GEOPHYSICAL RESEARCH LETTERS, VOL. 28, NO. 20, PAGES 3967-3970, OCTOBER 15, 2001

Arabian Sea and Bay of Bengal exchange of salt and tracers in an ocean model.

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Abstract. Exchanges of mass and salt between the mixed layers in the Arabian Sea and the Bay of Bengal are examined in a model of the Indian Ocean using passive tracers as a tool to map the pathways. Inflow of high salinity water from the Arabian Sea into the Bay of Bengal is significant and occurs after the mature phase of the southwest monsoon. Freshwater transport out of the Bay of Bengal is southward throughout the year along the eastern boundary of the Indian Ocean. Low salinity water transport into the Arabian Sea occurs in the Somali Current during the southwest monsoon, closing a clockwise path of water mass transport. Only a small fraction of low salinity water is advected into the eastern Arabian Sea from the Bay of Bengal.

Introduction

The climate in the northern Indian Ocean region varies from 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 high salinity in the Arabian Sea and 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. Analyses of observations [*Murty et al.*, 1992; *Suryanarayana et al.*, 1993] and recent model data [*Vinayachandran et al.*, 1999; *Han and McCreary*, 2001] show that the Southwest Monsoon Current (SMC), which flows eastward during the boreal summer, enters the Bay of Bengal between 80-90°E during the mature or late phase of the monsoon, i.e. July to September. The authors of the second study attribute this intrusion to a Rossby wave reflected from the eastern part of the Indian Ocean.

During the northeast monsoon, southward (northward) geostrophic currents along the east (west) coast of India [*Shetye et al.*, 1991; 1996], ship-drift currents [*Cutler and Swallow*, 1984] and direct current measurements south of Sri Lanka [*Schott et al*, 1994] suggest a transport from the Bay of Bengal to the Arabian Sea. However, the location and magnitude of transports of heat and salt associated with the currents during the two monsoon seasons have not yet been determined.

An interesting question is therefore if significant exchanges of water occur due to advection around the southern tip of India, and to what extent it involves a larger area of the Indian Ocean. *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 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. These questions have been addressed using a numerical model of the Indian Ocean.

Paper number 2001GL013422.
0094-8276/01/2001GL013422$05.00

Numerical model

The 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 [*Jensen*, 1998a]. Lateral stresses are proportional to the local deformation rate of the flow, while diffusivity of temperature, salinity and tracers were held constant at 1000 m^2/s. The model has 4 active layers with an infinitely deep layer below. The horizontal resolution is 1/3° and the average initial thickness is 80 m, 120 m, 250 m and 600 m for layers 1 to 4. The model covers the Indian Ocean north of 30°S to 120°E with open southern and eastern boundaries. A relaxation towards an Indonesian Throughflow of 10 Sv and an outflow of 40 Sv along 30°S, from Africa to 39°E, is used. East of that longitude the model inflow is allowed to evolve freely. Temperature, salinity and layer thickness are prescribed along the open boundaries, [*Jensen*, 1998b].

Climatological monthly mean wind stress from the European Center for Medium Range Forecast re-analysis is used and the heat and freshwater fluxes are computed by relaxation to Levitus surface conditions on a 6-day time scale. This forcing implicitly includes the effect of precipitation, evaporation and river discharges. The upper four layers of the model were initialized with January temperature and salinity [*Levitus and Boyer*, 1994; *Levitus et al.*, 1994] and geostrophic currents were computed poleward of 5° with a level of no motion at the base of layer 4. Within 5° of the equator, the Coriolis parameter at 5° was used, with a change of sign at the equator. This imbalance in the equatorial region adjusts within the first year, during which the temperature and salinity fields were kept constant. The circulation after 6 years of spin-up is investigated.

The monsoon seasons

The model currents are in very good agreement with earlier model results [*Jensen*, 1991; *McCreary et al.*, 1993; *Vinayachandran and Yamagata*, 1998] and observations [*Cutler and Swallow*, 1984; *Rao et al.*, 1989]. During the northern winter, the Indian Ocean circulation 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 Northeast Monsoon Current (NMC) with a strong westward component from about 3°N to 7°N. The NMC advects water from the eastern part of the northern Indian Ocean westward for about 4 months starting in December. During the boreal summer, the NMC is replaced by the eastward flowing SMC, advecting water from the Arabian Sea for 4 months beginning in June.

Extreme water mass displacements occur at the wind reversals, after being exposed to the full duration of a monsoon season. The extent of the relative fresh water into the Arabian Sea is at its maximum in April. In October, the eastward extent of high salinity water toward the Bay of Bengal is at its maximum (Fig. 1). The front between high salinity water and low salinity water remains sharp in the model, so the net transport of mass across it remains small. The model solution by *Han and McCreary* [2001] showed similarly strong gradients. In the Levitus salinity data the same fronts are found, but are much smoother.

During the height of the monsoons, strong zonal flow is found in the model south of Sri Lanka (Fig. 2), as observed [Fig. 4 in *Schott et al.*, 1994]. As in the observations, the flow is strongest between 3°N and Sri Lanka during July, while extending to 2°N in January. At 100 m, the observed July eastward flow of about 0.25 m/s north of 3°N and a westward flow between that latitude and the equator is also found in the model. The observed flow has a strong shear between 20 m and 100 m with currents up to 0.6 m/s in January and 1 m/s in July. The model mixed layer depth is 50-60 m and has monthly mean currents about half of those observed at 20 m. For the mixed layer as a whole the model currents are in good agreement with the observations, which gives confidence in the model advection of scalar quantities.

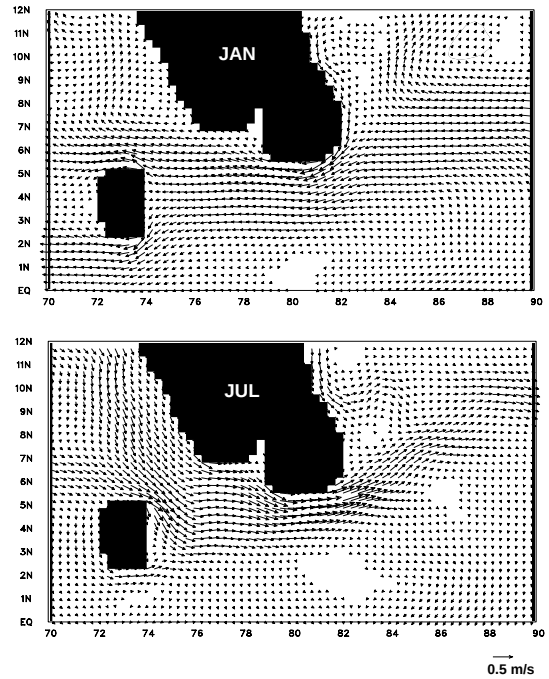

Figure 2. Monthly mean currents in the model mixed layer during January (top) and during July (bottom).

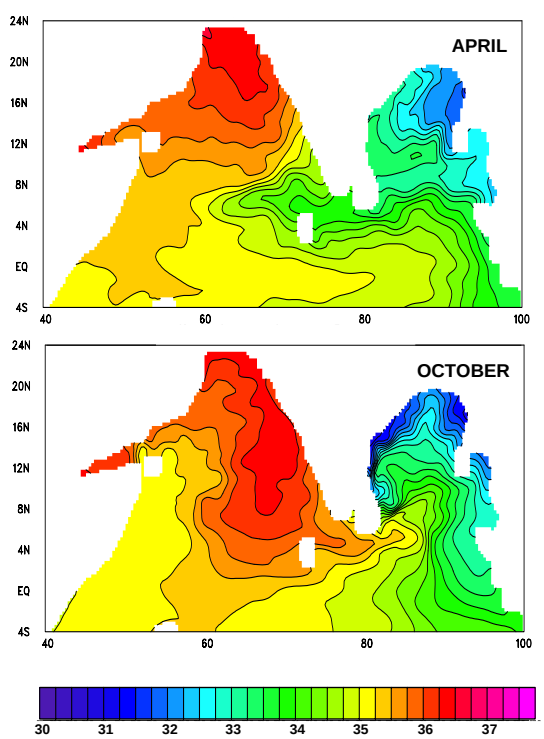

Figure 1. Mean salinity in the mixed layer in April during the transition from northeast to southwest monsoon (top) and in October during the change from southwest to northeast monsoon (bottom). Contour interval is 0.25 psu.

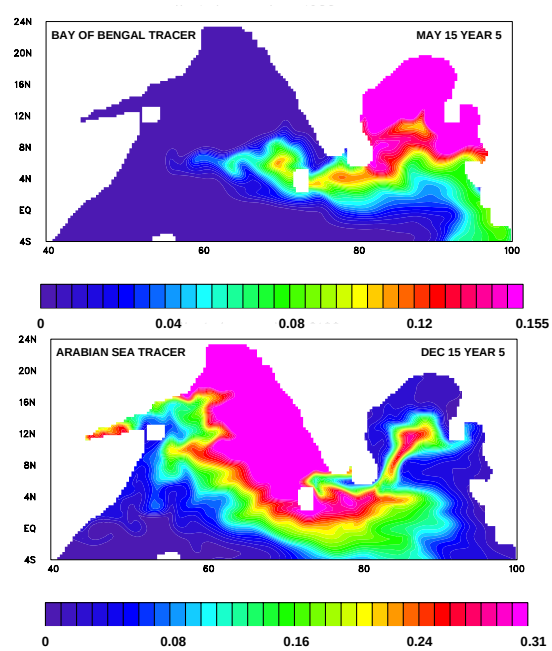

Figure 3. Westernmost extent of the tracer released in the Bay of Bengal occurs after the end of the northeast monsoon. The color shows the fraction of BB water in the mixed layer. Contour interval is 0.005 with fractions of 15.5% and higher shown in magenta (top). Arabian Sea water left in the Bay of Bengal after the southwest monsoon has subsided is clearly seen. Contour interval is 0.01 with fractions of 31% and higher shown in magenta (bottom).

Upper ocean salt and tracers transports

The 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, two passive tracers were released north of 9.6°N in the Arabian Sea and north of 11.3°N in the Bay of Bengal as a simple way to determine the fractions of water originating in the two seas. The tracers were released on January 15 after 3 years of integration. The Bay of Bengal tracer concentration was initialized to 100% in the mixed layer and to 0% in other layers. In the Arabian Sea, the tracer concentration was set to 100% in layer 2 and to 0% in other layers.

Based on the model tracers, which show intrusion of water from the Arabian Sea into the Bay of Bengal, we expect the same path for high salinity water (Fig. 3). Surprisingly, we do not find an equally significant transport of water from the Bay of Bengal into the Arabian Sea. The tracers also demonstrate, that water leaves the Bay of Bengal along the eastern side of the basin and along the east coast of India. The Bay of Bengal tracer extends to 55°E , but is not advected northward into the central Arabian Sea. Rather, both Arabian Sea water and Bay of Bengal water are transported southward across the equator in the central part of the Indian Ocean due to southward Ekman drift.

Analysis of salt transport across 7°N

To determine where and when net fluxes of freshwater and salt take place, the model 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 and zonal averaged salinity over a cross-section. For $\Delta S > 0$, we define the term *high salinity water* and for $\Delta S < 0$, the term *low salinity water*. Sections along 7°N are used. For the Arabian Sea, the section average model salinity in the mixed layer is 35.26 psu and for the Bay of Bengal it is 33.44 psu.

The analysis shows a southward transport of Arabian Sea water (Fig. 4a and 4c) during the transition from southwest

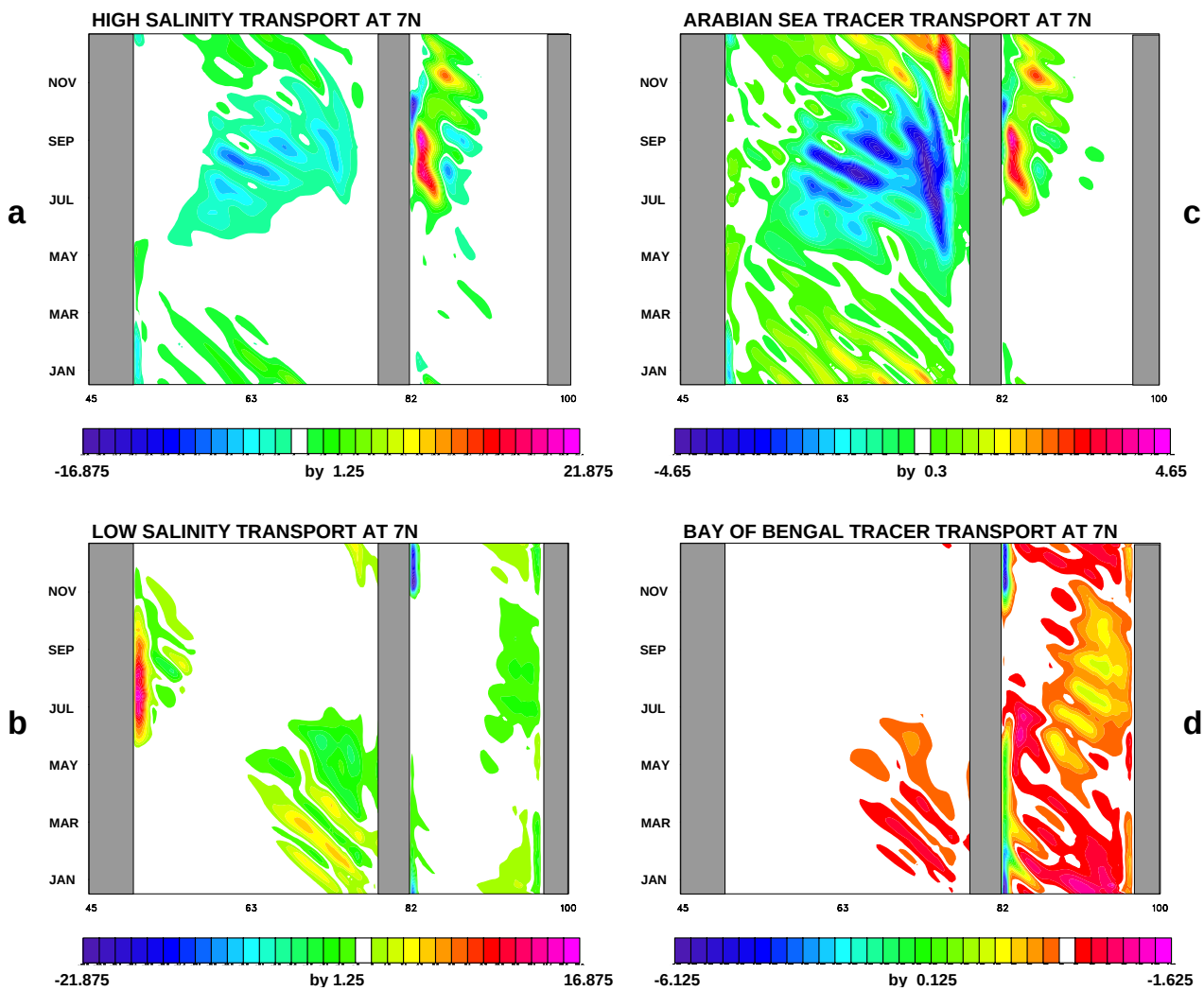

Figure 4. Longitude-time plot of northward flux of salinity and tracers anomalies in the mixed layer at 7°N during year 5. (a): Positive salinity anomaly flux. (b): Negative salinity anomaly flux. Contour interval is 1.2 psu m^2/s. (c): Arabin Sea tracer. Contour interval is 0.3 m^2/s (d): Bay of Bengal tracer. Contour interval is 0.24 m^2/s. White indicates zero flux.

to northeast monsoon from 50°-70°E. Also note that the northward flux of high salinity water into the Bay of Bengal during this time is Arabian Sea water. Southward transport of low salinity water east of 90°E takes place during most of the year. Northward transport of low salinity water near the Indian west coast occurs in three events from November to April, followed by southward transport until July. Most of this water originates in the Bay of Bengal.

Finally, the main source of low salinity water into the Arabian Sea is the western Indian Ocean just south of the equator (Fig. 4b). This water is carried northward by the Somali Current as suggested by *Jensen* [1991] using potential vorticity as a tracer.

Discussion

On the average, there is a clockwise circulation encompassing the tropical Indian Ocean to about 10°S dominated by the strong southwest monsoon. As a part of that gyre, it was shown that Arabian Sea water is an important source of high salinity water for the Bay of Bengal, which exports water of low salinity southward across the equator. Freshening of the Arabian Sea is due to southern hemisphere water advected northward by the Somali Current during the southwest monsoon.

The results do not show Bay of Bengal water with origin north of 10° to be a significant source of fresh water for the Arabian Sea. *Shetye et al.,* [1996] found water with salinity as low as 29 psu along the southeast coast of India. Our model solution shows a boundary current propagating as a front of low salinity water extending west of Sri Lanka, but it 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, and may, as demonstrated in an experiment by *Han and McCreary* [2001], provide a path for water with very low salinity to enter the Arabian Sea. Our model shows very sharp fronts, and relatively little mixing despite a low eddy viscosity. One possible reason is that monthly mean forcing is used. Including wind stress with higher frequency will likely lead to more dispersion of salt and tracers.

Acknowledgments. This research was supported by Frontier Research System for Global Change through its sponsorship of the International Pacific Research Center (IPRC). Model development was funded by U. S. Department of Energy through Grant DE-FG03-96ER62167 to Colorado State University. This manuscript is SOEST contribution 5821 and IPRC contribution IPRC-102.

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(Received May 8, 2001; revised July 18, 2001; accepted July 30, 2001.)