Deep–Sea Research I 185 (2022) 103770

Contents lists available at ScienceDirect

Deep-Sea Research Part I

journal homepage: www.elsevier.com/locate/dsri

Freshwater transport by eddies within the Bay of Bengal's central axis

Alexander J. Herron [a,1], Shannon M. Bohman [b], Arnold L. Gordon [b,*]

[a] Applied Physics and Applied Math Department, Columbia School of Engineering and Applied Science, Columbia University, New York, NY, 10027, USA
[b] Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY, 10964, USA

ARTICLE INFO

Keywords:
Bay of Bengal
Surface layer
Pycnocline
Mesoscale
Freshwater export

ABSTRACT

The excess of freshwater from rivers and precipitation delivered to the Bay of Bengal (BoB) must be exported to the neighboring ocean in order to establish a quasi-steady state salinity field. The BoB's sea surface salinity is approximately 3 PSU less than that of the Arabian Sea, which experiences net evaporation, a difference reflecting the efficiency of exchange between the two embayments (Gordon et al., 2019). Using Argo salinity profiles from 2003 to 2018 along the BoB's central axis, we investigate the significance of eddies in the removal of excess freshwater injected into the northern BoB by rivers. Southwestward freshwater volume flux is estimated by combining horizontal freshwater (salinity) gradients, as a function of latitude, depth, and season, with a realistic estimate of the horizontal mixing coefficient. The ratio of these fluxes for 0–50 m: 50–100 m: 100–300 m depth slabs is 5.68 : 1.75: 1 in the 15 ± 2° N (northern) study box and 4.61 : 2.24: 1 in the 10 ± 2° N (southern) study box, highlighting the importance of the upper 50 m in the removal of river runoff. In the northern BoB, boreal winter experiences the highest freshwater eddy flux, a consequence of the accumulated freshwater from the previous summer monsoon season. Lower latitudes reach their peak freshwater flux in the summer, a delayed response due to the time required to transport the freshwater southward. Southwestward eddy freshwater flux in the top 300 m can account for almost all of the export of the 0.094 Sv (Sv = 10^6 m^3/s) river runoff into the northern BoB.

1. Introduction

On annual average, the flux of freshwater from rivers into the Bay of Bengal (BoB) (Fig. 1) is 0.094 Sv (Sv = 10^6 m^3/s), accounting for more than 50% of the total freshwater runoff into the entire tropical Indian Ocean (Gordon et al., 2016). Maximum river runoff occurs from summer through fall, and is induced by the summer phase of the South Asian Monsoon. The monsoonal forcing also results in seasonal reversal of the Eastern Indian Coastal Current (EICC). The BoB and the Arabian Sea are linked in maintaining the salt balance between the two seas, as freshwater is exported from the BoB and saline water is imported from the Arabian Sea by monsoonal driven currents around the southern rim of Sri Lanka (Kantha et al., 2019).

Sengupta et al. (2006) found the annual precipitation minus evaporation (P-E) over the BoB (2.17×10^{12} m^2, including the Andaman Sea) yields a net freshwater input of 0.5 m/year, with the annual river input of 0.094 Sv spread throughout the BoB amounting to 1.37 m/year. Therefore, precipitation minus evaporation plus runoff (P-E + R) amounts to 1.87 m/year, with the river water contributing ~73% of the total freshwater input (Sengupta et al., 2006; Gordon et al., 2016). There are also substantial interannual variances in freshwater input. Dandapat et al. (2020) studied these annual differences, highlighting 4 positive river runoff anomaly years and 4 negative river runoff anomaly years between 1965 and 2016. Dandapat et al. (2020) analyzed the variation in salinity induced by river runoff into the northern BoB, finding that excess river runoff years resulted in sea surface salinity values around 2 PSU lower than deficit runoff years. Durack and Wijffels (2010) highlighted how the BoB has recently become fresher, while the Arabian Sea has become saltier. They attributed these changes to an intensification of the hydrological cycle or a decrease in the freshwater exchange between the BoB and the Arabian Sea.

Freshwater input into the BoB must be exported by advection and eddy diffusivity. Advection along the western boundary by the EICC is generally considered to be the primary means of freshwater export (Gordon et al., 2016). In addition to the EICC, the pathway along the eastern boundary of the BoB plays a significant role, however on a

* Corresponding author.
E-mail address: agordon@ldeo.columbia.edu (A.L. Gordon).

[1] Now at Center for Data Science, Graduate School of Arts and Sciences, New York University, New York, New York, 10011

https://doi.org/10.1016/j.dsr.2022.103770
Received 25 February 2022; Received in revised form 24 March 2022; Accepted 29 March 2022
Available online 27 April 2022

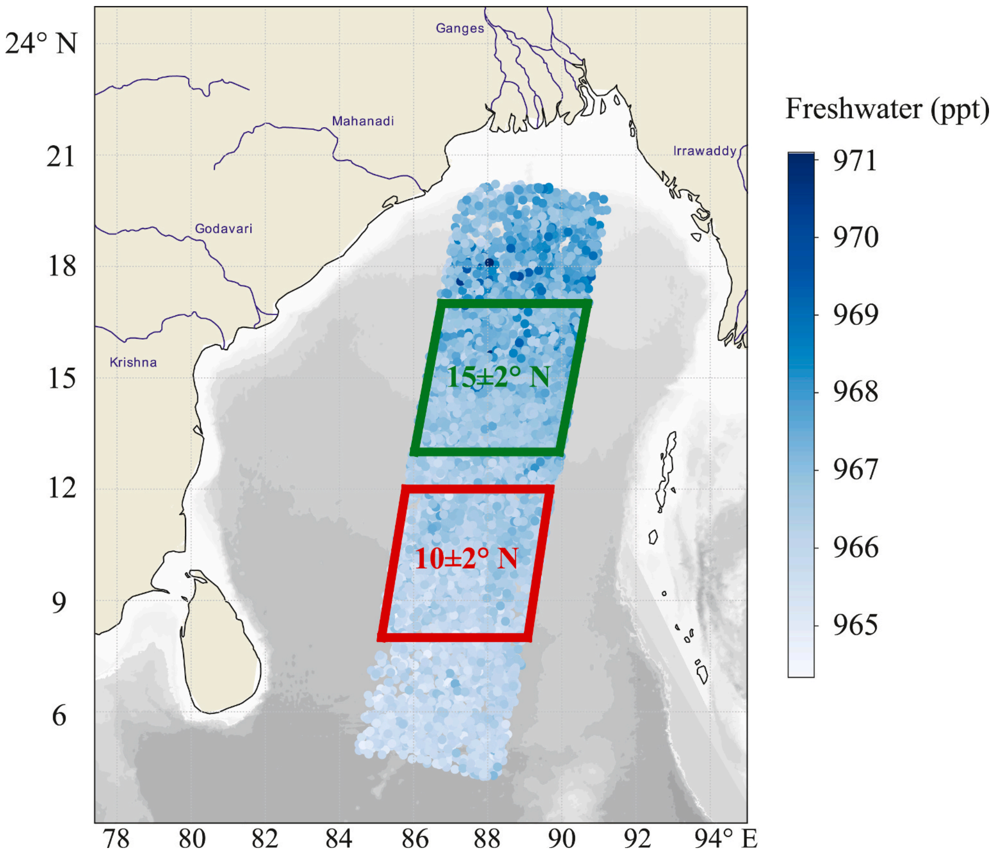


Fig. 1. Map showing the central axis of the BoB. Dots mark the positions of Argo salinity profiles recorded from 2003 through 2018. Shade of blue represents the 0–50 m mean freshwater content of the Argo profile. Freshwater is defined in units of parts per thousand, calculated by subtracting salinity (in Practical Salinity Units, or PSU) from 1000. The green box centered on 15° N marks the northern study box, and the red box centered on 10° N marks the southern study box. We divide the upper 300 m of the water columns of each box into six 50 m depth slabs. For each season and in each depth slab we calculate the southward and westward freshwater gradients and resulting southwestward volume fluxes.

different time scale. Hormann et al. (2019) highlighted how "the year-round export path along the eastern boundary may be dominant from an annual perspective compared to the highly seasonal pathway in the western BoB." Pant et al. (2015) found that freshwater in the northern BoB is advected southward in the eastern BoB. Sengupta et al. (2006) elaborated on this pathway, putting forward the idea that BoB freshwater turns westward upon meeting the Indonesian Throughflow near 10° S, spreading towards the Arabian Sea. Additionally, many eddies and internal waves enter the BoB through gaps in the Andaman and Nicobar Islands, traveling westward at rates of 6–7 cm/s (Gordon et al., 2019, 2020). To balance this freshwater transport, the "salty Arabian Sea water within the upper thermocline spreads largely as eddies under a barrier layer of surface water, whose buoyancy is maintained by massive input of freshwater" (Gordon et al., 2016). Wilson and Riser (2016) using Hybrid Coordinate Ocean Model (HYCOM) found that vertical salt fluxes within the pycnocline are the primary counterbalance of the summer monsoon freshwater input to the BoB's surface layer. However, they noted that "HYCOM is likely overestimating the strength of vertical mixing in the upper 50 m of the bay."

Mathur et al. (2019) studied the impact of freshwater advective stirring, pointing to implications for "the generation and/or evolution of frontal features in various quantities as the sea surface temperature, chlorophyll, biological activity, eddy kinetic energy and mixing rates in different parts of the ocean." Gonaduwage et al. (2019) highlighted how "insight on the spatial distribution and temporal variability of the eddy-induced heat and salt transport in the BoB remains ambiguous." In this study, we explore the relative importance of horizontal freshwater volume flux, as a function of latitude, depth, and season, within the central axis of the BoB (Fig. 1) by mesoscale eddies acting on meridional and zonal freshwater (salinity) gradients. To convert the salinity gradients to a freshwater flux, we use a representative value for the horizontal mixing coefficient (K_h), as discussed in the following section.

2. Methodology

We investigate the spatial and temporal distribution of eddy freshwater flux using Argo salinity profiles in the upper 300 m within the central axis of the BoB from 2003 through 2018 (Fig. 1). Freshwater is defined in units of parts per thousand, calculated by subtracting salinity (in Practical Salinity Units, or PSU) from 1000. Seasons are defined as follows: Spring – March, April, May; Summer – June, July, August; Fall – September, October, November; Winter – December, January, February. Summer marks the wet Southwest Monsoon season, while winter is characterized by the dry Northeast Monsoon.

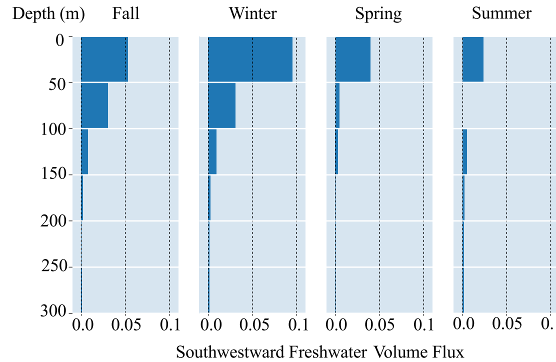
Freshwater gradients are used to estimate freshwater volume flux using a realistic value of the horizontal mixing coefficient. Rudnickas et al. (2019) estimated the horizontal (isopycnal) mixing coefficients for the tropical North Atlantic, concluding that for a maximum length scale of around 100 km, the effective zonal mixing coefficient was 1400 ± 500 m^2/s and the effective meridional mixing coefficient was 800 ± 300 m^2/s. Abernathey and Marshall (2013) approximated global surface eddy diffusivity from satellite altimetry data, estimating a K_h range of 3000–5000 m^2/s for tropical ocean, including the BoB, which tends towards the higher values (see their fig. 5). Busecke and Abernathey (2019), using satellite derived sea surface currents, investigated ocean eddy mixing dependence on climate indices. From their Fig. 4, the average K_h for the BoB is closer to 5000 m^2/s. Here we use the smaller K_h value of 1000 m^2/s as a horizontal mixing coefficient for both meridional and zonal mixing to assess the minimum eddy freshwater fluxes associated with the Argo based horizontal salinity gradients, which we find to be substantial relative to the total river inflow into the northern BoB.

We focus two boxes, spanning 4° of latitude and 4° longitude from the sea surface to 300 m of depth along the central axis of the BoB: the northern (green) box covers 15 ± 2° N, and the southern (red) box covers 10 ± 2° N (Fig. 1). The vertical dimension of each latitude box is

15 N

Depth (m)	Fall	Winter	Spring	Summer
0–50	0.0532 ±0.0018	0.0955 ±0.0015	0.0395 ±0.0014	0.0238 ±0.0010
50–100	0.0305 ±0.0001	0.0306 ±0.0011	0.0045 ±0.0010	0.0000 ±0.0010
100–150	0.0078 ±0.0002	0.0091 ±0.0002	0.0029 ±0.0004	0.0052 ±0.0003
150–200	0.0018 ±0.0001	0.0026 ±0.0001	-0.0005 ±0.0001	0.0020 ±0.0002
200–250	0.0004 ±0.0000	0.0011 ±0.0000	-0.0002 ±0.0000	0.0017 ±0.0000
250–300	0.0007 ±0.0000	0.0011 ±0.0000	0.0003 ±0.0000	0.0014 ±0.0000
0-300 m Sum:	0.0944	0.1399	0.0464	0.0342

0-300 m Annual Mean (Sv): 0.0787



10 N

Depth (m)	Fall	Winter	Spring	Summer
0–50	0.0637 ±0.0016	0.0193 ±0.0011	0.0666 ±0.0017	0.0710 ±0.0020
50–100	0.0225 ±0.0008	0.0174 ±0.0010	0.0393 ±0.0013	0.0282 ±0.0012
100–150	0.0060 ±0.0003	0.0030 ±0.0003	0.0043 ±0.0003	0.0111 ±0.0004
150–200	0.0022 ±0.0002	0.0013 ±0.0002	0.0025 ±0.0002	0.0041 ±0.0002
200–250	0.0018 ±0.0001	0.0007 ±0.0000	0.0020 ±0.0001	0.0026 ±0.0001
250–300	0.0014 ±0.0000	0.0009 ±0.0000	0.0020 ±0.0000	0.0020 ±0.0000
0-300 m Sum:	0.0975	0.0425	0.1167	0.1190

0-300 m Annual Mean (Sv): 0.0939

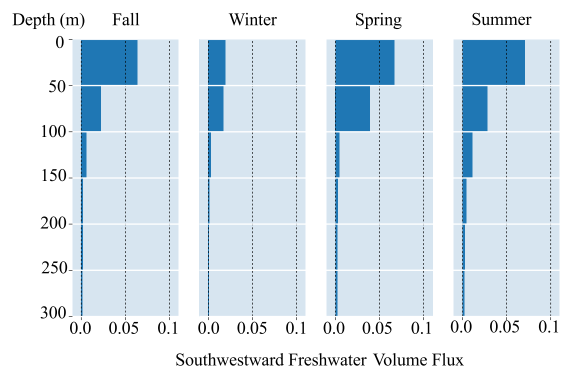


Fig. 2. Results for the 15 ± 2° N box are shown on top, and results for the 10 ± 2° N box are shown on the bottom. The left panel shows heatmap (colored according to magnitude: cells with greater flux are darker) tables of southwestward freshwater volume flux and standard error, in units of Sverdrups (1 Sv = 10^6 m^3/s), for each depth slab and season. Shade of blue corresponds to magnitude of flux. Values of total 0–300 m flux (sum of all depth slabs) are shown below each season column, and the annual mean of the 0–300 m sums are shown bolded below each table. The right panel shows corresponding bar charts of southwestward freshwater volume flux in each depth slab and season.

divided into six 50 m depth slabs from 0 to 300 m, which includes the mixed layer and pycnocline. To find the meridional (zonal) freshwater gradient, we calculate a linear least-squares regression and associated standard error for freshwater and latitude (longitude). This is performed in both latitudinal boxes for each depth slab and each season.

Density flux is defined as the product of the horizontal freshwater gradient and a horizontal mixing coefficient of $K_h = 1000$ m^2/s. Southward/westward freshwater volume flux, in units of Sverdrups, is calculated as the density flux across the southward/westward boundary of the depth slabs, each of which is 50 m deep and approximately 4.4 × 10^5 m wide. Southwestward volume flux is defined as the sum of the southward and westward volume fluxes. Total 0–300 m volume flux is defined as the sum of the fluxes of each slab, and annual volume flux is defined as the average of the fluxes of each season. We do not normalize freshwater flux values by season, depth, or spatial coordinate so as to not weight any individual observation more than another, and to include all available observations from the Argo data set.

3. Discussion

In the 15 ± 2° N box, the ratio of annual mean southwestward freshwater volume flux in the upper 50 m, to the 50–100 m layer, to the 100–300 m layer is 5.68: 1.75 : 1. This ratio is 4.61 : 2.24: 1 in the 10 ± 2° N box. These results, consistent with those of Gonaduwage et al. (2019), demonstrate that the surface layer is where the bulk of the freshwater flux occurs. This is expected as the upper layer experiences the largest spatial variability of freshwater input and greatest lateral freshwater gradients. Gordon et al. (2016) investigated meridional salinity gradients along the central axis of the BoB on various isopycnals. Salinity gradients, and therefore freshwater gradients, significantly diminish at the 24 kg/m^3 isopycnal, which occurs at an average depth of 76 m, close to the 100 m drop-off depth of freshwater fluxes found in this study.

In the 15 ± 2° N box, the annual mean meridional (southward) freshwater volume flux summed across all depth slabs from 0 to 300 m was 0.0331 Sv, while the annual 0–300 m zonal (westward) flux was 0.0456 Sv. In the 10 ± 2° N box, the annual 0–300 m southward and westward fluxes were 0.0513 Sv and 0.0426 Sv, respectively. The nearly unitary nature of these ratios highlights the high degree of similarity between meridional and zonal fluxes. This result is similar to that of Gonaduwage et al. (2019) who found the "meridional and zonal components of the total eddy-induced transport are basically of the same order, indicating that not only the meridional component but also the zonal component is important in the BoB, as the northward transport is restricted due to the semi-enclosed nature of the Bay." Although our study adopted a constant horizontal mixing coefficient, which certainly oversimplifies the complex dynamics of the BoB, these ratios also indicate that the freshwater fluxes of the northern and southern study boxes are comparable.

The annual mean 0.0787 Sv freshwater volumn flux towards the southwestward within the 0–300 m layer of the 15 ± 2° N box and 0.0939 Sv for the 10 ± 2° box (Fig. 2) account for almost all of the 0.094 Sv river discharge entering the northern BoB, even using 1000 m^2/s as a lower bound estimate for the horizontal mixing coefficient. The 10 ± 2° box flux is slightly larger than that of the 15 ± 2° box, as it likely includes the freshwater export from the Andaman Sea via the Preparis South Channel near 14°N and the Ten Degree Channel near 10°N.

If the zonal dimensions of our study boxes were extended to the

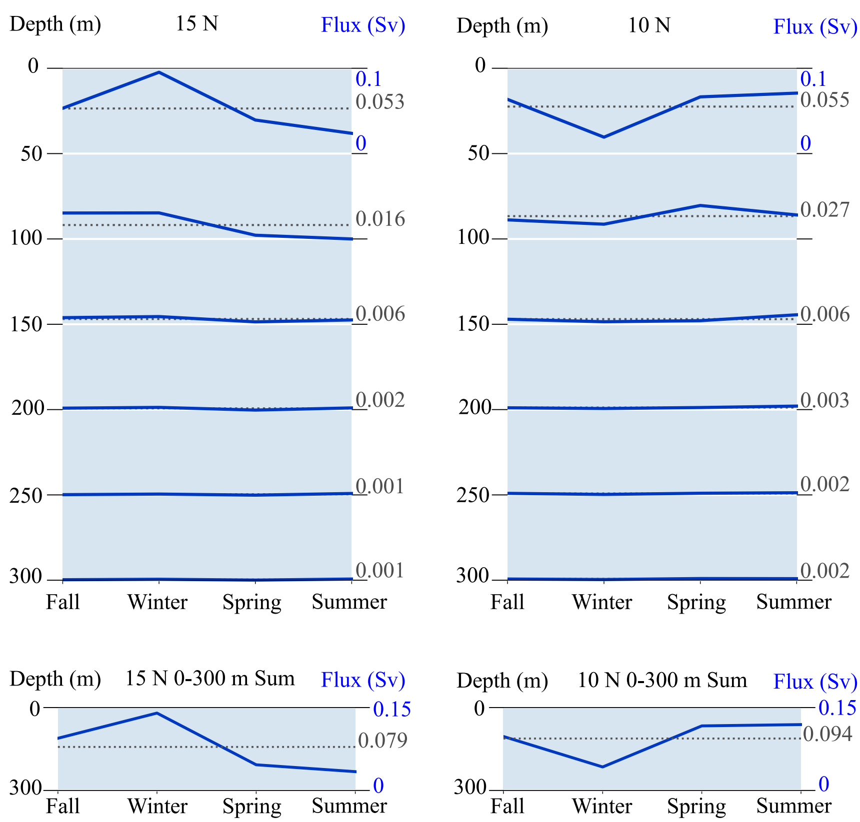


Fig. 3. Seasonal trends of southwestward freshwater volume flux by depth slab in the 15 ± 2° N (left) and 10 ± 2° N (right) boxes. Maximum and minimum flux values are labeled in blue on the right y-axis of the 0–50 m depth slab. Annual mean southwestward freshwater volume flux is shown as a dotted gray line and labeled in gray on the right y-axis. The seasonal trend of each depth slab can be compared to the 0–300 m sum seasonal trend, shown on the bottom.

entire width the BoB (roughly 81–92°E), the freshwater gradients previously calculated would correspond to a southwestward freshwater volume flux of about 0.14 Sv in the zonally extended 15 ± 2° box and 0.18 Sv in the zonally extended 10 ± 2° box. These flux values surpass the 0.094 Sv river discharge into the northern BoB, even without accounting for boundary current export of freshwater nor the excess precipitation over evaporation over the BoB. Our study has demonstrated that eddy diffusion can account for almost all of the export of the river inflow into the BoB, with the western boundary current accounting for the remainder.

Significant seasonality is apparent in the horizontal eddy freshwater fluxes (Figs. 2 and 3). Fluxes in the 15 ± 2° N box were lowest in the summer and increased to a maximum in the winter. Gonaduwage et al. (2019) similarly found the peak of eddy-induced salt transport to be the winter. By contrast, peak freshwater flux in the 10 ± 2° N box occurred in summer. The lag is likely due to the time required for the river water injected into the northern rim of the BoB to reach the more southern latitudes, as well as the direct summer input of FW via P-E over the expanse of the BoB. In both the northern and southern study boxes, the seasonal trend of the 0–50 m depth slab very closely matches the overall seasonal trend when the depth slabs are summed from 0 to 300 m (Fig. 3), supporting the notion that the uppermost layers drive southwestward freshwater flux along the central axis of the BoB.

While significant seasonal variance is evident in these results (Figs. 2 and 3), seasonal averages ignore important intraseasonal timescales. Paul et al. (2021) highlighted how mesoscale eddies in the BoB trap freshwater, through the analysis of a single BoB mesoscale eddy in 2015. Their paper highlighted the rapid changes in salinity gradients that can be brought about by mesoscale eddies. Using *in situ* and satellite data, Paul et al. (2021) demonstrated that horizontal sea surface salinity gradients halved over the course of 6 weeks (6 PSU/200 km on 10/31 down to 3 PSU/200 km on 12/15). Their study concluded that "in contrast to seasonal timescales where vertical diffusion is important, we have shown that freshwater becomes significantly saltier within a month's timescale, apparently by horizontal mixing when trapped in a mesoscale eddy." While seasonal analysis provides useful insight into the variance of freshwater inflow and its dynamics within the BoB, there are complex freshwater transport mechanisms operating at shorter timescales.

4. Summary

Even using 1000 m^2/s, the lower number of the K_h range (Rudnickas et al., 2019), eddy diffusion in the top 300 m can account for almost all of the export of 0.094 Sv of river water from the BoB's northern rim within a 4 degrees of longitude band of the central meridional axis of the BoB (see Fig. 1). The remainder would then be exported within the western and eastern boundary currents. The K_h upper estimate of 5000 m^2/s (Abernathey and Marshall, 2013; Busecke and Abernathey, 2019) exceeds the river water input, even if P-E is included. The message is clear: ocean eddies provide a major pathway for the export of the BoB's excess freshwater. The seasonality of these fluxes varies between the northern and southern bay. In the northern BoB, maximum freshwater flux occurred in winter, a response to the accumulated freshwater content at the end of the wet summer monsoon season. Lower latitudes experienced a delayed peak in freshwater flux during summer.

Future research is needed to quantify the complexities of the horizontal mixing coefficients, particularly as they vary horizontally, vertically, and temporally. In this study, we utilized a uniform horizontal mixing coefficient of $K_h = 1000$ m^2/s, which falls to the lower end of estimates, acting on the lateral salinity gradients observed by Argo profilers. As explained by Zhou et al. (2017), assigning "K_h to a constant value is a zeroth-order approximation, where vertical variations are ignored." At greater depths, water is less prone to wind-induced eddy mixing. Furthermore, Zhou et al. highlighted how the "fundamental issue in such an approach is that it fails to account for the temporal variations of K_h." Additionally, the spatial patterns of the seasonal trends of the freshwater (salinity) warrants further investigation. The southern BoB experiences a delayed peak in freshwater flux being more remote from freshwater entering at the northern BoB. Varying local wind patterns might also play a role in these latitudinal differences. Finally, to better understand the mechanisms governing eddy freshwater transport, analysis on sub-seasonal timescales and sub-mesoscale is necessary, as well as vertical advection and mixing across the barrier layer.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Data source US Department of Commerce, and NOAA National Centers for Environmental Information. "World Ocean Database Select." *National Centers for Environmental Information*, 30 Jan. 2019, www.nodc.noaa.gov/OC5/SELECT/dbsearch/dbsearch.html. The research was funded by Office of Naval Research, Award N00014-20-1-2639.

References

Abernathey, R.P., Marshall, J., 2013. Global surface eddy diffusivities derived from satellite altimetry. J. Geophys. Res. Oceans 118, 901–916. https://doi.org/10.1002/jgrc.20066.

Busecke, J.M., Abernathey, R.P., 2019. Ocean mesoscale mixing linked to climate variability. Sci. Adv. 5 eaav501.

Dandapat, S., Gnanaseelan, C., Parekh, A., 2020. Impact of excess and deficit river runoff on Bay of Bengal upper ocean characteristics using an ocean general circulation model. Deep Sea Res. Part II Top. Stud. Oceanogr. 172 https://doi.org/10.1016/j.dsr2.2019.104714.

Durack, P.J., Wijffels, S.E., 2010. Fifty-year trends in global ocean salinities and their relationship to broad-scale warming. J. Clim. 23, 362. https://doi.org/10.1175/2010JCLI3377.1, 4,342–4.

Gonaduwage, L.P., Chen, G., McPhaden, M.J., Priyadarshana, T., Huang, K., Wang, D., 2019. Meridional and zonal eddy-induced heat and salt transport in the bay of bengal and their seasonal modulation. J. Geophys. Res.: Oceans 124, 8079–8101. https://doi.org/10.1029/2019JC015124.

Gordon, A.L., Shroyer, Emily L., Fernando, Harindra J.S., Amit, Tandon, Mathur, Manikandan, Sinhalage Udaya Priyantha Jinadasa, 2019. Introduction to "atmosphere-ocean dynamics of bay of bengal" volume 1. Deep Sea Res. Part II Top. Stud. Oceanogr. 168, 1–2. https://doi.org/10.1016/j.dsr2.2019.104670.

Gordon, A.L., Shroyer, Emily L., Fernando, Harindra J.S., Amit, Tandon, Mathur, Manikandan, Sinhalage Udaya Priyantha Jinadasa, 2020. Introduction to "Atmosphere-Ocean dynamics of bay of bengal. volume 2 Deep Sea Res. Part II Top. Stud. Oceanogr. 172, 1–2. https://doi.org/10.1016/j.dsr2.2019.104724.

Gordon, A.L., Shroyer, E.L., Mahadevan, A., Sengupta, D., Freilich, M., 2016. Bay of Bengal: 2013 northeast monsoon upper-ocean circulation. Oceanography 29 (2), 82–91. https://doi.org/10.5670/oceanog.2016.41.

Hormann, V., Centurioni, Luca R., Gordon, Arnold L., 2019. Freshwater export pathways from the bay of bengal. Deep Sea Res. Part II Top. Stud. Oceanogr. 168 https://doi.org/10.1016/j.dsr2.2019.104645.

Kantha, L., Weller, Robert A., Farrar, J. Thomas, Rahaman, Hasibur, Jampana, Venkata, 2019. A note on modeling mixing in the upper layers of the Bay of Bengal: importance of water type, water column structure and precipitation. Deep Sea Res. Part II Top. Stud. Oceanogr. 168 https://doi.org/10.1016/j.dsr2.2019.104643.

Mathur, M., Jimreeves David, M., Sharma, Rashmi, Agarwal, Neeraj, 2019. Thermal fronts and attracting Lagrangian coherent structures in the north bay of bengal during december 2015–march 2016, Deep Sea Res. Part II Top. Stud. Oceanogr. https://doi.org/10.1016/j.dsr2.2019.104636, 168.

Paul, N., Sukhatme, J., Sengupta, D., Gayen, B., 2021. Eddy induced trapping and homogenization of freshwater in the Bay of Bengal. J. Geophys. Res.: Oceans 126, e2021JC017180. https://doi.org/10.1029/2021JC017180.

Pant, V., Girishkumar, M.S., Udaya Bhaskar, T.V.S., Ravichandran, M., Papa, F., Thangaprakash, V.P., 2015. Observed interannual variability of nearsurface salinity in the Bay of Bengal. J. Geophys. Res. 120, 329. https://doi.org/10.1002/2014JC010340, 3,315–3.

Rudnickas Jr., D., Palter, J., Hebert, D., Rossby, H.T., 2019. Isopycnal mixing in the North Atlantic oxygen minimum zone revealed by RAFOS floats. J. Geophys. Res.: Oceans 124. https://doi.org/10.1029/2019JC015148.

Sengupta, D., Bharath Raj, G.N., Shenoi, S.S.C., 2006. Surface freshwater from bay of bengal runoff and Indonesian Throughflow in the tropical Indian ocean. Geophys. Res. Lett. 33, L22609. https://doi.org/10.1029/2006GL027573.

Wilson, E.A., Riser, S.C., 2016. An assessment of the seasonal salinity budget for the upper bay of bengal. J. Phys. Oceanogr. 46, 1361–1376. https://doi.org/10.1175/JPO-D-15-0147.1.

Zhou, B., Zhu, K., Xue, M., 2017. A physically based horizontal subgrid-scale turbulent mixing parameterization for the convective boundary layer. J. Atmos. Sci. 74 (8), 2657–2674. https://doi.org/10.1175/JAS-D-16-0324.1.