Mixed Layer Response to Monsoonal Surface Forcing in the Arabian Sea

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LONG-TERM GOALS

Our long-range scientific objectives are to observe and understand the temporal and spatial variability of the upper ocean and to identify the role of air-sea interaction in determining that variability. We seek to do this over a wide range of environmental conditions in order to improve our understanding of upper ocean dynamics and of the physical processes that determine the vertical and horizontal structure of the upper ocean.

OBJECTIVES

Prior to the Arabian Sea Mixed Layer Dynamics Experiment, efforts to observe and understand air-sea interaction and upper ocean variability had never been made in a region characterized by strong, sustained forcing; and the separation of oceanic variability due to atmospheric forcing from that associated with mesoscale variability has been difficult. The combination of strong, sustained monsoonal forcing and mesoscale variability associated with eddies and coastal jets characteristics of the Arabian Sea presented a unique opportunity to add to our understanding of the upper ocean response to atmospheric forcing.

Objectives of the field experiment were to test these ideas: the upper ocean physical and biological responses are largely one-dimensional; Ekman pumping velocities significantly affect the mixed layer evolution; summer mixed layer cooling results from one or a combination of increased cloud cover, large latent heat loss, lateral advection of coastally-upwelled water, open-ocean upwelling, and entrainment; entrainment is dominated by shears associated with sub-inertial wind-driven flow; and mesoscale variability provides the primary source of vertical circulation at the base of the mixed layer. In this continuing effort following the fieldwork, our objective has been to additionally test the following hypotheses: three-dimensional flow divergences due high-frequency and small spatial structure in the wind field are important in the vertical velocity field at the base of the mixed layer, diurnal cycling during the NE monsoon produces a horizontally homogeneous mixed layer, resolution of high frequency wind and diurnal heat forcing significantly modifies the large-scale heat transport, and additional upwelling and vertical mixing associated with the mesoscale contributes significantly tot he evolution of the mixed layer.

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14. ABSTRACT
Our long-range scientific objectives are to observe and understand the temporal and spatial variability of the upper ocean and to identify the role of air-sea interaction in determining that variability. We seek to do this over a wide range of environmental conditions in order to improve our understanding of upper ocean dynamics and of the physical processes that determine the vertical and horizontal structure of the upper ocean.

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APPROACH

As part of the ONR-sponsored Arabian Sea Mixed Layer Dynamics experiment we deployed an array of surface and subsurface moorings in cooperation with Rudnick (SIO), Eriksen (UW), Dickey (USC), and Marra (LDEO) from October 1994 to October 1995 at a site just south of the climatological maximum of the Findlater jet in the surface winds in the north-central Arabian Sea (Trask et al., 1995a, b; Ostrom et al., 1996; Baumgartner et al., 1997). The observations showed that there were errors in some widely used flux climatologies, and showed striking differences in the surface forcing between the NE monsoon (November to January), characterized by moderate wind forcing and strong oceanic surface heat and freshwater loss, and the SW monsoon (June-August), with strong winds, significant oceanic heat gain, and reduced evaporation. The mixed layer was observed to cool and deepen during each monsoon, driven primarily by convection during the NE monsoon and wind-driven mixing during the SW monsoon. Mesoscale variability was the major signal in the velocity record, and provided significant horizontal heat fluxes.

Analysis has had two major thrusts. First, quantitative descriptions of the upper ocean response were developed, including heat budgets and identification of the relative roles of various physical processes. Second, one- and thee-dimensional models were used to test our understanding of the response at the site of the moored array and to extend it to the entire Arabian Sea.

WORK COMPLETED

This analysis effort followed the fieldwork, which was completed in 1995. The field program provided an unprecedented look at the response of the mixed layer to the wide range of surface forcing found to be associated with the annual cycle in the Arabian Sea (Weller et al., 1998). The effort integrated other data to examine the mesoscale horizontal heat flux and to investigate the effect of the diurnal cycle on the mixed layer in one- and three-dimensional models. This is the final annual report on this project, which had a one-year no cost extension to support completion of the publication of results.

A quantitative analysis of the upper ocean heat budget at the moored array was developed (Fischer, 1997, 2000; Fischer et al., 2002). The ocean variability was documented at the site using the moored data (Weller et al., 2002). Additional data sets of combined TOPEX/ERS altimetry (courtesy of Leben and Fox, CCAR), satellite SST (JPL), and SeaSoar surveys (Brink, WHOI; Lee, UW APL) have allowed identification of the dynamic origins of the strong horizontal heat fluxes found at the site (Fischer, 2000; Fischer et al. 2002). A collaboration with Craig Lee used climatological data supplied in part by Simon Josey (SOC) to examine the relative effects of Ekman pumping and locally driven entrainment on the deepening of the mixed layer across the Arabian Sea (Lee et al., 2000).

The three-dimensional model of McCreary was used to investigate the Arabian Sea response to diurnal variability in the solar heat flux and to high frequency and high spatial variability in the wind stress forcing. The collaboration with Jay McCreary (UH/IPRC) also included model/data comparisons and cooperation on studies of the effect of the diurnal cycle in a coupled physical-biological model (McCreary et al., 2001). To further examine how the diurnal cycle affects the vertical mixing and redistribution of heat, the responses of a number of one-dimensional mixed layer models were examined under a variety of surface forcing conditions.

RESULTS

The field experiment captured the first yearlong high quality surface flux and upper ocean record in the Arabian Sea. The process that supported the strong horizontal advection of water during the SW monsoon seen in the heat budget of the moored array was identified using satellite SST imagery and altimetry as the advection of water upwelled at the Omani coast and subsequent transport of it well offshore by a filament. During the NE monsoon, strong horizontal heat advection at the moored array was found to be associated with mesoscale eddies that had been generated in the previous SW monsoon and then propagated westward. The altimetric record shows that mesoscale activity is elevated along the Arabian coast during the SW monsoon, suggesting that these coastal filaments play an important role in the offshore transport and mixing of coastally upwelled water.

The SST and mixed layer depth were observed to respond to high frequency (diurnal to atmospheric synoptic time scales) variability in the surface heat flux and wind stress. The rectified effect of this high frequency forcing was investigated using the McCreary three-dimensional reduced gravity thermodynamic model of the Arabian Sea and Indian Ocean. Both the diurnal cycle and high frequency wind forcing acted locally to increase vertical mixing in the model, reducing the SST. Interactions between the local response to the surface forcing, Ekman divergences, and remotely propagated signals in the model can reverse this, particularly at low latitudes. The annual mean SST, however, is lowered under both diurnal heat and high frequency wind forcing, changing the balance between the net surface heat flux (which is dependent in turn on the SST) and the meridional heat flux in the model.

The additional vertical mixing caused by a resolved wind stress field has been studied before and can be understood simply based on the energy balance. The net effect of the diurnal cycle on SST and MLD has not been studied systematically, and cannot be understood as simply. The rectification of the diurnal cycle was explored across a wide parameter space in net heat and wind forcing using several one-dimensional upper ocean models with different representations of vertical mixing processes. All show increased vertical mixing in response to the diurnal cycle in net heating conditions, but the degree of enhanced mixing is highly dependent on the model formulation used.

IMPACT/APPLICATIONS

The fieldwork produced the first long time series of high quality surface meteorology and air-sea fluxes to be obtained in the Arabian Sea. This data provides a means to guide the selection of forcing products for ocean models forcing products for ocean models to be used for research and operations. Observations of the strong cooling heat flux associated with offshore transport give insight into the dynamic mechanisms connecting coastal upwelling and upper ocean cooling. Similarly, the new understanding of the physics of the upper ocean in the Arabian Sea will influence future studies and operational modeling. The net effect of the diurnal cycle and the importance of high-frequency wind forcing on the vertical mixing of temperature and on larger-scale circulation changes will be applicable to any modeling study of upper ocean circulation or biology, particularly in regions where mixed-layer diurnal variability is important. The comparison of mixed layer models suggests some simple improvements in the parameterizations could be made in lieu of resolution of the diurnal cycle.

TRANSITIONS

Cooperation with Kindle (NRL) in modeling should lead to improvement of Navy ocean forecast models in the region and has led to confirmation of the quality of FNMOC winds in the region (Rochford et al, 2000).

RELATED PROJECTS

This effort included close collaborations with other efforts: numerical modeling (McCreary, UH/IPRC; Kindle, NRL), satellite remote sensing (Leben and Fox, CCAR; Arnone, NRL; Halpern, JPL)(Halpern et al., 1998), and with the other ONR Arabian Sea investigators (Lee, Brink, Eriksen, Rudnick, Dickey, Marra). The role of mesoscale eddies in pulses in productivity has been investigated with these investigators (Marra et al., 1998; Dickey et al., 1998; Wiggert et al., 2000; Kinkade et al., 2000) and also with Honjo (WHOI), Prell (Brown), and Dymond (OSU).

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