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Stable isotopes and salinity in the surface waters of the Bay of Bengal: Implications for water dynamics and palaeoclimate

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ABSTRACT

Surface water mixing in the Bay of Bengal (BOB) inferred from spatio-temporal distribution of $\delta^{18}O$ and salinity based on synthesis of 194 new samples together with published data is reported. In general, both $\delta^{18}O$ and salinity have low values in northern part of the BOB, progressively increasing towards SW. The lowest values are observed during July–September (southwest monsoon season) and the highest in pre-monsoon. The most prominent $\delta^{18}O$–salinity relationship is seen for samples collected during June to October when the Himalayan river influx dominates. When this influx decreases in other seasons the $\delta^{18}O$–salinity relationship is poor.

The $\delta^{18}O$–δD regression of samples north of 10°N is similar to the GMWL. However, for samples south of ~10°N, this regression has a significantly lower slope. This is interpreted as due to absence of direct riverine inflow in this region of the BOB, coupled with –ve (P − E; Precipitation minus Evaporation) almost throughout the year.

This study shows that the seasonal distribution of $\delta^{18}O$ and salinity over the northern BOB is dominantly governed by the variation in the (P + R − |E|) in spite of the fact that ocean currents transfer several times more water between the two basins of northern Indian Ocean.

1. Introduction

Studies on the dynamics of surface water of the northern Indian Ocean are important as they significantly affect monsoon systematics and consequently the water availability over India. A complex interplay of several factors/processes which include river influx and ocean currents, direct precipitation and evaporation govern these dynamics. Natural or anthropogenic perturbations in any of these controlling factors/processes can have far reaching and non-linear consequences to meteorology, atmospheric chemistry and heat budget of the region. Study of tracers such as oxygen and hydrogen isotopic ratios ($\delta^{18}O$ and δD) that essentially track the water molecules, and salinity are best suited for studying the involved dynamical processes.

The BOB is a unique ocean basin influenced by seasonally reversing monsoon winds, high precipitation [~2 m/year; (Prasad, 1997)] and large influx of freshwater from Himalayan and Peninsular Rivers of the Indian sub-continent. The geographical location of the BOB and the regions where major rivers discharge freshwater into it are shown in Fig. 1a. The monthly distribution of precipitation (P), runoff (R), evaporation (E) and sea surface salinity (SSS), is shown in Fig. 1b (Rao and Sivakumar, 2003). While the maximum of precipitation occurs in months of June–July, most of the runoff occurs in June through November. The evaporation on the other hand is bimodal with a maximum in March–April and another high in September–October. The maximum value of (P + R − |E|) occurs in the month of July–August–September consequently the minimum values of SSS are observed in August and September. The SSS progressively increases through November until a second minimum occurs in December in response to winter monsoon over Peninsular India.

The total freshwater discharge from the major rivers is estimated to be ~1630 $km^3 a^{-1}$ based on data from gauge stations (Biksham and Subramanian, 1980; Chakrapani and Subramanian, 1990; Martin et al., 1981; Ramesh and Subramanian, 1993; Subramanian, 1993). Monthly distributions of river discharges of the major rivers draining into the

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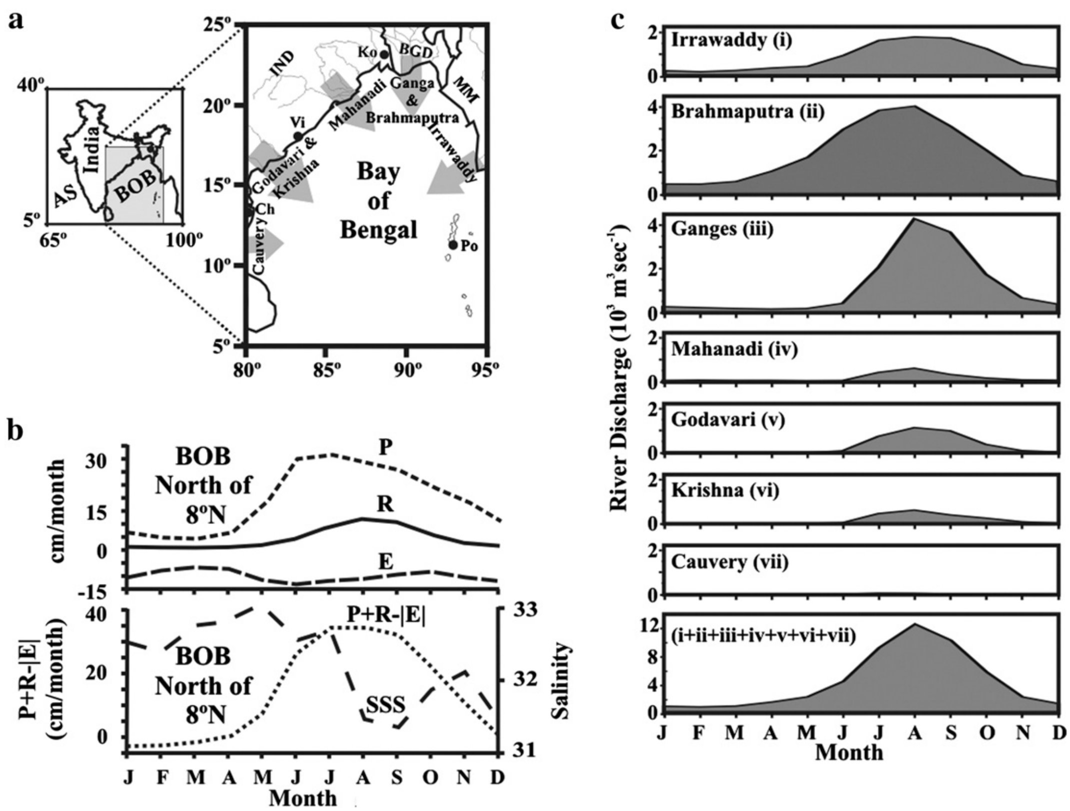

Fig. 1. (a) The geographical locations of the regions in the BOB where major rivers from Peninsular India (Cauvery, Godavari, Krishna and Mahanadi) and Himalaya (Ganga, Brahmaputra and Irrawaddy) discharge freshwater. The acronyms indicate: IND: India; Ch: Chennai; Vi: Visakhapatnam; Ko: Kolkata; BGD: Bangladesh; MM: Myanmar and Po: Port Blair. (b) Annual cycle of evaporation 'E', precipitation 'P', river discharges 'R' from all the major rivers flowing into the BOB, also shown are 'P + R − |E|' and sea surface salinity 'SSS' for the entire BOB (north of 8°N); redrawn from (Rao and Sivakumar, 2003). (c) Average annual cycle of discharge from major rivers in the BOB (Data source: http://www.sage.wisc.edu/riverdata/).

BOB are shown in Fig. 1c. Maximum river discharge occurs during June to November peaking in August. The southern Peninsular Rivers (Cauvery, Mahanadi, Godavari and Krishna) contribute limited river discharge to the BOB in comparison to the major rivers draining the Himalayan region (Brahmaputra, Ganges and Irrawaddy).

In addition to major rivers that are gauged, numerous smaller streams also discharge into the BOB. The total annual continental run-off along the BOB coast line north of 6°N was estimated at 2950 km^3 which is about 60% of the total runoff into the entire tropical Indian Ocean north of 30°S (Sengupta et al., 2006). The annual total precipitation and evaporation over the BOB are estimated to be 4700 km^3 and 3600 km^3 respectively (Sengupta et al., 2006), resulting in overall positive $(P - E)$ for the BOB. However, during summer, $(P - E)$ is negative as discussed subsequently. But, due to large river discharges, $(P + R - |E|)$ is positive even during summer. As a result, the upper layers of the BOB have lower salinity (by 3–7), and warmer sea surface temperature (by 1.5−2 °C) than the ocean basin to the west of the Indian land mass, namely, the Arabian Sea (AS) (Prasanna Kumar et al., 2002). During this period, winds are unable to break the strongly stratified surface layer of the BOB; thereby restricting the turbulent wind-driven vertical mixing to a shallow depth of <20 m (Prasanna Kumar et al., 2002). This stratified layer also restricts exchange of heat between the deeper layer and the atmosphere, maintaining sea surface temperature (SST) in BOB >28 °C. This phenomenon supports large scale deep convection in the atmosphere during the summer monsoon (Shenoi et al., 2002). It has been calculated that SST of 28–29 °C is needed for charging the cloud-base air-mass with the required moist static energy for clouds to reach the upper troposphere, i.e. ~200 hPa (Gadgil, 2003; Gadgil et al., 1984; Sud et al., 1999).

As with the winds (Fig. 2a), the oceanic currents (Fig. 2b) in the northern Indian ocean also reverse from summer to winter. The major ocean surface currents that flow between the AS and the BOB are: (i) The Summer Monsoon Current (SMC), flowing eastward during May to September; and (ii) the Winter Monsoon Current (WMC), flowing westward during November to February. These ocean currents extend over the entire northern Indian Ocean from the Somali coast to the eastern BOB but they arise or decay over this whole region at different times. Only in their mature phase these currents exist as trans-basin flows (Shankar et al., 2002). The eastward flowing SMC first appears in the southern BOB during May. In its mature phase, peaking with the summer monsoon in July, the SMC in the AS is a continuation of the Somali Current and the coastal current of Oman. The SMC flows eastward south of Sri Lanka and into the BOB (Fig. 2b; upper panel) as East India Coastal Current (EICC). The westward WMC first forms south of Sri Lanka in November and is fed mainly by the equatorward East India Coastal Current (EICC). In its mature phase during December to March, the WMC flows westward across the southern BOB (Fig. 2b; lower panel) and divides into two branches in the AS. One of these branches continues flowing westward whereas the other turns around to flow northwards along the western coast of India and is known as West India Coastal Current (WICC). It is thus seen that EICC is a western boundary current in the BOB, along east coast of India that reverses with monsoon. Shankar et al. (2002) indicated that SMC and WMC transport $\sim 10 \times 10^6 m^3 s^{-1}$ (i.e. ~10 Sverdrup or $\sim 3 \times 10^5 km^3 a^{-1}$) of water either way, in the upper 400 m, with most of the transport being restricted to upper 100 m. This transport of water is more than 100 times the total river discharge into the BOB.

Another important source of water into the southern Indian Ocean is the Indonesian Throughflow (ITF) that provides large amount (10