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Final Report – The Response of the Upper Ocean to Monsoonal Forcing

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This grant provided support for the collection, analysis and publication of results from the Arabian Sea Accelerated Research Initiative. The Arabian Sea is a unique setting for observations of the upper ocean because of the strength and directional steadiness of the monsoonal forcing. As part of the Arabian Sea ARI, we deployed two surface moorings of a five-mooring array to study the ocean's response to the monsoon. Each of our buoys was equipped with a meteorological package for estimating air-sea fluxes of heat and momentum, and subsurface instrumentation for measuring temperature and horizontal velocity. A variety of projects, discussed below, was brought to completion.

The ultimate goal of my research is a complete characterization of the upper ocean's response to atmospheric forcing. The forcing takes place through surface fluxes of heat, fresh water, and momentum. The response may be local and direct, or may be modified by advection and wave propagation. The Arabian Sea was an attractive region for an air-sea interaction experiment because of the strength and steadiness of the monsoons. The wind-stress spectrum was more energetic at low frequencies in the Arabian Sea than in mid-latitude locations where the forcing is dominated by storms. The Arabian Sea ARI thus provided an interesting contrast to previous experiments done at higher latitudes such as LOTUS, FASINEX, and Ocean Storms.

The ONR-funded surface moored array in the Arabian Sea consisted of a heavily instrumented central mooring (R. Weller, Woods Hole Oceanographic Institution), two profiling current meters (C. Eriksen, University of Washington), and two lightweight surface moorings (D. Rudnick, Scripps Institution of Oceanography). The array was centered at 15°30'N, 61°30'E, and the moorings were separated by 50 km to resolve mesoscale oceanic features. The site was chosen to be near the climatological maximum wind in July. The moorings were set in October 1994, replaced in April 1995, and recovered in October 1995. The year-long deployment allowed observation of both the winter NE monsoon and the stronger summer SW monsoon.

A lightweight low-power meteorological package (MARMET) was developed specifically for this experiment. The variables measured were wind speed and direction, air and sea temperature, atmospheric pressure, and short-wave solar radiation. Each variable was recorded independently, and two of each sensor was carried. Raw data taken every 4-16 s were averaged over 7.5 min and stored in the individual sensor modules. Both 15-min and 8-h averages were computed and stored in a central logger, which also telemetered the 8-h averages via ARGOS. MARMET now forms the core meteorological suite on the ONR-sponsored SIO Marine Observatory monster buoy, and is being used on other buoys along the California coast.

The subsurface instrumentation was chosen for simplicity and ruggedness. The ADCP was mounted looking downward in the buoy bridle rather than upward in the mooring line to avoid the use of a load cage. The potential problem caused by deploying the ADCP on the buoy is aliasing by surface waves. This problem was overcome by burst sampling at once per second over 3 min once every 7.5 min. Thus, surface waves were resolved while conserving power and storage for the 6-month deployment. The ten temperature recorders per mooring, clamped directly on the wire to avoid load bearing members in the mooring line, recorded temperature at 15-min intervals.

Overall data recovery was excellent. All meteorological data on all buoys were returned except for wind during the first deployment of the southern buoy. The wind sensor electronics failed during a strong storm, presumably due to a lightning strike. The overall data return of meteorological variables was thus 95%. The ADCPs worked flawlessly so that horizontal velocity data return was 100%. All temperature recorders worked perfectly during the first six months. Unfortunately, we suffered some failures and losses during the SW monsoon. Five recorders were stripped from the mooring line on the north mooring, two recorders had short records, and one was recovered with the end caps and electronics gone. In spite of the problems, overall temperature data return was 82%. Weighting meteorological variables, currents, and temperatures equally, the data return on the two SIO moorings was 92%.

An early publication summarized preliminary results from the moored array (Rudnick et al. 1997). Typical wind speeds were 5 m s^{-1} during the NE monsoon, increasing to greater than 10 m s^{-1} during the SW monsoon. Thus, wind stress was four times stronger during the SW monsoon. The atmosphere to ocean heat flux was negative during the NE monsoon. The mixed layer deepened during both monsoons, but for different reasons. The deepening during the NE monsoon was caused by convection, while that during the SW monsoon was a result of wind stirring. Velocity was dominated by mesoscale geostrophic eddies. Direct wind driving was especially evident during the SW monsoon. Mesoscale events had a controlling effect on chlorophyll.

A complete description of the ocean's response to the monsoon has been submitted, and is very close to publication (Weller et al. 2001). One-dimensional budgets of heat and salt were proven to hold except at times of strong advective events associated with geostrophic eddies. The relative effects of buoyancy-flux-driven convection and wind stirring on mixed-layer deepening was quantified through the ratio of the Obukhov length to the mixed-layer depth. The moored observations were put in context using satellite altimetry, confirming the presence of eddies.

The effect of horizontal advection on the heat budget was explicitly quantified (Fischer et al. 2001). The most striking effect was the offshore advection of upwelled water in the form of a filament. The upwelled water was strongly correlated with maxima in chlorophyll. Remarkable is the long distance the water traveled (~600 km) offshore to reach the moorings.

The 1995 SW monsoon was notable for having a double onset. The dynamics of double onsets was the topic of a study examining the moored observations, satellite data, and atmospheric analyses (Flatau et al. 2001). An examination of double onsets over 32 years revealed the 1995 onset to be, in a sense, the best example. The development of the first "bogus" onset depends on the timing of the Madden-Julian oscillation and the development of warm sea surface temperature in the Bay of Bengal.

The density ratio in the world's oceans was studied using data collected in a variety of ONR-sponsored experiments, including the Arabian Sea (Rudnick and Martin 2001). The mixed-layer density ratio was found to be typically one when mixed layer were deep, and when significant thermohaline variability existed. This behavior is consistent with recent theoretical models suggesting the horizontal diffusivity in the mixed layer is a growing function of density gradient. The density ratio was observed to be two in the thermocline, consistent with previous results. The transition from a density ratio of one in the mixed layer to two beneath is surprisingly sharp.

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