SAGAR-ARGO: an ARGO-based analysis of the year-to-year sea surface salinity variability in the Bay of Bengal during the 2009 – 2014 period

F. Durand [1,2], Chaitanya A.V.S.[3], S. Mathew[4], V.V. Gopalakrishna[3], F. Papa[1,2], M. Lengaigne[5,6], J. Vialard[5], Ch. Krantikumar[3] and R. Venkatesan[4]

(1) IRD/Laboratoire d'études en Géophysique et Océanographie Spatiales (LEGOS), Toulouse, France
(2) Indo-French Cell for Water Sciences, IISc-NIO-IITM–IRD Joint International Laboratory, IISc, Bangalore, India
(3)CSIR/National Institute of Oceanography (NIO), Goa, India
(4) National Institute of Ocean Technology (NIOT), Chennai, India
(5) Sorbonne Universités, UPMC Univ Paris 06, UMR 7159, LOCEAN, F-75005, Paris, France
(6) Indo-French Cell for Water Sciences, National Institute of Oceanography, Dona Paula, India

Contact: fabien.durand@ird.fr

ABSTRACT: The Bay of Bengal forms the northeastern part of the Indian Ocean. It is forced by the seasonally-reversing monsoon winds. It is a recipient of intense precipitation and continental river runoff during summer monsoon and post-monsoon season. As a result, sea surface salinity (SSS) is consistently very low in the northern BoB. The stratification due to these low salinities has a pronounced effect on SST: it maintains surface waters above 28˚C throughout the year. This leads to a sustained atmospheric convection[1] and to the formation of tropical cyclones over the bay. While the seasonal variability of SSS is rather well known[4,5], the interannual variability of SSS is not known. Here we analyze a novel observational in situ SSS product covering the 2009-2014 period, based on ARGO data (among which some were collected from 10 floats deployed through the SAGAR-ARGO GMMC project) and other in situ data. It reveals a strong interannual variability over the North Eastern Bay of Bengal (NEB). During this 5 year period SSS shows intense year-to-year oscillations, with anomalously salty conditions in 2009-2011 and anomalously fresh conditions in 2012 onwards. In the present study we investigated the forcing factors of these anomalies using a simple mixed-layer budget model. The results show that rainfall and river discharge are the main factors for the observed SSS oscillations (with advection also playing a significant role for the 2011 freshening period). These results were published in Chaitanya et al. (Ocean Dynamics 2015; DOI 10.1007/s10236-014-0802-x)

1. Context: the seasonal cycle of SSS over the Bay

The Bay of Bengal shows very strong seasonal variations of salinity in the northern part of the basin, with freshening in the post-monsoon season, and saltening in the subsequent seasons.

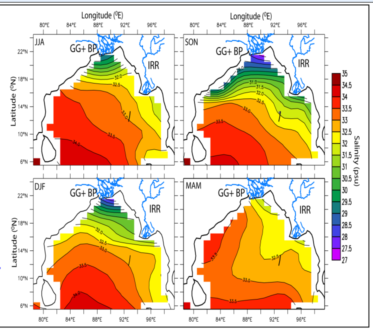


Fig 1: Seasonal evolution of SSS over the BoB from NIOA climatology[2]. Isocontours every 0.5.

2. Data sets

In the present study we have considered all available salinity observations shown in Fig 2a: Argo profiles (black dots), XCTD profiles (red) along Kolkata-Port Blair (K-PB), bucket samples (yellow) along C-PB and K-PB ship tracks, thermosalinograph transects (pink), shipborne CTD stations (blue), RAMA moorings (orange diamonds) and OMNI moorings (green circles) during the study period 2009-2014.

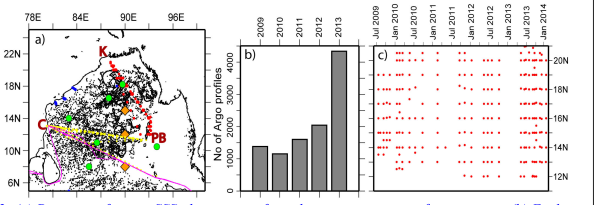


Fig 2: (a) Positions of in situ SSS observations from the various sources of instruments. (b) Evolution of the yearly number of individual Argo profiles from 2009 to 2013. (c) Latitude-time distribution of XCTD casts, along K-PB transect.

In a similar way to C. de Boyer Montégut[3], we merged these datasets by computing the median of all available individual measurements on a 2°×2°×3 months grid. We then computed the anomalies by substracting the seasonal climatology. The standard deviation of the interannual anomalies (Fig. 3) illustrates the strong variability in the north-eastern quarter of the basin, and in the coastal strip hugging the western boundary. The central bay shows a comparatively lower variability.

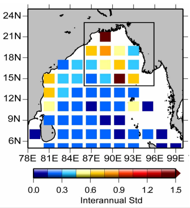


Fig 3: (a) Standard deviation of SSS interannual variability over 2009-2014 in our blended in situ product.

3. Observed characteristics of the SSS over the NEB Box

The SSS evolution observed over NEB box displays a marked seasonal cycle, with freshening in post-monsoon followed by saltening during winter and spring (Fig. 4). The year-to-year variations show that the freshening is stronger than normal in 2011 and 2013, resulting in fresh anomalies during the post-monsoon season (-0.5 in SON 2011 and -0.9 in SON 2013). Conversely, the monsoonal freshening is weaker than normal in 2010, resulting in a +1 salty anomaly in SON 2010. Fig. 5 shows that these anomalies spread over most of NEB box, for each anomalous event.

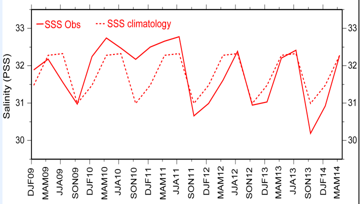


Fig. 4: Trimonthly evolution of SSS averaged over the NEB box, from our blended product (solid red) and from NIOA seasonal climatology (red dashes).

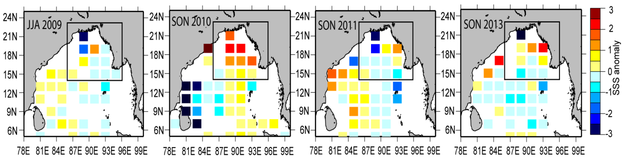
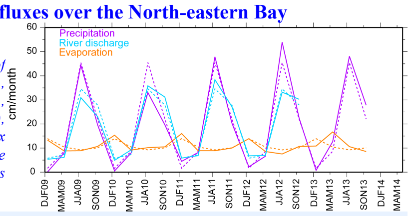


Fig 5: Map of interannual SSS anomalies at the peak of the fresh events (JJA 2009, SON 2011, SON 2013) and at the peack of the salty event (SON 2010). The limits of the NEB box are shown in black.

4. Freshwater forcing fluxes over the North-eastern Bay

Fig 6: Trimonthly evolution of precipitation (purple solid), evaporation (orange solid), river discharge (blue solid), integrated over the NEB box (oceanic area only); the corresponding climatologies are shown in dashed lines.



We considered the interannually varying precipitation and river runoff from Ganges, Brahmaputra and Irrawaddy watersheds[7]. The year-to-year variations of precipitation and runoff show that both fluxes can deviate significantly from their climatology, but they do not always vary in phase. In 2009 precipitation is close to normal whereas discharge is deficient. On the contrary, in 2010, precipitation is deficient while discharge is above normal. In 2011, both precipitation and runoff are above normal. In 2012, precipitation is also above normal, but runoff is close to normal.

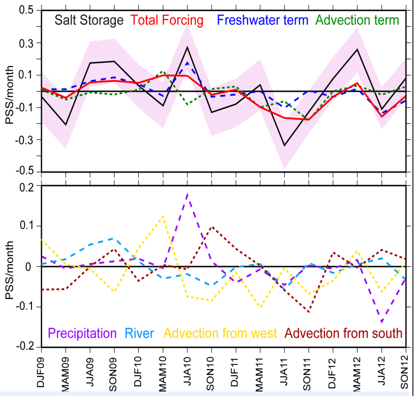
5. Simple Mixed layer Salt budget model

To quantify the role of each of the forcing terms in the observed variability of SSS we use a simplified mixed-layer salinity budget equation. It has already been used in several previous studies of SSS variability (e.g. [6] in the equatorial Indian ocean). From the law of salt conservation in the ocean mixed layer, the mixed layer salinity anomalies evolution averaged over NEB box reads as follows:

$$\frac{dS'}{dt} = \frac{1}{hA}\left[\iint_{\substack{west\ and\ south\\ boundaries}} \overline{u'_{normal}\left(S_{boundary} - S\right)}\, ds + \iint_{\substack{ocean\\ surface}} \left(E' - P' - R'\right) S\, ds\right]$$

where S is the box-averaged mixed-layer salinity, h is the mixed-layer thickness (prescribed, assumed to be constant in time and in space), A is the area of the box, u_{normal} is the horizontal current in the normal direction to the box boundaries; $S_{boundary}$ is the salinity at the boundary of the box; E is evaporation, P is precipitation and R is the freshwater flux of all rivers entering the box. This model neglects the space and time variations of mixed layer depth, exchanges with the subsurface, transport at the eastern box boundary, and advection of salinity anomalies by the climatological currents. Prime (') denotes interannual anomalies of the variables.

Fig 7: Time derivative of the tendency of the SSS interannual anomaly averaged over the NEB box, observed (black) and estimated (red). The pink envelope features the error bar of the salt storage term. The evolution of the various terms of the mixed-layer model is also shown, as follows: freshwater forcing in dark blue, horizontal advection in green. The bottom panel displays the corresponding evolution of the individual terms of the mixed-layer model.



The evolution of SSS tendency estimated from the simplified mixed-layer salinity budget (Fig. 7, red) displays a reasonable agreement with the observed tendency in terms of timing of the freshening and saltening periods as seen from the observations (black). This implies that our simplified budget is reasonably closed. The underestimation of the magnitude of model tendency term during the saltening and freshening peaks may be due to the unaccounted physical mechanisms in our simple model (e.g. vertical physics and/or advection of salt anomalies by the seasonal currents.)

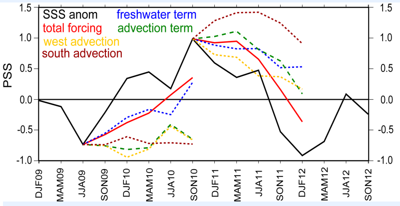


Fig 8: Trimonthly evolution of observed SSS interannual anomaly averaged over the NEB box (black). The coloured lines show the SSS estimated from our simple mixed-layer salt budget, integrated over two periods, one starting in JJA 2009 and one starting in SON 2010.

The time integral of the various forcing terms of SSS evolution shows that the 2009-2010 saltening event (more than +1.5pss) appears to be largely driven by fresh water forcing (Fig. 8), prominently from rainfall (Fig. 7). The freshening event from late 2010 to early 2012 (- 2 pss) is driven both by the freshwater term (rainfall and river runoff) and advection terms. The variability of advection terms is consistent with the succession of Dipole Mode events (IOD) in the tropical Indian ocean (negative IOD in 2010, followed by positive IOD in 2011).

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6. Conclusions:

We present a first-of-its-kind description of the pluri-annual evolution of SSS in the Bay of Bengal. Interannual variability is primarily locked to the North-eastern part of the basin. Over the study period, SSS evolution takes the form of two successive and opposite phases: a saltening phase from mid-2009 to late 2010, immediately followed by a freshening phase from late 2010 to late 2011. A simple mixed-layer salt budget indicates that year-to-year SSS variability in the North-eastern Bay of Bengal is primarily driven by freshwater fluxes variability, with rather independent contributions from precipitation and river runoff. The oceanic surface circulation variability contributes less systematically to the large-scale SSS evolution in the Northern Bay of Bengal over the entire record, despite strong contributions at times, in particular during the 2011 freshening. This circulation anomalies appear to be associated with the succession of IOD events in 2010-2011.

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