

RESEARCH ARTICLE

HEAT TRANSPORT VARIABILITY WITHIN THE INLET AND OUTLET OF MAKASSAR STRAIT

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ABSTRACT

The Indonesian Throughflow (ITF) transports warm water masses from the Pacific Ocean to the Indian Ocean through the Makassar Strait. Ocean currents and sea temperature data from the HYCOM model estimate the heat transport associated with the ITF within the Makassar Strait. Heat transport is calculated as the product of volume transport, temperature, density, and specific heat. The calculation is applied to two study areas, the northern and southern sides of the Makassar Strait, representing the incoming and outgoing passages, respectively. Heat transport within the Makassar Strait is directed southward, with Maximum heat transport occurring between 0 and 100 meters, where the ITF is strong. Makassar Strait heat transport is influenced by the monsoon. The most substantial average seasonal heat transport occurs during the east monsoon, reaching a maximum value of 1.09 PW in the incoming passage and 1.05 PW in the outgoing passage. The minimum volume transport occurred during the second transitional monsoon, with values of 0.82 PW in the incoming passage and 0.78 PW in the outgoing passage. Heat transport in the outgoing passage decreased by an average of 0.03 PW. This variability is due to the temperature in the outgoing passage varying more significantly over time. Additionally, the dynamics of adjacent seas to the south of the Makassar Strait directly influence the outgoing passage. Interannual variations also influence heat transport, specifically El Niño and La Niña. During El Niño, both southward volume and heat transport decrease in both passages. However, the impact of La Niña is not clearly observed, likely because its peak during this study period occurred between the second transitional monsoon and the west monsoon, a period in which southward transport is weakened.

KEYWORDS

Heat transport; Indonesian Throughflow; Makassar Strait; Seasonal variation

1. INTRODUCTION

Indonesia's strategic location between the Pacific and Indian Oceans positions its waters as a vital conduit for inter-ocean exchange (Gordon, 2001; Wang, 2024). Commonly referred to as the Indonesian Throughflow (ITF). The ITF plays a crucial role in transporting water masses from the Pacific Ocean to the Indian Ocean, forming one of the key components of the global thermohaline circulation (Gordon, 2005; Sprintall et al., 2014). Approximately 80% of the ITF volume passes through the Makassar Strait, predominantly carrying warmer and saltier Pacific-origin waters (Gordon et al., 1999; Susanto et al., 2016). This flow has significant implications for regional heat distribution, climate variability, and the tropical oceans' energy budget.

Previous research has emphasized the Makassar Strait's dominant role in regulating ITF transport and associated heat flux (Vranes et al., 2002). Estimated heat transport in the Makassar Strait using mooring data collected between December 1996 and early July 1998, reporting an average heat transport of 0.55 petawatts (PW) under normal conditions and 0.41 PW during El Niño events. These findings highlight the sensitivity of heat transport to interannual climate variability, particularly the El Niño-Southern Oscillation (ENSO). During El Niño events, reduced ITF volume transport leads to decreased heat flux (Zhu et al., 2021; Baier et al., 2022). While La Niña phases are associated with intensified ITF transport and higher heat flux (Li et al., 2023).

Subsequent studies have refined our understanding of ITF dynamics. Using Acoustic Doppler Current Profiler (ADCP) data from the same period, (Susanto and Gordon, 2005) estimated total transport through the Makassar Strait at 8.1 ± 1.5 Sv ($1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$). However, during the peak of the 1997/1998 El Niño, transport declined to 4.6 ± 0.9 Sv, demonstrating the modulation of ITF transport by large-scale climate variability. Later, (Gordon et al., 2008) revisited ITF transport from 2004 to 2006 using mooring data from the Labani Channel, reporting a 27% increase in transport compared to 1997. This increase was attributed to weaker El Niño conditions during the later period, underscoring the strong relationship between ITF variability and ENSO dynamics.

Comprehensive analyses conducted under the International Nusantara Stratification and Transport (INSTANT) program (2004–2006) further explored the spatial variability of ITF transport. (Gordon et al., 2009) reported that the ITF's inlet and outlet transports averaged 13 Sv and 15 Sv, respectively, over the INSTANT observation period. These findings highlighted the variability of ITF pathways and their contributions to oceanic heat redistribution at both regional and global scales.

Despite these advancements, long-term variability in ITF heat transport—particularly within the inlet and outlet of the Makassar Strait—remains poorly understood. This study addresses this gap by analyzing heat transport variability in the Makassar Strait over an extended period (2002–2012). By leveraging an 11-year dataset, this research aims to provide deeper insights into the temporal and spatial dynamics of heat

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transport within this critical segment of the ITF.

2. METHODOLOGY

2.1 Data

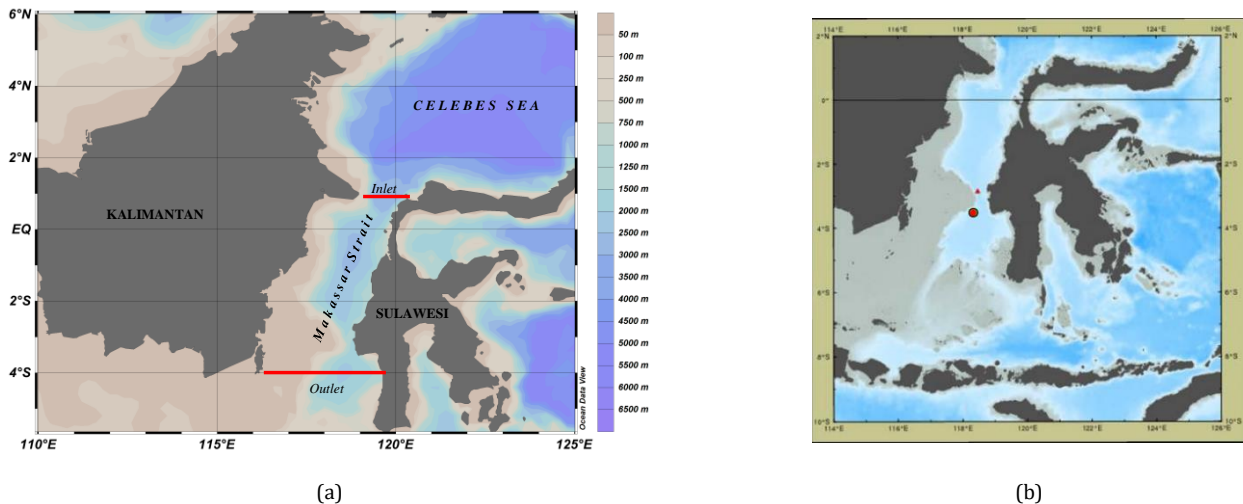


Figure 1 : (a) The research locations are indicated by the red lines. (b) Red triangles and red circles show the point of verification of meridian currents and temperature respectively.

This research used primary data and secondary data. Primary data has two types: the first was used as verification of reanalysis data. This includes meridian current velocity at depths of 60 m and 100 m, in the form of time series from November 28, 2006, until May 28, 2009, and temperature data at depth 0 - 1000 m (about the height of the Burj Khalifa, the tallest building in the world) dated July 8, 2005. These two data were a result of MITF (Monitoring Indonesian Throughflow) field measurements conducted by the Lamont - Doherty Earth Observatory of Columbia University in collaboration with the Ministry of Marine and Fisheries Research and Development Division (Figure 1b).

The next primary data used in this study were the reanalysis data of depth, temperature, and meridian current velocity magnitude, hereinafter referred to as current which provided by HYCOM in the form of daily averages. All the data were taken from the surface to a depth of 800 m, as values below this depth were not considered because of its exceedingly small value. The period of data used was January 2002 to December 2012. The data were downloaded from <http://ncss.hycom.org/>.

Secondary data used in this study were the NINO index 3.4 from January 2002 until December 2012, downloaded from <http://www.cpc.ncep.noaa.gov/data>. These data were used to analyze the relationship between heat transport to interannual variations (ENSO).

Table 1: Used HYCOM data details.		
HYCOM	Inlet	Outlet
Spatial resolution	1/12° x 1/12°	1/12° x 1/12°
Horizontal grids	553	966
Vertical layers	31 (800 m)	31 (800 m)
Length of data	11 years (2002 - 2012)	11 years (2002 - 2012)

Current and temperature data were analyzed visually based on their spatial distribution and Hovmöller diagrams. The next method used to estimate heat transport in the Makassar Strait in this study was a quantitative calculation method. To obtain the heat transport, it is first necessary to calculate the volume transport by multiplying the current velocity by the cross-sectional area on each grid. The volume transport is then multiplied by the temperature to determine the heat transport. Statistical analysis was performed on verification, volume transport and heat transport. Data verification was performed using Pearson linear correlation and significance analysis.

2.2 Verification

The HYCOM reanalysis data was verified with field data from the MITF program. Verification was performed on the correlation, significance and RMSE between the observational data and the model results. The verified variables were currents and temperatures, with the location adjusted to the MITF observing stations. The current observation stations were at 2.86°S and 118.47°E and the temperature observation stations were at

This research is located in Makassar Strait and divided into two study areas (Figure 1a). Both areas of this study are vertical cross-sections that run from east to west of Makassar Strait. The study area is located at 1.04° N and 119° E to 1.04° N and 120° 11'E as the inlet passage and 4°S and 116° 21'E to 4°S and 119° 31'E as the outlet passage.

3.49°S and 118.32°E. The verified velocity data consisted of time series data from November 28, 2006, to May 28, 2009, at 60 m depth. The reanalysis temperature data were verified with observed temperature data on July 8, 2005, from the surface to 1000 m.

The first step of verification is to see the correlation between reanalysis data and field data using Pearson's correlation equation, as follows (Pratisto, 2005):

$$r_{xy} = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2} \cdot \sqrt{\sum(y_i - \bar{y})^2}}$$

where r is the Pearson's correlation coefficient, x_i and y_i are the correlated variables i.e. reanalysis data and field data. \bar{x} and \bar{y} are the mean of the variables x and y . Further verification is performed by performing a significant test. Significance gives the big picture most likely the data is true. Using a significant number of 0.05 to prove whether the data has a 95% confidence level. The last verification step is by calculate RMSE, as follows:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (x_i - y_i)^2}$$

2.3 Heat Transport

The heat transport passing through the Makassar Strait was calculated using the following equation:

$$F_H = \rho C_p \int_A (T - T_0) v dA$$

F_H is the heat transport in the PW, ρ the density of sea water is 1021 kgm⁻³, C_p is the specific heat, ρC_p can be expressed as heat capacity per unit volume 4.1×10^6 J m⁻³ K⁻¹. T and T_0 are the temperature and reference temperature in °C, respectively. v is the current velocity in m/s and dA denotes the element area of the cross section in m² (Fang et al., 2010).

Various studies use different reference temperature values. The choice of reference temperature values is arbitrary (Schiller et al., 1998; Ffield et al., 2000) and depends on where the investigator closes the study cross section for zero net transport volume (Ffield et al., 2000). Using reference temperatures aims to cover the cross-section at suitable locations where all the backflow intersects, thus creating a closed temperature. The reference temperatures are between 0 °C and 4 °C (Vranes et al., 2001). Referring to a researcher, reference temperature in this study is 3.4 °C (Vranes et al., 2001).

3. RESULT

3.1 Data verification

Figure 2a shows the results of verification between reanalysis data and observation data at 60 m depth which shows the correlation value of 0.71102 with RMSE is 0.23904 m/s. It is said by (Pratisto et al., 2005). That the correlation of 0.7 is fairly high. The scatter diagram of current velocity over time at 60 m indicates good regression value, as shown by the distribution of data approaching linear regression line (Figure 2b). Based

on the significance test conducted on the data current velocity at 60 m by using the significance number of 0.05 obtained p value at 60 m depth is 2.49×10^{-141} . The results show the value of $p < 0.05$ so it can be concluded that the relationship between reanalysis data with observation data is significant.

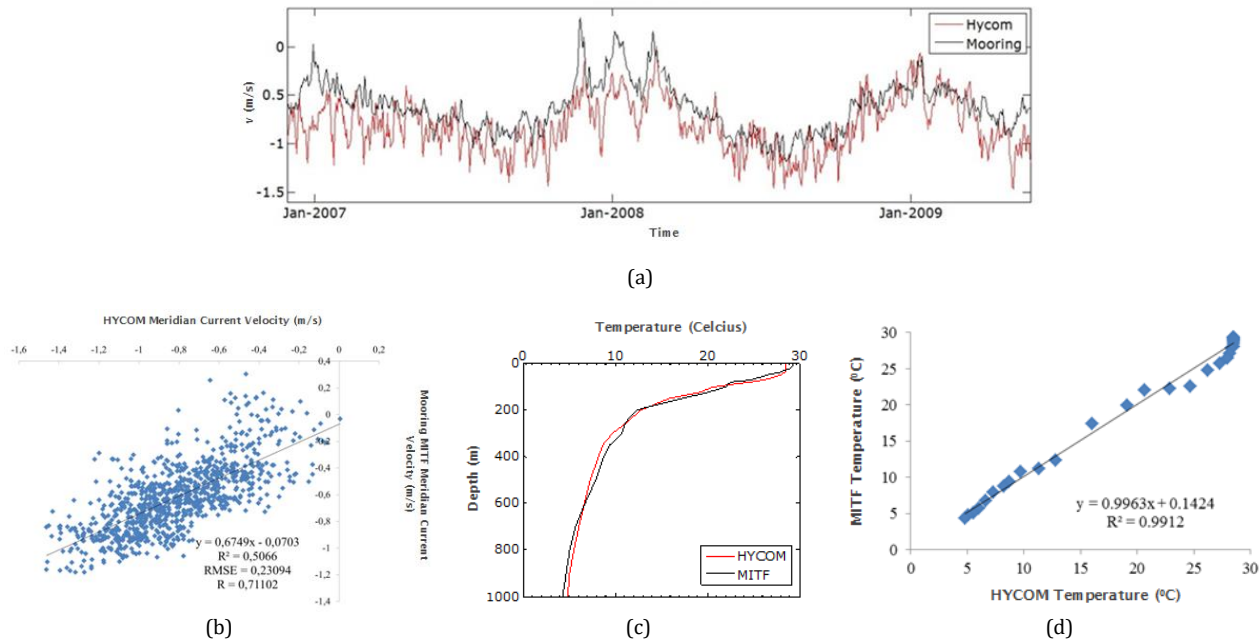


Figure 2 : (a) Verification of meridional current velocity data of HYCOM reanalysis with MITF meridional current rate data at 60 m depth. Scatter diagram of meridional current velocity between HYCOM reanalysis data and MITF. (b) Scatter diagram of meridional current velocity between HYCOM reanalysis data and MITF observation data November 28, 2006 - May 28, 2009 at depth 60 m. (c) Verification of HYCOM reanalysis temperature data with MITF observation data July 8, 2005 at a 0 - 1000 m depth. (d) Scatter diagram of HYCOM reanalysis temperature data with MITF observation data July 8, 2005 at 0 - 1000 m depth.

The results of temperature verification showed a high correlation of 0.99557 (Figure 2c) with RMSE at 0.8854 °C and the results of significance test obtained p value $< 10^{-33}$ so it can be said there are a significant relationship between the two data. The scatter diagram of temperature to depth indicates good regression value, shown by the distribution of data close enough to linear regression line (Figure 2d).

period can be seen in Figure 3. At a depth of 0 - 300 m, temperatures increase at the end and the beginning of the year, and decrease by mid-year. However, the increase and decrease values are not large enough and this can be seen from the variation in time which is quite slow. The temperature variation over time in the outlet is very large. There is a fairly steep drop in temperature throughout the study time from a depth of about 70 m. There is a pattern of significant rise and fall in temperature at 70 - 100 m depth throughout the year in which temperatures increase at the end of the year and at the beginning of the year, and decrease by mid-year.

3.2 Temperature

Temperature profiles to depth at the inlet and outlet throughout the study

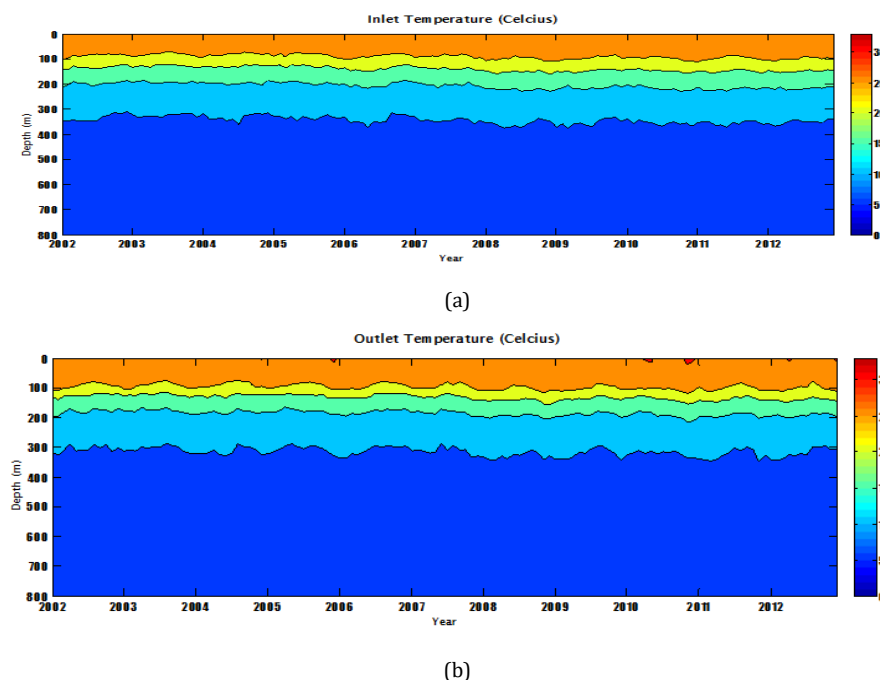


Figure 3: (a) Inlet temperature profile towards depth in °C. (b) Outlet temperature profil towards depth in °C.

The climatology average temperature profile and year-round research in the inlet experienced consistent heating seen from insignificant temperature changes throughout the year (Figure. 3a and Figure 4). Unlike the outlet temperature where the increase in temperature occurring at the end of the year to the beginning of the year on the outlet indicates that the temperature gets a seasonal influence (Figure 3b). In addition, the fall in

temperatures around mid-year is allegedly out due to upwelling in the southern Makassar Strait (Figure 4). As the eastern currents of the Makassar Strait met the mass of water flowing from the Flores Sea to the Java Sea, resulting in a vacuum in the southern region of the Makassar Strait, this vacuum increased the underlying mass of water (Nontji, 1987 and Illahude, 1970).

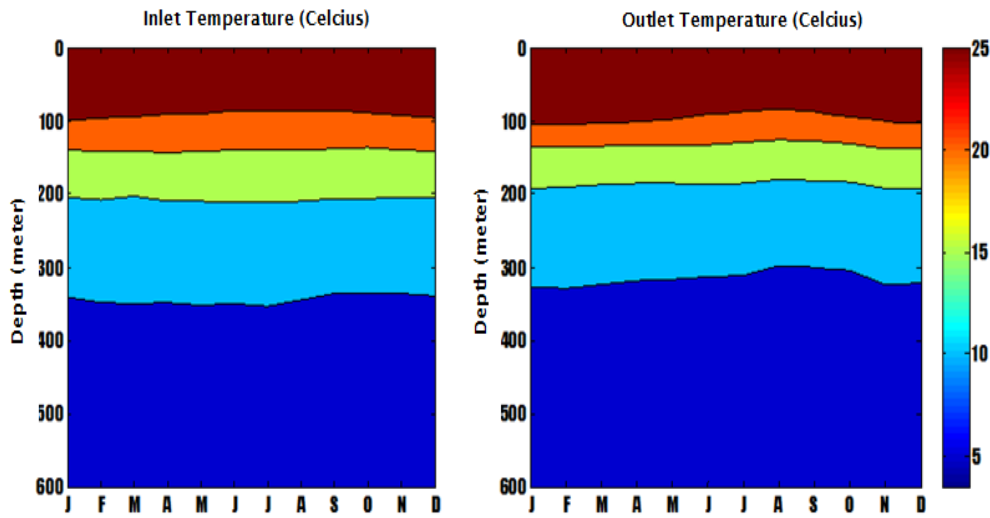


Figure 4 : Inlet and outlet climatological temperature against depth in °C.

3.3 Heat transport

In addition to being influenced by temperature, heat transport is also affected by volume transport. It is said by (Sprintall et al., 2014) that the transport volume passing through each strait in Indonesia plays an important role in heat transfer. Volume transport moves to the South throughout the time of the research, this is influenced by ITF which throughout the year flows through the Strait of Makassar.

The average annual and climatology heat transport throughout the study

period (Figure. 5) also shows that heat transport in the Makassar Strait moves south with the largest heat transport being at 0 - 300 m depth on both lines. In this layer, ITF plays a major role as ITF strengthens in the thermocline layer (Gordon et al., 2012; Susanto et al., 2012) where the thermocline layer is at 60 - 300 m (Illahude, 1999). These results are also consistent with (Sprintall et al., 2009) which states that approximately 2/3 of transport is in a layer above 300 m. (Sprintall et al., 2009) stated that ITF's surface tends to strengthen during the east monsoon and weaken during the west monsoon.

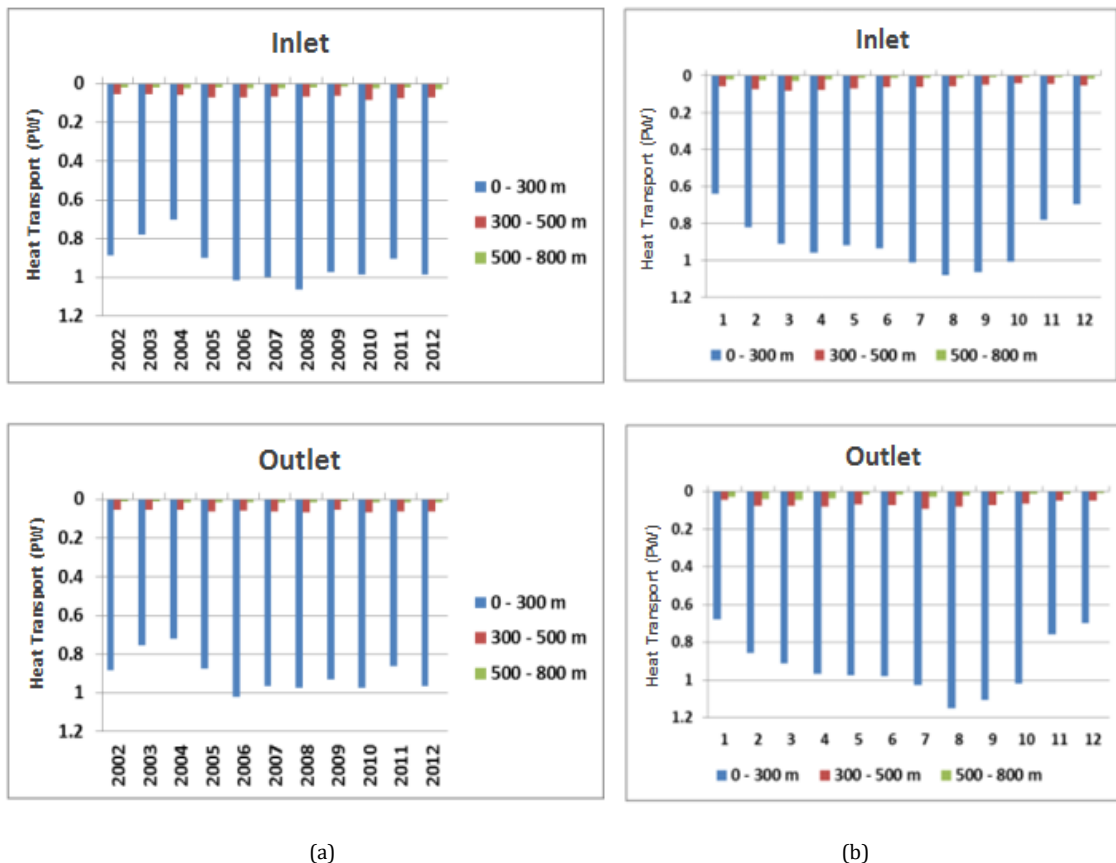


Figure 5 : (a) Inlet and outlet average heat transport per depth from 2002 to 2012 (b) Inlet and outlet climatology heat transport per depth.

The average of heat transport each month during the year of the study is calculated per depth of 0 - 100 m, 100 - 200 m, 200 - 300 m, 300 - 500, and

500 - 800 m to find out at which depth most heat transport occurs. It results in maximum heat transport at 0 - 100 m and relatively large at 100

- 200 m. Starting from 200 - 300 m depth, heat transport is very small, this is suspected because this layer is below the thermocline with a temperature that is quite small and homogeneous.

Figure 6 shows the total climatology variation of total heat transport throughout the depth. From January to October, heat transport in the inlet is greater than in the outlet, while in November and December, the outlet heat transport slightly outweighs the inlet. This is thought to be due to the

dynamics of waters in the inlet, which is more influenced by the western Pacific Ocean water masses. During the second transition monsoon occurred several times El Niño incidents in 2002, 2006, and 2009 which peak at the end of the year and temperatures in the south tend to be larger this monsoon, so in November and December heat transport in the inlet is smaller than in the outlet. Both the inlet and outlet show increase in heat transport from July to August and a decline from November to January.

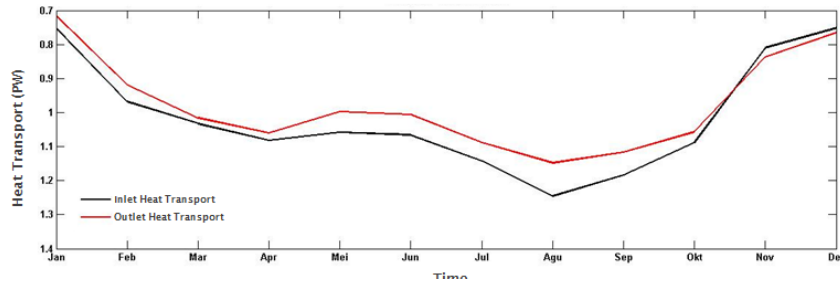


Figure 6 : Total climatology heat transport in the Makassar Strait’s inlet and outlet passage.

4. DISCUSSION

ITF flows from the Pacific Ocean through the Makassar Strait into the Indian Ocean, carrying warm, low-salinity water (Katavouta et al., 2022; Atmadipoera et al., 2024). Variations in ITF volume and heat transport significantly impact the regional heat budget and climate systems (Iskandar et al., 2023). The Southeast Asian monsoon system plays a critical role in modulating surface currents and heat transport in this region. During the boreal summer (June–August), the South Asian summer monsoon strengthens the southward flow in the Makassar Strait, enhancing heat transport. In contrast, during the winter monsoon (December–February), northerly winds weaken ITF transport. Furthermore, southerly winds during the summer monsoon amplify ITF transport (Wang et al., 2023; Liao et al., 2025). The El Niño-Southern Oscillation (ENSO) also exerts a notable influence. During El Niño events, ITF transport weakens due to a reduced pressure gradient between the Pacific and Indian Oceans, which decreases heat flow through the Makassar Strait. Conversely, La Niña events strengthen ITF transport, leading to increased heat flow into the Indian Ocean (Wang et al., 2023; Liao et al., 2025).

Heat transport in the upper 0 – 300 m layer was analyzed with respect to monsoonal variations. Volume transport plays a crucial role, as water masses passing through the Indonesian straits are significant contributors to heat transfer (Sprintall et al., 2014). Maximum heat transport occurs during the east monsoon, while minimum values are observed during transitional periods and the west monsoon. Specifically, at the inlet, minimum values align with the west monsoon, whereas at the outlet, they also occur during the west monsoon. Similar patterns have been reported by (Schneider et al., 1997; Lebedev et al., 2000; Schiller, 1998), indicating that east monsoons coincide with larger sea-level gradients between the Pacific and Indian Oceans, resulting in stronger southward flows. Conversely, west monsoons are characterized by diminished gradients that weaken ITF transport (Gordon et al., 1999; Murray & Arief, 1988).

The difference in minimum values between the inlet and outlet is

attributed to local water dynamics. At the inlet, Pacific Ocean water masses primarily influence the dynamics. For instance, during the second transitional monsoon, El Niño events (e.g., 2002, 2006, and 2009) weakened the ITF due to reduced Pacific winds and a degraded thermocline structure (Gordon et al., 1999; Ffield et al., 2000). At the outlet, the dynamics are influenced by water masses from the Java and Flores Seas. During the west monsoon, for example, water from the South China Sea and Indian Ocean enters through the Sunda Strait, reducing the inflow of ITF water masses (Fang et al., 2009; Susanto et al., 2016). Consequently, cooler ITF water masses are observed at the outlet (Gordon et al., 2012). Velocity and temperature profiles at the outlet (Figure. 6 and 7) show a more pronounced monsoonal influence compared to the inlet.

Season	Inlet (PW)	Outlet (PW)
West Monsoon (JFM)	0.82	0.78
Transitional Monsoon I (AMJ)	0.97	0.93
East Monsoon (JAS)	1.09	1.05
Transitional Monsoon II (OND)	0.82	0.83

To investigate the ENSO-ITF relationship, heat transport was compared with Niño 3.4 indices (Fig. 7a). During El Niño events, weakened Pacific winds reduce ITF transport and lower thermocline depths, resulting in decreased heat flow (Gordon et al., 1999; Ffield et al., 2000). Additionally, increased South China Sea water inflow into Indonesian waters during El Niño further cools ITF water masses (Gordon et al., 2012). In contrast, La Niña events, such as in 2010, displayed opposite effects, with weaker southern heat transport. Unlike (Vranes et al., 2001), who reported amplified heat transport during La Niña, this study suggests that monsoonal influences dominate during La Niña peaks, particularly during the second transitional and west monsoon periods, when southern transport decreases.

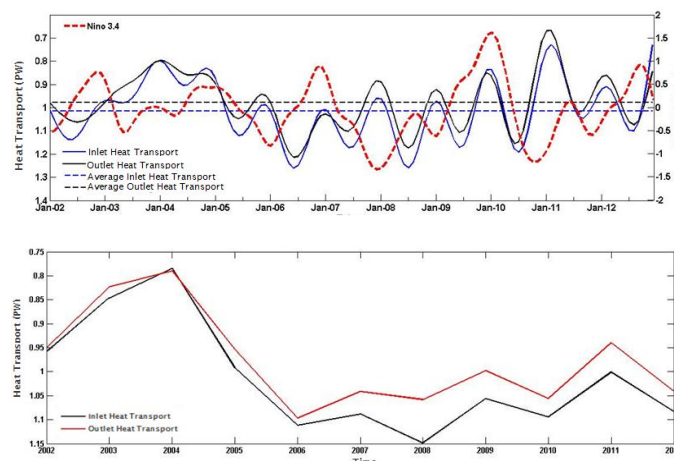


Figure 7 : (a) Heat transport (12 months filter) at the Makassar Strait inlet and outlet passage compared to Niño 3.4. (b) Average annual heat transport in the Makassar Strait’s inlet and outlet.

Annual heat transport extremes occurred in 2004 (minimum) and 2008 (maximum) for both inlet and outlet locations (Figure. 7b). On average, incoming heat transport (1.01 PW) exceeded outgoing transport (0.98 PW) by 0.03 PW. This difference is attributed to greater temperature variations at the outlet, driven by Java and Flores Sea dynamics and upwelling south of the Makassar Strait (Wibowo et al., 2020; Inaku, 2011; Nontji, 1987; Illahude, 1970). Discrepancies in heat transport findings across previous studies (Table 3) can be explained by variations in datasets, methodologies, calculation periods, and study areas.

Table 3: Previous heat transport studies.

Previous Studies	Methods	Years of Calculation	Average Heat Transport (PW)
Schneider and Barnett 1997	ECHO (1.6° x 2.8°)	100 years	0.9
Schiller et al. 1998	GFDL, MOM2 (2° x 0.5°)	1985 - 1990	1.15
Vranes et al. 2001	Field Observatory	1996 - 1998	0.57
Pandey and Pandey, 2006	POM (0.25° x 0.25°)	1994	1.08
Sprintall and Liu, 2005	Field Observatory	1999-2005	0.9
Current studied	HYCOM (1/12° x 1/12°)	2002-2012	1.01 (inlet) 0.98 (outlet)

The discrepancies among studies underscore the importance of methodological choices and model configurations in estimating ITF heat transport (Ding et al., 2023). The higher resolution of the current study's HYCOM model (1/12° x 1/12°) likely allowed for better representation of mesoscale eddies and boundary currents, improving the accuracy of heat transport estimates (Pandey and Pandey et al., 2006; Cao et al., 2025). By capturing spatial variations between the inlet and outlet, the current study provides nuanced insights into heat loss processes, including mixing, upwelling, and interactions with surrounding seas (e.g., Java and Flores Seas) (Fritz et al., 2023).

Field observation-based studies, such as (Vranes et al., 2001) and (Guo et al., 2023), typically provide lower estimates of heat transport, possibly due to the limited temporal and spatial scope of measurements. Conversely, coarse-resolution models like ECHO (Schneider and Barnett et al., 1997) may oversimplify ocean dynamics, leading to under- or overestimation of transport. The relatively high value reported by (Schiller et al., 1998) using GFDL/MOM2 reflects the influence of model physics, resolution, and parameterizations. Temporal coverage is another critical factor. For instance, (Vranes et al., 2001) observed ITF during a period dominated by El Niño conditions, which are known to weaken ITF transport. This highlights the need for multi-decadal simulations, such as those conducted by (Schneider and Barnett et al., 1997) and the current study, to capture variability driven by ENSO, monsoons, and other long-term climatic drivers.

5. CONCLUSION

Heat transport in the Makassar Strait has a southerly direction in both the northern and southern sides of the Makassar Strait, representing the incoming and outgoing passages, respectively, it is influenced by ITF indicated by the maximum value being in the depth of 0 - 100 m. Heat transport in the Makassar Strait has a seasonal influence on both sides, it reaches maximum during east monsoon, while minimum heat transport during second transitional monsoon at the inlet and west monsoon is at the outlet. There is an average heat transport difference of 0.03 PW where the average heat transport in the inlet is greater, the difference is influenced by the temperature variation in the outlet which its change over time is greater and the dynamics of other waters in the southern of Makassar Strait. The Makassar Strait heat transport gets an inter-annual El Niño influences and a few La Niña influences. At the time of El Niño, heat transport to the south weakened while the occurrence of La Niña is not clearly visible in strengthening of southern heat transport, allegedly the peak of La Niña in this study is between the second transitional monsoon and the west monsoon, where in this season the southern transport weakened. Heat transport in the inlet is affected by ITF, seasons, and antelope phenomena, while heat transport in the outlet other than influenced by ITF, seasons, and inter-year phenomena is also influenced

by the dynamics of waters in the southern of Makassar Strait.

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