Dynamics of Boundary Currents and Marginal Seas

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Award Number: N00014-95-1-0025
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LONG TERM GOALS:

To describe and understand the dynamics of ocean circulation, with emphasis on western boundary current systems and interactions between the oceans and marginal seas.

OBJECTIVES:

Research during the past year has been focused on studies of the marginal seas of the northwestern Indian Ocean: the Red Sea and the Arabian Gulf. Our objective has been to use recent field measurements in the Bab el Mandeb and Straits of Hormuz, respectively, to study the exchange dynamics in these straits and to constrain the general circulation and air-sea exchange budgets of the marginal seas.

APPROACH:

Measurements collected in these programs have consisted of moored time series observations of currents using profiling (ADCP) and conventional current meters, and water properties using temperature/salinity chain arrays, along with seasonal hydrographic surveys and local meteorological and tide gauge measurements. A large scale hydrographic/ADCP survey of the Red Sea was also completed this year (August 2001). Modeling of the exchange dynamics includes application of both analytical models for study of atmospherically forced fluctuations in the straits and numerical simulations with the MICOM model to study the combined buoyancy and wind forced circulations and exchanges in the marginal seas.

WORK COMPLETED:

The 1995 Bab el Mandeb experiment has resulted in four published journal articles (Murray and Johns, 1997; Pratt et al., 1999, 2000; Sofianos and Johns, 2001) that describe the observed exchange structure, its hydraulics, and the forced sea level variations in the Red Sea. Papers in press or submitted include an analysis of the net heat and freshwater fluxes through the strait with comparison to available surface flux climatologes for the Red Sea (Sofianos et al., 2001), and two MICOM papers describing the three-dimensional circulation and water mass formation in the Red Sea and the roles of wind and buoyancy forcing in driving the seasonally varying exchange with the Indian Ocean (Sofianos and Johns, 2001a,b).

The 1997 Strait of Hormuz experiment has resulted in new estimates of the seasonal exchange between the Gulf and the Indian Ocean (Johns et al., 2000) and of the annual mean heat and evaporative flux over the Gulf (Smeed et al., 2000). These presentations are now being written up into journal articles.

Study of the shorter-term flow and watermass variations in the Bab el Mandeb and Strait of Hormuz and their forcing and dynamics is continuing. Additional MICOM simulations of the Red Sea/Gulf of Aden region have recently been carried out to further evaluate the performance of MICOM and to address new aspects of the regional circulation, namely (i) investigation of the effects of forcing with different seasonal cycles and/or derived from different surface forcing products; (ii) higher resolution simulations to investigate in more detail boundary currents and other circulation features; and (iii) extension of the model domain to the full length of the Gulf of Aden to investigate the external effects on the exchange flow at Bab el Mandeb.

In addition to the analysis of the above data sets and modeling activities, a cruise was carried out this summer to survey the summer circulation and hydrography in the Red Sea. This was an opportunistic cruise added onto a transit of the Red Sea by the R/V MAURICE EWING, which gave a rare view of the summer conditions in the Red Sea. The cruise collected over 90 hydrographic stations along the axis of the Red Sea and on several cross sections in the northern and southern parts of the basin including the area of the Hanish Sill in the Bab el Mandeb Strait.

RESULTS:

Principal results from the Bab el Mandeb Experiment include:

(1) The annual mean outflow of Red Sea water was determined to be 0.37 Sv, with a large seasonal variation ranging from more than 0.6 Sv in winter to nearly zero in late summer.

(2) The heat and freshwater budgets of the Red Sea determined from the measured fluxes through the strait yield robust estimates of 2.1 m/yr and 10 W/m^2 for the mean evaporation rate and annual heat loss over the Red Sea, respectively. These new estimates confirm the existence of large biases in available climatological surface fluxes (e.g., COADS and SOC) for the Red Sea.

(3) Synoptic transport variability in the strait on time scales from a few days to weeks is driven by two primary forcing mechanisms: wind stress variability over the strait, and variation in the large-scale barometric pressure over the Red Sea. These transport variations have amplitudes of nearly twice the mean rate of exchange through the strait, and are well predicted by a 2-layer analytical model of the exchange that accounts for the Helmholtz resonance of the basin.

(4) Numerical simulations with a Red Sea version of MICOM are able to capture all of the important features of the observed seasonal exchange cycle, and show that the wind forcing is the dominant forcing mechanism for the annual cycle. However, the model also shows that proper account of the large annual cycle of buoyancy forcing over the Red Sea is necessary to accurately model the annual mean exchange rate with the Indian Ocean.

Results from the Strait of Hormuz Experiment include:

(1) The deep outflow from the Persian Gulf does not have a strong annual cycle, despite a significant annual cycle in both the wind and buoyancy forcing over the Arabian Gulf. However, the speed of the outflow and its salinity vary considerably on shorter time scales, with pulse-like events of high salinity outflow occurring during the winter months.

(2) The surface inflow from the Indian Ocean varies significantly on seasonal as well as shorter time scales, and a weak outflow occurs in the southern part of the Strait during boreal fall and winter. The

total exchange through the strait appears to involve a seasonally active horizontal water exchange in addition to the more steady two-layer thermohaline exchange through the Strait.

(3) The magnitude of the annual mean deep outflow of Persian Gulf water through the Strait is approximately 0.20 Sv, implying a net evaporation rate over the Gulf of 2.0 m/yr. As for the Red Sea, the heat flux through the strait estimated from these direct measurements implies a significant positive bias of order 40 W/m^2 in the surface heat flux over these marginal seas in most available flux climatologies.

IMPACT/APPLICATIONS:

The observations we have collected in this region have provided the first detailed, long-term time series observations in the Bab el Mandeb and Strait of Hormuz, both strategically important straits, and new data on the summer circulation and hydrography of the Red Sea. These data are providing a new level of understanding of the circulation and exchange processes in these marginal seas and their dynamics. Comparative studies with other marginal seas and straits (e.g., Gibraltar) will help to improve and broaden our understanding of the dynamical controls regulating ocean-marginal sea exchange. The heat and freshwater transports determined from these measurements will provide powerful constraints on air-sea fluxes in these regions to help eliminate biases in existing climatologies and operational products.

TRANSITIONS:

The data and results from these projects are being provided to the Naval Research Lab and Naval Oceanographic Office data and modeling groups to provide accurate boundary conditions for their Red Sea and Persian Gulf models and for coupling of these models to the NRL Indian Ocean model.

RELATED PROJECTS:

Analysis of the Strait of Hormuz moored time series data is being carried out in collaboration with U.K investigators David Smeed and Simon Josey of the Southampton Oceanography Centre, who performed extensive shipboard surveys in the strait region during the period of the moored deployments and are developing and evaluating surface flux climatologies for the region. We are also working with Dr. Amy Bower of Woods Hole to investigate the hydrography and circulation in the Arabian Gulf in relation to the Strait of Hormuz exchange, and the characteristics of the outflow plume from the Gulf. The recent Red Sea study will share data and results with a related NSF study by the P.I. (in collaboration with H. Peters of RSMAS and A. Bower and D. Fratantoni of WHOI) on the dynamics and spreading of the Red Sea outflow in the Gulf of Aden.

PUBLICATIONS:

Sofianos, S. and W. E. Johns, Wind-induced sea surface variability in the Red Sea, *Geophys. Res. Lett.*, 28, 3175-3178, 2001.

Sofianos, S., W. E. Johns, and S. P. Murray, The heat and freshwater budgets of the Red Sea from direct observations at Bab el Mandeb (*Deep Sea Res.*, in press), 2001.

Johns, W. E., T. L. Townsend, D. Fratantoni, and W. D. Wilson, On the Atlantic inflow to the Caribbean Sea (*Deep Sea Res.*, in press), 2001.

Sofianos, S. and W. E. Johns, An OGCM investigation of the Red Sea. Part 1: The exchange between the Red Sea and the Indian Ocean (*J. Geophys. Res*., submitted), 2001.

Sofianos, S. and W. E. Johns, An OGCM investigation of the Red Sea. Part 2: The three-dimensional circulation of the Red Sea (*J. Geophys. Res*., submitted), 2001.