Correlation between subsurface salinity anomalies in the Bay of Bengal and the Indian Ocean Dipole and governing mechanisms

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Abstract. Lead-lag correlations between the subsurface temperature/salinity anomalies in the Bay of Bengal (BoB) and the Indian Ocean Dipole (IOD) are revealed in model results, ocean synthesis, and observations. Mechanisms for such correlations are further investigated using the Hamburg Shelf Ocean Model (HAMSOM), mainly on the salinity variability. It is found that the subsurface salinity anomaly of the BoB positively correlates to the IOD with a lag of three months on average, while

5 the subsurface temperature anomaly negatively correlates. The model results suggest the remote forcing from the equatorial Indian Ocean dominates the interannual subsurface salinity variability in the BoB. The coastal Kelvin waves carry signals of positive (negative) salinity anomalies from the eastern equatorial Indian Ocean and propagate counterclockwise along the coasts of the BoB during positive (negative) IOD events. Subsequently westward Rossby waves propagate these signals to the basin at a relatively slow speed, which causes a considerable delay of the subsurface salinity anomalies in the correlation. By

10 analyzing the salinity budget of the BoB, it is found that the diffusion dominates the salinity changes near the surface, while the advection dominates the subsurface; the vertical advection of salinity contributes positively to this correlation, while the horizontal advection contributes negatively. These results suggest that the IOD plays a crucial role in the interannual subsurface salinity variability in the BoB.

1 Introduction

15 The Bay of Bengal (BoB) is a monsoon-controlled tropical ocean located in the northeast of the Indian Ocean. The robust monsoon significantly influences the ocean circulation, vertical water exchange, and water characteristics in the BoB (Shetye et al., 1991, 1996; Vecchi and Harrison, 2002; Li et al., 2017). During the summer monsoon, the Southwest Monsoon Current brings saltier Arabian Sea water into the BoB, whereas the Northeast Monsoon Current brings fresher water from the BoB to the Arabian Sea during the winter monsoon (Vinayachandran et al., 1999; Jensen, 2001; Sanchez-Franks et al., 2019).

20 Water from the Arabian Sea also enters the BoB as a subsurface flow during the northeast monsoon, which is proved by observations and model works (Wijesekera et al., 2015; Gordon et al., 2016). The salinity exchanges between the BoB and the equatorial Indian Ocean also show a seasonality associated with the monsoon (Jensen et al., 2016; Trott et al., 2019). In addition to the local monsoon, remote forcing from the equator also affects the ocean circulation and thermocline in the BoB, by which equatorial signals pass through the Andaman Sea (Potemra et al., 1991; Yu et al., 1991; McCreary et al., 1993, 1996;

25   Girishkumar et al., 2013). The Andaman and Nicobar Islands, as well as the eastern border of the Andaman Sea, significantly
alter the circulation in the BoB (Chatterjee et al., 2017). A recent numerical study suggests that the equatorial forcing plays a
dominant role in interannual variations of sea surface height and thermocline in the BoB during Indian Ocean Dipole (IOD)
and El Nino/Southern Oscillation (ENSO) events, especially for their spatial pattern (Pramanik et al., 2019).

The IOD is an east-west dipole mode that dominates the interannual sea surface temperature (SST) variability in the tropical

30   Indian Ocean (Saji et al., 1999; Webster et al., 1999; Schott et al., 2009; Deser et al., 2010), and it is physical entity independent
of the ENSO (Ashok et al., 2003; Fischer et al., 2005). The spatiotemporal coupling among ocean dynamics, SST, winds, rain-
fall revealed by the IOD have inspired many studies regarding the relationship and processes between the IOD and variations
of surface/subsurface temperature/salinity in the tropical Indian Ocean (Rao et al., 2002; Shinoda et al., 2004; Thompson et al.,
2006; Grunseich et al., 2011; Du et al., 2012; Zhang et al., 2013; Sayantani and Gnanaseelan, 2015; Kido and Tozuka, 2017;

35   Kido et al., 2019a). The research on both sea level and annual mean subsurface temperature anomalies revealed a see-saw of
the thermocline that related to the IOD (Saji et al., 1999). During the positive IOD (pIOD) phase, westerly winds weaken,
allowing cold water to rise in the eastern equatorial Indian Ocean and warm water to move toward to the west, therefore lifts
the equatorial thermocline in the east; during the negative IOD (nIOD) phase, vice versa, and lifts the equatorial thermocline
in the west.

40   Previous studies have discussed the impact of IOD on the subsurface dynamics in the equatorial Indian Ocean. However,
mechanisms and quantitative understandings for the impact of IOD on the subsurface dynamics in the BoB have not been
established yet, especially for the impact on subsurface salinity. Subsurface salinity is of great importance for determining
the ocean barrier layer and mixed layer depth (Lukas and Lindstrom, 1991; Montégut et al., 2007; Li et al., 2018; Kido
et al., 2019b). Understanding the variations and dynamics of the subsurface salinity is helpful to understand the evolution of

45   stratification and upper ocean properties, to further understand the response of the ocean to the atmosphere and its role on
climate. Nevertheless, it is not clear how the subsurface salinity in the BoB varies and whether it is affected by the IOD.
The questions addressed here are; is there an identifiable correlation between the subsurface salinity in the BoB and the
surface temperature in the tropical Indian Ocean on the interannual scale, how are these two variabilities related, how does the
subsurface salinity in the BoB respond to the IOD.

50   To answer the above questions, the subsurface salinity variability in the BoB and its relation with the IOD and the corre-
sponding mechanisms are investigated in this paper. Unless otherwise specified, anomalies used in this paper are residuals
subtracting monthly climatology from monthly data. The rest of this paper is organized as follows. In section 2, we introduce
four data sets and a regional ocean model used in this study, and the model validation is also presented in this section. In section
3, we examine the correlation between the subsurface temperature/salinity anomaly of the BoB and the IOD through analyzing

55   the four independent data sets and the model results. Connecting mechanisms and contributions of advection and diffusion are
discussed in section 4. Section 5 gives the summary and discussion.

Table 1. Summary of Data Sets

Data set	Grid [°]	Period	Type
EN4	1×1	1951-2005	global quality controlled monthly objective analyses
GECCO2	1×1	1951-2005	ocean synthesis
MPI-ESM-MR	0.4×0.4	1951-2005	free run under historical condition
RC_Clim	1×1	2004-2018	Argo-based data

2 Data and model

2.1 Data sets

In order to examine the potential correlation between the surface temperature pattern in the tropical Indian Ocean and the
60 subsurface salinity variability in the BoB on the interannual scale, four independent data sets (Table 1) are used in this study.
The first is the global quality controlled monthly ocean temperature and salinity objective analyses of version 4.2.1 of the Met
Office Hadley Centre 'EN' series (Good et al., 2013), named as EN4. The second is an ocean synthesis, which is the German
contribution of the Estimating the Circulation and Climate of the Ocean project GECCO2 (Köhl, 2015). The third is the free run
of mixed resolution of MPI-ESM (Jungclaus et al., 2013) under historical condition, named as MPI-ESM-MR. The fourth is the
65 Roemmich-Gilson Argo Climatology (Roemmich and Gilson, 2009), named as RG_Clim, which offers a basic description of
the modern upper ocean based entirely on Argo data. Due to the limitation of the data period, monthly anomalies of RG_Clim
are defined on its monthly climatology from 2004 to 2016. Monthly anomalies of the other three data sets are defined on their
monthly climatology from 1971 to 2000.

2.2 Model setting

70 For the purpose of discussing the relevant processes and mechanisms, a regional ocean model is performed. The Hamburg
Shelf Ocean Model (HAMSOM) we applied in this study is a three-dimensional baroclinic primitive equation model based
upon a semi-implicit numerical scheme (Backhaus, 1985; Pohlmann, 1996, 2006). In contrast to explicit shelf sea models, the
semi-implicit scheme proposed is faster and allows the simulation of the shelf and the deep ocean regions together without
being limited by stability considerations for the free surface (Backhaus, 1985). The underlying primitive equations are defined
75 in z-coordinates and Arakawa C-grid under the hydrostatic and Boussinesq assumption. For temperature and salinity, the
second order Lax-Wendroff scheme is applied for advection, the horizontal eddy viscosity is defined according to Smagorinsky
diffusivity (Smagorinsky, 1963), and vertical viscosity is calculated using the Kochergin scheme (Pohlmann, 1996, 2006).

In principle, we perform a dynamic downscaling simulation on the model domain using HAMSOM with the external forcing
derived from MPI-ESM-MR historical scenario. The model domain covers the Bay of Bengal and the Andaman Sea, ranging
80 zonally from $77.4°E$ to $103.5°E$ and meridionally from 0 to $22.83°N$, with bathymetry derived from SRTM30_PLUS (Becker
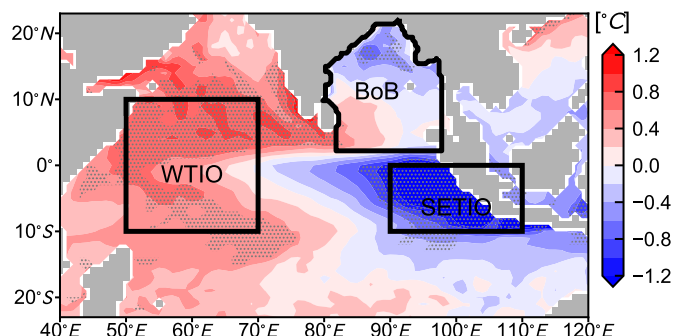
Figure 1. Composite of sea surface temperature anomalies during ASO of pIOD years from MPI-ESM-MR. The contour intervals are $0.2°C$. Anomalies significant at the 95% confidence level by a two-tailed Welch's t-test are hatched with grey dots. Western tropical Indian Ocean (WTIO) and southeastern tropical Indian Ocean (SETIO), the two areas related to the dipole mode index (DMI), are marked with black boxes. Our research domain, the Bay of Bengal (BoB), is marked with black borders.

et al., 2009). The horizontal model resolution is set to $5' \times 5'$. A total of 58 model layers are specified in vertical, of which there are 26 layers over upper 200 meters and 33 layers over upper 400 meters.

Figure 1 offers an overview of our research domain and the tropical Indian Ocean, as well as showing a composite of sea surface temperature anomalies (SSTa) during August-October (ASO, for ease of presentation, the months in the following are simplified to initials) of pIOD years from MPI-ESM-MR. The pIOD years (1974, 1978, 1993, 1997, 2000) are identified by the normalized dipole mode index (DMI) calculated from the data set itself, in the places with peaks above two and located around September (see Figure 7d). The distribution of composited SSTa presents a significant dipole mode in the tropical Indian Ocean, which indicates the MPI-ESM-MR can reproduce IOD events.

Sea level height, temperature, and salinity at lateral boundaries are monthly prescribed and derived from the oceanic part MPI-OM of MPI-ESM-MR. Atmospheric forcing, such as air temperature, cloud cover, precipitation, specific humidity, air pressure, wind stress, and wind speed at the open boundary, are six-hourly prescribed and derived from the atmospheric part ECHAM6 of MPI-ESM-MR. Under the consideration of a large amount of freshwater input through river discharge to our research domain, the river discharge is also prescribed six-hourly derived from ECHAM6. We applied a bias correction for forcing parameters on the climatological scale in order to bring the climatology of our simulation closer to the reality, because they are extracted from a purely free run. Principally, the monthly climatology of the external forcing was corrected by reference data by this bias correction procedure. The reference data for atmospheric forcing except air pressure are extracted from ERA5 (Hersbach et al., 2020). The air pressure kept unchanged since it only affects sea surface height due to the inverse barometer effect in HAMSOM, and its seasonal pattern matches well with the local monsoon system. The reference data for sea temperature and salinity are derived from the World Ocean Atlas 2018. The amplitude of river discharge was corrected by WaterGAP (Döll et al., 2003), and the location where the river discharge enters the ocean was also corrected. Although we applied the bias correction, the interannual signals from MPI-ESM-MR have not been changed, so the IOD signal input to our
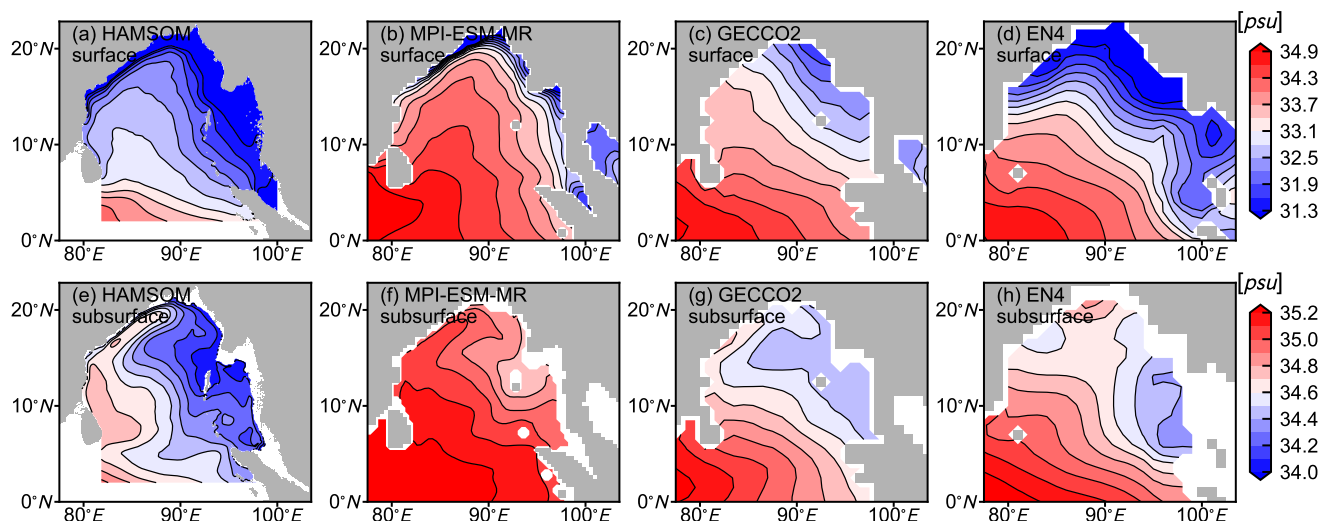
Figure 2. Spatial pattern of climatological surface (a, b, c, d) and subsurface (100 m; e, f, g, h) salinity from HAMSOM, MPI-ESM-MR, GECCO2, and EN4, respectively. The contour intervals are 0.3 psu for surface, but 0.1 psu for subsurface.

regional model is consistent with MPI-ESM-MR. Nevertheless, it is noteworthy that HAMSOM is a regional uncoupled ocean model, so no response of the atmosphere to the ocean is considered. Therefore, our model result must be treated as a pure response of the ocean to external signals rather than a two-way air-sea coupling simulation.

105   The simulation runs from 1951 to 2005 with 3 minutes time step and daily average output. In addition to typical output like temperature, salinity, and velocity, six terms concerning salinity change rate related to the contribution of advection and diffusion at U, V, W directions are conducted separately. Terms estimated from monthly outputs may differ significantly from those directly outputted by an online calculation, especially when high-frequency changes occur (Hasson et al., 2013; Köhler et al., 2018). This so-called 'online analysis' avoids the problem of large residual when directly using monthly data and allows 110 us to precisely close the salinity budget and track relevant exchange processes of salinity.

2.3   Model Validation

Before investigating the interannual variability and detailed mechanisms of subsurface salinity in the BoB, the HAMSOM result is validated on the climatological scale by comparing it with other data sets. Figure 2 shows their spatial pattern of climatological surface and subsurface salinity. River discharge and distribution affect this spatial pattern at the surface, as well 115 as the saline water from the western boundary. Reasons for the subsurface salinity pattern are complicated, ocean circulation and upwelling/downwelling systems may be involved. Both in the surface and in the subsurface, the climatological salinity from HAMSOM presents a gradient from southwest to northeast, which is more consistent with both individual data sets GECCO2 and EN4 than from MPI-ESM-MR. Hence it can be concluded that the bias correction we applied here improves our modeling by offering a more realistic climatological background.
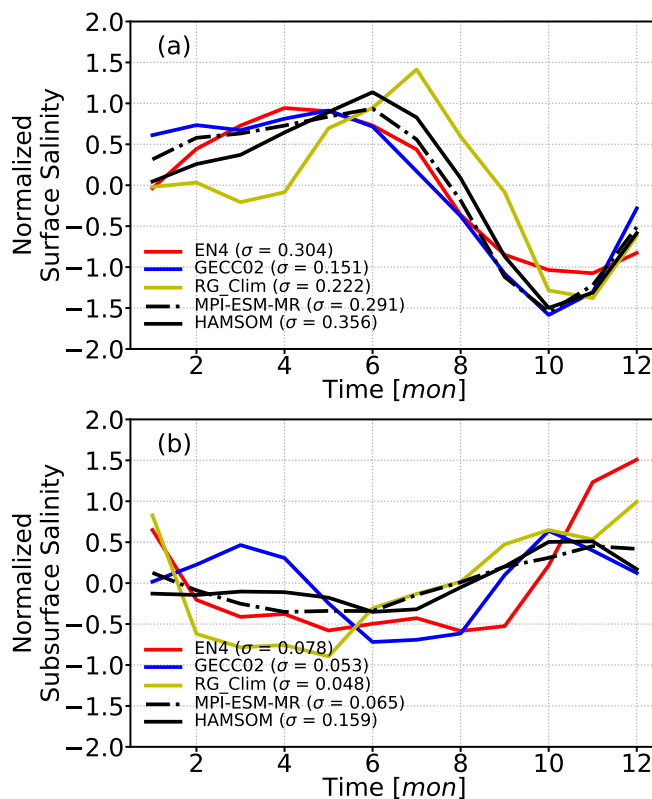
Figure 3. Normalized monthly climatology of surface (a) and subsurface (b) salinity of the BoB from EN4, GECCO2, RG_Clim, MPI-ESM-MR, and HAMSOM, respectively. The standard deviation σ corresponding to each data set is labelled.

120   Noteworthy that the seasonality is one of the most crucial characteristics in the research region. For the overall monthly climatology of salinity, HAMSOM results also show a reliable seasonal variability (Figure 3). At the surface, the significant seasonal salinity variability is supposed to be the consequence of freshwater flux variability caused by the monsoon. All five data sets show a consistent seasonality of the surface, which indicates the domination of monsoon in this region. The monthly climatological salinity of these data sets differs more for the subsurface than for the surface, the lack of subsurface observations

125 and more complex subsurface thermodynamics and hydrodynamics can be the reasons.

    The upper ocean circulation is also validated in two sections (Figure 4 and Figure 5). In general, circulations from HAMSOM is in well agreement with those from MPI-ESM-MR and GECCO2. The direction of upper ocean currents is reversed in MJJ and NDJ, which indicates that the monsoon dominates the upper ocean flow field in the BoB. Given the higher model resolution and more accurate terrain, HAMSOM is expected to perform better in coastal areas. The western boundary current simulated

130 by HAMSOM, also known as the East Indian Current, is stronger than that given by GECCO2 (Figure 4), which should be attributed to the higher resolution.
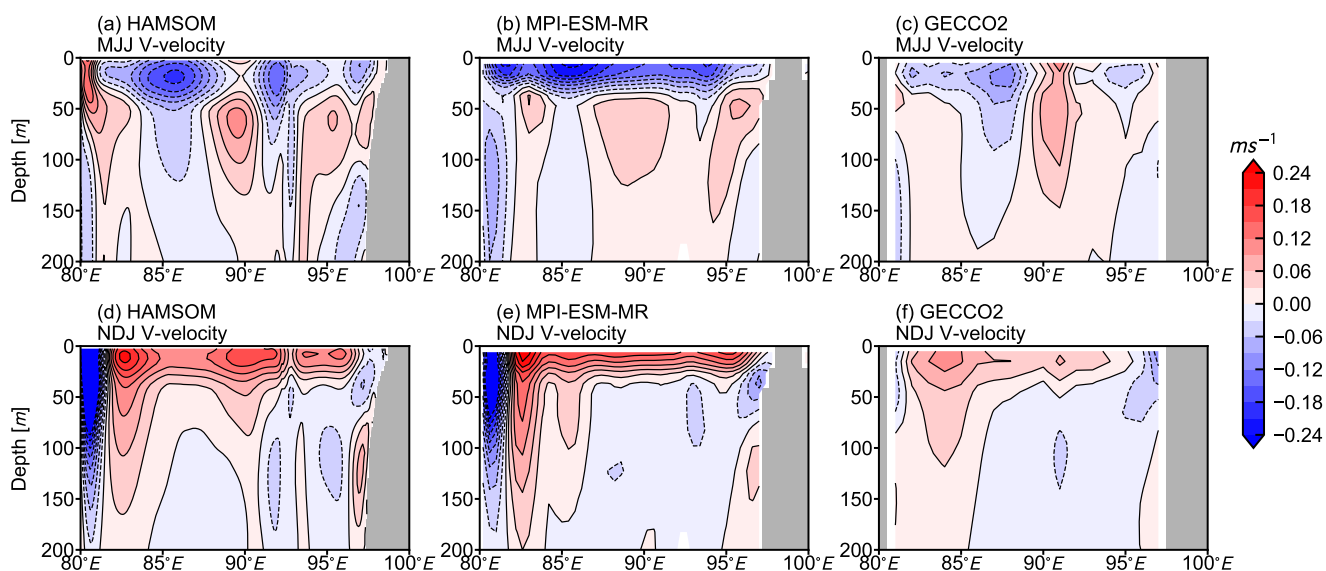
Figure 4. Depth-longitude section of climatological V-velocity (averaged over $10°N$ to $12°N$) during MJJ (a, b, c) and NDJ (d, e, f) from HAMSOM, MPI-ESM-MR, and GECCO2, respectively. The contour intervals are 0.03 ms^{-1}.
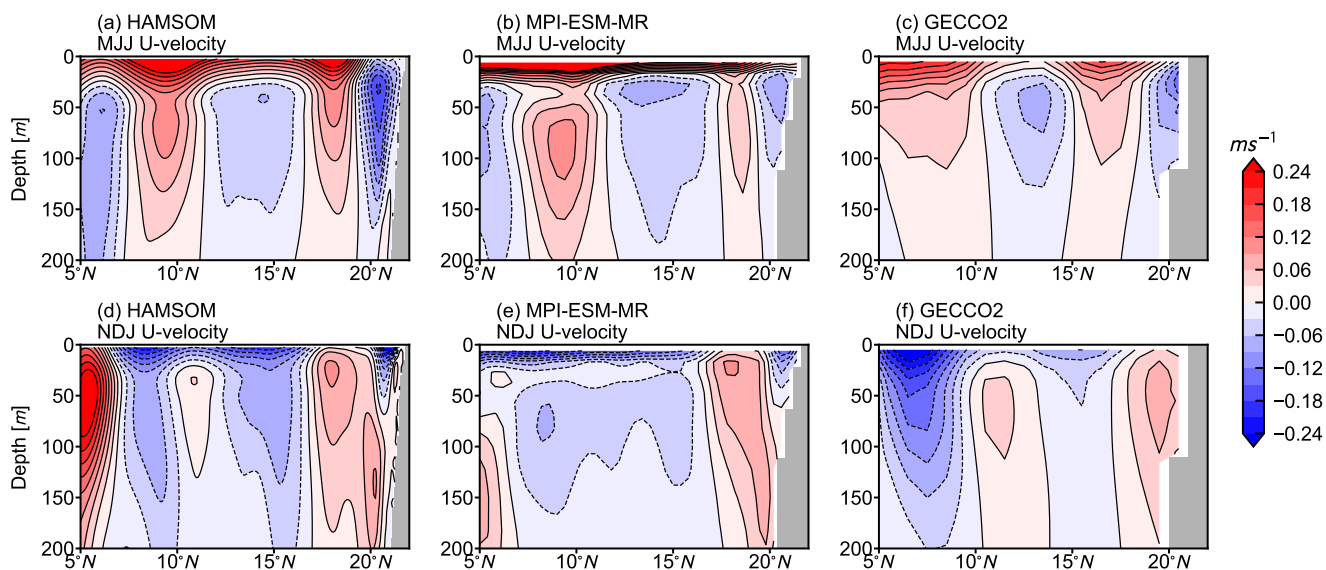
Figure 5. Depth-latitude section of climatological U-velocity (averaged over $88°E$ to $90°E$) during MJJ (a, b, c) and NDJ (d, e, f) from HAMSOM, MPI-ESM-MR, and GECCO2, respectively. The contour intervals are 0.03 ms^{-1}.
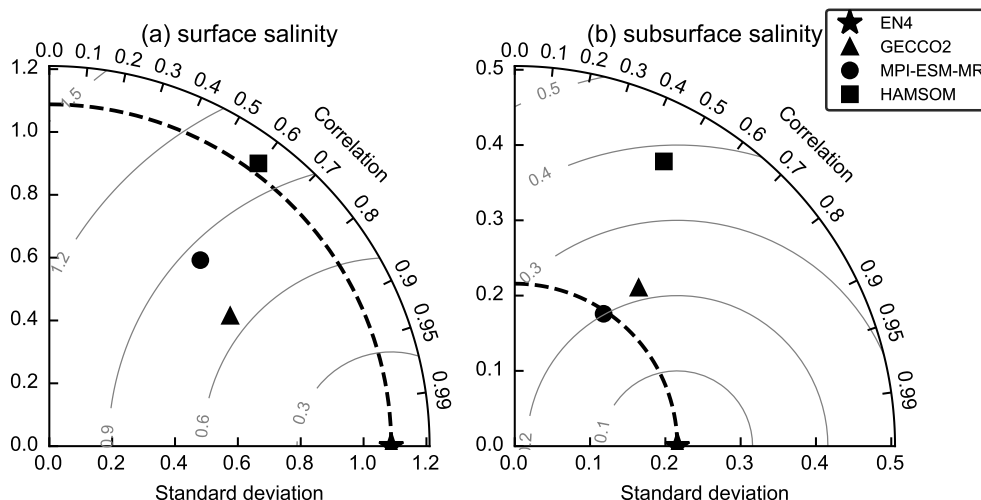
Figure 6. The Taylor diagram of (a) the surface salinity and (b) the subsurface salinity from 1971 to 2000 for different data sets. The observation-based EN4 (pentagon) is chosen as the reference data set. Grey lines indicate the centered RMS difference from the reference data set.

Figure 6 shows the Taylor diagram of the surface and subsurface salinity from HAMSOM and other data sets. The surface salinity standard deviation of HAMSOM is consistent with the observation-based EN4, indicating the realistic extent of HAMSOM in simulating realistically the amplitude of variations. For the subsurface salinity, observations are sparse in the BoB, so

135 the standard deviation of EN4 may not represent the reality. Overall, the standard deviations of HAMSOM and other data sets are in close agreement.

The above validation indicates that HAMSOM model can reproduce reasonable climatological fields and is reliable to be used as a numerical approach to study the physical processes and their specific contributions for the BoB. The interannual variations simulated by HAMSOM are combinations of external signals from MPI-ESM-MR and internal variabilities produced

140 by HAMSOM itself. Hence, it can be concluded that it is reasonable to discuss the interannual variability and corresponding physical processes simulated by HAMSOM in the following sections.

3 Lead-lag correlation

Four individual data sets and the downscaling model results are used in this section to examine if there is a statistically significant relationship between the subsurface temperature/salinity anomalies of the BoB and the SSTa of the tropical Indian

145 Ocean on the interannual scale, specifically, the IOD. The DMI describes the difference in SSTa between the western tropical Indian Ocean (WTIO) and the southeastern tropical Indian Ocean (SETIO, see Figure 1). It has a strong correlation with the principal component of EOF2 in the tropical Indian Ocean and is considered to be a reliable representation of the IOD (Saji

et al., 1999). The time series of DMI can indicate different phases of the IOD, so in this study, DMI also covers the meaning of IOD variability.

150   In order to focus on interannual variations, a 3-month running mean is applied on the monthly time series of DMI and the domain averaged subsurface temperature and salinity anomalies of the BoB. Normalized time series from HAMSOM, MPI-ESM-MR, GECCO2, and EN4 are shown in the first column of Figure 7. Subsurface is defined at a depth of $100\ m$, where wind-induced mixing is negligible, while upwelling/downwelling still plays a role. The DMI time series of HAMSOM is extracted from MPI-ESM-MR. DMI extracted from different data set have similar interannual variation characteristics,

155   but they do not precisely match. EN4 and GECCO2 both well capture some typical pIOD events like in the year 1994 and 1997. While the free run of MPI-ESM-MR shows a reasonable amplitude and interannual variations and does not exactly repeat the positive event in 1994, which has to be expected, since in this historical run only the statistical features have to be consistent. Lead-lag running Pearson correlation coefficients with a windows of 30 years between the DMI and the domain averaged subsurface temperature/salinity anomaly of the BoB are calculated. The value of the Pearson correlation determines

160   the extent of linearity between two variables. All these four data sets show that the subsurface temperature anomaly of the BoB negatively correlates to the DMI with a notable lag of about three months on average. Results from HAMSOM, MPI-EMS-MR, and GECCO2 also show a similar but positive correlation between the subsurface salinity anomaly of the BoB and the DMI, but results from EN4 do not.

     At the same time, by comparing the correlation magnitudes obtained from different data sets, it is noticeable that the cor-

165   relation is stronger when the data set shows a lower degree of freedom. For example, HAMSOM has less complexity than MPI-EMS-MR because it is a regional ocean model not including the ocean-atmosphere feedback processes. GECCO2 has a higher degree of freedom because assimilation processes are included. EN4 shows the highest degree of freedom of these four data sets because it is based on observations. However, the lack of observations and the objective analysis method used in EN4 limits its capability to reproduce the interannual subsurface salinity variability in the BoB. There is a weight index from

170   0 to 1 in EN4 which states the total weighting given to the observation increments when forming this analyses, and the mean weight of subsurface temperature and salinity for the BoB is 0.57 and 0.22, respectively, which points out the lack of salinity observations in the BoB. For example, there are almost no observations from 1951 to 1956 for subsurface salinity of the BoB, so the subsurface salinity anomaly shows artificial oscillations during this period (Figure 7j).

     The situation of lack of subsurface salinity observations in the BoB has improved since 2000, especially with the devel-

175   opment of Argo. We present related time series and their lead-lag relation calculated from RG_Clim in Figure 8. These time series support the correlations described by the other four data sets, and the subsurface salinity anomaly positively correlates with the DMI. The DMI leads the subsurface temperature anomaly, which can be seen for $100\ m$ and $150\ m$ depth. Such a leading relationship corresponding to the subsurface salinity anomaly suggested by model-related results does not show for $100\ m$, but a broad, positive correlation with a peak value close to 0.4 is clear. Moreover, at $150\ m$ depth, the DMI leads the

180   salinity anomaly for four months with a peak correlation of over 0.4. Although the time length of RG_Clim is not as long as the other data sets, this Argo-based data clearly shows that the subsurface salinity anomaly of the BoB is correlated to the zonal gradient of SSTa in the tropical Indian Ocean.
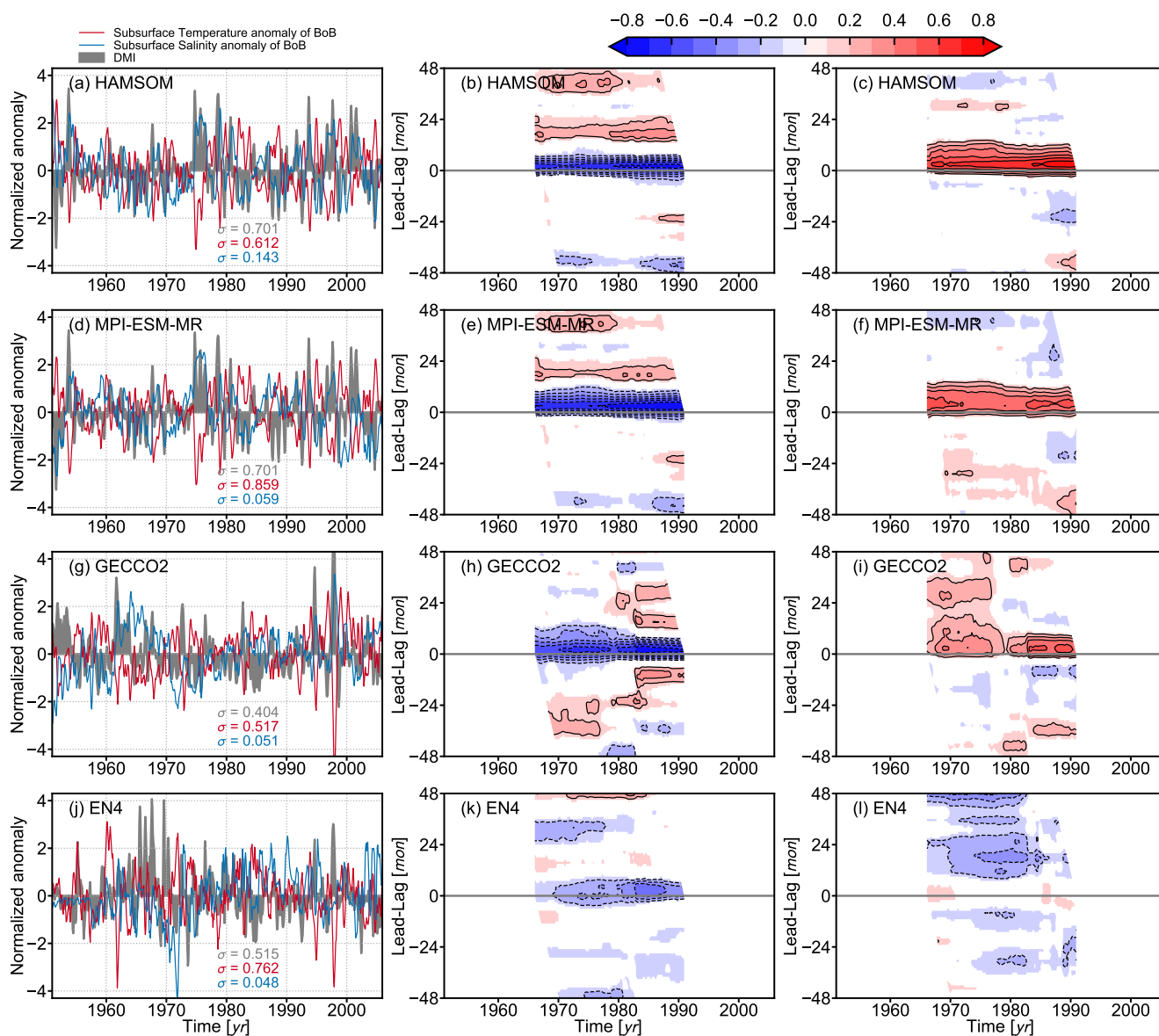
Figure 7. Normalized 3-month running mean of DMI, temperature anomaly and salinity anomaly at subsurface ($100\ m$) of the BoB from HAMSOM (a), MPI-ESM-MR (d), GECCO2 (g), and EN4 (j), respectively, are shown in the first column. The standard deviation σ is labelled with the corresponding color. Lead-lag running Pearson correlation coefficient with a windows of 30 years between the DMI and the subsurface temperature (salinity) anomaly from each data set is shown in the second (third) column, respectively. The contour intervals are 0.1. Only significant correlation coefficients with $p-value < 0.05$ are shaded.
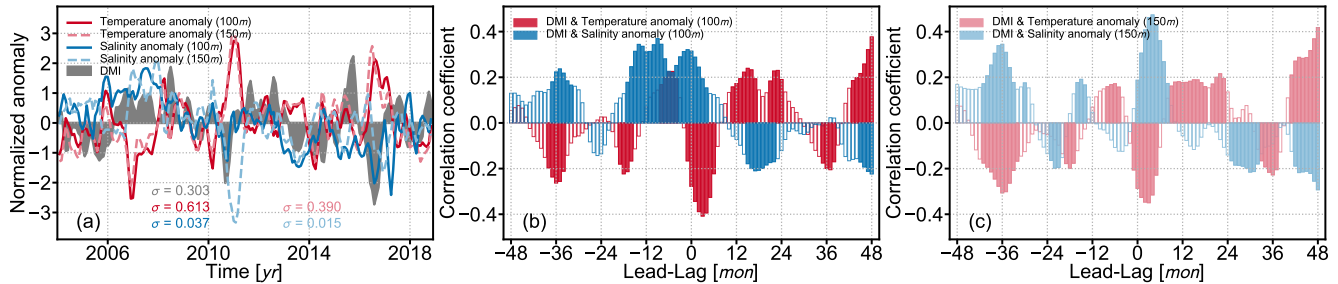
Figure 8. Normalized 3-month running mean of DMI, temperature anomaly and salinity anomaly at subsurface of the BoB from Argo based RG_Clim are shown in (a). The standard deviation σ is labelled with the corresponding color. Their respective lead-lag relations described by Pearson correlation coefficient between the DMI and subsurface anomalies are shown in (b, of $100\ m$) and (c, of $150\ m$). Only significant correlation coefficients with $p-value < 0.05$ are shaded.
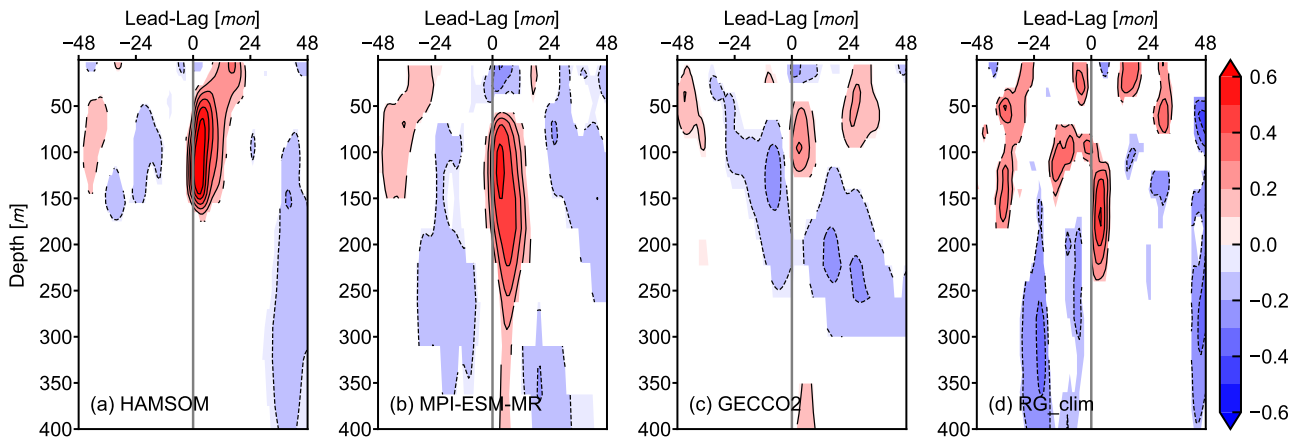
Figure 9. Lead-lag Pearson correlation coefficient between the DMI and salinity anomalies of the BoB at different depths from HAMSOM (a), MPI-ESM-MR (b), GECCO2 (c), and RG_Clim (d), respectively. The contour intervals are 0.1. Analysis period is from 1960 to 2005 for (a), from 1951 to 2005 for (b) and (c), and from 2004 to 2018 for (d), respectively. Only significant correlation coefficients with $p-value < 0.05$ are shaded.

Lead-lag Pearson correlation coefficients between the DMI and the salinity anomalies of the BoB at different depths are shown in Figure 9. Three aspects shown by these data sets are noteworthy. First, the most significant positive correlation appears below $50\ m$, and it is possible to be as deep as $250\ m$. Second, the DMI is leading a few months. Third, no obvious positive correlation is validated for the sea surface. These results suggest that the subsurface salinity anomalies of the BoB are indeed related to the IOD with a considerable delay. On average, their correlation reaches its maximum at a three-month delay. The local intense wind-induced mixing and other surface factors that are not closely related to the IOD are the reasons for the upper $50\ m$ of the BoB does not reflect this correlation.

190   By analyzing time series and their Pearson correlation coefficients, a time-delayed of about three months and positive correlation between the subsurface salinity anomaly of the entire BoB and the IOD represented by the DMI is revealed by observations, ocean synthesis, and modeling. A similar but negative correlation is also revealed between the subsurface temperature anomaly of the BoB and the IOD. The correlation between them differs in different data sets and becomes smaller when the data set has a higher degree of freedom; this is because some other variations may obscure the correlation we are focusing on.

195   However, this correlation can still be detected in the observational data, and it is very significant in the model-related data.

4   Mechanisms

In the above analysis, we have determined and discussed the lead-lag correlation between the domain averaged subsurface salinity anomaly of the BoB and the IOD. In this section, we mainly study how are these two variabilities connected by analyzing the HAMSOM result. Besides the connecting mechanisms, related physical processes of BoB's responses to IOD

200   events are also a subject of this section. Several reasons may result in changes in salinity anomalies of the BoB, for example, the salinity redistribution within the BoB or the salinity exchange between the BoB and its surroundings. Whatever the reason is, it will eventually be reflected in the salinity advection and diffusion. In this manner, an online analysis of the salinity budget is used in this section.

4.1   Connecting mechanism

205   To figure out the general feature of the response of the subsurface salinity in the BoB to the IOD, we construct composites of subsurface salinity anomalies during ASO, NDJ, FMA, and MJJ, of pIOD and nIOD years, respectively (Figure 10). The nIOD years (1979, 1988, 1992, 1998, 2004) are defined similarly to pIOD years, but with valleys below minus two normalized anomaly(see Figure 7d). The pattern of subsurface salinity anomalies is opposite during pIOD and nIOD events in ASO, as well as in NDJ when IOD events end with the DMI is returning to 0. This opposite feature is getting weaker over time, which

210   can be seen in FMA and MJJ. When a pIOD or nIOD event happened in the tropical Indian Ocean, areas near the BoB coasts first show large and statistically significant anomalies (Figure 10a, e). Next, these large and statistically significant anomalies show in most areas of the eastern basin but are limited to the western boundary areas (Figure 10b, f). This developing process is consistent with the characteristics of the coastal Kelvin wave and westward Rossby waves. We speculate the propagation process is as follows. First, the subsurface disturbance signals in the eastern equatorial Indian Ocean related to the IOD propa-

215   gate counterclockwise along the BoB coasts in the form of coastal Kelvin waves. The estimated wave phase speed is about 2.65 ms^{-1}, so it takes approximately two weeks to propagate from the equator to the northern BoB (Moore and McCreary, 1990; Cheng et al., 2013). These coastal Kelvin waves travel fast explaining why the related significant anomalies first shown-up near the coasts. Subsequently, these signals are reflected at the eastern boundary and propagate westward into the interior of the basin, since the phase speed of Rossby waves is predominantly moving westward. This also explains, why the signal near the

220   western boundary seems to be trapped there. From the significant area of influence in NDJ, these Rossby waves travel slower, which accounts for the domain averaged subsurface salinity anomaly lags the DMI.
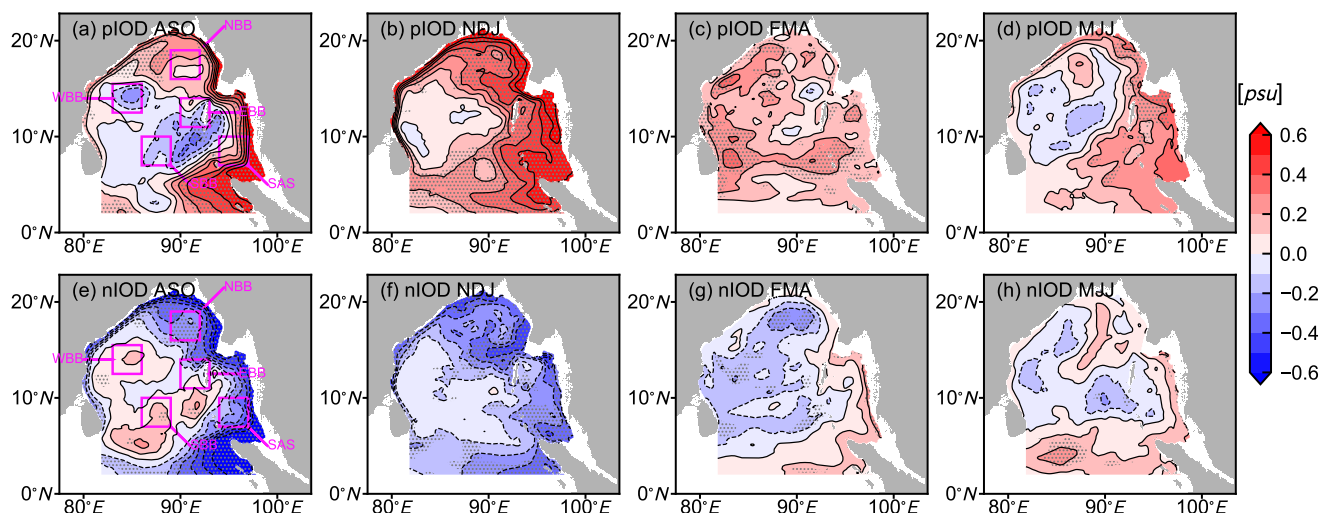
Figure 10. Composite of subsurface ($100\ m$) salinity anomalies during ASO (a, e), NDJ (b, f), FMA (c, g), and MJJ (d, h), of pIOD and nIOD years, respectively, from HAMSOM. The contour intervals are $0.1\ psu$. Anomalies significant at the 95% confidence level by a two-tailed Welch's t-test are hatched with grey dots. Selected subareas are marked with magenta boxes in (a) and (e).

Five subareas are selected in order to further investigate the response of different areas to the IOD (Figure 10a, e). A similar plot as Figure 9 but for subareas is presented in Figure 11. The closer the subarea is to the eastern boundary, the stronger the Pearson correlation between the DMI and the local salinity anomaly. When the subarea is close to but not directly at the western boundary, the correlation is relatively weak, which indicates that the signal is trapped at the west boundary (Figure 11d). Results from the subarea closest to the equator also show weaker correlations (Figure 11e), while results from the subarea that is far away from the equator but closer to the eastern boundary show stronger correlations (Figure 11c), suggesting that the signal propagates along the boundary rather than directly goes north. These features support our speculation that the interannual subsurface salinity variability in the BoB is connecting to the IOD through both coastal Kelvin waves and westward Rossby waves.

It is challenging to observe Rossby waves in the BoB if we only use monthly data because of the basin size. Therefore, daily data from HAMSOM is used for tracking Rossby waves. As the Hovmöller diagram of daily climatological subsurface salinity averaged over $10°N$ to $12°N$ shown in Figure 12a, a westward Rossby wave signal can be seen by the westward low-salinity water. This signal takes approximately four months to cross the basin zonally, and from this, it can be estimated that its propagation speed is about $0.16\ ms^{-1}$. Low-salinity water already appears at the western boundary before the westward Rossby wave had reached here. In May, even though the westward Rossby wave signal represented by the low-salinity water has reached the western boundary, the water at the western boundary is as salty as the water at the eastern boundary, demonstrating that coastal Kelvin waves travel faster and dominate the coastal zone in the BoB.
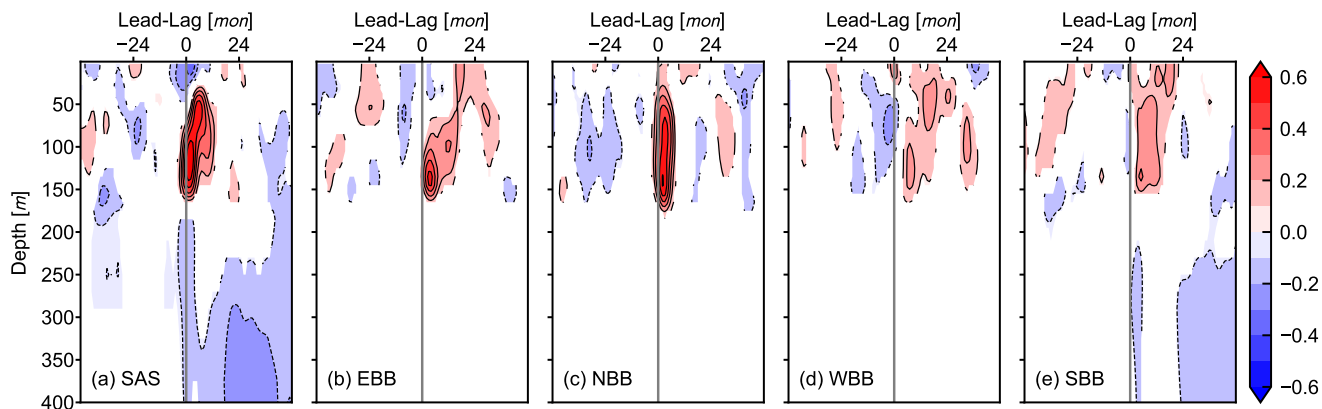
Figure 11. Lead-lag Pearson correlation coefficient between the DMI and the salinity anomaly of subareas SAS (a), EBB (b), NBB (c), WBB (d), and SBB (e), respectively, at different depths, from HAMSOM. The contour intervals are 0.1. Analysis period is from 1960 to 2005. Only significant correlation coefficients with $p - value < 0.05$ are shaded.
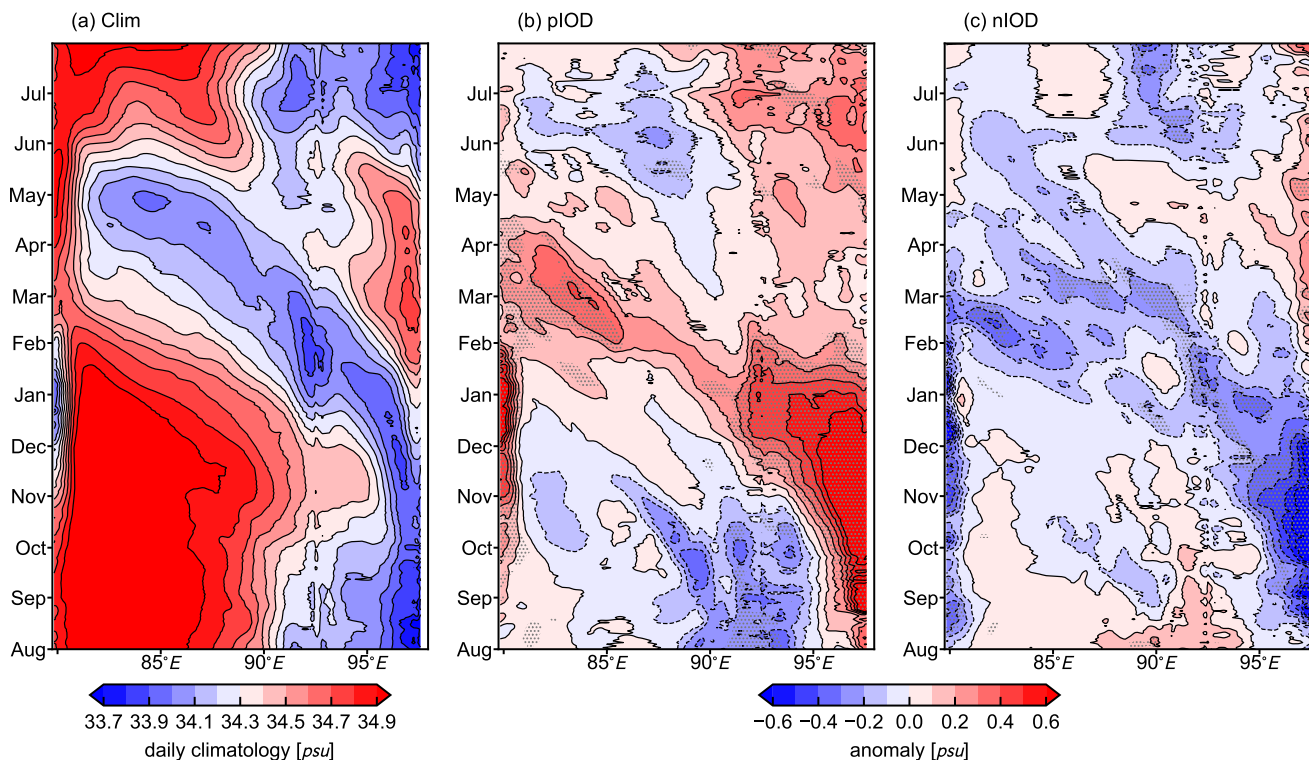
Figure 12. Hovmöller diagram of daily climatological subsurface ($100\ m$) salinity (a; averaged over $10°N$ to $12°N$) from HAMSOM. The intervals are $0.1\ psu$. (b and c) as in (a), but for composite of subsurface salinity anomalies for pIOD (b) and nIOD (c). The intervals are also $0.1\ psu$. Anomalies significant at the 95% confidence level by a two-tailed Welch's t-test are hatched with grey dots.

In pIOD and nIOD years, the propagation characteristics of coastal Kelvin waves and westward Rossby waves are essentially the same as the climatology, but carrying positive and negative anomalies, respectively (Figure 12b, c). These statistically significant anomalies first appear at the eastern boundary, then at the western boundary, then in the basin interior, which indicates that the extreme IOD signal is propagated to the entire BoB by both coastal Kelvin waves and westward moving Rossby waves. Previous studies have demonstrated the dominant role of coastal Kelvin waves in sea level variability in the BoB, especially near the eastern and northern boundaries (Han and Webster, 2002; Cheng et al., 2013). Our analysis about subsurface salinity anomalies suggests that the coastal Kelvin waves also dominate the western boundary when extreme IOD events occur. The positive anomalies associated with pIOD reduce the zonal gradients of subsurface salinity, while the negative anomalies associated with nIOD increase their zonal gradients and result in different baroclinic Rossby wave modes with different propagating speed.

We also calculated the correlation between the local wind curl and salinity in the BoB and all subareas (not shown). The results show that these two parameters are strongly correlated on the seasonal scale, but there is no significant correlation on the interannual scale, which indicates that the interannual signal is not from the wind field. Therefore, the model result suggests that the propagation process through coastal Kelvin waves and westward Rossby waves is the primary connecting mechanism of the delayed positive correlation between the subsurface salinity anomaly of the BoB and the zonal SSTa gradient in the tropical Indian Ocean. The interannual variability of thermocline depth in the eastern Indian Ocean is dominated by equatorial Indian Ocean winds, which drive eastward moving equatorial Kelvin waves that are blocked at the Sumatra-Java coasts (Du et al., 2012; Chen et al., 2015). It has been shown that enhanced upwelling occurs in the eastern Indian Ocean during pIOD years (Chen et al., 2016). This enhanced upwelling signal is converted into coastal Kelvin waves, which propagate counterclockwise along the boundary of the BoB. Subsequently, this signal is reflected at the eastern boundary forming westward moving Rossby waves that keep propagating into the central basin. During nIOD events the related subsurface anomalies in the BoB are modulated in a similar way.

4.2 Contributions of advection and diffusion

By outputting terms concerning salinity change rate related to the contribution of advection and diffusion, we can precisely close the salinity budget and analyze changes of advection and diffusion in the BoB in different IOD phases. The salinity budget can be written as follows:

$$\frac{\partial S}{\partial t} = -u\frac{\partial S}{\partial x} - v\frac{\partial S}{\partial y} - w\frac{\partial S}{\partial z} + \frac{\partial}{\partial x}\left(\kappa_H \frac{\partial S}{\partial x}\right) + \frac{\partial}{\partial y}\left(\kappa_H \frac{\partial S}{\partial y}\right) + \frac{\partial}{\partial z}\left(\kappa_V \frac{\partial S}{\partial z}\right), \tag{1}$$

where S is salinity, u, v and w are zonal, meridional and vertical velocity, respectively, κ_H and κ_V are horizontal and vertical diffusion coefficients, respectively. The left side represents the salinity tendency (ST), while the right side from left to right represents the salinity change rate of zonal (UADV), meridional (VADV), vertical (WADV) advection, and of zonal (UDIF), meridional (VDIF), vertical (WDIF) diffusion, respectively.

A salinity budget of the BoB at $100\ m$ during ASO is presented in Figure 13. For terms on the right side of the equation 1, at this depth, the advection term is much larger than the diffusion term, and the vertical diffusion term is larger than the
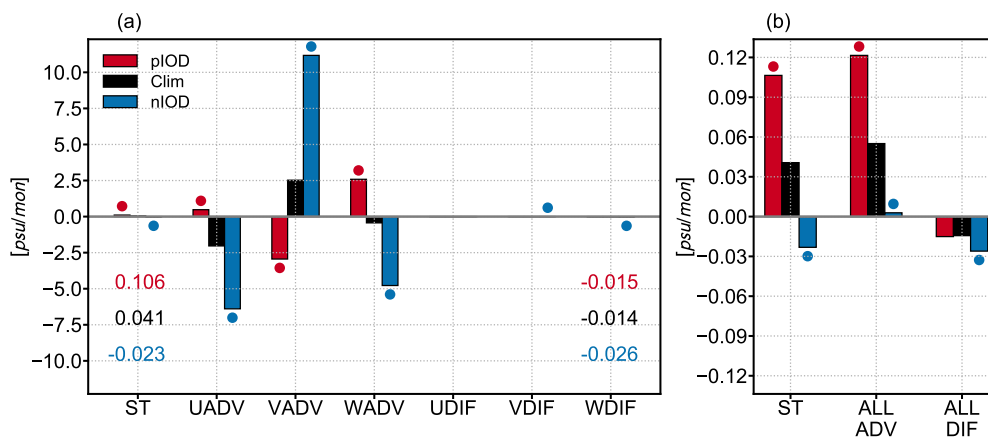
Figure 13. Domain-averaged subsurface (100 m) salinity tendency and related salinity change rate terms of the BoB during ASO of pIOD years, nIOD years, and climatological period, respectively, from HAMSOM (a). The values of ST and WDIF in different cases are labelled with the corresponding color. The sum of all advection terms and the sum of all diffusion terms are shown in (b). Dots with corresponding color indicate that they are significant different at the 95% confidence level by a two-tailed Welch's t-test comparing to the climatology.

horizontal diffusion term. The sum of these large advection terms becomes much smaller and about the same magnitude as the salinity tendency and the vertical diffusion (Figure 13b). All advection terms show significant differences in pIOD and nIOD events comparing to the climatology. Especially during nIOD, the salinity changes caused by advection at each direction

275   increase, which is believed to be the result of increased zonal subsurface salinity gradients associated with nIOD. Meanwhile, it can be seen that at this depth, on the average for the entire BoB, the vertical advection contributes positively to the positive salinity tendency of pIOD and the negative salinity tendency of nIOD. In contrast, the summed horizontal advection contributes negatively.

Figure 14 shows the sum of advection terms, the sum of diffusion terms, and the final salinity tendency at different depths

280   of the BoB and other selected subareas during ASO. The salinity tendency shows a subsurface salinity increase (decrease), indicating a positive (negative) anomaly for pIOD (nIOD) years, which in this season show an obvious response to the IOD signal (Figure 14m, n, o). The results in different regions show that the salinity tendency is dominated by diffusion near the surface, while it is dominated by advection for the subsurface. The dominant role of diffusion near the surface can be explained by the wind-induced mixing. The salinity change rate due to advection shows more obvious responses in the subsurface during

285   both extreme IOD events, especially in the subareas SAS and EBB, and the entire BoB, suggesting that the correlation we are discussing is mainly caused by advection processes.

As we analyzed through multiple data sets, there exists a delayed positive correlation between the subsurface salinity anomaly of the BoB and the zonal SSTa gradient in the tropical Indian Ocean represented by the DMI. Therefore, by analyzing the salinity budget of the BoB, the model results suggest that the contribution of advection plays a dominant role in this
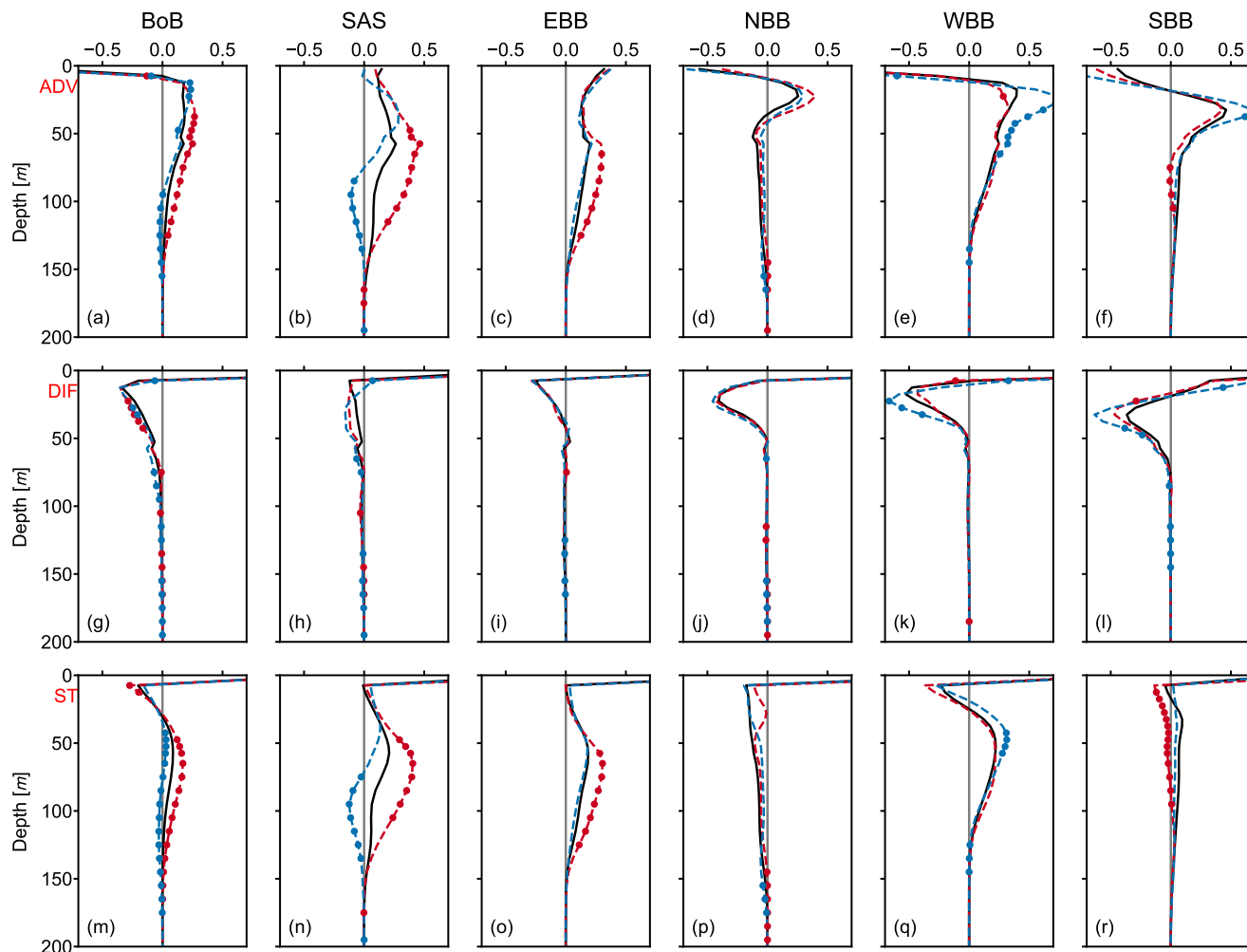
Figure 14. Sum of domain-averaged advection terms (in psu/mon) at different depths of the BoB (a) and subareas (b, c, d, e, f) during ASO. Black solid line is for the climatology; red and blue dashed line is for the composite of pIOD and nIOD years, respectively. Dots with corresponding color indicate that they are significant different at the 95% confidence level by a two-tailed Welch's t-test comparing to the climatology. The second and third row as in the first row, but for sum of domain-averaged diffusion terms and salinity tendency, respectively.

290   correlation. Particularly, the vertical advection contributes positively, while the horizontal advection contributes negatively to the correlation stated above.

5   Conclusions

In this study, we have investigated the subsurface salinity variability in the BoB on the interannual scale and its relation with the IOD through multiple data sets, and we have also investigated the corresponding mechanisms through a regional ocean model

295   simulation. The regional downscaling model successfully reproduces the reasonable climatology of the salinity and flow field, proving its capability for investigating the physical processes in the BoB. In order to further discuss advection and diffusion contributions to salinity, we have performed an online analysis of salinity budget. This approach can precisely close the salinity budget, and hence, reflects the response of salinity in the BoB to the IOD, also with respect to the driving mechanisms in a quantitative manner.

300   A delayed positive correlation between the subsurface salinity anomaly of the BoB and the IOD was revealed by analyzing their Pearson correlation coefficient. This correlation is not only shown in the modeling data but also in the ocean synthesis and observations. On average, a lag of three months shows the strongest correlation. Meanwhile, the correlation is relatively weaker when the data set shows a higher degree of freedom, suggesting that some processes exist in reality, which are not well resolved by numerical simulations that may disturb the relation between the subsurface salinity variability of the BoB and the

305   IOD on the interannual scale. From this perspective, the numerical simulation is a more suitable method for investigating the physical processes behind this correlation.

The model results suggested that the interannual subsurface salinity variability in the BoB and the IOD variability in the tropical Indian Ocean are connected by both coastal Kelvin waves and westward moving Rossby waves. First, coastal Kelvin waves carry the disturbance signal in the eastern equatorial Indian Ocean that is related to the IOD, propagating counterclockwise

310   along the BoB coasts. subsequently, the signal reflects at the eastern boundary and propagates westward to the basin interior in the form of Rossby waves. The main reason that the domain averaged subsurface salinity anomaly lags the DMI several months is that the westward Rossby waves travel slowly. The analysis of the salinity budget revealed that the contribution of advection plays a dominant role in this correlation. Particularly, the vertical advection shows a positive contribution, while the horizontal advection shows a negative contribution.

315   For the eastern equatorial Indian Ocean, the weakening of Wyrtki jet and the strengthening of upwelling caused by the easterly wind anomalies during pIOD result in freshening at the surface and saltening at the subsurface (Kido and Tozuka, 2017). Large-scale wind stress anomalies play the dominant role in the salinity anomalies of this area during IOD events through modulating salinity advection mainly (Kido et al., 2019a). For the BoB, the model results suggest that the remote forcing from the equatorial Indian Ocean converted into coastal Kelvin waves and westward moving Rossby waves is the

320   principal mechanism, which is responsible for the interannual salinity variability in the subsurface. Correlation analysis shows that the subsurface salinity anomaly positively correlates with the IOD, while the subsurface temperature anomaly negatively correlates, which implies that the IOD remotely modulates the vertical advection in the BoB subsurface. The salinity budget

of HAMSOM results proves that the vertical advection positively contributes to the correlation between the subsurface salinity anomaly of the BoB and the IOD. The decomposition of advective anomalies (Zhang et al., 2013; Li et al., 2016; Kido and Tozuka, 2017) will be helpful to understand the specific contribution of each specific process. For instance, it will allow separately diagnose the contribution of the anomalous vertical salinity gradient and the contribution of the anomalous vertical velocity. During the pIOD phase, intensified upwelling occurs in the eastern Indian Ocean (Nyadjro and McPhaden, 2014; Chen et al., 2016), inducing an uplift of cold, more saline water along the eastern BoB coasts. This anomaly in turn induces coastal Kelvin waves, which are reflected at topographic disturbances, inducing Rossby waves that move westward to the central basin. Through this chain of processes, the remote forcing from the equatorial Indian Ocean is able to dominate the interannual subsurface temperature/salinity variability in the BoB. The BoB is known as a region with vigorous mesoscale eddy activity (Chen et al., 2012, 2018). How these eddies affect the evolution of subsurface salinity anomalies requires future studies.

Based on this discovered correlation and related mechanisms, one application is using the DMI to predict the subsurface ocean state in the BoB. The subsurface ocean state affects the barrier layer and mixed layer depth, as well as the near-surface state and the air-sea energy transfer. However, how the subsurface parameters response to the IOD affects its local upper ocean still needs more studies. Previous studies have demonstrated the importance of forcing from the equator to the BoB, such as sea surface height, thermocline, and circulation structure (Girishkumar et al., 2013; Chatterjee et al., 2017; Pramanik et al., 2019), especially for the mechanisms forcing the East India Coastal Current (Yu et al., 1991; McCreary et al., 1996; Shankar et al., 1996). The response of the subsurface salinity field we discussed may also affect the local flow field and mesoscale eddies. Coastal Kelvin waves and westward Rossby waves play a vital role in the process of receiving information from the equator in the BoB, and similarly, they also play their role on the interannual scale. Especially during the nIOD phase, the increase of the zonal subsurface salinity gradients makes it easier to excite high mode westward Rossby waves, suggesting the effect of IOD on the subsurface thermohaline circulation in the BoB.

In addition to these, in the future we will investigate how the relationship between the BoB subsurface parameters and the tropical Indian Ocean surface parameters will be affected by the impact of climate change. The sea surface is more susceptible to global warming, and the BoB subsurface has a notable connection to the tropical Indian Ocean surface. The sea surface warming may also affect the subsurface and even deeper through dynamic mechanisms. Therefore, how the BoB subsurface responds to climate change is the next subject we are going to study.

Data availability. The HAMSOM data are available at https://cera-www.dkrz.de/WDCC/ui/cerasearch/entry?acronym=DKRZ_LTA_119_ds00001. The objective analyses EN4 data are available from this site (https://www.metoffice.gov.uk/hadobs/en4/). The ocean reanalysis GECCO2 data are available in the Integrated Climate Data Center (https://icdc.cen.uni-hamburg.de/). The data of MPI-ESM-MR historical run are avaiable from the CMIP5 database (https://esgf-node.llnl.gov/projects/cmip5/). The Roemmich-Gilson Argo Climatology data are avaiable from this site (http://sio-argo.ucsd.edu/RG/_Climatology.html). The bathymetric data were obtained from the SRTM30_PLUS (ftp://topex.ucsd.edu/pub/srtm30_plus).

355 The reference data for bias correction were obtained from ERA5 (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5), WOA18 (https://www.nodc.noaa.gov/OC5/woa18/), and WaterGAP (http://www.watergap.de/).

Author contributions. The idea and the methodology was first proposed and discussed by all authors. ZZ deployed the numerical modeling under the supervision of TP. ZZ performed the data analyse. TP and XC validated the investigation. All authors contributed to the discussion of the results and the review and editing of the manuscript.

360 *Competing interests.* The authors declare that they have no conflict of interest

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