8.8 A MODEL STUDY OF EXCHANGES OF SALT AND TRACERS IN THE NORTHERN AND EQUATORIAL INDIAN OCEAN

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1. INTRODUCTION

The climate in the northern Indian Ocean region varies from very dry deserts over the Arabian Peninsula to humid rain forests in Southeast Asia. The associated pattern of net evaporation in the western part and net precipitation in the eastern part of the region gives rise to relative high salinity in the Arabian Sea and relatively low salinity in the Bay of Bengal. To maintain long-term average salinities, a net freshwater flux must occur into the Arabian Sea and out of the Bay of Bengal. Recent analysis of observations and model data (Vinayachandran et al. 1999) shows that the Southwest Monsoon Current (SMC), which flows eastward during the northern summer, enters the Bay of Bengal during July and August. The authors attribute this intrusion to a Rossby wave reflected from the eastern part of the Indian Ocean. Current measurements along the west and east coasts of India support the possibility of exchange of water between those two basins [Shetye et al 1991; 1996]. However, the location and magnitude of transports of heat and salt associated with this current has not yet been determined.

An interesting question is therefore if any significant exchange of water occurs around the southern tip of India, and to what extent it involves a larger area of the Indian Ocean, in particular if cross-equatorial flow takes place. Hacker et al., 1998 found observational evidence of high salinity water in the Bay of Bengal as far east as 95°E at 5°N, and it is well-known that the intense annual reversal of the Indian monsoon results in large annual changes in the oceanic circulation in the northern Indian Ocean. Are any exchanges between the Arabian Sea and the Bay of Bengal linked to the reversals of the atmospheric winds?

Another interesting question is to what extent salt transport occurs in the western boundary current, i.e. the Somali Current, compared to the salinity transport across the equator in the interior of the basin.

These questions have been addressed using a numerical model of the Indian Ocean. Due to lack of quality rainfall data and river discharge data, relaxation to surface salinity was used as freshwater forcing. Since freshwater is not conserved due to surface sources and sinks, passive tracers are used as a simple way to determine the fractions of water originating in the Arabian Sea or the Bay of Bengal.

2. METHODOLOGY

2.1 Ocean Model

The ocean model is based on the multi-layer upper-ocean model (Jensen 1991; 1993), extended to include prognostic temperature, salinity, passive tracers, mixed layer physics and convective adjustment. The vertical coordinate is a general Arbitrary Lagrangian Eulerian formulation, which allow for control of mass between layers, and the bulk mixed layer is a turbulent kinetic energy equilibrium model, which includes wind generation and shear production of turbulent kinetic energy (Jensen, 1998a; 2001). Lateral stresses are assumed to be proportional to the product of the local deformation rate of the flow and the area of a grid cell. Diffusivity of temperature, salinity and tracers were held constant at 1000 m^2/s. For tracers a third order upstream finite difference scheme is used to maintain non-negative concentrations.

The model configuration used here have 4 active layers with an infinitely deep layer below (4.5 layer model). The horizontal resolution is 1/3° in the meridional and in the zonal directions. The average initial thickness is 80 m, 120 m, 250 m and 600 m for layers 1 to 4 respectively. The model covers the Indian Ocean north of 30°S, from Africa to 120°E. The southern boundary and the eastern boundary are open using a flow relaxation scheme combined with a radiation condition (Jensen 1998b). This is done as follows: A relaxation towards an Indonesian Throughflow of 10 Sv is used at the eastern

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boundary, while the flow is nudged to an outflow of 40 Sv along 30°S, from the coast of Africa to 39°S E. From this longitude to the coast of Australia, the model inflow is allowed to evolve freely. Temperature, salinity and layer thickness is also prescribed long the open boundaries, with relaxation in a 4°S wide zone using an 8. order polynomial (see Jensen 1998b for details).

2.2 Forcing

Climatological monthly mean wind stress from the European Center for Medium Range Forecast (ECMWF) re-analysis was interpolated to the model grid using cubic splines in space, while linear interpolation in time is done to each model time step. The heat and freshwater flux is computed by relaxation to Levitus surface conditions on a 6-day time scale.

The upper four layers of the model were initialized with January temperature and salinity climatology from World Ocean Atlas 1994 (Levitus et al. 1994; Levitus and Boyer 1994), and geostrophic currents were computed poleward of 5° with a level of no motion at the base of layer 4. Between the equator and 5°N, the Coriolis force is computed at 5°N, while the region just south of the equator use the Coriolis force at 5°S for the purpose of initialization. Since equatorial adjustment is fast, the imbalance in the equatorial region adjust within the first year. During this adjustment, temperature and salinity fields were kept constant at January spin-up is investigated.

2.3 Analysis Method

In order to determine where a net flux of freshwater and salt takes place, the salinity transport is separated into a low salinity flux and a high salinity flux. We define the salinity anomaly flux as

$$F_S = V(S - \overline{S}^{\phi t}) = V\Delta S \qquad (1)$$

where $\overline{S}^{\phi t}$ is a time averaged salinity over a zonal cross-section. For $\Delta S > 0$, we define the term *high salinity water* and for $\Delta S < 0$ we use the term *low salinity water*. Two sections along 7°N and along the equator are discussed.

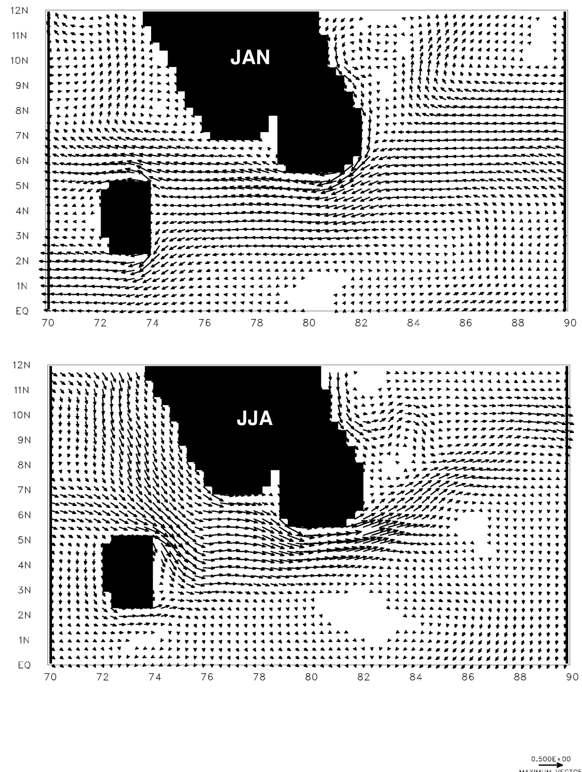

Figure 1: Monthly mean currents in the mixed layer during the northeast monsoon during January (top) and during July (bottom). Length of the vectors is proportional to the current speed, with a maximum of 0.5 m/s.

3. MODEL CIRCULATION

The model current are in very good agreement with earlier model results (Jensen 1991; Semtner and Chervin 1992; McCreary et al. 1993; Vinayachandran and Yamagata 1998) as well as available observations, e.g. Cutler and Swallow (1984); Rao et al. (1989).

3.1 The Monsoon Seasons

During the boreal winter the circulation in the Indian ocean is similar to that found in other tropical oceans. Most important for the exchange between the Bay of Bengal and the Arabian Sea is the North East Monsoon Current (NMC), also referred to as the North Equatorial Current (NEC), with a strong westward component from the equator to 7°N. This current advects water from the eastern part of the northern Indian Ocean towards the west for about 4 months starting in December. Figure 1, (top) shows the model currents in the mixed layer during the northeast monsoon in the region south of Sri Lanka, with advection out of the Bay of Bengal.

During the boreal summer, the NMC is replaced by the eastward flowing Southwest Monsoon Current (SMC) in the northern Indian Ocean, which advects water from the Arabian Sea eastward for 4 months beginning in June. These eastward currents extend into the Bay of Bengal (Fig. 2, (bottom).

3.2 Upper Ocean Salt and Tracer Transports

Relaxation towards surface temperature and salinity climatology ensures that all heat and freshwater sources are included, but also tends to underestimate the importance of advection. For this reason, passive tracers were released north of 9.6°N in the Arabian Sea and north of 11.3°N in the Bay of Bengal. The tracers were released on January 15 after 3 yr of integration. The Bay of Bengal tracer concentration was initialized to 100% in the mixed layer and 0% in other layers. In the Arabian Sea, the tracer concentration was set to 100% in layer 2 and 0% in other layers. Our model runs suggest mixed layer inflow of high salinity water from the Arabian Sea into the Bay of Bengal, but surprisingly not a significant transport of low salinity water from the Bay of Bengal into the Arabian Sea. Low salinity water leaves the Bay of Bengal along the eastern side of the basin and along the east coast of India. These transports have been confirmed using two passive tracers, with one introduced in the Arabian Sea, and a second in the Bay of Bengal (Fig. 2). Another surprise was that both Arabian Sea water and Bay of Bengal water are transported southward across the equator in the central part of the Indian Ocean, closely tied to the annual cycle. In particular we see the southward transport of Arabian Sea water during the transition from southwest monsoon to northeast monsoon in the section from 47°-60°E. The northward transport of salt in the eastern section is actual a southward net freshwater flux.

Finally, we found that source of low salinity water into the Arabian Sea is the western Indian Ocean just south of the equator. The water is carried northward along the African coast in the Somali Current as suggested by Jensen (1991) using potential vorticity as a tracer. The pathways have been confirmed using drifter calculations.

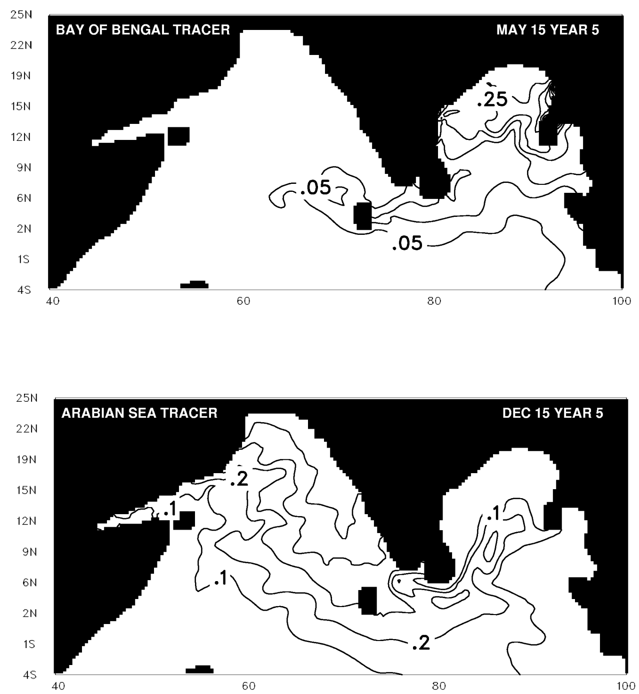

Figure 2: Westernmost extent of the tracer released in the Bay of Bengal occurs after the end of the northeast monsoon. The contours show the fraction of BB water in the mixed layer. Contour interval is 0.05 (top). Arabian Sea water left in the Bay of Bengal after the southwest monsoon has subsided is clearly seen. Contour interval is 0.1 (bottom)

5. DISCUSSION

Our results clearly show a significant inflow of Arabian Sea water into the Bay of Bengal, while only small amounts of Bay of Bengal water enters the Arabian Sea. However, it is most likely that wind stress variations with higher frequency will lead to more dispersion of salt and tracers. For instance, Shetye et al. (1996) found water with salinity as low as 29 psu along the southeast coast of India. Our model solution does show a boundary current propagating as a front of low salinity extending west of Sri

Lanka, but this water does not penetrate northward along the west coast of India. The shallow strait between Sri Lanka and India is closed in the model. In reality it has a sill depth of only 10 m, but may still provide a path for water with very low salinity to enter the Arabian Sea.

6. ACKNOWLEDGEMENT

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