Eddy induced trapping and homogenization of freshwater in the Bay of Bengal

Nihar Paul[1], Jai Sukhatme[2], DEBASIS SENGUPTA[2], and Bishakhdatta Gayen[3]

[1]Centre for Atmospheric and Oceanic Sciences, Indian Institute of Science, Bangalore, India
[2]Centre for Atmospheric and Oceanic Sciences, Indian Institute of Science, Bangalore, India.
[3]Mechanical Engineering Department, University of Melbourne, Australia.

November 26, 2022

Abstract

Freshwater from rivers influences Indian summer monsoon rainfall and tropical cyclones by stratifying the upper layer and warming the subsurface ocean in the Bay of Bengal. Here, we use {\it in situ} and satellite data with reanalysis to showcase how river water experiences a significant increase in salinity on sub-seasonal timescales. This involves the trapping and homogenization of freshwater by a cyclonic eddy in the Bay. Using a specific example from 2015, river water is shown to enter an eddy along its attracting manifolds within a period of two weeks. This leads to the formation of a highly stratified subsurface layer within the eddy. When freshest, the eddy has the largest sea-level anomaly, spins fastest, and supports strong lateral gradients in salinity. Subsequently, observations reveal a progressive increase in salinity inside the eddy within a month. In particular, salty water spirals in, and freshwater is pulled out across the eddy boundary. Lagrangian experiments elucidate this process, whereby horizontal chaotic mixing provides a mechanism for the rapid increase in surface salinity. A salinity budget also suggests that horizontal advection explains much of the change in mixed layer salinity. Further, the adjustment of this freshwater eddy triggers submesoscale dynamics which appear to be an integral part of the process of salinity homogenization. This pathway is distinct from vertical diffusive mixing and is likely to be important for the evolution of salinity in the Bay of Bengal.

Eddy induced trapping and homogenization of freshwater in the Bay of Bengal

Nihar Paul

Centre for Atmospheric and Oceanic Sciences, Indian Institute of Science, Bangalore, India.

nihar@iisc.ac.in

Abstract

Using *in situ* and satellite data with reanalysis to showcase how river water experiences a significant increase in salinity on subseasonal timescales in the Bay of Bengal. This involves the trapping and homogenization of freshwater by a cyclonic eddy in the Bay. In particular, salty water spirals in, and freshwater is pulled out across the eddy boundary. Lagrangian experiments elucidate this process, whereby horizontal chaotic mixing provides a mechanism for the rapid increase in surface salinity. A salinity budget also suggests that horizontal advection explains much of the change in mixed layer salinity. Further, the adjustment of this freshwater eddy triggers submesoscale dynamics which appear to be an integral part of the process of salinity homogenization.

Problem Statement

The Bay of Bengal is the freshest marginal sea in the tropical oceans with the lowest sea-surface salinity values (24-32 psu) during September-November due to post-monsoon river discharge. Eddies play a crucial role in the stirring of passive fields [3], in the transport of salt and heat, enhancing biological productivity and chlorophyll concentration, and is well-represented at the mesoscale, and the issue is whether unbalanced submesoscale dynamics are implicated in the evolution of the salinity field. Here, we address these issues by presenting freshwater evolution in a specific long-lived cyclonic eddy in the BoB during the post-monsoon period October-November of 2015.

The Eddy and the Entry of Freshwater

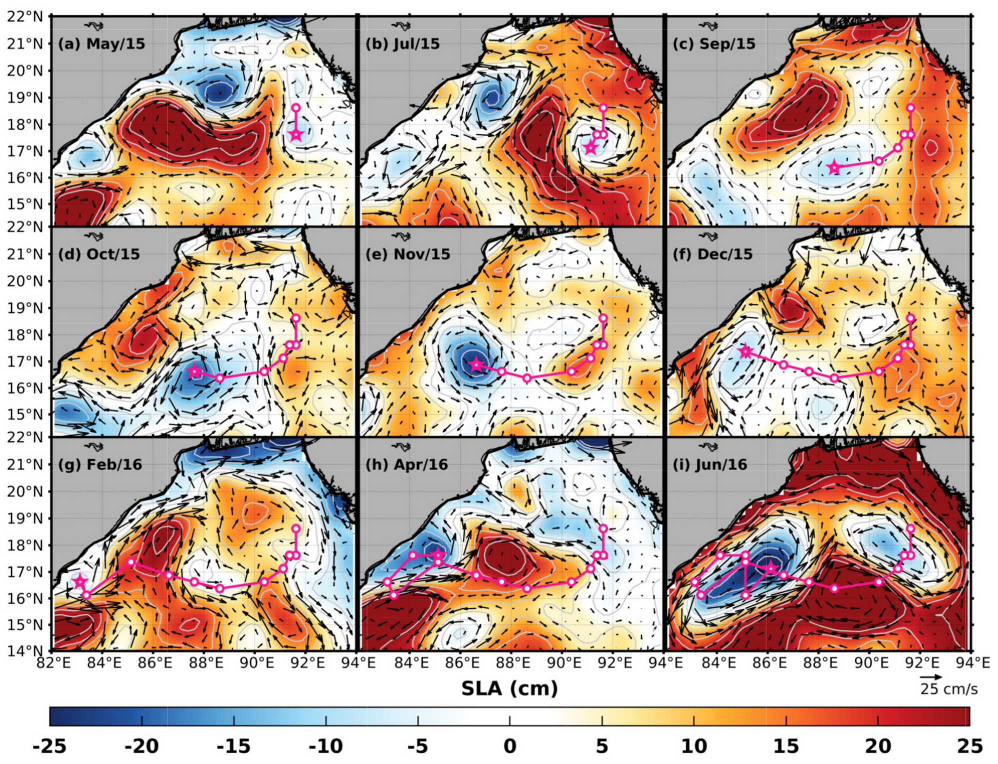

Figure 1: (a)-(i) Mean sea level anomaly (SLA) contours with geostrophic velocity quivers overlaid on 1st day of the month for May, July, September, October, November, December 2015, and February, April, June 2016. The track of the cyclonic eddy is shown with "star" indicating the SLA minimum of the eddy (centre) and "dot" denoting the position in preceding months from its origin.

Backward-Finite Time Lyapunov Exponents (b-FTLEs)

$$\frac{d\phi}{dt} = \frac{u(\phi,\lambda,t)}{R\cos(\lambda)},\ \frac{d\lambda}{dt} = \frac{v(\phi,\lambda,t)}{R}. \quad (1)$$

Here, ϕ, λ, u and v are the latitude, longitude, zonal and meridional velocity, respectively. R is the radius of the earth. The numerical method employed is the 4th order Runge-Kutta scheme for advection. We then compute the right Cauchy-Green Lagrange tensor $C^t_{t_0}$ associated with the flow map $F^t_{t_0}(\mathbf{x_0})$, which is defined as,

$$C^t_{t_0}(\mathbf{x_0}) = (\nabla F^t_{t_0}(\mathbf{x_0}))^T \nabla F^t_{t_0}(\mathbf{x_0}) = \lambda_i \xi_i,\ 0 < \lambda_1 \le \lambda_2, i = 1, 2.. \quad (2)$$

$$\lambda_\tau(\mathbf{x_0}) = -\frac{1}{|t-t_0|}\log\left(\sqrt{\lambda_{\max}[C^t_{t_0}(\mathbf{x_0})]}\right). \quad (3)$$

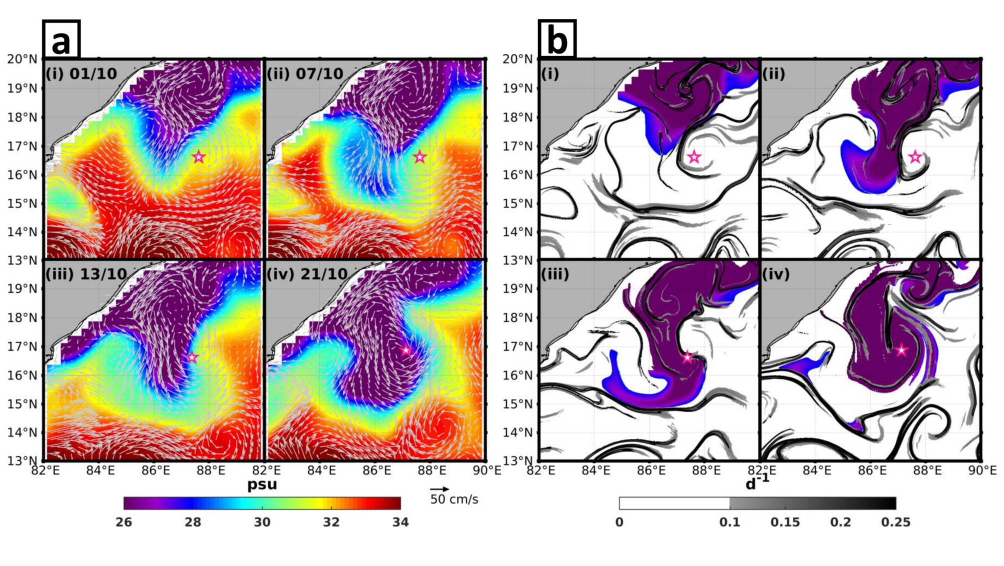

Figure 2: (a) Sea Surface Salinity (SSS) with BoBcat current quivers on 01/10, 07/10, 13/10, 21/10, respectively. (b) Advected passive scalar maps with tracer initialized to SSS< 28 psu on 01/10 for days as in (a). In addition, attracting Lagrangian Coherent Structures (a-LCS) or b-FTLE computed by integrating backward for 20 days are shown on the top of the tracer field. Only values above 0.1 day^{-1} (stronger stable manifolds) are shown.

Homogenization of Freshwater Within the Eddy

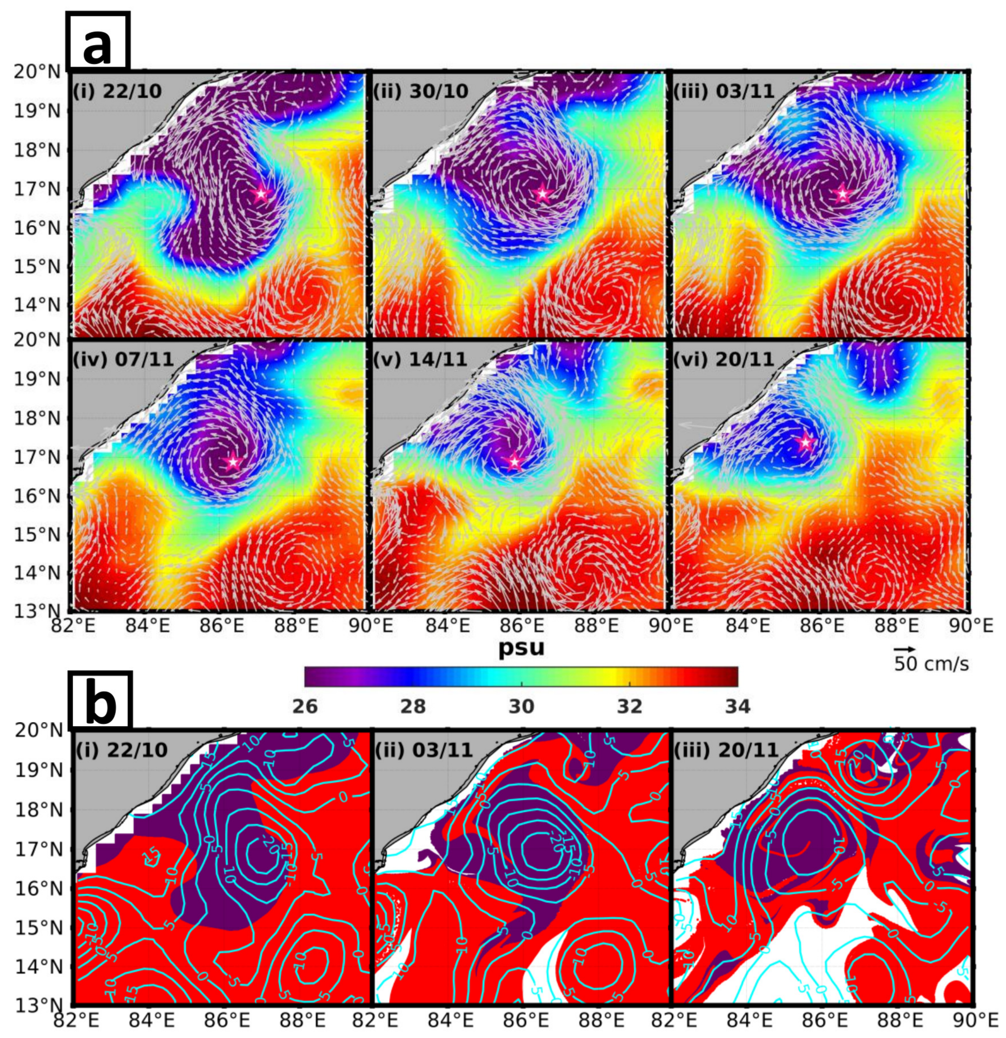

Figure 3: (a)(i)-(vi) shows Sea Surface Salinity (SSS) with BoBcat current quivers on 22/10, 30/10, 03/11, 07/11, 14/11, 20/11, respectively. Star marks the center of the eddy. (b) Tracers with SSS ≤ 28 (>28) psu initialized on 22/10/2015 are marked in violet (red) colors. These are advected forward in time by BoBcat currents and shown for 22/10, 03/11, and 20/11 of 2015 with contours of SLA (contours in color 'cyan') overlaid on the top.

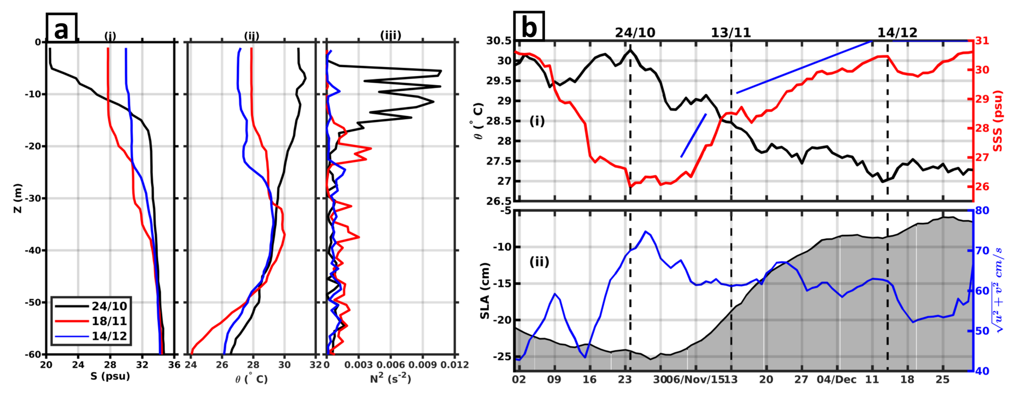

Figure 4: (a)(i), (ii) and (iii) show S (psu), θ ($^\circ$ C) and N^2 (s^{-2}) with depth for upper 60 m on 24/10, 18/11 and 14/12 from Argo AOML-5904302, respectively. (b) Daily time series of (i) mean θ, SSS (with straight lines to guide the eye), and (ii) maximum current speed and minima of SLA over a circle of diameter 300 km around the eddy center from 01/10/2015 to 31/12/2015.

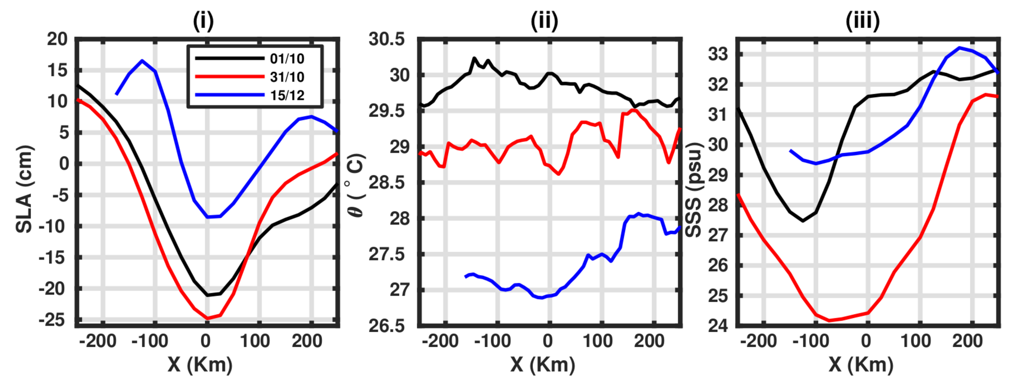

Figure 5: (i), (ii) and (iii) show SLA, θ and SSS cross-sections through the center of the eddy (defined by the minima of SLA) on 01/10, 31/10, and 15/12 representing pre-freshening, freshening, and post-freshening days, respectively.

Mixed Layer Salinity Budget During Trapping Event From Ocean Reanalysis Data

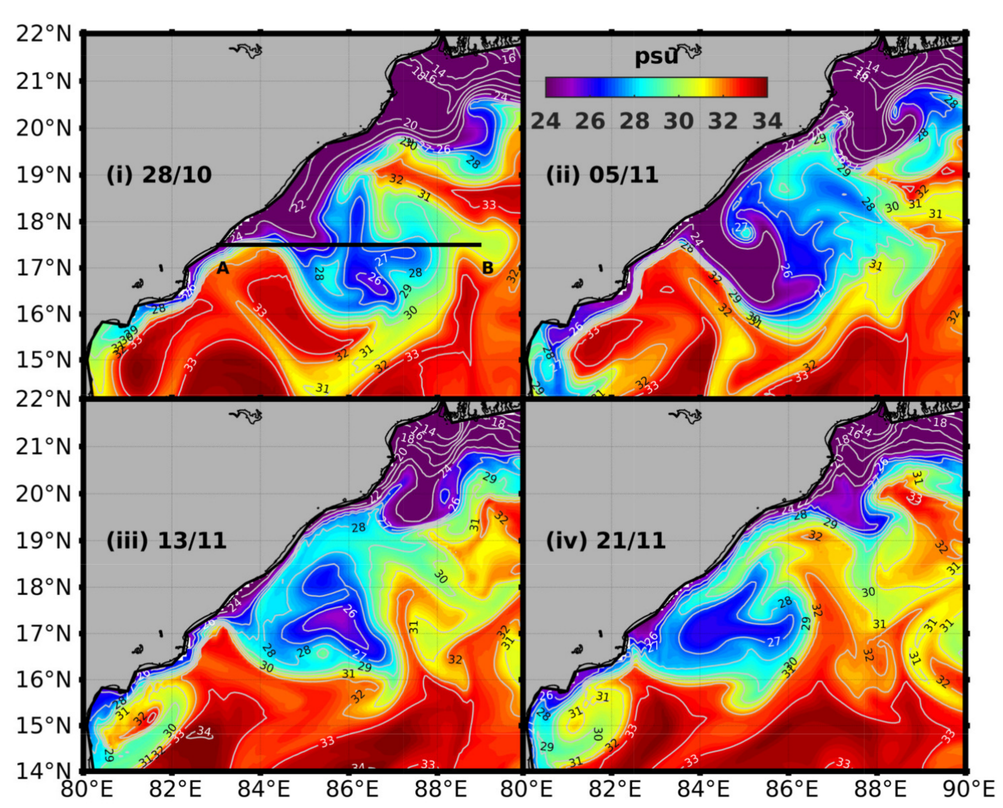

Figure 6: (i)-(iv) SSS (psu) (with contours) at 0.5 m from NEMO reanalysis from 28/10 to 21/11 (freshwater trapping days) with an 8-day interval. AB denotes the cross-section of the eddy from 83°E-89°E shown in subpanel (i).

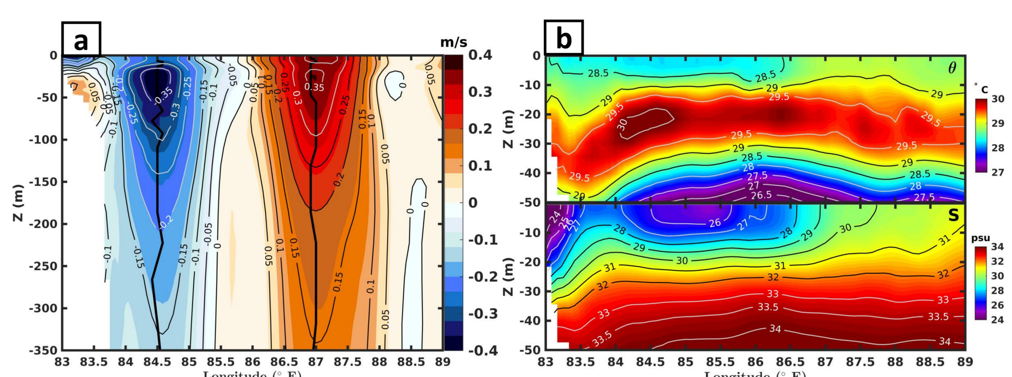

Figure 7: (a) Mean meridional velocity profile along the longitudinal section AB of the eddy up to a depth of 350 m shown in Figure 7(i) averaged over freshwater trapping days (28/10–21/11) from NEMO reanalysis data. The vertical black lines indicate the contours of maximum speed on each side of the lobes of the eddy. (b) Variation of mean potential temperature (θ) (upper panel) and mean salinity (lower panel) within upper 50 m of the eddy averaged for the same section and time period as in (a).

$$\frac{\partial S}{\partial t} = -\left(u\frac{\partial S}{\partial x} + v\frac{\partial S}{\partial y}\right) + \frac{S_0(E-P)}{h} + \epsilon. \quad (4)$$

Here, S is the mixed layer salinity (based on density-based criteria, i.e., $\delta\rho \approx 0.125$ kgm^{-3} from the depth $z = -0.41$ m), u and v are the zonal and meridional velocities in the mixed-layer. S_0 is the salinity at a depth of -0.41 m from the ocean surface. E and P are the evaporation and precipitation rates. h is the mixed layer depth and ϵ is the contribution of vertical advection, entrainment as well as mixing.

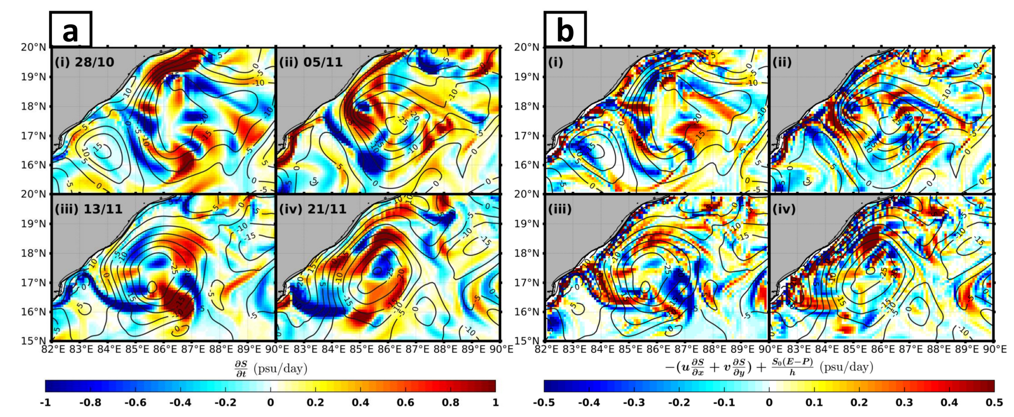

Figure 8: (a) $\partial S/\partial t$ (b) $-[u\partial S/\partial x + v\partial S/\partial y] + [S_0(E-P)/h]$. Mixed layer salinity budget as per Equation 4 from NEMO reanalysis for the freshwater trapping event on 28/10, 05/11, 13/11 and 21/11, respectively.

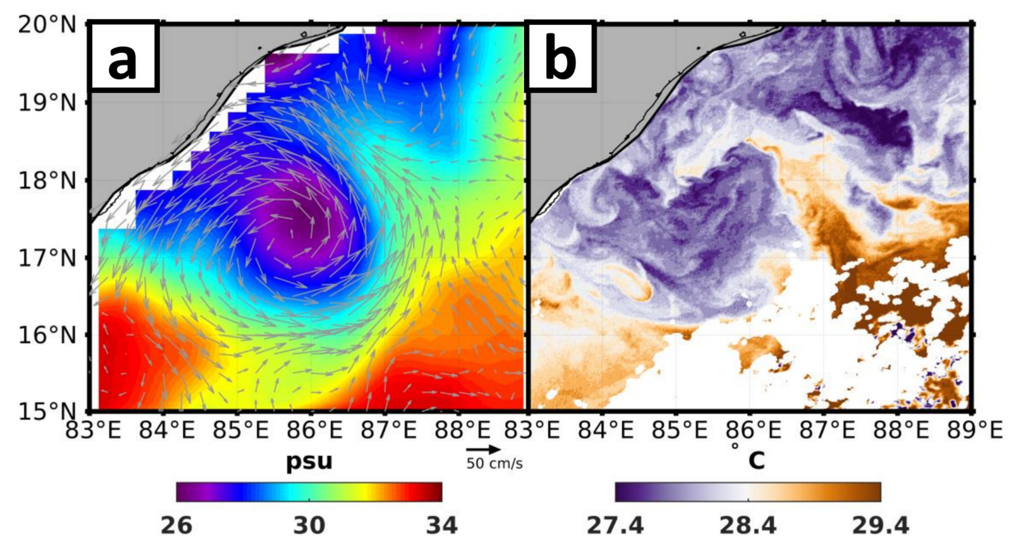

Figure 9: (a) SSS with BoBcat quiver (b) AVHRR-METOP2 SST on 13/11/2015, respectively.

Conclusion and Discussion

- Freshwater from rivers is trapped in a long-lived cyclonic eddy in the north Bay of Bengal during the postmonsoon season.
- Observations show a substantial increase in sea surface salinity of trapped freshwater on the timescale of a month.
- Lagrangian tracer advection elucidates horizontal mixing across the eddy boundary.
- The adjustment of the freshwater eddy triggers mesoscale and submesoscale dynamics across the edges [4, 2].
- The "wavy" disturbances generated on the eddy boundary can perhaps even induce ageostrophic secondary circulations via baroclinic and barotropic instabilities [1].

Forthcoming Research

Simulation and understanding the process of homogenization of freshwater in the mesoscale eddy via Regional Ocean Modelling System (ROMS) in the Bay of Bengal (To be submitted).

References

[1] RW Griffiths and PF Linden. The stability of vortices in a rotating, stratified fluid. *Journal of Fluid Mechanics*, 105:283–316, 1981.

[2] James C McWilliams. Submesoscale currents in the ocean. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 472(2189):20160117, 2016.

[3] Nihar Paul and Jai Sukhatme. Seasonality of surface stirring by geostrophic flows in the Bay of Bengal. *Deep Sea Research Part II: Topical Studies in Oceanography*, 172:104684, 2020.

[4] Nihar Paul, Jai Sukhatme, Debasis Sengupta, and Bishakhdatta Gayen. Eddy induced trapping and homogenization of freshwater in the Bay of Bengal. *Journal of Geophysical Research: Oceans*, page e2021JC017180, 2021.

Supporting Information for "Eddy induced trapping and homogenization of freshwater in the Bay of Bengal"

Nihar Paul[1], Jai Sukhatme[1,2], Debasis Sengupta[1,2] and Bishakhdatta Gayen[1,3]

[1]Centre for Atmospheric and Oceanic Sciences, Indian Institute of Science, Bangalore - 560012, India.

[2]Divecha Centre for Climate Change, Indian Institute of Science, Bangalore - 560012, India.

[3]Mechanical Engineering Department, University of Melbourne, Australia.

Contents of this file

1. Figures S1 to S9

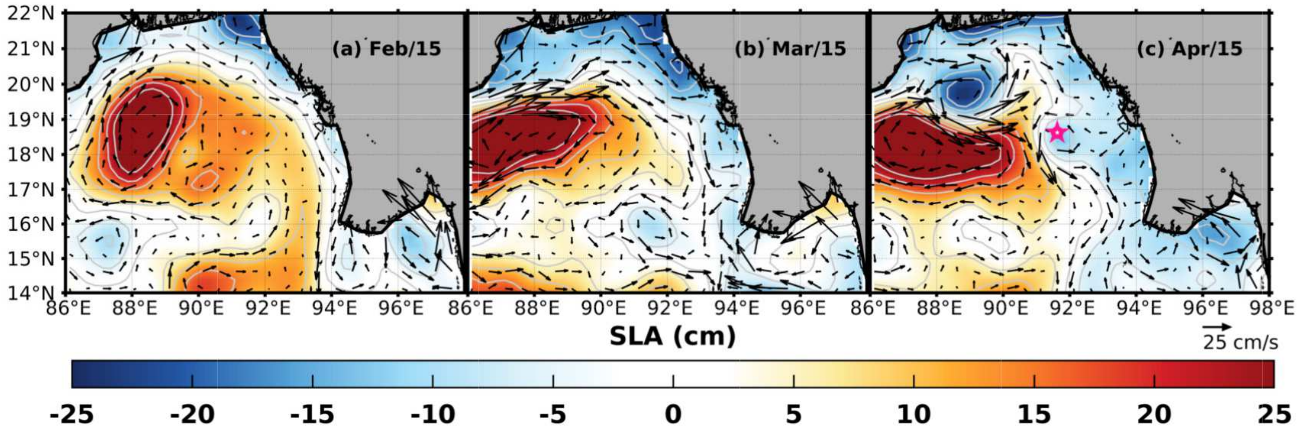

Figure S1. Sea level anomaly (SLA) contours with geostrophic quiver on 1st day of month for February (a), March (b) and April (c), 2015. The contours of SLA are in the range of -25 cm to 25 cm with an interval of 5 cm. The centre of the eddy (defined by minimum of SLA within the periphery of the eddy) is marked by the symbol “star” in (c).

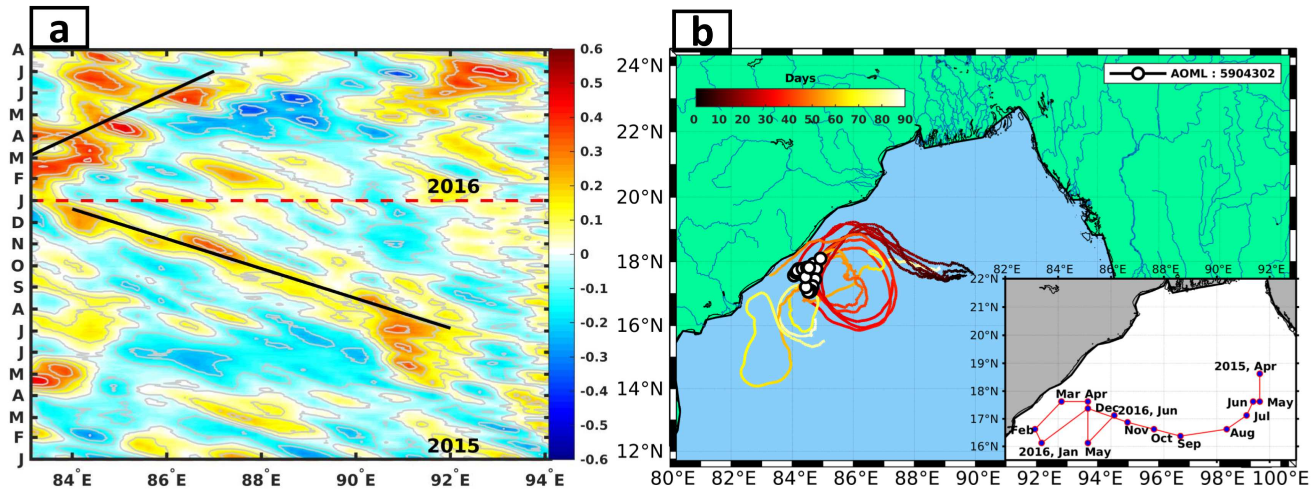

Figure S2. (a) Hovmöller diagram of Rossby number (ξ/f) computed from geostrophic currents averaged over 16.625°N-17.625°N shown for the year 2015-2016. (b) Track of Argo float (AOML-5904302) and trajectories of Surface Velocity Program (SVP) "drifters" (drouged at 15 m depth) within the eddy from 01/10 to 31/12 of 2015 and entire track of eddy in inset from the first day of April 2015 to June 2016 in an interval of a month.

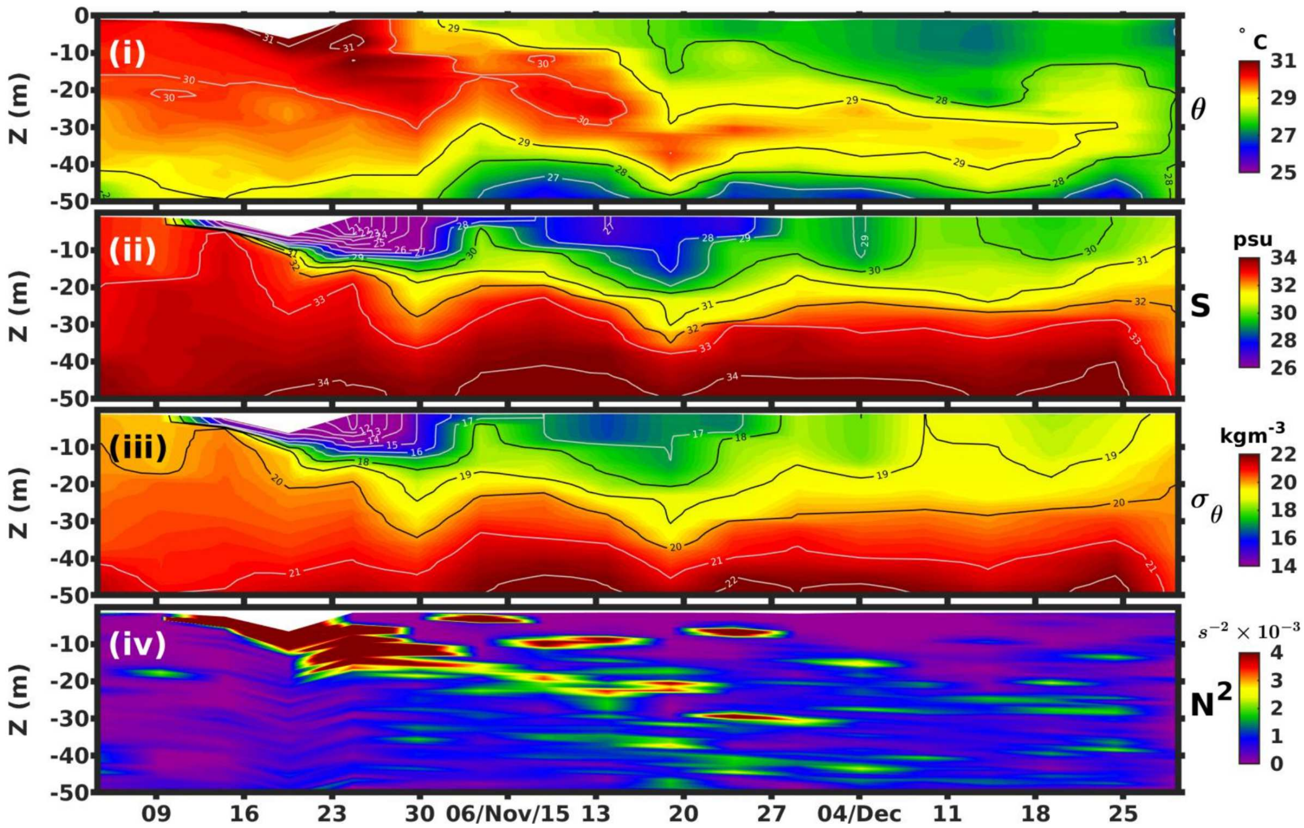

Figure S3. (i) Potential temperature (θ), (ii) salinity (S), (iii) potential density (σ_θ) and (iv) squared Brunt-väisälä frequency (N^2), respectively with depth using Argo AOML-5904302 data for the upper 50 m from October to December, 2015.

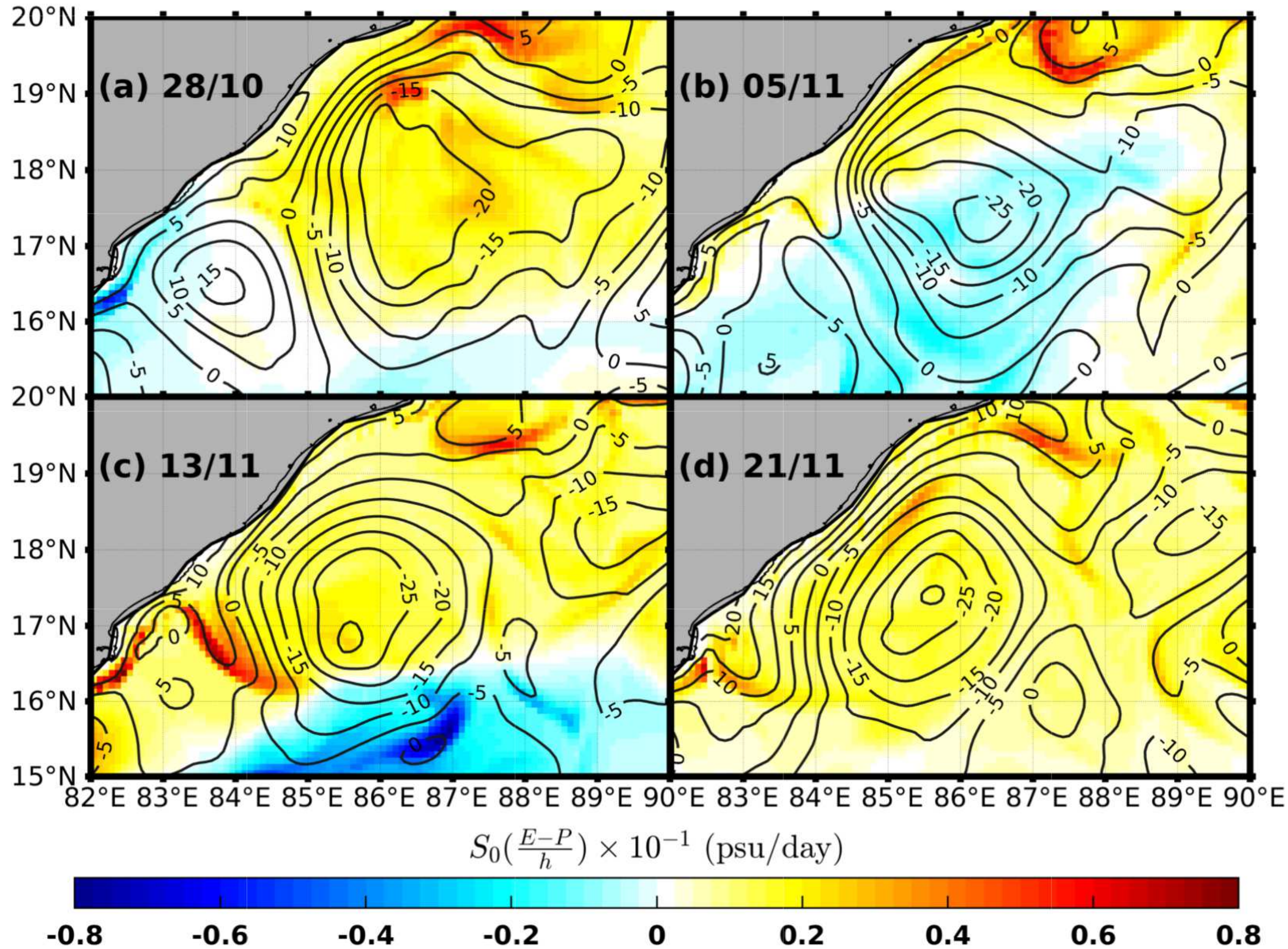

Figure S4. Evolution of contribution to mixed layer salinity change by $E - P$ (Evaporation- Precipitation rates).

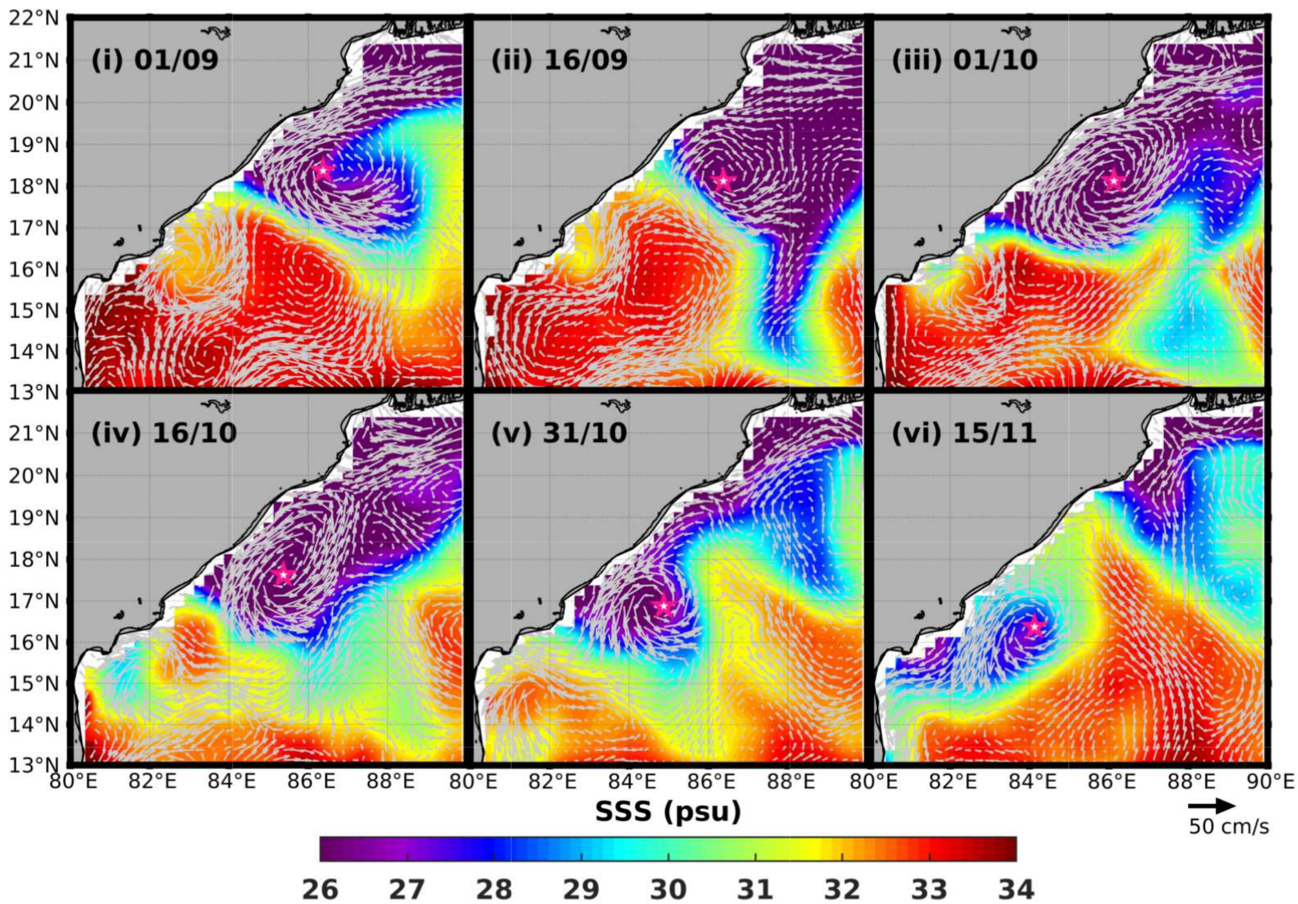

Figure S5. (i)-(vi) SSS with geostrophic current quivers from 1st September 2017 to 15th November 2017 in intervals of 15 days. “star” indicates the eddy’s SLA minimum (centre).

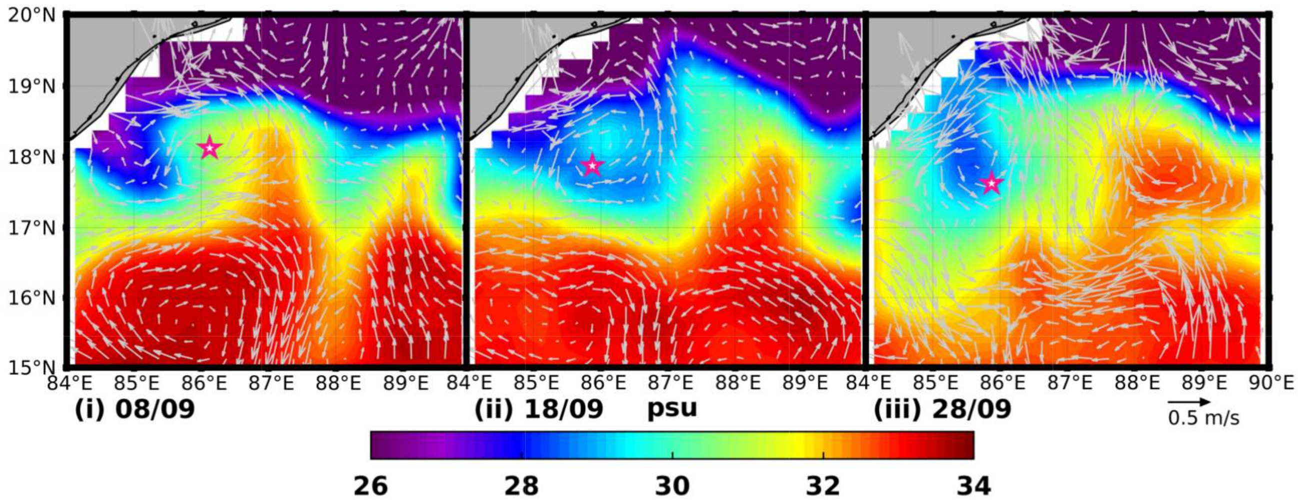

Figure S6. (i)-(iii) SSS with geostrophic current quivers from 1st September 2020 to 15th November 2020 in intervals of 15 days. "star" indicates the eddy's SLA minimum (centre). The entry of freshwater takes place within 10 days as can be seen by comparing (i) and (ii).

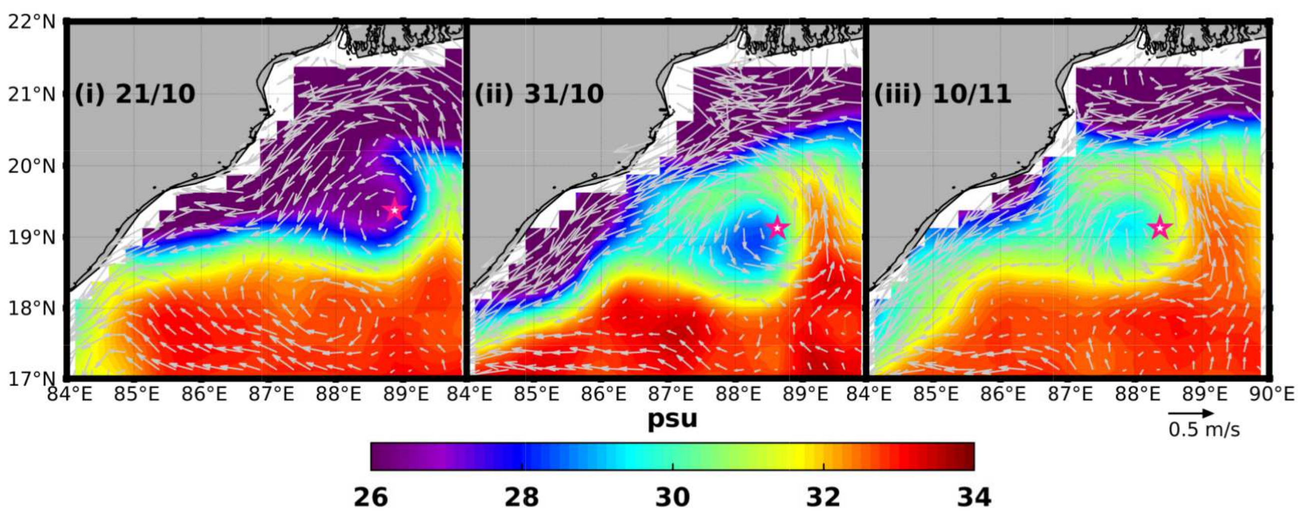

Figure S7. (i)-(iii) SSS with geostrophic current quivers from 8th September 2020 to 28th September 2020 in intervals of 10 days. "star" indicates the eddy's SLA minimum (centre).

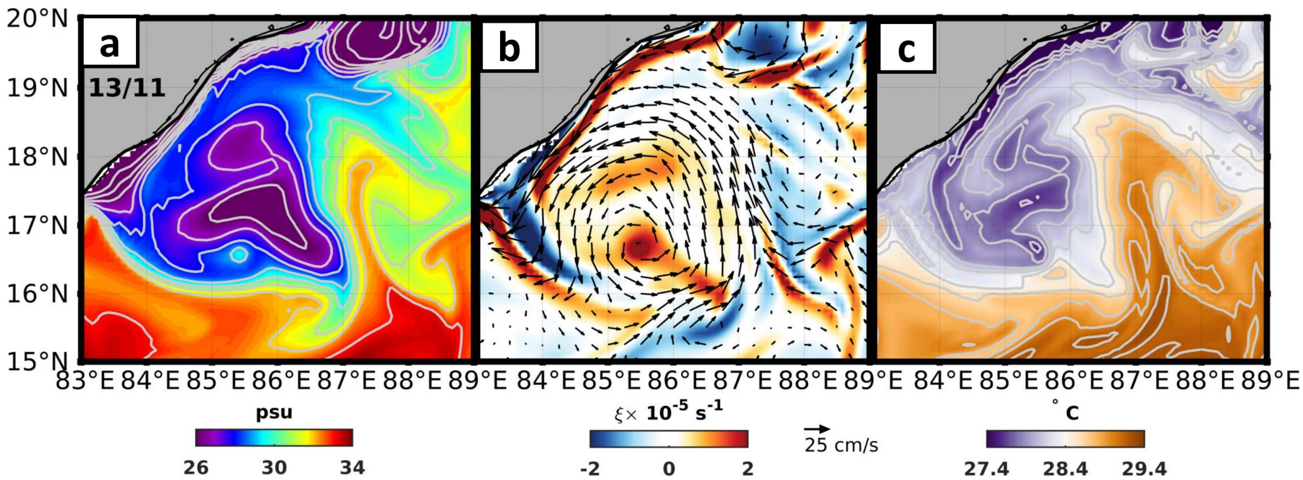

Figure S8. (a) SSS with contours with an interval of 1 psu (b) vorticity with surface current quivers (c) SST with contours with an interval of 0.2°C at 0.5 m depth on 13/11/2015 from NEMO reanalysis data.

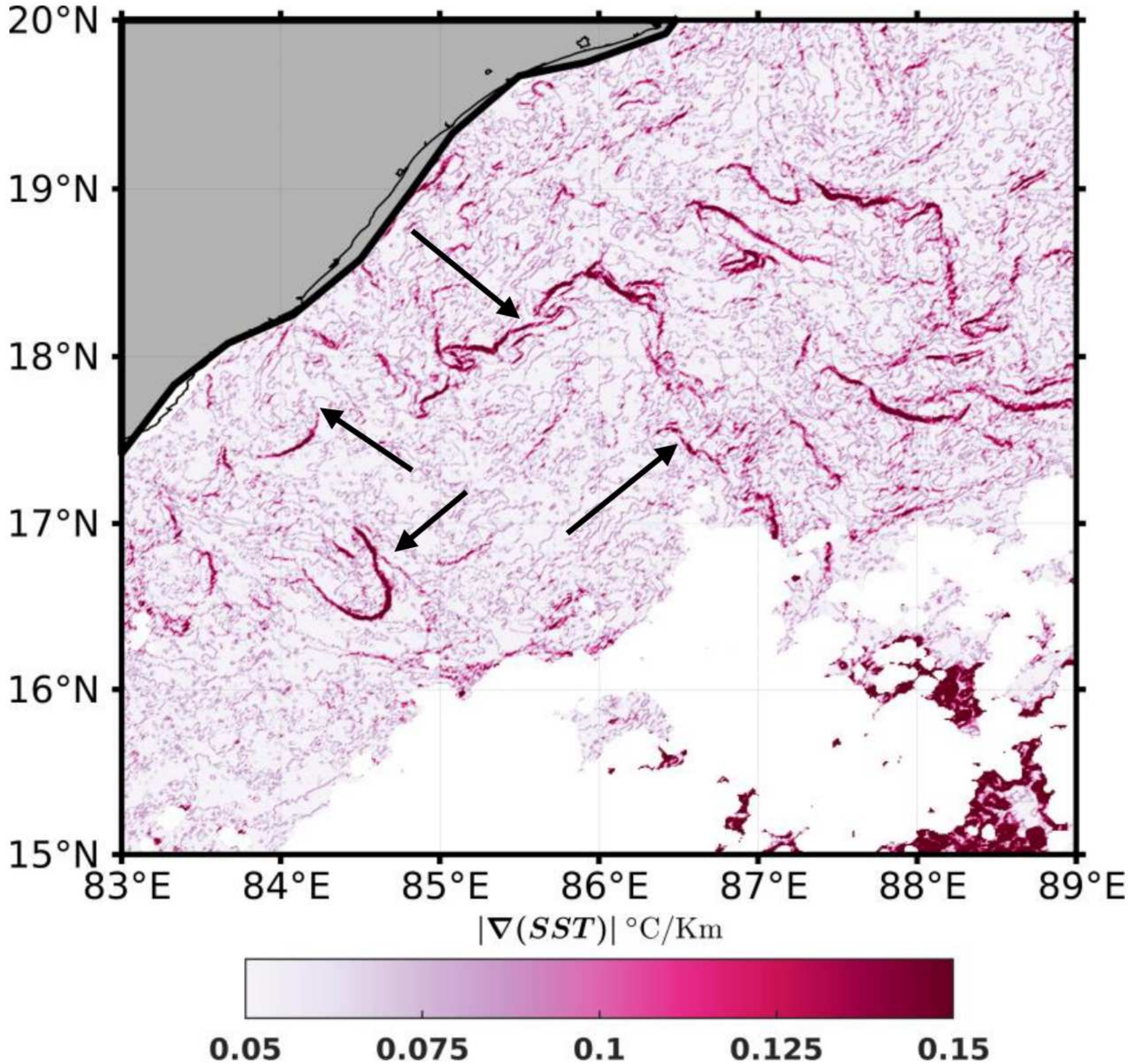

Figure S9. The magnitude of the gradient of METOP2-AVHRR SST (° C/km) on 13/11/2015. The four arrows point to thermal fronts ($|\nabla SST| > 0.1$°C/Km) around the periphery of the eddy.

Supporting Information for "Eddy induced trapping and homogenization of freshwater in the Bay of Bengal"

Nihar Paul[1], Jai Sukhatme[1,2], Debasis Sengupta[1,2]and Bishakhdatta Gayen[1,3]

[1]Centre for Atmospheric and Oceanic Sciences, Indian Institute of Science, Bangalore - 560012, India.

[2]Divecha Centre for Climate Change, Indian Institute of Science, Bangalore - 560012, India.

[3]Mechanical Engineering Department, University of Melbourne, Australia.

Contents of this file

1. Text S1

Text S1. Attracting Lagrangian Coherent Structures (a-LCSs or Backward Finite Time Lyapunov Exponents (b-FTLEs): The mixing of freshwater is characterized from a Lagrangian perspective via so-called backward Finite Time Lyapunov Exponents (b-FTLEs) (Wiggins, 2005). These are ridges that represent attracting Lagrangian coherent structures in a flow (Haller, 2002). To compute the b-FTLEs, we first advect fluid parcel by integrating the following equations backward in time,

$$\frac{d\phi}{dt} = \frac{u(\phi, \lambda, t)}{R\cos(\lambda)}, \frac{d\lambda}{dt} = \frac{v(\phi, \lambda, t)}{R}. \tag{1}$$

Here, ϕ, λ, u and v are the latitude, longitude, zonal and meridional velocity, respectively. R is the radius of the earth. The time span is $t = t_0$ to $t = t_o - \tau$ and the numerical method employed is the 4th order Runge-Kutta scheme. The velocity data (u, v) is given on a fixed grid and the flow has been interpolated by a bilinear interpolation scheme. We then compute the right Cauchy-Green Lagrange tensor $C_{t_0}^{t}$ associated with the flow map $F_{t_0}^{t}(\mathbf{x_0})$, which is defined as,

$$C_{t_0}^{t}(\boldsymbol{x_0}) = \left(\nabla F_{t_0}^{t}(\boldsymbol{x_0})\right)^{T} \nabla F_{t_0}^{t}(\boldsymbol{x_0}). \tag{2}$$

$F_{t_0}^{t}(\boldsymbol{x_0})$ denotes the position of a parcel at time t backward in time, advected by the flow from an initial time and position $(t_0, \boldsymbol{x_0})$. $C_{t_0}^{t}(\boldsymbol{x_0})$ is symmetric and positive definite, its eigenvalues ($\lambda' s$) and eigenvectors ($\xi' s$) can be written as,

$$C_{t_0}^{t}(\boldsymbol{x_0}) = \lambda_i \xi_i,\ 0 < \lambda_1 \leq \lambda_2, i = 1, 2. \tag{3}$$

The gradient of the flow map $\nabla F_{t_0}^{t}(\boldsymbol{x_0})$ is computed using an auxiliary grid about the reference point (Onu et al., 2015), and can be written as,

$$\nabla F_{t_0}^{t}(\boldsymbol{x_0}) \approx \begin{pmatrix} \alpha_{11} & \alpha_{12} \\ \alpha_{21} & \alpha_{22} \end{pmatrix}, \tag{4}$$

where,

$$\alpha_{i,j} \equiv \frac{x_i(t; t_0, x_0 + \delta x_j) - x_i(t; t_0, x_0 - \delta x_j)}{2|\delta x_j|}. \tag{5}$$

Finally, the largest b-FTLE (Haller, 2002; Haller & Sapsis, 2011; Mathur et al., 2019) associated with the trajectory $\boldsymbol{x}(t, t_0, \boldsymbol{x_0})$ over the time interval $[t_0, t]$ is defined as,

$$\lambda_\tau(\boldsymbol{x_0}) = -\frac{1}{|t-t_0|}\log\left(\sqrt{\lambda_{\max}[C_{t_0}^t(\boldsymbol{x_0})]}\right). \tag{6}$$

The backward integration time $|\tau| = |t - t_0|$ has been taken as 20 days and computed on a finer grid resolution $0.01° \times 0.01°$.

References

Haller, G. (2002). Lagrangian coherent structures from approximate velocity data. *Physics of Fluids*, *14*(6), 1851–1861. doi: 10.1063/1.1477449

Haller, G., & Sapsis, T. (2011). Lagrangian coherent structures and the smallest finite-time Lyapunov exponent. *Chaos: An Interdisciplinary Journal of Nonlinear Science*, *21*(2), 023115. doi: 10.1063/1.3579597

Mathur, M., David, M. J., Sharma, R., & Agarwal, N. (2019). Thermal fronts and attracting Lagrangian Coherent Structures in the north Bay of Bengal during December 2015–March 2016. *Deep Sea Research Part II: Topical Studies in Oceanography*, *168*, 104636. doi: 10.1016/j.dsr2.2019.104636

Onu, K., Huhn, F., & Haller, G. (2015). LCS Tool: A computational platform for Lagrangian coherent structures. *Journal of Computational Science*, *7*, 26–36. doi: 10.1016/j.jocs.2014.12.002

Wiggins, S. (2005). The dynamical systems approach to Lagrangian transport in oceanic flows. *Annu. Rev. Fluid Mech.*, *37*, 295–328. doi: 10.1146/annurev.fluid.37.061903.175815