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Key Points:

- The Makassar Strait throughflow (MST) shows significant seasonality associated with the along-strait sea surface height gradient
- Halosteric dynamic height (DH) dominates the seasonal variability of the sea surface DH gradient and MST
- Advection of freshwater from the Karimata Strait and local precipitation constitute the major freshwater forcing for the MST

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Quantifying the Contribution of Salinity Effect to the Seasonal Variability of the Makassar Strait Throughflow

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Abstract The Makassar Strait throughflow (MST) constitutes a significant component of the Indonesian throughflow (ITF) and plays a pivotal role in the interbasin exchange between the Indian and Pacific Oceans. While previous studies have suggested that the buoyancy forcing plays a role in influencing the seasonality of the MST, the quantitative contribution of salinity effect on MST seasonality remains unclear. Here we use the measurements from the Monitoring ITF program and the Global Ocean Physics Reanalysis product to investigate the seasonality of MST and quantify the impact of the salinity effect. We find that the halosteric variability due to the salinity effect contributes to approximately $(69.6 \pm 11.7) \%$ of the total seasonal variability of surface dynamic height gradient along the Makassar Strait, and dominates the seasonality of the upper layer MST. The primary drivers for freshwater forcing are horizontal advection through the Karimata Strait and precipitation in the Java Sea.

Plain Language Summary The Indonesian throughflow (ITF) connects the tropical Pacific and Indian Oceans, playing a big role in moving heat and freshwater between them. The Makassar Strait throughflow (MST), which is a major part of the ITF, is important for both regional and global climate systems. Previous studies suggest that the freshwater flux can affect the transport and vertical structure of MST throughout the year. In this study, we used current observations in the Makassar Strait and other high-resolution data to investigate how MST changes with each season, specifically focusing on how salinity changes affect it. The impact of salinity changes on the seasonal variations in MST overwhelms that of temperature changes. Most of the freshwater in the Makassar Strait comes from water flowing through the Karimata Strait, with some contribution from local rainfall in the Java Sea.

1. Introduction

The Indonesian throughflow (ITF) flows through the Indo-Pacific warm pool, connecting the tropical Pacific and Indian Oceans (Gordon, 1986; Han et al., 2014; D. Hu et al., 2015; Wijffels et al., 2008). It plays a crucial role in facilitating the cross-basin exchange of water mass and energy (Du et al., 2023; Gordon & Fine, 1996; S. Hu et al., 2019; Jyoti et al., 2019; Sprintall & Révelard, 2014; Sprintall et al., 2019), thereby regulating the Indo-Pacific climate and influencing the global thermohaline circulation (Feng et al., 2018; S. Hu et al., 2019; Liu et al., 2016; Makarim et al., 2019; Sprintall et al., 2014; Ummenhofer et al., 2021). During the International Nusantara Stratification and Transport (INSTANT) program from 2004 to 2006, observational data indicate that ITF volume transport is approximately 15 Sv (1 Sv = 10^6 m³/s). The ITF exhibits significant seasonal variability with a weaker flow during boreal winter influenced by the local monsoon (Gordon, 1996; Gordon et al., 2010; Peña-Molino et al., 2022; Sprintall et al., 2009; Wei et al., 2016), substantial interannual variability mainly related to El Niño-Southern Oscillation (ENSO) (England & Huang, 2005; S. Hu & Sprintall, 2016; Potemra & Schneider, 2007; Santoso et al., 2022; Susanto et al., 2012; van Sebille et al., 2014), and considerable decadal fluctuations influenced by the Pacific Decadal Oscillation/Interdecadal Pacific Oscillation (PDO/IPO) (Feng et al., 2011, 2016; S. Hu & Sprintall, 2017; Li et al., 2018, 2020; Phillips et al., 2021).

The Makassar Strait throughflow (MST) constitutes a significant component of the ITF. Observations from the Monitoring ITF (MITF) program, which deployed moorings in Labani Channel, indicate that the mean volume transport of the MST during the INSTANT period is 11.6 Sv, which is approximately 77% of the total volume transport of ITF observed by the INSTANT program (Gordon et al., 2010). Measurements from the MITF

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program suggest that the mean volume transport of the MST during 2004–2017 was approximately 12–13 Sv (Gordon et al., 2019; Li et al., 2018).

Wyrki (1987) hypothesized that the basin-scale pressure gradient between the Pacific and the Indian Oceans drives the ITF, and the hypothesis is then developed based on observation (Andersson & Stigebrandt, 2005; Sprintall & Révelard, 2014; Zhuang et al., 2013), reanalysis data (Tillinger & Gordon, 2009; Shilimkar et al., 2022), numerical models (Feng et al., 2011), and a deep-learning approach (Xin et al., 2023). While wind forcing is suggested to be a major driver of multi-scale variability of ITF and MITF, the salinity effect related to freshwater forcing is thought to be crucial as well on several time scales (e.g., Gordon et al., 2003, 2012; S. Hu & Sprintall, 2016, 2017; Lee et al., 2019). S. Hu and Sprintall (2016) found that the salinity effect contributes approximately $(36 \pm 7) \%$ of the total interannual variability of the ITF, and the trend of ITF during 2004–2014 was mainly caused by intensified freshwater input (S. Hu & Sprintall, 2017), consistent with the salinity-caused increasing trend of 1.3 Sv/decade over 1993–2018 (Guo et al., 2023).

On a seasonal time scale, Gordon et al. (2003) proposed the “freshwater plug” mechanism that fresher waters from the South China Sea (SCS) through the Karimata Strait feed the Java Sea in boreal winter, and thus depress the southward sea surface height gradient along the Makassar Strait, resulting in the weakening of MST. Lee et al. (2019) found that strong freshening due to precipitation in the Indonesian seas in boreal winter reduces the southward sea surface height gradient and weakens the ITF. However, the detailed dynamic processes that modulate the freshwater input associated with this freshwater plug remain largely unexplored. In particular, the quantitative contribution of salinity effect on the seasonality of the MST remains unclear.

The objective of this study is to quantitatively investigate the contribution of the salinity effect on the seasonal fluctuation of the MST and related dynamic processes within the Makassar Strait. To do this, we will separate the halosteric and thermosteric components and quantitatively evaluate the contribution of the halosteric component on the seasonality of steric height and MITF, using in situ mooring observations and a high-resolution ocean reanalysis product.

2. Data and Methods

Current measurements from the Arlindo (Gordon & Fine, 1996) and MITF (Gordon et al., 2019) moorings in the Labani Channel (marked with a diamond in Figure 1a) are used to obtain the seasonal variability of the volume transport through the Makassar Strait. The Arlindo moorings measured velocities in the upper 300 m layer at $2^{\circ}52'S$, $118^{\circ}27'E$ and $2^{\circ}52'S$, $118^{\circ}37'E$ during November 1996–July 1998, and the MITF mooring measured the velocity at $2^{\circ}52'S$, $118^{\circ}27'E$ over the 40–760 m layer during 2004–2017.

High-resolution salinity, temperature, and current data over 1993–2020 from the Global Ocean Physics Reanalysis (GLORYS, Jean-Michel et al., 2021) product are used as well. The GLORYS product from the Copernicus Marine Service is a global ocean eddy-resolving reanalysis with a horizontal resolution of $1/12^{\circ}$ and 50 vertical levels and spans from 1993 to 2020. The GLORYS product is based on the Nucleus for European Modeling of the Ocean (NEMO) platform, which is driven by the ECMWF Reanalysis-Interim (ERA-Interim) and ECMWF Reanalysis 5 (ERA5) and assimilates remote sensing and in situ observations with a reduced-order Kalman filter (Jean-Michel et al., 2021).

We also used the absolute dynamic topography (ADT, 1993–2020) data from the Archiving, Validation, and Interpretation of Satellite Oceanographic data (AVISO, Ubelmann et al., 2021). The satellite-derived sea surface salinity (SSS) during 2015–2020 is from the Soil Moisture Active Passive (SMAP, Colliander et al., 2017) and provided by the National Aeronautics and Space Administration (NASA). The freshwater flux due to precipitation is estimated with the monthly data from the Global Precipitation Climatology Project (GPCP) from 1979 to 2020 (Adler et al., 2018). The data sets including AVISO ADT, SMAP SSS, and GPCP precipitation have a resolution of $1/4^{\circ}$.

The halosteric component $DH(S, \bar{T})$ and thermosteric component $DH(\bar{S}, T)$ are calculated following the method proposed by S. Hu and Sprintall (2016), where T and S are time varying variables, and $\bar{S}$ or $\bar{T}$ are climatological mean values. The freshwater transport (FW) is calculated following the method of Xu et al. (2021):

$$FW = \iint v \left(\frac{S_{xz} - S_{js}}{S_{xz}} \right) dx dz \quad (1)$$

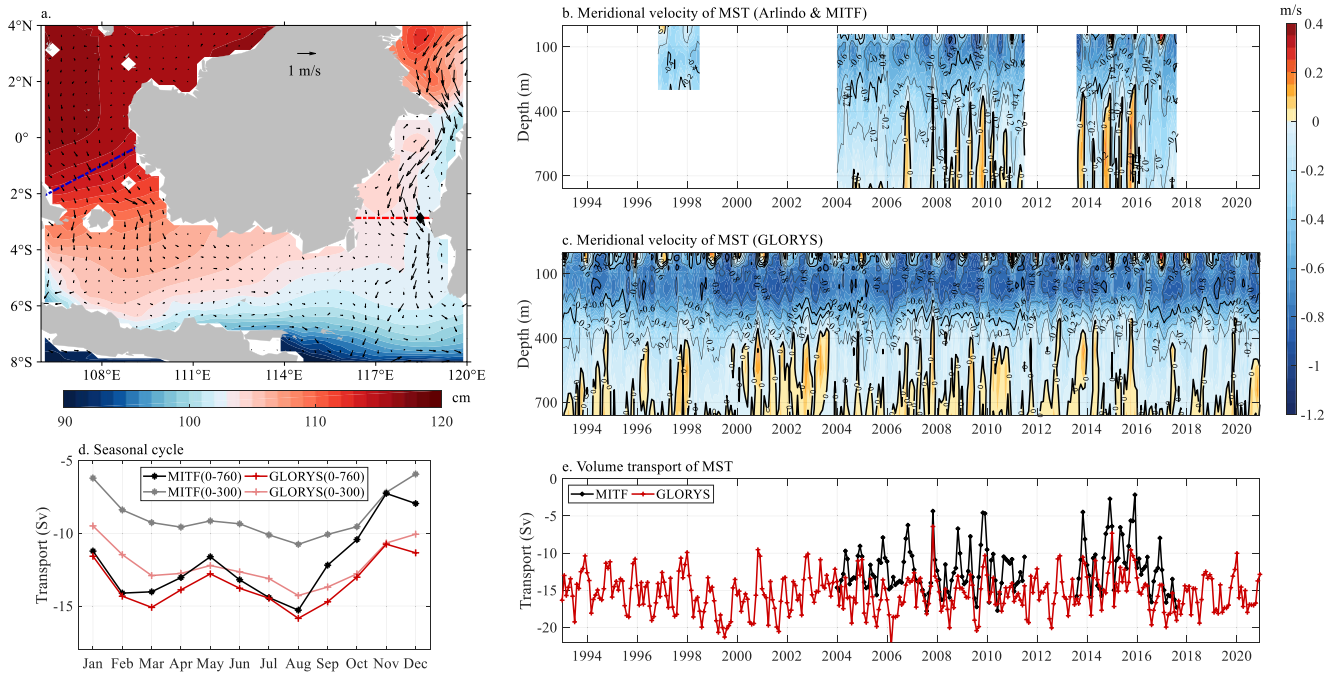


Figure 1. The Makassar Strait throughflow (MST) in observations and GLORYS. (a) Climatological mean surface current field (vectors) from GLORYS and absolute dynamic topography (color shading) from AVISO averaged over 1993–2020. Black diamond in panel (a) indicates the location of the Labani Channel, and dashed lines in panel (a) indicate the sections to calculate freshwater transport through the Karimata Strait (blue) and the Labani Channel (red). (b) Observational meridional velocity at the Labani Channel. (c) As in panel b, but for GLORYS. (d) The seasonal cycle of the volume transport of the MST in the indicated layers from the MITF (black) and GLORYS (red). (e) The volume transport of the MST (integrated in the upper 760 m) from the MITF (black) and GLORYS (red). Negative values represent southward.

where v is velocity perpendicular to the vertical section, S_{xz} is the salinity of the grid box, and S_{js} is the spatially mean salinity of the Java Sea.

3. Results

Figure 1 presents the mean sea surface current and time series of MST from observations and GLORYS. The GLORYS velocity indicates that there is a strong southward current (~ 0.6 m/s) in the Makassar Strait and a relatively weak southward current (~ 0.2 m/s) across the Karimata Strait (Figure 1a), which is in agreement with previous studies (e.g., Gordon et al., 2012; Xu et al., 2021). The MST in the Labani Channel predominantly flows southward and is mainly confined in the upper 400 m layer with a peak in the subsurface layer (Figures 1b and 1c). Significant seasonal variations of the MST are found in both the MITF and GLORYS (Figure 1d). It should be noted that anomalous northward currents exist in the surface layer, indicating a reverse of the surface MST in certain seasons (Figures 1b and 1c).

The GLORYS velocity field is consistent with the observed sea surface height gradient shown in ADT, which is high in the SCS and the Sulawesi Sea, and low in the Java Sea. Even though the GLORYS velocity in the upper layer is stronger than observations, the MST in the Labani Channel is well simulated by GLORYS in terms of the vertical velocity structure and seasonal cycle of volume transport (Figure 1). The mean volume transport of MST in GLORYS is (-14.3 ± 2.3) Sv over 1993–2020, and (-14.1 ± 2.3) Sv over the MITF period, which is close to the observed transport of (-12.2 ± 2.8) Sv. The correlation coefficient between the MST transports from the MITF and GLORYS is 0.8 (significant at the 99% confidence level), indicating that the GLORYS does a good job in reproducing the observed variability of MITF transport (Figure 1e).

To further illustrate the seasonal variability of MST, we calculated the seasonal mean meridional velocity, DH, halosteric DH, and thermosteric DH in boreal winter (December, January and February, DJF) and summer (June, July and August, JJA), and then the seasonal anomalies are calculated by removing the annual mean values (Figure 2). The meridional velocity has a core near the Labani Channel, which is approximately -0.8 m/s at ~ 110 m in boreal winter (Figure 2a) and -1 m/s at ~ 90 m in boreal summer (Figure 2b). The seasonal variations

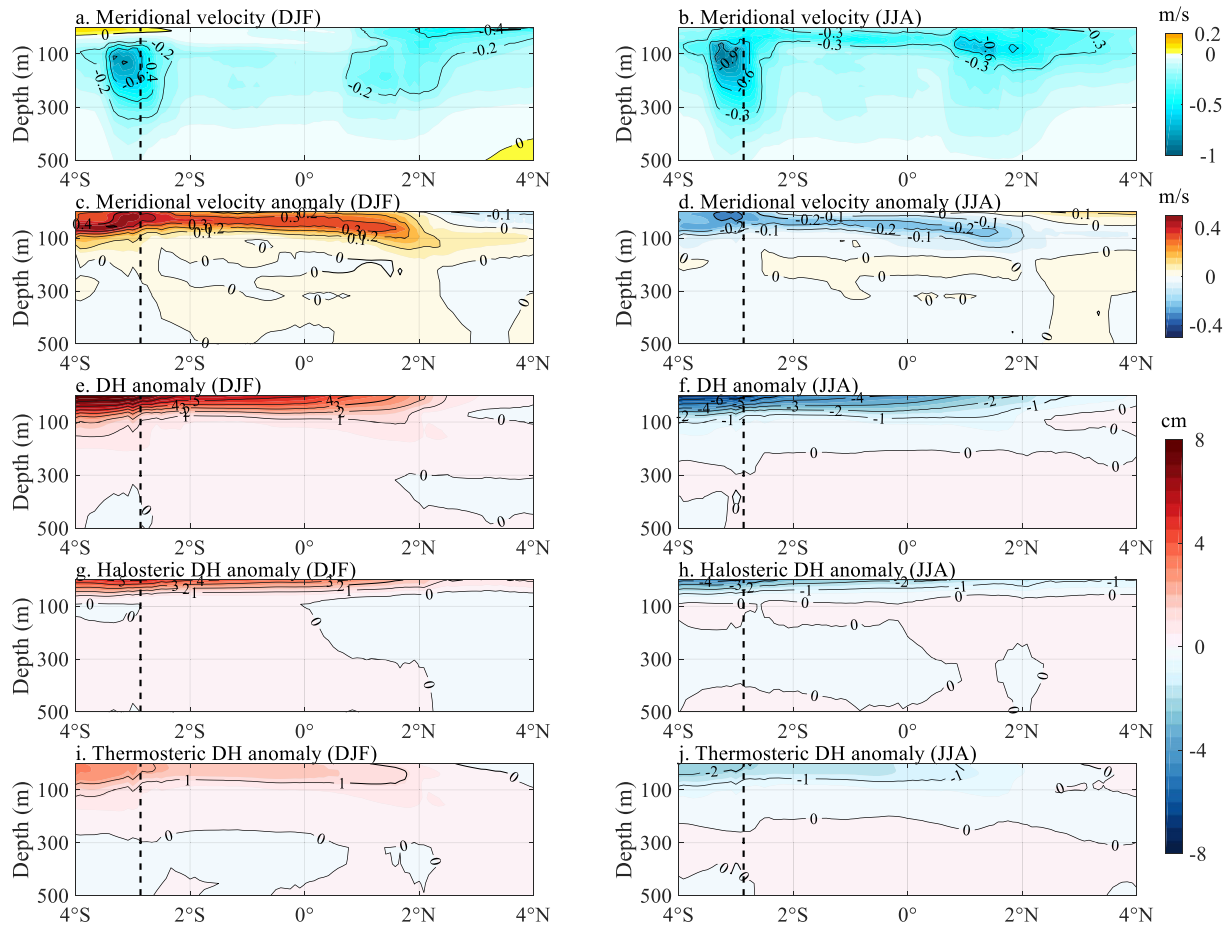


Figure 2. Seasonal variability of meridional velocity, anomalies of meridional velocity, dynamic height (DH), halosteric DH, and thermosteric DH referenced to 1,000 m depth along the Makassar Strait in GLORYS, for (a, c, e, g, and i) DJF and (b, d, f, h, and j) JJA. Dashed lines indicate the location of the Labani Channel. Positive values in panels (a–d) indicate northward velocities or velocity anomalies.

of meridional velocity are mainly confined in the upper 100 m and decrease northward along the Makassar Strait (Figures 2c and 2d). The seasonal change of MST velocity can be explained by the seasonality of DH, which shows a northward gradient anomaly in boreal winter but a southward gradient anomaly in summer (Figures 2e and 2f).

To separate the contributions of salinity and temperature to the seasonality of DH, we calculated the seasonal anomalies of halosteric DH (Figures 2g and 2h) and thermosteric DH (Figures 2i and 2j) referenced to 1,000 m depth. The halosteric and thermosteric DH anomalies both exhibit significant seasonal variability consistent with the DH anomaly particularly within the upper 100 m, thereby generating northward DH gradients during boreal winter and southward DH gradients in summer. For both the halosteric and thermosteric components of DH, seasonal anomalies occur south of the Makassar Strait. Interestingly, the seasonal change of the halosteric DH is stronger than that of the thermosteric DH (Figure 2).

Figure 3 presents the seasonal cycles of the ADT, DH, halosteric DH, and thermosteric DH at the surface referenced to 1,000 m depth along the Makassar Strait. The DH exhibits a similar seasonal cycle to that of the ADT (Figure 3), indicating that the sea surface DH gradient in GLORYS is in good agreement with satellite-based observations. In boreal winter, the surface DH anomaly leads to a northward gradient that weakens the southward MST (Figure 3a). This northward sea surface DH gradient diminishes during boreal spring (Figure 3b). Conversely, during boreal summer, the DH reverses and creates a southward gradient that intensifies the MST (Figure 3c). This southward sea surface DH gradient is weakened in boreal autumn (Figure 3d).

The seasonal anomalies of halosteric and thermosteric DH exhibit similar, albeit weaker, seasonal variability compared to the along-channel DH anomaly. Notably, during boreal spring and autumn, the thermosteric DH

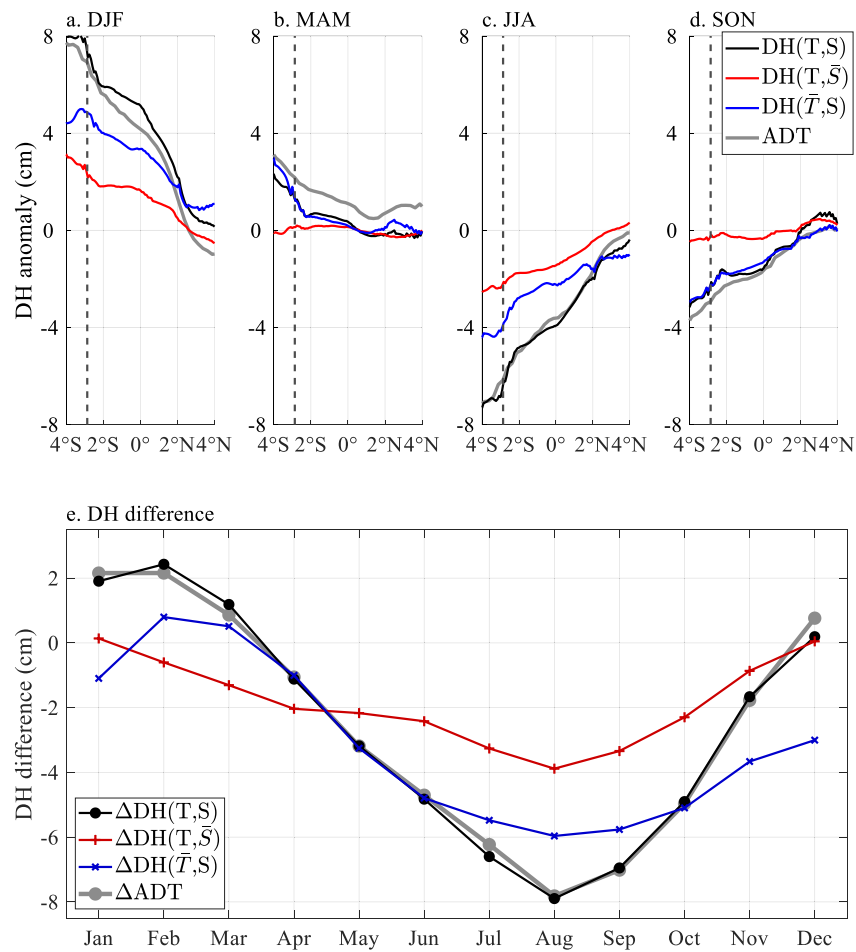


Figure 3. The seasonal cycles of absolute dynamic topography (ADT), dynamic height (DH), halosteric DH, thermosteric DH, and DH difference at the surface referenced to 1,000 m depth along the Makassar Strait. (a–d) GLORYS seasonal cycles for DJF, MAM, JJA, and SON, and (e) DH difference of GLORYS and ADT. The DH and ADT differences are defined as the mean DH/ADT in the southern part of the Makassar Strait (4°–2.8°S) minus that in the northern part (2.8°S–2°N). Dashed lines indicate the location of moorings in the Labani Channel.

shows minimal change along the Makassar Strait, while the halosteric DH demonstrates nearly identical variability as the total DH (Figure 3). It appears that in these seasons, salinity plays a crucial role while temperature has limited influence.

We further examined the DH difference between the south and north sides of the Makassar Strait and the contributions of salinity and temperature with GLORYS and AVISO ADT data (Figure 3e). The surface DH difference from the GLORYS is in good agreement with that in ADT. Both the DH difference and ADT difference are northward in boreal winter and southward in summer (Figure 3e). The halosteric and thermosteric components of the DH difference show similar but weaker seasonal anomalies than the DH. Importantly, the seasonal anomalies of the halosteric DH are significantly stronger than that of the thermosteric DH. We find that the halosteric DH difference contributes $(69.6 \pm 11.7)\%$ of the total seasonal variability of the along-channel DH difference, and contributes 68.2%, 72.3%, 66.5%, and 71.7% for DJF, MAM, JJA, and SON, respectively. Therefore, the halosteric component dominates the seasonal variability of sea surface DH gradient along the Makassar Strait, and hence plays a crucial role in the seasonality of MST transport.

The seasonal variability of halosteric and thermosteric DH gradients is controlled by temperature and salinity variability. As shown in Figure 4, both the temperature and salinity have significant seasonal variations in the upper layer, being fresher and warmer in boreal winter (Figures 4a and 4b) than in boreal summer (Figures 4c and 4d). The seasonal variability of temperature and salinity displays a clear gradient along the Makassar Strait

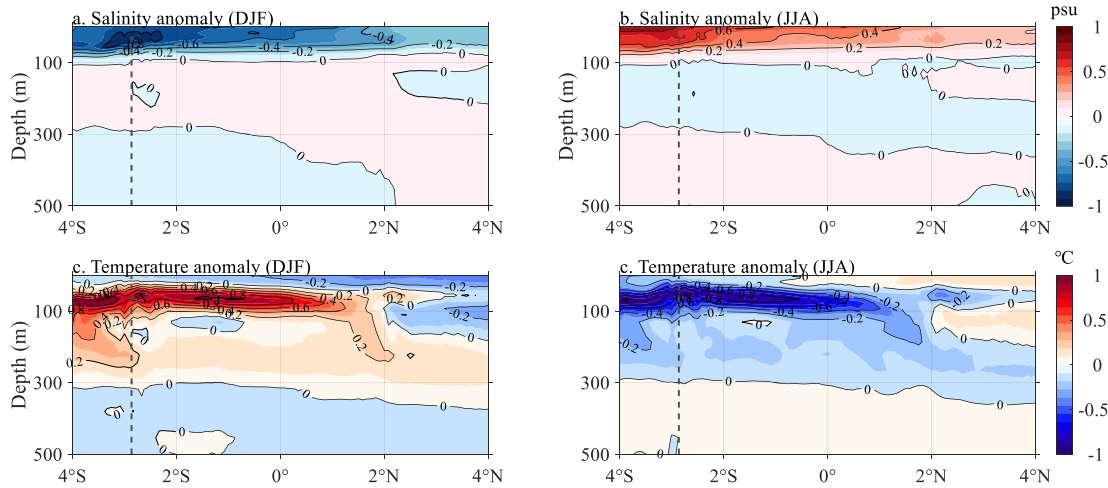


Figure 4. Seasonal salinity and temperature anomalies in GLORYS along the Makassar Strait, for (a and b) boreal winter (DJF) and (c and d) boreal summer (JJA). Dashed lines indicate the location of the Labani Channel. Seasonal anomalies of salinity and temperature are calculated by subtracting the 1993–2020 mean.

and is stronger in the southern strait than the northern part, which is similar to the seasonal fluctuations of DH gradient. It should be noted that the seasonal salinity anomaly is mainly confined in the upper 100 m layer, but the temperature seasonal anomaly is in the upper 300 m layer with a peak in the upper 100 m layer.

Previous studies suggest that cool and fresh water from the SCS feeds the Java Sea through the Karimata Strait in boreal winter and encounters the southward warm water from the western Pacific Ocean, leading to cooling and freshening in the surface (Gordon et al., 2003; Lee et al., 2019). In boreal winter, the northwest monsoon winds intensify freshwater transport through the Karimata Strait, and stronger precipitation occurs in the Java Sea (Figure 5a), leading to surface freshening in the Java Sea (Figure 5d) and then the Makassar Strait (Figure 5f), generating a northward DH gradient along the Makassar Strait. However, in boreal summer when the local monsoon turns southeast, the weakened freshwater input through the Karimata Strait and decreasing precipitation in the Java Sea (Figure 5b) together lead to salinization in the Java Sea (Figure 5e), which decreases the DH in the southern of the Makassar Strait and drives a southward DH gradient (Figure 3c) that intensifies the MST.

To further estimate the roles of freshwater advection and surface freshwater flux, we estimated freshwater fluxes of the advection from the Karimata Strait and local precipitation following Xu et al. (2021), and compared them

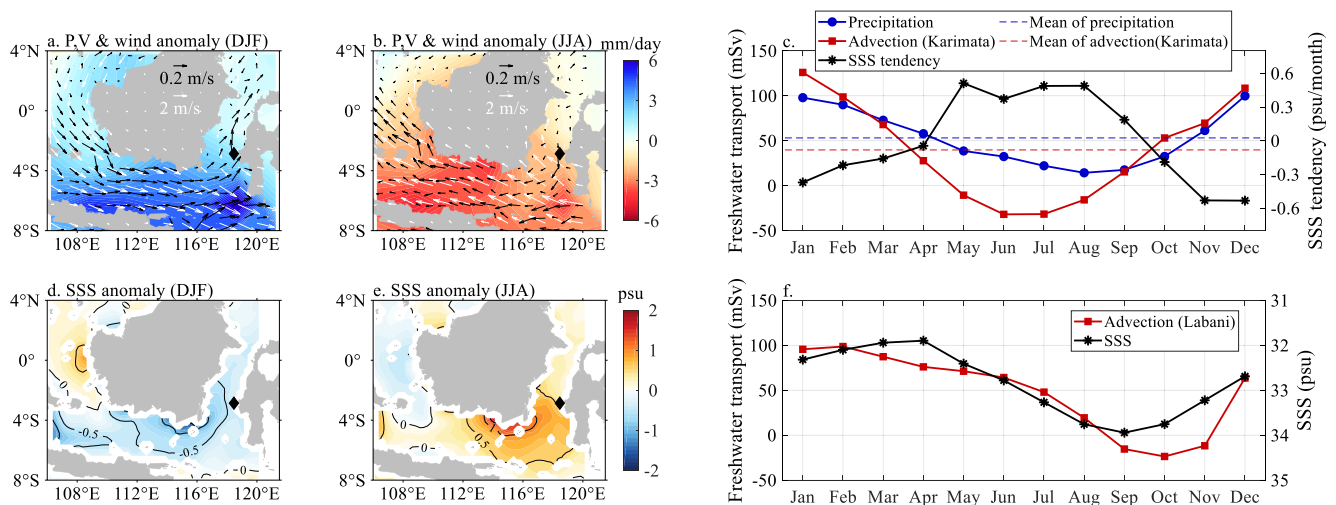


Figure 5. Upper: Anomalous precipitation (shading, Global Precipitation Climatology Project), sea surface current (black vector, GLORYS), and sea surface wind (white vector, ERA5) for (a) DJF and (b) JJA, and (c) the freshwater fluxes ($1 \text{ mSv} = 10^3 \text{ m}^3/\text{s}$) and sea surface salinity (SSS) tendency in the Java Sea. Soil Moisture Active Passive SSS anomalies in (d) DJF and (e) JJA. (f) SSS in the Java Sea and freshwater transport (positive indicates northward) through the Labani Channel. Seasonal anomalies are calculated by subtracting the annual mean. Black diamonds in panels (a–d) indicate the Labani Channel mooring.

with the SSS tendency (Figure 5). The freshwater transport from the Karimata Strait and local precipitation in the Java Sea both exhibit significant seasonal variability, with a stronger manifestation during boreal winter compared to summer. In boreal winter-spring, the freshwater advection and precipitation increase in Java Sea (Figure 5c), and lead to fresher SSS. The SSS in the Java Sea lags the precipitation by 1 month, lags the Karimata freshwater transport by 2 months, and shows a good agreement with the freshwater transport through the Labani Channel (Figure 5f).

The mean freshwater transport through the Karimata Strait is (39.8 ± 55.6) mSv ($1 \text{ mSv} = 10^{-3} \text{ Sv}$) over 1993–2020, which is consistent with the (36.08 ± 58.2) mSv observed over 1993–2017 (Xu et al., 2021). The seasonal mean freshwater flux of precipitation in the Java Sea is (53.1 ± 31.4) mSv over 1993–2020. The total freshwater flux due to advection and precipitation is approximately 92.9 mSv, and the freshwater transport from the Karimata Strait contributes about 63.9% of the seasonal variability of the total freshwater flux, implying that the freshwater transport through the Karimata Strait plays a very important role in the seasonal cycle of MST.

4. Summary

In this study, we quantitatively investigate the role of salinity effect, that is, the freshwater plug (Gordon et al., 2003), on the seasonal fluctuation of MST and related dynamic processes. We separate the halosteric and thermosteric components and quantitatively evaluate their contributions to the seasonality of steric height and MST, using in situ mooring observations and a high-resolution data product.

Both the MITF measurements and GLORYS product demonstrate the seasonal cycle of MST, which is weak and deep in boreal winter and strong and shallow in summer. The seasonality of MST is regulated by the meridional DH gradient along the Makassar Strait. We find that the seasonal variability of DH gradient along the Makassar Strait is primarily controlled by the halosteric component resulting from seasonal variability of salinity. We conclude that the salinity effect determines the seasonal variability of DH gradient along the Makassar Strait and plays a crucial role in the seasonality of the MST.

The halosteric contribution to the seasonality of MST is higher than that of interannual to decadal variability of ITF (e.g., Guo et al., 2023; S. Hu & Sprintall, 2016, 2017). This might be because the role of salinity effect is quite different on different time scales. On a seasonal time scale, local processes such as monsoon, advection, and precipitation are important (Gordon et al., 2003; Lee et al., 2019), while on lower frequency scales, basin-scale processes and large-scale climate modes such as ENSO and the Indian Ocean Dipole might be more important.

The seasonal variability of salinity within the Makassar Strait, particularly in the southern part, is caused by freshwater transport through the Karimata Strait and local precipitation in the Java Sea. Previous studies suggested that the monsoonal precipitation during boreal winter and spring is the major regulator of the freshwater plug (Lee et al., 2019). However, through quantifying the contributions from advection and precipitation, we find that freshwater transport from the Karimata Strait contributes approximately 63.9% of the total seasonal variability of the freshwater forcing of the Makassar Strait.

Given the importance of ITF and salinity effect, the findings presented in this paper can serve as a valuable reference for conducting future observations and enhancing numerical models.

Data Availability Statement

The Arlindo data (Gordon & Fine, 1996), the Makassar Strait data (Gordon et al., 2019), AVISO ADT (Ubelmann et al., 2021), SMAP SSS (Colliander et al., 2017), and GPCP precipitation (Adler et al., 2018) are available online. The GLORYS (Jean-Michel et al., 2021) data are downloaded from the CMEMS.

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Acknowledgments

The Arlindo data (<https://www.ldeo.columbia.edu/res/fac/physocean/Arlindo/>) and the Makassar Strait data (http://ocp.ldeo.columbia.edu/res/div/ocp/projects/MITF/cm_data/) are available online. The GLORYS data are downloaded from the CMEMS (<https://doi.org/10.48670/moi-00021>). The AVISO data are available online (<https://www.aviso.altimetry.fr/en/data.html>). The SMAP data are downloaded online (<https://smap.jpl.nasa.gov/news/1265/smap-sees-sea-surface-salinity/>). The GPCP data can be found online (<https://climatedataguide.ucar.edu/climate-data/gpcp-monthly-global-precipitation-climatology-project>). This study is supported by the Laoshan Laboratory (No. LSKJ202202702), Interdisciplinary Innovation Team of Chinese Academy of Sciences (JCTD-2020-12), the Strategic Priority Research Program of Chinese Academy of Sciences (No. XDB42010403, National Natural Science Foundation of China (Grant 42022040), and the Shandong Provincial Natural Science Foundation (Grant ZR2020JQ18). Shijian Hu is a member of the Youth Innovation Promotion Association of CAS (No. Y2022066).

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