discussed last year concerns Lagrangian dispersion at the surface of the Gulf of Mexico as measured by surface drifters. The second relates to predicting depth-averaged currents in sub-polar and polar regions from known winds.

1) Lagrangian dispersion in the Gulf of Mexico: This work centered on testing ideas regarding stirring and mixing of fluid parcels using in situ oceanic data. The theories include "chaotic advection" (a central process in dynamical systems theory) and turbulence theory. The testing was carried out using various statistical measures. The data consisted of surface drifter trajectories from the Gulf of Mexico (kindly provided by P. Niiler and co-workers). With over 500 drifter tracks, this particular data set (from the "SCULP" program) permitted analysis with essentially unparalleled statistical confidence.

The calculations focused on the "relative dispersion" of drifters, or specifically on how quickly drifter pairs separated as a function of separation. This measure directly reflects the distortion of a tracer (for example, how an oil slick is strained out by ocean currents). Interestingly, this exercise yielded what appears to be the first oceanic evidence of exponential growth of pair separations. Similar dispersion was seen with atmospheric balloons during the 1970's, but while plausible in the ocean, it has not seen before (probably due to insufficient spatial resolution in the data). Exponential growth reflects a "sensitive dependence on initial conditions", because two particles, released near one another, will separate exponentially fast. Such growth is in fact possible under both dynamical systems theory and turbulence theory, so this finding does not in itself answer whether either theory is preferable. However, it does significantly narrow the possibilities within each theory, as a function of scale. Exponential growth evidently occurs in some regions and not in others, consistent perhaps with advection by coherent features such as vortices ("rings"). Similar particle dispersion is probably occurring at scales of 1 to 100 km in most of the energetic regions of the world ocean, so the present results represent an important step towards characterizing (and parameterizing) lateral mixing.

2) Depth-averaged currents in the Norwegian and Greenland Seas and in the Arctic ocean: Barotropic ocean models are probably best suited for regions with weak stratification, such as in the Northern and Southern latitudes. This work concerns formulating such a model to predict wind-driven currents in the Nordic seas and Arctic.

We are concerned with large-scale flows, and so are interested in a linear model. The simplest such model assumes a flat bottom, but the bottom in these regions is far from flat; indeed, hydrography suggests mean currents which tend to follow topography. So instead we develop a model in which topography can be severe.

In a linear, flat-bottomed ocean, a convergence/divergence of mass transport in the surface Ekman layer drives a meridional flow (the Sverdrup relation). With strong topography however, the contours of ambient potential vorticity (f/H) can close, in which case a Sverdrup balance is impossible. Then an alternate balance, in which the surface Ekman convergence/divergence is balanced by a divergence/convergence in the bottom Ekman layer, can be achieved. Such a balance demands a strong barotropic flow parallel to the f/H contours (essentially along the isobaths with strong topography). By exploiting this balance, one can diagnose currents in gyre regions knowing only the wind, the bottom topography and an estimate of the bottom Ekman drag.

This prediction has been tested in the Nordic seas and Arctic using data from both in situ current meters and from a primitive equation model (with data kindly provided by Sirpa Hakkinen, NASA). The velocities in all regions are predominantly barotropic and along the isobaths, consistent with the above assumptions. The model in turn does exceptionally well at predicting the currents. The coherences between the model and depth-averaged currents for the current meters (off Greenland) and in the (model) Norwegian Sea exceed 0.9. The coherences elsewhere are somewhat less but generally exceed 0.5. The results in some cases can be improved drastically if surface ice motion is taken into account. By and large then, this simple model works remarkably well in these Northern regions. While not specifically providing forecasts for the Eulerian flow in gyre regions, the present model would in any event allow one to diagnose the currents given only the wind and bottom topography. This would represent a substantial savings in time and resources compared to running a full numerical model.

IMPACT/APPLICATIONS

During Kernel Blitz 2001 we located our shoreside operations alongside ONR advanced technology operators at the Army Reserve Center on Camp Pendleton. As part of the ONR Detachment we participated in Distinguished Visitor day and had the opportunity to brief visitors and operational Navy personnel on our observing efforts and the high variability that was evident in the telemetered data. We spread the word about the availability of the real-time data by attending the pre-sail MCM brief on the USS Tarawa and visiting the North Island METOC staff. Throughout and following the experiment, the web site did see traffic originating from Navy installations involved in the exercise.

Comparison of observed variability and the performance of models such as COAMPS during this work indicates the need for continuing work to fully couple the ocean and atmosphere in COAMPS. In particular, it is evident that mesoscale ocean variability can imprint itself on the lower atmosphere; capturing this effect requires coupling the ocean to the atmosphere. Prediction of high frequency ocean variability, which has dramatic impact of fields such as sound speed, also remains a challenge.

TRANSITIONS

One potential transition at the completion of this project might be the adoption of a moored observing system as a "Battle Space Buoy", that the Navy could deploy in stride, like the Battle Space Profiler, to monitor the environment in real-time during operational activities.

Documentation of our coastal observing system was passed on to Lt. Colonel C. Reid Nichols (USMC, II MEF Headquarters, G-7) to aid in the planning of a Camp Lejeune Integrated Observation Network.

RELATED PROJECTS

A related project is the ONR Coupled Boundary Layers Air-Sea Transfer (CBLAST) DRI (http://www.whoi.edu/science/AOPE/dept/CBLASTmain.html) . Pilot experiments were carried out in the summer of 2001. Our effort under this program supplemented observations in the summer of 2002 and provided additional analysis support in 2003 through 2005. The pilot experiment allowed testing of our telemetry development and at the same time a valuable additional data source for CBLAST. As with our Kernel Blitz efforts, the results from our portion of the pilot experiment were updated hourly on a web site (http://flux.whoi.edu/cblast). The regional array data collected in the summer of 2002 has been shared in real time with the CBLAST community and ocean and atmosphere modelers via (http://uop.whoi.edu/cblast/cblast2argos.html). Mooring data from the Kernel Blitz deployment has been provided to researchers from Scientific Solutions, Inc. for use in an ONR sponsored model validation effort. Researchers from NRL Ocean Optics Code 7333 used our visibility data for comparison purposes on their web site during the exercise (http://www7333.nrlssc.navy.mil/ocolor/Exercises/kernal_blitz2001/kbindex.html).

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