Earth and Space Science

RESEARCH LETTER
10.1029/2022EA002327

Key Points:
- $k$-$\epsilon$ vertical mixing scheme gives better results for surface and subsurface ocean circulation compared to K-profile parametrization (KPP)
- SST and MLD biases show significant reduction with $k$-$\epsilon$ mixing scheme
- Improved representation of turbulent buoyancy flux and viscous dissipation is the primary reason for the superior performance of $k$-$\epsilon$ mixing scheme

Supporting Information:
Supporting Information may be found in the online version of this article.

Correspondence to:
S. Balasubramanian,
sridharb@iitb.ac.in

Citation:
Tirodkar, S., Murtugudde, R., Behera, M. R., & Balasubramanian, S. (2022). A comparative study of vertical mixing schemes in modeling the Bay of Bengal dynamics. Earth and Space Science, 9, e2022EA002327. https://doi.org/10.1029/2022EA002327

Received 15 MAR 2022
Accepted 9 JUL 2022

Author Contributions:
Conceptualization: Manasa R. Behera, Sridhar Balasubramanian
Formal analysis: Siddhesh Tirodkar, Raghu Murtugudde, Manasa R. Behera, Sridhar Balasubramanian
Funding acquisition: Manasa R. Behera, Sridhar Balasubramanian
Methodology: Manasa R. Behera, Sridhar Balasubramanian
Software: Siddhesh Tirodkar
Supervision: Manasa R. Behera, Sridhar Balasubramanian
Visualization: Siddhesh Tirodkar

A Comparative Study of Vertical Mixing Schemes in Modeling the Bay of Bengal Dynamics

Siddhesh Tirodkar1, Raghu Murtugudde1,2, Manasa R. Behera1,3, and Sridhar Balasubramanian1,4

1IDP in Climate Studies, IIT Bombay, Mumbai, India, 2ESSIC, University of Maryland, College Park, MD, USA, 3Department of Civil Engineering, IIT Bombay, Mumbai, India, 4Department of Mechanical Engineering, IIT Bombay, Mumbai, India

Abstract The choice of vertical mixing scheme in ocean models plays an important role in modeling the surface and subsurface circulation and the vertical structure. This work performs a comparative study between K-profile parametrization (KPP) and $k$-$\epsilon$ mixing schemes for a regional domain in the Bay of Bengal (BoB) using the Modular Ocean Model version 5 (MOM5). It is observed that sea surface temperature (SST) and the mixed layer depth (MLD) show significant improvement with the $k$-$\epsilon$ mixing scheme. Energetic analysis shows that changes in the viscous dissipation and turbulent buoyancy flux are the primary reason for improvement with $k$-$\epsilon$. The overestimation of viscous dissipation in the KPP scheme is corrected by $k$-$\epsilon$, resulting in a deeper mixed layer closer to observations. The tendency of buoyancy flux to retain stability in the water column also results in a better representation of SST in $k$-$\epsilon$. Overall, we conclude that the $k$-$\epsilon$ mixing scheme works better for the BoB region.

Plain Language Summary A comparison of two different vertical mixing schemes, namely K-profile parametrization (KPP) and $k$-$\epsilon$, is performed in the Bay of Bengal region using the Modular Ocean Model. Basic ocean properties such as the sea surface temperature (SST), sea surface salinity (SSS), and mixed layer depth (MLD) are computed and analyzed using these two mixing schemes. The results show that $k$-$\epsilon$ is a superior mixing scheme for representing the circulation and vertical structure. The characterization of eddy kinetic energy, buoyancy flux, and dissipation rate reveals the physics behind improvements brought about by using the $k$-$\epsilon$ scheme. Our study suggests that $k$-$\epsilon$ is a better model for representing the Bay of Bengal dynamics.

1. Introduction

Seasonal wind reversal (Tomczak & Godfrey, 1994), strong temperature, and salinity gradients (Howden & Murtugudde, 2001; Shetye et al., 1996), and a suite of mesoscale mixing processes make the Bay of Bengal (BoB) an interesting region of study for sea surface temperature (SST) variations, mixed layer depth (MLD), barrier layer formation, vertical structure, and heat budget (Shenoi et al., 2002). In the past, several modeling studies have been performed with various horizontal resolutions and different ocean circulation models (Behara & Vinayachandran, 2016; Murtugudde & Busalacchi, 1999; Srivastava et al., 2018; Zhang & Du, 2012) to understand the effect of mesoscale and submesoscale processes on the BoB dynamics. As expected, wind forcing has the strongest contribution to circulation variability. It is also noted that baroclinic instability plays a vital role in the meander growth and eddy generation near the east coast of India (Kurien et al., 2010). Behara and Vinayachandran (2016) studied the effect of freshwater forcing on the BoB using a numerical model (MOM). Srivastava et al. (2018) investigated air-sea forcing effects on the ocean circulation, buoyancy frequency, and vertical shear for the Arabian Sea and BoB. Mesoscale numerical study of BoB suggests that interaction of anticyclonic eddies with East India coastal current (EICC) weakens the strong surface flow and reverses the weak subsurface flow in the northern part of the western BoB, contributing poleward undercurrents important in EICC dynamics (Francis et al., 2020).

The seasonal analysis of BoB to understand the effect of freshwater forcing, radiation flux, and reversing wind on the BoB upper layer has been reported in various studies (Behara & Vinayachandran, 2016; Schott & McCreary, 2001; Shankar et al., 2002; Srivastava et al., 2018; Thompson et al., 2006). The study regarding the impact of rain and river water forcing suggests that northwestern Bay warms by 1.5°C in the presence
of fresh water during summer due to greater heat absorption within a shallow mixed layer (e.g., Howden & Murtugudde, 2001). The BOBMEX experiment looked into the heat advection in BoB and its influence on MLD (Bhat, 2003; Bhat et al., 2001). Measurements taken during BoBBLE (Vijith et al., 2020; Vinayachandran et al., 2018) highlighted the SST variability and formation of the barrier layer. Salinity effects in the Indian Ocean were modeled by Murtugudde and Busalacchi (1998) and Han et al. (2001). Girishkumar et al. (2013) used RAMA buoy measurements to document temperature inversions and their influence on the mixed layer heat budget. Kumar et al. (2016) examined the long-term variability of BoB SSTs to reveal that they are influenced predominantly by seasonal forcing.

Most of the modeling studies so far for the BoB have used the K-profile parametrization (KPP) vertical mixing scheme (Behara et al., 2019; Behara & Vinayachandran, 2016; Chatterjee et al., 2013; Kurian & Vinayachandran, 2007; Mukherjee et al., 2018; Srivastava et al., 2018) to represent turbulence and the associated mixing. It has been observed from these studies that the KPP scheme shows a relatively large bias in the ocean properties, especially in the southern and central regions of the BoB. It is primarily due to the parametric nature of KPP, which does not model the regional-scale processes. Therefore, it is imperative to test other vertical mixing schemes that could improve the representation of ocean processes and associated dynamics, reflecting improvements in the ocean properties such as SST and MLD. Among the other available mixing schemes, k-e turbulence closure has been known to work well for modeling ocean dynamics. The k-e scheme has been adopted for the Liverpool Bay, the Mediterranean Sea, and some Pacific Ocean studies (Fernández et al., 2006; Simpson et al., 2002; Walsh et al., 2017) and it has been documented that it performs well for these domains. However, none of these studies contrasted k-e with other mixing models for the BoB domain. Fernández et al. (2006) compared KPP and k-e for the Mediterranean Sea and found that KPP produces slightly deeper MLDs in summer than observations, which is rectified by using k-e. The study mentioned that the differences in MLDs are due to changes in values of viscosity and diffusivity at the base of the mixed layer, indicating suppressed entrainment with the KPP mixing scheme.

To the best of our knowledge, the k-e mixing scheme for modeling BoB dynamics has not been reported. Given that BoB has a multitude of processes that generate turbulence and mixing, it would be prudent to test a mixing scheme that focuses on modeling the turbulent processes. Therefore, the objective of the present study is to implement k-e into MOM5 and perform an intercomparison of the results with the most trusted mixing scheme in ocean modeling (KPP). Mechanisms leading to the differences observed between the two mixing schemes are diagnosed. The rest of the paper is structured as follows: Section 2 provides a model description, data set, experiments performed, and model setup information. Section 3 is focused on model output comparison for surface properties like currents, surface temperature, and mixed layer depth. Subsurface analysis with vertical temperature profile and turbulent flux quantification is discussed in Section 4. A summary and conclusion are provided in Section 5.

2. Data and Methodology

Modular Ocean Model (MOM) version 5 (MOM5), developed by NOAA's Geophysical Fluid Dynamics Laboratory (GFDL), is used for this study (for details on MOM5, refer to Griffies (2012)).

2.1. Model Domain Specification

The model domain considered for the present study is a part of the Indian Ocean from 10°S to 25°N and 75° to 95°E. While the model run considers this entire domain, the analysis and discussions in the forthcoming sections are only shown for 0° to 25°N and 75° to 95°E. The Arakawa B-grid is used for computing tracers and velocity. A uniform horizontal grid resolution of 0.25° is employed in zonal and meridional directions. The non-uniform vertical grid with a 5 m uniform grid till 60 m depth is utilized. The Indian Ocean ETOPO2V2 (Sindhu et al., 2007) is used for ocean topography.

For open ocean interactions, the radiation boundary condition is used with the Orlanski (1976) formula, and the tracers are prescribed at the open boundaries. Surface height data are prescribed at the open boundaries to consider the effect of incoming and outgoing waves. Temperature and salinity are prescribed as tracers at open boundaries of the domain. An inflow relaxation time $\tau_{in}$ of 1 hr and outflow relaxation time $\tau_{out}$ of 1 month is applied to avoid shocks between inflow to outflow in the model setup. Many previous studies (Courtois et al., 2017; Cox & Bryan, 1984; Francis et al., 2020; Large & Yeager, 2004; Griffies et al., 2009; Francis et al., 2013; Shaji
et al., 2003; Srivastava et al., 2018; Thompson et al., 2006) relaxed tracers at the boundaries to prevent systematic drift. This study also has relaxed temperature and salinity with a 30-day timescale. This flux correction method considers both models simulated and prescribed data as explained by Griffies (2003).

The model setup uses the β-plane approximation to represent the Coriolis effect. As base case, the model uses the KPP scheme for simulating vertical mixing with a background vertical viscosity of $10^{-4}$ m$^2$ s$^{-1}$; background diffusivity is set to $10^{-5}$ m$^2$ s$^{-1}$; constant for pure convection is 1.8 (Large et al., 1994); critical Richardson number is chosen as 0.25 (Kundu & Cohen, 1990). For comparative purposes, another vertical mixing scheme from the General Ocean Turbulence Model (GOTM) (Umlauf et al., 2006) is used, namely, the k-ε turbulence model. Technical documents with source code of GOTM are available in public domain: https://gotm.net and the coupling between GOTM and MOM has been described in Villareal et al. (2005). Following the work by Rodi (1987), the constants used in k-ε model are chosen as $\sigma_t = 1$, and $\sigma_c = 1.3$; empirical constants, $c_{1}= 1.44$, $c_{2} = 1.92$, $c_{3} = 0$.

### 2.2. Data Set Used in Study

The model uses annual averaged temperature and salinity profiles taken from World Ocean Atlas (WOA18) (Locarnini et al., 2018; Zweng et al., 2019) to initialize the model simulation. For shortwave penetration into the upper ocean, a chlorophyll-based scheme (Morel & Antoine, 1994) has been used. Wind stresses are prescribed from Quick Scatterometer (QuikSCAT), short wave, long wave, sensible, and latent heat fluxes from WHOI OAFlux, precipitation from Tropical Rainfall Measuring Mission (TRMM), and chlorophyll from MODIS data set. All input parameters are available at http://apdrc.soest.hawaii.edu/data/data.php. Simple Ocean Data Assimilation (SODA) reanalysis data (Carton et al., 2018) and North Indian Ocean Atlas (NIOA) monthly Climatology (Chatterjee et al., 2012) are used to validate model output. The differences between the model and validation data are analyzed to depict model simulation accuracy and ocean physics. The model simulations are spun up by converting the model forcing data from 2003 to 2009 to climatological data for performing the control run for 10 years. To ensure the stability of total kinetic energy from the control run, experimental runs with interannual data for 2003–2008 are performed, and the output is analyzed for these 6 years.

### 3. Ocean Properties

We denote the seasons as DJF (December-January-February), MAM (March-April-May), JJAS (June-July-August-September), and ON (October-November) based on the direction of wind flow. The response in resultant ocean currents was analyzed (figure not shown). Depth averaged surface currents agree with observed basin-scale seasonal features like EICC and the strong equatorial currents such as the spring and fall Wyrtki Jets. There are no significant differences between the k-ε mixing scheme and KPP mixing scheme in ocean currents (Supporting Information S1). Also, sea surface salinity (SSS) (Supporting Information S1) has no significant difference between the two mixing schemes compared with the NIOA data.

#### 3.1. Sea Surface Temperature

Sea surface temperature is an important property determined by the surface and subsurface ocean processes, especially in the BoB, where the high mean SSTs drive a strong response in the atmosphere. The BoB is known to exhibit a variety of mesoscale processes that also vary meridionally, which control the SST in this region. The model and observations show cooler SST in DJF and warmer SST in MAM. This is due to the variation in the amount of radiation received and the latent heat losses in different seasons (Murtugudde & Busalacchi, 1999). The north-south temperature gradient in DJF and warmer temperature near the equator in all seasons are also well represented in our model simulations.

Figure 1a shows the comparison of observational SST from NIOA data and KPP model output. We observe that the KPP model tends to predict cooler SST (positive bias) except in the North Bay for all seasons. KPP shows warmer SST (negative bias) near the northern Bay than observational data. This negative bias could partly be due to the absence of river runoff forcing in the model setup. However, it is prudent to note that salinity restoration has been implemented in our study that acts as a proxy for river runoff. For similar forcing conditions, Figure 1b shows the SST difference between KPP and k-ε mixing schemes. In all the seasons, bias is reduced in the k-ε...
Figure 1. Seasonal sea surface temperature (SST) (a) Observation—K-profile parametrization (KPP), (b) Observation—$k$-$\epsilon$ and mixed layer depth (MLD), (c) Observation—KPP, (d) Observation—$k$-$\epsilon$ plots for the Bay of Bengal (BoB) domain.
mixing scheme compared to KPP. The improvement is especially evident in central and southern BoB, where $k-e$ shows warmer SST (negative bias) that is closer to observations.

3.2. Mixed Layer Depth

Next, we consider MLD variability in the two vertical mixing schemes. The temperature criteria ($\Delta T = 0.2^\circ C$) (Courtois et al., 2017; de Boyer Montégut et al., 2004) has been used for MLD computation. Both the mixing schemes well replicate the basic pattern of MLD, but the differences are subtle and important. During DJF, MLD is higher in the northern part of the Bay, whereas, during JIAS, MLD is higher in the southern part of BoB. During MAM, the model-generated MLD is relatively on the shallow side. These MLD seasonal patterns show a positive correlation with seasonal winds. The more the wind stresses, deeper the MLD.

Figure 1c shows the difference between SODA reanalysis and KPP model simulation. It clearly shows that the KPP mixing scheme renders shallower (positive bias) MLD than reanalysis data. This bias is larger in JIAS and the near-equatorial region when winds are stronger. In some regions, the bias is as high as 30 m, which is significantly large. Figure 1d shows comparison of MLD from KPP and $k-e$ mixing schemes. There is a clear reduction in bias, by as much as 10 m, with implementation of the $k-e$ scheme. We see that the $k-e$ scheme has helped deepen the MLD by up to ~10 m over most of the domain for all the seasons, thereby leading to a closer match with the reanalysis data. The impact on the MLD heat and momentum budgets and the circulation are significant (not shown).

4. Characterization of Vertical Structure and Turbulent Fluxes

In order to understand and quantify the impact of the $k-e$ mixing scheme in improving the SST and MLD, we look at the vertical structure and turbulent fluxes.

4.1. Vertical Structure

Figure 2 shows 5° to 10°N averaged longitude-depth seasonal plots for JIAS and ON seasons, where we see the most significant improvement with the $k-e$ mixing scheme. Figure 2 shows that near 85°E, the observed thermocline is deeper, while the KPP model leads to a shallow thermocline. The $k-e$ scheme deepens the thermocline, resulting in a better vertical structure closer to observations. In general, we note that the model output from $k-e$ better represents the vertical structure of temperature compared to KPP. This is one possible reason for improving SST and MLD while using the $k-e$ mixing scheme. The $N^2$ vertical structure figure is attached (Supporting Information S1). We see that at the base of the mixed layer a negative bias is seen, which is a representation of more stable water column produced by the $k-e$ mixing scheme. The stable water column shows a better representation of the vertical temperature profile, thereby resulting in improvements in both SST and MLD.

4.2. Quantification of Turbulent Fluxes

Turbulent fluxes play an important role in governing the mixing in the ocean and hence the controlling the evolution of SST and MLD. The turbulent kinetic energy, also referred to as the eddy kinetic energy (EKE), formulated below in Equation 1, provides a mechanistic approach to understanding the role of turbulent fluxes on ocean energetics and stability (Pope, 2000).

$$\frac{\partial K}{\partial t} + \vec{U}_j \frac{\partial K}{\partial x_j} = Tr + P - B - \epsilon$$

(1)

Here $K = \frac{1}{2} (\vec{u}'^2 + \vec{v}'^2 + \vec{w}'^2)$ is the eddy kinetic energy, $\vec{u}'$, $\vec{v}'$, and $\vec{w}'$ are the fluctuating components of velocity, $\vec{U}$ is the mean flow velocity. The terms on the right hand side of Equation 1 could be expanded as follows: $Tr = \frac{1}{\rho_i} \frac{\partial (\overline{\rho_i \vec{u}'} \vec{v}')}{\partial x_i} \frac{\partial (\overline{\rho_i \vec{u}'} \vec{v}')}{\partial x_j}$ is the transport term, $P = -\overline{\rho_i \vec{u}' \frac{\partial \vec{v}'}{\partial x_j}}$ is the shear production, $B = \frac{\rho_i}{\rho_i} \overline{\rho_i \vec{u}' \vec{v}' \delta_x}$ is the buoyancy production and $\epsilon = \nu e \delta_j$ represents the viscous dissipation, where $\rho'$ and $\rho'$ are the fluctuating components.
of pressure, and density, $\rho_0$ is the reference density (taken at the surface), $\nu$ is the kinematic viscosity, and $\epsilon_{ij}$ is the strain tensor described as follows:

$$
\epsilon_{ij} = \begin{bmatrix}
\frac{\partial u'_{ij}}{\partial x} & \frac{1}{2} \left( \frac{\partial u'_{ij}}{\partial y} + \frac{\partial u'_{ij}}{\partial x} \right) & \frac{1}{2} \left( \frac{\partial u'_{ij}}{\partial z} + \frac{\partial u'_{ij}}{\partial x} \right) \\
\frac{1}{2} \left( \frac{\partial u'_{ij}}{\partial y} + \frac{\partial u'_{ij}}{\partial x} \right) & \frac{\partial u'_{ij}}{\partial y} & \frac{1}{2} \left( \frac{\partial u'_{ij}}{\partial z} + \frac{\partial u'_{ij}}{\partial y} \right) \\
\frac{1}{2} \left( \frac{\partial u'_{ij}}{\partial z} + \frac{\partial u'_{ij}}{\partial x} \right) & \frac{1}{2} \left( \frac{\partial u'_{ij}}{\partial z} + \frac{\partial u'_{ij}}{\partial y} \right) & \frac{\partial u'_{ij}}{\partial z}
\end{bmatrix}
$$

In this study, we look into the seasonal variations of $K$, $P$, $B$, and $\epsilon$ to understand the mechanisms of turbulence production and dissipation. The following methodology is employed to compute the seasonal mean of EKE budget terms. First, the velocity and density fields are time-averaged over a particular season (highlight JJAS) to obtain a single mean-field. Any mean-field, say $\bar{\mathbf{A}}$, takes the form

$$
\bar{\mathbf{A}}(x, y, z) = \frac{1}{T} \int_0^T \mathbf{A}(x, y, z, t) dt,
$$

where $T$ is the total duration, and $dt$ is the time step at which each field is available. The fluctuation field is obtained as

Figure 2. A section of vertical temperature averaged over 5°N to 10°N for two different seasons. Here black lines indicate observations, blue lines show K-profile parametrization (KPP) model simulation and red lines show $k$-$\epsilon$ model depiction.
The fluctuation fields are then used to calculate $K$, $P$, $B$, and $\epsilon$. Finally, these quantities are time-averaged, and 30 m depth averaged to obtain the seasonal plots of the energetics.

First, we consider the eddy kinetic energy, $K$, which denotes the turbulent energy available for mixing. Figure 3a shows the difference in $K$ between KPP and $k$-$\epsilon$ mixing schemes. It is noticed that there is no basin-wide change in $K$ since the difference is mostly zero. We see some differences very close to the equator, which could be

\[ a'(x, y, z, t) = a(x, y, z, t) - \overline{a}(x, y, z) \]
attributed to strong equatorial dynamics. This indicates that the total energy available for mixing is the same in both the mixing schemes. However, the contributions of the individual terms, namely, $P$, $B$, and $\epsilon$, are important in understanding the improvements brought about by the $k$-e scheme.

The turbulent buoyancy flux, $B$, represents the potential energy in the system and denotes the water column’s stability. Figure 3b shows the difference in buoyancy flux between the two mixing schemes. The basin-wide difference is primarily negative. This means that the $k$-e mixing scheme retains stability in the water column compared to KPP. The relatively stable water column better represents the vertical temperature profile, thereby resulting in improvements in both SST and MLD. The improved stability in $k$-e is a direct consequence of the increase in the potential energy that helps maintain the thermocline.

The dissipation, $\epsilon$, is a sink term in the EKE budget equation. It is a process by which eddy kinetic energy is lost to viscosity. Figure 3c shows the difference in $\epsilon$. It is seen that the KPP model shows higher viscous dissipation compared to $k$-e. This fundamentally means that energy is getting dissipated at a higher rate within the water column, thereby restricting the energy available for mixing to a shallower depth. This is the reason for the underestimation of MLD in the KPP model. On the other hand, $k$-e allows the energy to penetrate deeper depths, resulting in a better representation of the vertical structure and the MLD closer to observations.

The turbulent production flux, $P$, does not show any difference between KPP and $k$-e, so we do not discuss it further. The negligible difference in $P$ means that the shear production mechanism in both KPP and $k$-e is similar, which is understandable since no significant change in ocean currents is seen from one scheme to the other.

The quantification of turbulent fluxes provides another avenue for understanding the superior performance of $k$-e over KPP for estimating SST and MLD in the BoB. Along with the improvement in the vertical structure (see Section 4.1), the better representation of turbulent buoyancy flux, $B$ and viscous dissipation, $\epsilon$ are the main reasons for $k$-e vertical mixing scheme showing better results.

### 5. Summary and Conclusion

A comparative study of two different vertical mixing schemes, namely KPP and $k$-e, was carried out for the Bay of Bengal (BoB) domain using MOM5. It was noted that both the mixing schemes do an excellent job of capturing the basin-wide patterns of surface and subsurface features like the currents, SST, SSS, and MLD. Quantification of SST and MLD revealed that the $k$-e mixing scheme shows a closer match to observations than KPP for all seasons. In some regions of BoB, a significant change in SST and MLD was brought about by implementing $k$-e, which showed the superiority of this scheme compared to KPP. The reasons for better performance of $k$-e were probed. It was documented that the improvements in the vertical temperature structure and better representation

| Variable name       | Data set                        | Version       | Frequency            | Data name                                      |
|---------------------|---------------------------------|---------------|----------------------|------------------------------------------------|
| Initial temperature and salinity | World Ocean Atlas (Levitus; WOA) | NODC World Ocean Atlas 2018 | Annual (2005–2017) 0.25° | Objectively analyzed mean sea water temperature and Salinity |
| Wind stress         | QuikSCAT                        |               | Daily                | $u$ or $v$ wind component ascending pass       |
| Shortwave           | WHOI OAFlux                     | Version 3     | Daily                | Net surface shortwave radiation flux (positive downward) |
| Longwave            | WHOI OAFlux                     | Version 3     | Daily                | Net surface longwave radiation flux (positive upward) |
| Sensible heat       | WHOI OAFlux                     | Version 3     | Daily                | Daily mean surface sensible heat flux, positive upward |
| Evaporation rate    | WHOI OAFlux                     | Version 3     | Daily                | Daily mean evaporation rate                    |
| Precipitation rate  | TRMM                            | TRMM_TMI V7.1 | Daily                | Rain rate—ascending maps                      |
| Chlorophyll         | MODIS Aqua Chlorophyll-a level 3 |               | Daily (4 km)         | Chlorophyll concentration, oci algorithm       |
of turbulent buoyancy flux and viscous dissipation are the prime reasons for the $k$-$\epsilon$ mixing scheme showing a closer match to observations. This study concludes that the $k$-$\epsilon$ mixing scheme is better for modeling BoB dynamics. Further contrasts are needed at subseasonal and interannual timescales to establish the superiority of $k$-$\epsilon$ under varying background states, especially since the BoB SSTs in monsoon variability at these timescales is of great interest.

**Data Availability Statement**

The details of the forcing data set used in this study is given in Table 1. This includes the type of variable, version, frequency and data name. In order to access this data set, which is freely available use the below link: http://apdrc.soest.hawaii.edu/data/data.php. For example, to obtain ‘Initial temperature’ data go to. http://apdrc.soest.hawaii.edu/data/data.php select data set from Table 1 that is, “World Ocean Atlas (Levitus; WOA)” and click on “LAS” -> then select version “NODC World Ocean Atlas 2018” -> then select file format, specify latitude and longitude, select exact year and submit query to download the data. The NIOA data used for validation can be accessed from the link below: https://publica- tion-data.nio.org/s/q7g6t84j4YTkiGz. All the information about the Modular Ocean Model V5 employed for this study is available at below link: https://github.com/mom-ocean/MOM5.

**References**

Behera, A., & Vinayachandran, P. N. (2016). An OGCM study of the impact of rain and river water forcing on the Bay of Bengal. *Journal of Geophysical Research: Oceans, 121*, 2425–2446. https://doi.org/10.1002/2015JC010699

Behera, A., Vinayachandran, P. N., & Shankar, D. (2019). Influence of rainfall over eastern Arabian Sea on its salinity. *Journal of Geophysical Research: Oceans, 124*(7), 5003–5020. https://doi.org/10.1029/2019JC014999

Bhat, G. (2003). Some salient features of the atmosphere observed over the north Bay of Bengal during Bobnex. *Journal of Earth System Science, 112*(2), 131–146. https://doi.org/10.1007/BF02701983

Bhat, G., Gadgil, S., Haresh Kumar, P., Kalsi, S., Madhusoodanan, P., Murty, V., et al. (2001). Bobnex: The Bay of Bengal monsoon experiment. *Bulletin of the American Meteorological Society, 82*(10), 2217–2243. https://doi.org/10.1175/1520-0477(2001)082<2217:BTBOBM>2.3.CO;2

Carton, J. A., Chepurin, G. A., & Chen, L. (2018). SODA3: A new ocean climate reanalysis. *Journal of Climate, 31*(17), 6967–6983. https://doi.org/10.1175/JCLI-D-18-0149.1

Chatterjee, A., Shankar, D., McCreary, J. Jr., & Vinayachandran, P. (2013). Yanai waves in the Western equatorial Indian Ocean. *Ocean Modelling, 69*, 59–84. https://doi.org/10.1016/j.ocemod.2013.02.007

Chatterjee, A., Shankar, D., Shinou, S., Reddy, G., Michael, G., Ravichandran, M., et al. (2012). A new atlas of temperature and salinity for the Arabian Sea and Bay of Bengal. *Regional Studies in Marine Science, 1*, 67–75.

Courtois, P., Hu, X., Pennelly, C., Spence, P., & Myers, P. G. (2017). Mixed layer depth calculation in deep convection regions in ocean numerical models. *Ocean Modelling, 120*, 60–78. https://doi.org/10.1016/j.ocemod.2017.10.007

Cox, M. D., & Bryan, K. (1984). A numerical model of the ventilated thermocline. *Journal of Physical Oceanography, 14*(4), 674–687. https://doi.org/10.1175/1520-0485(1984)014<0674:ANMODT>2.0.CO;2

de Boyer Montégut, C., Madec, G., Fischer, A. S., Lazar, A., & Iudicone, D. (2004). Mixed layer depth over the global ocean: An examination of profile data and a profile-based climatology. *Journal of Geophysical Research, 109*, C12003. https://doi.org/10.1029/2004JC002378

Fernández, V., Umlauf, L., Dobricic, S., Burchard, H., & Pinardi, N. (2006). Validation and intercomparison of two vertical-mixing schemes in the Mediterranean sea. *Ocean Science Discussions, 3*(6), 1945–1976.

Francis, P., Jithin, A. K., Chatterjee, A., Mukherjee, A., Shankar, D., Vinayachandran, P. N., & Ramakrishna, S. S. V. S. (2020). Structure and dynamics of undercurrents in the Western boundary current of the Bay of Bengal. *Ocean Dynamics, 70*(3), 387–404. https://doi.org/10.1007/s10236-019-01340-9

Francis, P., Vinayachandran, P., & Sheni, S. (2013). The Indian Ocean forecast system. *Current Science, 104*(10), 1354–1368.

Girishkumar, M., Ravichandran, M., & McPhaden, M. (2013). Temperature inversions and their influence on the mixed layer heat budget during the winters of 2006–2007 and 2007–2008 in the Bay of Bengal. *Journal of Geophysical Research: Oceans, 118*, 2426–2437. https://doi.org/10.1002/jgrc.20192

Griffies, S. (2003). Fundamentals of ocean climate models. Princeton University Press.

Griffies, S. M. (2012). *Elements of the modular ocean model (mom)* (Tech. Rep. 7, p. 620). GFDL Ocean Group.

Griffies, S. M., Biastoch, A., Böning, C., Bryan, F., Danabaasoglu, G., Chassignet, E. P., et al. (2009). Coordinated ocean-ice reference experiments (cores). *Ocean Modelling, 26*(1–2), 1–46. https://doi.org/10.1016/j.ocemod.2008.08.007

Han, W., McCreary, J. P., & Kohler, K. E. (2001). Influence of precipitation minus evaporation and Bay of Bengal rivers on dynamics, thermodynamics, and mixed layer physics in the upper Indian Ocean. *Journal of Geophysical Research, 106*(C4), 6895–6916. https://doi.org/10.1029/2000JC000403

Howden, S. D., & Murtugudde, R. (2001). Effects of river inputs into the Bay of Bengal. *Journal of Geophysical Research, 106*(C9), 19825–19843. https://doi.org/10.1029/2000JC000656

Kumar, P. D., Paul, Y. S., Muraleedharan, K., Murty, V., & Preenu, P. (2016). Comparison of long-term variability of sea surface temperature in the Arabian Sea and Bay of Bengal. *Regional Studies in Marine Science, 3*, 67–75.

Kundu, P., & Cohen, L. (1990). *Fluid mechanics* (p. 638). Academic.
Kurian, J., & Vinayachandran, P. (2007). Mechanisms of formation of the Arabian Sea mini warm pool in a high-resolution ocean general circulation model. *Journal of Geophysical Research, 112*, C05009. https://doi.org/10.1029/2006JC003631

Kurien, P., Ikeda, M., & Valsala, V. K. (2010). Mesoscale variability along the East Coast of India in spring as revealed from satellite data and OGCM simulations. *Journal of Oceanography, 66*(2), 273–289. https://doi.org/10.1007/s10872-010-0024-x

Large, W. G., McWilliams, J. C., & Doney, S. C. (1994). Oceanic vertical mixing: A review and a model with a nonlocal boundary layer parameterization. *Reviews of Geophysics, 32*(4), 363–403. https://doi.org/10.1029/94RG01872

Large, W. G., & Yeager, S. G. (2004). Diurnal to decadal global forcing for ocean and sea-ice models: The data sets and flux climatologies. National Center for Atmospheric Research.

Locarnini, M., Mishonov, A., Baranova, O., Boyer, T., Zweng, M., Garcia, H., et al. (2018). *World ocean atlas 2018: Temperature* (NOAA Atlas NESDIS 81, Vol. 1, 52p). National Oceanic and Atmospheric Administration, Department of Commerce.

Morel, A., & Antoine, D. (1994). Heating rate within the upper ocean in relation to its bio-optical state. *Journal of Physical Oceanography, 24*(7), 1652–1665. https://doi.org/10.1175/1520-0485(1994)024<1652:HRTUOU>2.0.CO;2

Mukherjee, A., Shankar, D., Chatterjee, A., & Vinayachandran, P. (2018). Numerical simulation of the observed near-surface east India coastal current on the continental slope. *Climate Dynamics, 50*(11–12), 3949–3980. https://doi.org/10.1007/s00382-017-3856-x

Murtugudde, R., & Busalacchi, A. J. (1998). Salinity effects in a tropical ocean model. *Journal of Geophysical Research, 103*(C2), 3283–3300. https://doi.org/10.1029/97JC02438

Murtugudde, R., & Busalacchi, A. J. (1999). Interannual variability of the dynamics and thermodynamics of the tropical Indian Ocean. *Journal of Climate, 12*(8), 2300–2326. https://doi.org/10.1175/1520-0442(1999)012<2300:IVOTDA>2.0.CO;2

Orlanski, I. (1975). A simple boundary condition for unbounded hyperbolic flows. *Journal of Computational Physics, 2*(1), 251–269. https://doi.org/10.1016/0021-9991(76)90223-1

Pope, S. B. (2000). *Turbulent flows*. Cambridge University Press. https://doi.org/10.1017/CBO9780511840531

Rodri, W. (1987). Examples of calculation methods for flow and mixing in stratified fluids. *Journal of Geophysical Research, 92*(C5), 5305–5328. https://doi.org/10.1029/JC092iC05p05305

Schott, F. A., & McCreary, J. P. (2001). The monsoon circulation of the Indian Ocean. *Progress in Oceanography, 51*(1), 1–123. https://doi.org/10.1016/S0079-6611(01)00017-5

Shaji, C., Iizuka, S., & Matsuura, T. (2003). Seasonal variability of near-surface heat budget of selected oceanic areas in the north tropical Indian Ocean. *Journal of Oceanography, 59*(1), 87–103. https://doi.org/10.2307/102287252478

Shankar, D., Vinayachandran, P., & Unnikrishnan, A. (2002). The monsoon currents in the north Indian Ocean. *Progress in Oceanography, 52*(1), 63–120. https://doi.org/10.1016/S0079-6611(02)00024-1

Shenoi, S. C., Shankar, D., & Shetye, S. R. (2002). Differences in heat budgets of the near-surface Arabian Sea and Bay of Bengal: Implications for the summer monsoon. *Journal of Geophysical Research, 107*(C6), 3052. https://doi.org/10.1029/2000JC000679

Shetye, S. R., Gouveia, A. D., Shankar, D., Shenoi, S. C. S., Vinayachandran, P. N., Sundar, D., et al. (1996). Hydrography and circulation in the Western Bay of Bengal during the northeast monsoon. *Journal of Geophysical Research, 101*(C6), 14011–14025. https://doi.org/10.1029/95JC03307

Simpson, J. H., Burchard, H., Fisher, N. R., & Rippeth, T. P. (2002). The semi-diurnal cycle of dissipation in a ROFI: Model-measurement comparisons. *Continental Shelf Research, 22*(11–13), 1615–1628. https://doi.org/10.1016/S0278-4343(02)00025-0

Sindhu, B., Suresh, I., Unnikrishnan, A. S., Bhaskar, N. V., Neetu, S., & Michael, G. S. (2007). Improved bathymetric datasets for the shallow continental shelf regions in the Indian Ocean. *Journal of Earth System Science, 116*(3), 261–274. https://doi.org/10.1007/s12040-007-0025-3

Srivastava, A., Dwivedi, S., & Mishra, A. K. (2018). Investigating the role of air-sea forcing on the variability of hydrography, circulation, and mixed layer depth in the Arabian Sea and Bay of Bengal. *Oceanologia, 60*(2), 169–186. https://doi.org/10.1007/s10027-017-0011-1

Thompson, B., Gnanaseelan, C., & Salvekar, P. (2006). Variability in the Indian Ocean circulation and salinity and its impact on SST anomalies during dipole events. *Journal of Marine Research, 64*(6), 853–880. https://doi.org/10.1357/002224006779698350

Tomczak, M., & Godfrey, J. S. (1994). *Regional oceanography: An introduction*. Pergamon.

Umlauf, L., Burchard, H., & Bolding, K. (2006). GOTM: Source code and test case documentation (Version 4).

Vijith, V., Vinayachandran, P., Webber, B. G., Matthews, A. J., George, J. V., Kannu, V. K., et al. (2020). Closing the sea surface mixed layer temperature budget from in-situ observations alone: Operation advection during bobble. *Scientific Reports, 10*(1), 1–12. https://doi.org/10.1038/s41598-020-63320-0

Villareal, M. R., Bolding, H. B., & Demirov, E. (2005). Coupling of the GOTM turbulence module to some three-dimensional ocean models. In H. Z. Baumert, J. Simpson, J. Simpson, J. Sündermann, & J. Sündermann (Eds.), *Marine turbulence: Theories, observations, and models* (pp. 225–237). Cambridge University Press.

Vinayachandran, P., Matthews, A. J., Kumar, K. V., Sanchez-Franska, A., Thushara, V., George, J., et al. (2018). BoBBLE: Ocean–atmosphere interaction and its impact on the south Asian monsoon. *Bulletin of the American Meteorological Society, 99*(8), 1569–1587. https://doi.org/10.1175/BAMS-D-16-0230.1

Walsh, K., Govekar, P., Babanin, A. V., Ghattoussi, M., Spence, P., & Scocciamaro, E. (2017). The effect on simulated ocean climate of a parameterization of unbroken wave-induced mixing incorporated into the k-epsilon mixing scheme. *Journal of Advances in Modeling Earth Systems, 9*, 735–758. https://doi.org/10.1002/2016MS000707

Zhang, Y., & Du, Y. (2012). Seasonal variability of salinity budget and water exchange in the northern Indian Ocean from HYCOM assimilation. *Chinese Journal of Oceanology and Limnology, 30*(6), 1082–1092. https://doi.org/10.1007/s00343-012-1284-7

Zweng, M., Seidov, D., Boyer, T., Locarnini, M., Garcia, H., Mishonov, A., et al. (2019). *World ocean atlas 2018: Salinity* (Vol. 2). National Oceanic and Atmospheric Administration.