

The Impact of Tidal Mixing on the Indonesian Throughflow and the surrounding Seas

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題 目

The Impact of Tidal Mixing on the Indonesian Throughflow and Surrounding Seas
インドネシア通過流および周辺海域における潮汐混合の影響

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The Impact of Tidal Mixing on the Indonesian Throughflow and Surrounding Seas

Kohei Matsubara

Abstract

The Indonesian Seas, located on the equator, is a unique sea with a mixture of small islands and seas. It is known as an important place that connects the Pacific Ocean and the Indian Ocean. Past observations have revealed the existence of ocean currents flowing from the Pacific Ocean to the Indian Ocean through the narrow straits of Indonesia Archipelago, known as the Indonesian Throughflow (ITF). Sasaki et al. (2018) found that the volume transport of this ITF increases in the presence of tidal mixing due to the increase of sea surface height (SSH) over the entire Equatorial Pacific. In this study, the impact of tidal mixing on the ITF and the Equatorial Pacific is investigated by using OFES2, which a quasi-global high-resolution OGCM. The oceanic changes induced by tidal mixing is examined based on simulations with and without a tidal mixing scheme.

We find that the changes in the depth of the thermocline in the Equatorial Pacific as an important factor for the enhanced ITF transport to occur. In the Equatorial Pacific, the thermocline depth increases where SSH increases. The temperature thus increases at the depth of 200 m. This warming signal is especially strong where a seamount is located (8S, 140W) and where strong tidal mixing occurs. An increase in the depth of 26.0 kg/m³, an isopycnal of the lower thermocline, and a reversing zonal velocity signal is also found in this same area. Such impact of local tidal mixing on the thermocline likely resulted in an SSH increase over the Equatorial Pacific. At the straits of the Indonesian seas, enhanced southward flow occurs at the depth of 300 to 500 m around the thermocline in the Makassar Strait. This enhanced flow is found to account for most of the increase in the volume transport of the ITF.

Chapter 1 Introduction

1.1 Background

Global climate change due to the increase in greenhouse gas emissions has become a social problem (IPCC, 2014). The ocean constitutes a large component of this global climate system since it accounts for 70% of the Earth's surface. Since the ocean has a much larger heat capacity than the atmosphere, the oceanic temperature increase tends to be relatively small compared to the atmosphere. On the other hand, its changed state tends to remain and does not easily return to the original state. Therefore, if oceanic temperature increases due to global warming and change the water mass distribution and ocean currents, its impact on local climate will likely reside for some time. Oceanic changes can have a major impact on our society and we need to understand how the oceans behave if we wish to understand the process of climate change.

In this study, we focus on the Indonesian Seas located on the equator. An equatorial region is a place that receives significant solar radiation (Hartman, 1994). Climate variability due to air-sea interaction such as the El Nino and the Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) actively occur, which can affect the whole earth. The sea surface temperature in the Indonesian Seas and the western equatorial Pacific Ocean has a strong influence on the tropical atmospheric circulation and the ENSO generation mechanism (MacCreary et al, 1991) and the IOD (Annamalai et al. 2010) (Figure 1.1).

The Indonesian Archipelago is located between two oceans, the Pacific Ocean and the Indian Ocean. It has over 10,000 islands. The Indonesian Seas are thus a collection of various seas between these islands. The Indonesian Throughflow (ITF) is known to flow through the Indonesian Seas (Figure 1.2) and is a major branch of the global ocean circulation known as the global conveyor belt (Broecker, 1991). The ITF is driven by the difference in sea level difference (pressure difference) between the Pacific Ocean and the Indian Ocean (Wrtyki, 1987). The volume transport of the ITF is considered to be about 10-15 Sv. (Gordon, 2005). The ITF advects relatively warm water of the western Pacific to the Indian Ocean through the Indonesian seas as well as play a role on warming the water of the Indonesian seas (Kida and Wijffels, 2012).

The Ocean General Circulation Model (OGCM) is a useful tool to understand the dynamics of the ocean. However, the Indonesian Seas were considered a difficult region to simulate because it was

historically difficult to resolve its narrow straits. Strong vertical mixing due to tides also plays a central role in creating the vertical water mass structure within these seas (Field and Gordon, 1996). This mixing is considered to occur on the fine-scale of only a few meters (Nagai et al., 2017). Moreover, the ITF exists and this flow is induced not by the local winds but by the large-scale winds over the Pacific (Godfrey, 1989). Small-scale phenomena such as tides and large-scale phenomena such as ITF co-exist in the Indonesian seas. Because it requires high spatial resolution to resolve tidal mixing and a basin scale domain to force the ITF, it was difficult to reproduce the water mass and the flow through the Indonesian seas using an OGCM. While the dynamics of tidal mixing are still difficult to resolve, significant improvement in computational power in recent decades has made it possible to resolve the complicated topography and straits of the Indonesian Seas in global ocean models. In Japan, the supercomputer "Earth Simulator" started operation in 2002, and an optimized high-resolution ocean general circulation model OFES (OGCM for Earth Simulator) was developed (Masumoto et al. 2004; Sasaki et al 2008). As a result, long-term calculation with a horizontal resolution of 0.1 degrees (about 10 km) is now feasible. Tidal mixing was still left unresolved but recently, OFES was updated to OFES2 to implement a tidal mixing parameterization (Sasaki et al. 2018). The implementation of this scheme improved the water mass structure in the Indonesian Seas, which was originally not well reproduced in OFES.

Sasaki et al. (2018) found that the presence of tidal mixing increases the transport of ITF by about 0.88 Sv ($1\text{ Sv} = 10^6 \text{ m}^3/\text{s}$) based on a sensitivity experiment using OFES2 (Figure 1.3). They found that an increase of sea surface height occurs at the western Pacific and the Indian ocean, but more on the Pacific side. As a result, the sea surface height difference between the Pacific Ocean and the Indian Ocean increased and thus increased the ITF transport (Figure 1.4). The sea level rise in the Pacific Ocean, which occurred on the basin scale, was suggested as the main factor responsible for the increase in the ITF transport but how tidal mixing led to an increase in the Pacific surface height remained unknown.

1.2 Purpose of this study

The purpose of this research is to reveal the cause of the increase of sea surface height over the equatorial Pacific Ocean in OFES2, which led to changes in the water mass properties and enhancement of the ITF transport at the straits in the Indonesian Seas. As this sea surface rise is caused by tidal mixing that occurs close to the ocean bottom, we first need to investigate how tidal mixing

affects the ocean interior. To investigate the impact of tidal mixing on the SSH increase over the Equatorial Pacific, we will analyze the simulation results of ocean general circulation model OFES2. There are two types of simulations. “OFES2” is that simulated with a tidal mixing scheme. “OFES2_NT” is that simulated without a tidal mixing scheme. The impacts of tidal mixing are revealed by comparing the two simulation results. In Section 2, a detailed description of OFES2 and its datasets is described. In Section 3, OFES2 and OFES2_NT datasets are compared in detail. Summary and conclusion are presented in Section 4.

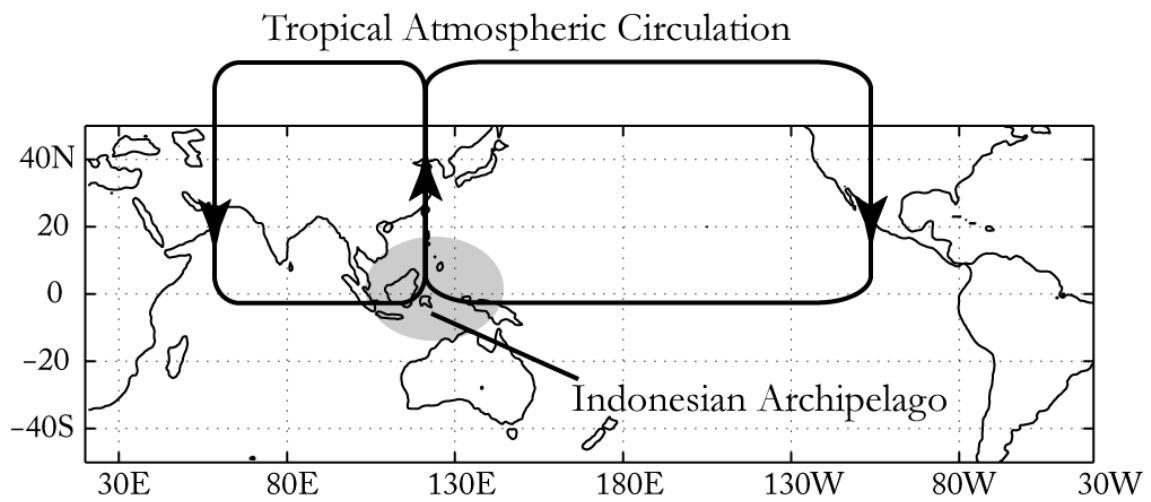


Fig 1.1 The location of the Indonesian Seas and the tropical atmospheric circulation (Kida, 2016).

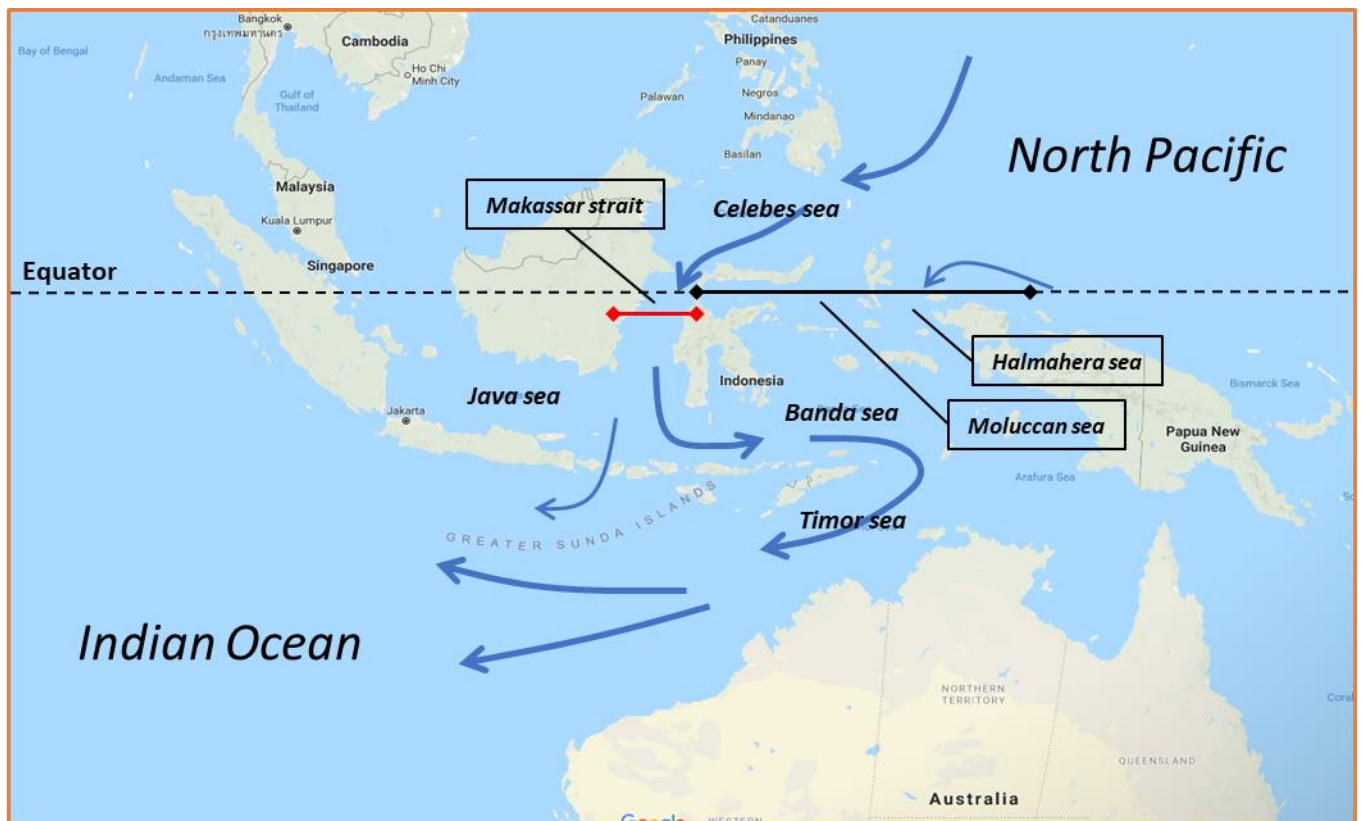


Fig 1.2 A schematic of the ITF based on Google Maps (Google Maps, 2018). Blue arrows represent the ITF. Red and black horizontal lines represent the western and eastern route of the ITF, respectively (described in Chapter 3.2).

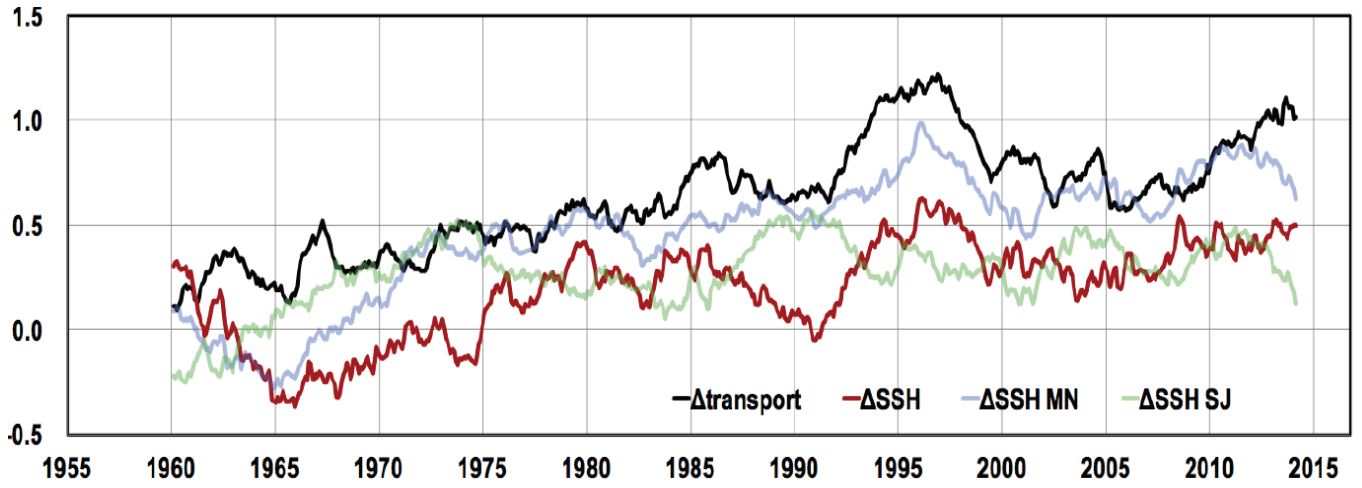


Fig 1.3 The difference of the ITF transport and the SSH between OFES2 and OFES2_NT (Figure 1 of Sasaki et al. 2018). Black line is the ITF transport difference. Red line is the sea surface height (SSH) difference. Blue line is the SSH gap on the western Pacific. Green line is the SSH gap on the Indian Ocean.

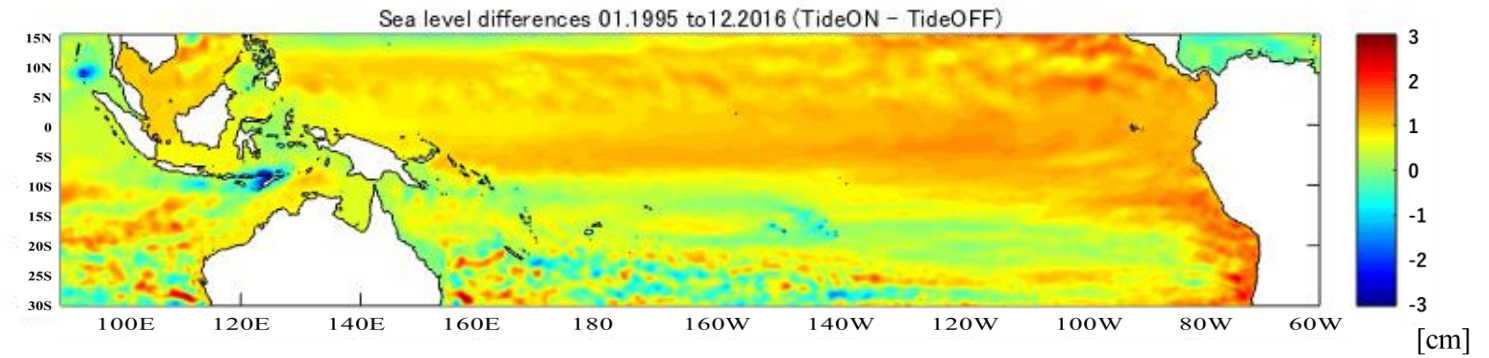


Fig 1.4 The difference in the SSH between OFES2 and OFES_NT averaged from 1995 to 2016.

Chapter2 Dataset

2.1 The Ocean General Circulation Model: OFES2

To clarify the cause of the rise in sea surface height in the Pacific Ocean, we will investigate the model outputs from OFES2 (Sasaki et al. 2018). OFES2 is an updated version of OFES (Ocean General Circulation Model for the Earth Simulator; Figure 2.1) where OFES is a quasi-global high-resolution ocean simulation model developed at JAMSTEC (Masumoto et al. 2004; Sasaki et al. 2008). OFES2 is based on MOM3 (Modular Ocean Model ver.3) that was developed by National Oceanic and Atmospheric Administration (NOAA) and is optimized for the supercomputer known as the Earth Simulator. The horizontal resolution of OFES2 is about 0.1 degrees and is integrated for more than 50 years. One of the significant changes from OFES to OFES2 is the vertical mixing parameterization. In addition to the use of Noh and Kim (1995), tidal mixing parameterization of St. Laurent et al. (2002) is now implemented throughout the model domain (see Sasaki et al. 2018 for details). While OFES was capable of simulating various seas it also became clear that it could not capture where tidal mixing was considered important. By adding tidal parameterization to the model, the water mass structure in these seas improved, such as the Indonesian seas.

The spatial domain of OFES2 is from 76 °S to 76 °N and the horizontal resolution of is 0.1 degree (about 10 km). The bottom topography is based on ETOPO1 (Amante & Eakins 2009). The number of vertical levels is 105 layers and maximum depth set to 7500 m. Vertical resolution is 5 m near the surface but increases towards the bottom. Surface forcing is based on JRA55-based dataset (Tsujino et al. 2018).

2.2 Dataset

To investigate the effect of tidal mixing, we will compare two datasets. The first dataset is based on the default OFES2 setup, which includes global tidal mixing parameterization. We will call this dataset OFES2. The second dataset is based on OFES2 but with tidal mixing parameterization is turned off. We will call this dataset OFES2_NT. These two datasets are outputs of simulations integrated from 1958 to 2016, which is longer than 50 years.

In this study, the parameters examined from the datasets are SSH, temperature, density, zonal velocity, and meridional velocity. We will analyze within the domain of 30 °S to 15 °N and 90 °E to 90 °W. Results presented are 22 years average of monthly-averaged data from January 1995 to

December 2016. This period of 22 years is the same as Sasaki et al. (2018) where the enhanced ITF transport was estimated. As mentioned in Sasaki et al. (2018), the difference of volume transport of ITF increase gradually for the first few decades due to the spin-up of the model but reaches a quasi-steady state after that (Figure 1.3).

We will first examine the horizontal spatial variability with a focus on the temperature at the depth of 200 m. This depth roughly represents the thermocline in the equatorial Pacific. Isopycnal depths are presented next. Isopycnal depths are interpolated from vertical density profile for 25.0, 25.5, and 26.0 kg/m^3 isopycnals. These isopycnals represent middle, lower, and near the bottom of the thermocline, where temperature decreases sharply in the vertical. Zonal velocity on the depth of these isopycnals is also presented.

We will then show the changes of the ITF at the entrance strait of the Indonesian Seas; the western route at the Makassar Strait (from 115 °E to 120 °E) and the eastern route (from 120 °E to 135 °E). Temperature and potential density are examined from 0 to 1000 m depths and 1000 to 2000 m depths. The meridional velocity and volume transport between the depths of 0 to 1000 m and 1000 to 2000 m are then presented.

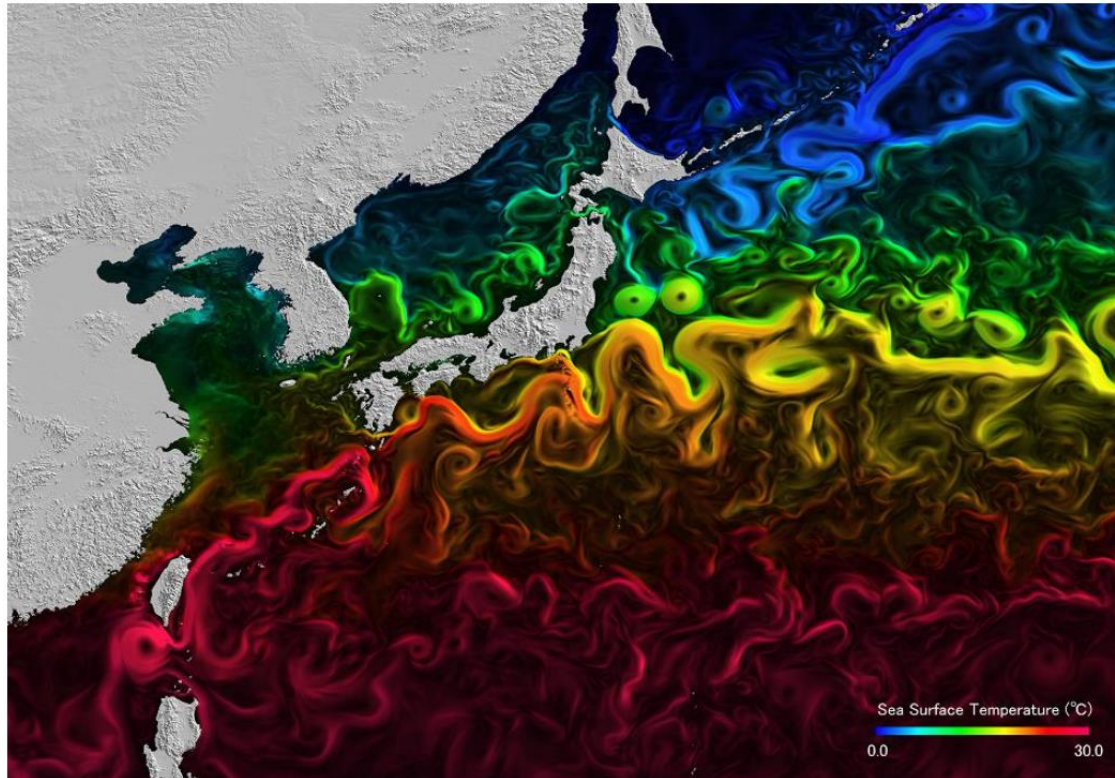


Fig 2.1 A snapshot of OFES near Japan (JAMSTEC/Center for Earth Information Science and Technology, Advanced Visualization and Computation Research Group, 2012). Color represents the sea surface temperature and brightness represents the flow speed.

Chapter3 Result and Discussion

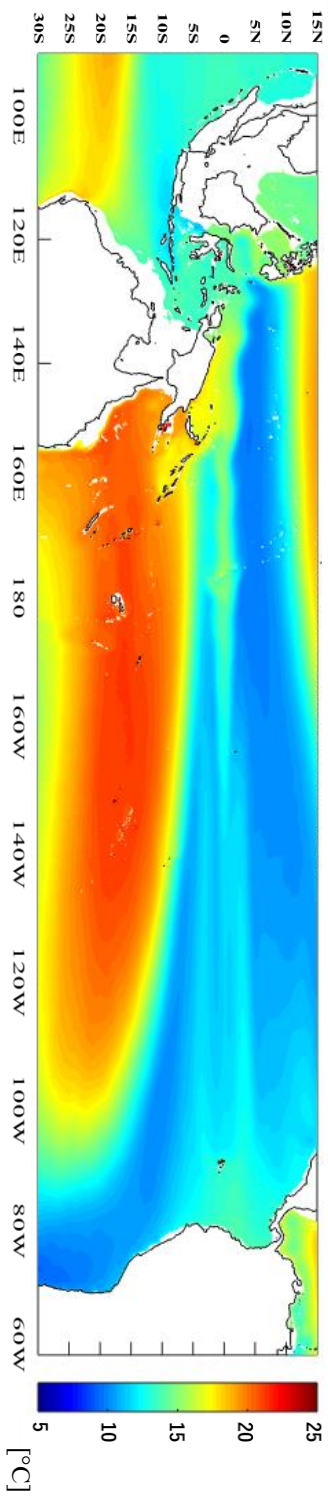
3.1 The spatial difference from the Equatorial Pacific to the Indonesian Seas

To clarify the cause of the SSH increase, we investigated the water mass properties of the Equatorial Pacific and the Indonesian Seas; temperature and the potential density. We will focus on the changes that occurred in the mid to lower thermocline, which is about 200 m in depth and 25 - 26 kg/m³ isopycnals for density.

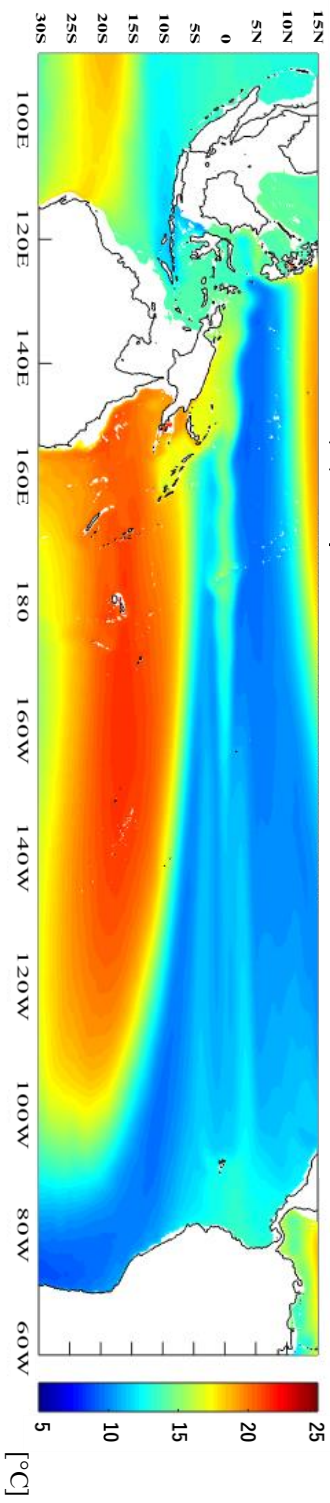
3.1.1 Temperature

Figures 3.1.1A shows the temperature distribution at 200 m depth for OFES2 (with tidal mixing). Figure 3.1.1B shows the temperature distribution at 200 m depth for OFES2_NT (without tidal mixing). Cold water mass of about 10 °C is distributed mainly from the Equatorial Pacific to 10 °S and spreads north and south towards the east. It is also found along the coast of Chili. The warm water of about 20 °C is distributed on the eastern side of Australia (from 30 to 10 °S and from 160 °E to 100 °W) and on the eastern side of Philippines (from 10 °N to 15 °N). In the Indonesian Seas, the temperature is about 10 to 15 °C, with low temperature found in the Celebes Sea (from 1 to 5 °N and from 118 to 125 °E), the Timor Sea (from 9 to 11 °S and 120 to 130 °E), and the Indian Ocean. When comparing Figures 3.1.1A and 3.1.1B, the basic temperature spatial distribution and the magnitude remains almost the same. The difference between OFES2 and OFES2_NT (OFES2 minus OFES2_NT) is shown in Figure 3.1.1.C. In the Pacific, the temperature increase is found with a zonal distribution spreading from west to east and centered around the equator. Weak temperature decrease is found at the eastern side of New Guinea Island in the Indonesian seas. Around the Philippines, the temperature increase by about 1 °C. Large temperature increase is found on the eastern side of New Guinea Island, along 5 °S with a maximum of 3.4 °C. Such strong change occurred only in this place. In the Indonesian Seas, the increase is found along the western route of the ITF, from the Makassar Strait to the Timor Strait. At the western side of Australia, the difference of the temperature is not found.

(A) Temperature at 200m for OFES2



(B) Temperature at 200m for OFES2 NT



(C) Difference of OFES2 and OFES2_NT

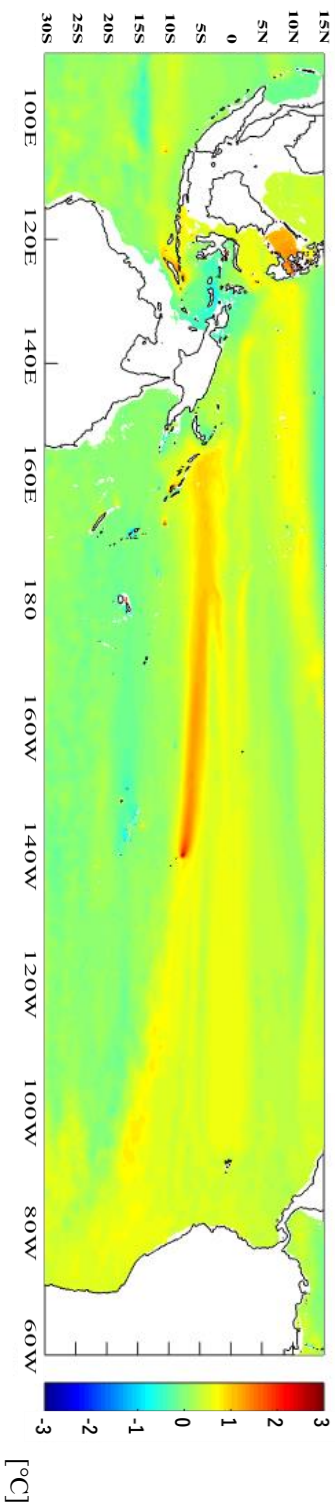


Fig3.1.1 Temperature at depth of 200m in (A) OFES2 and (B) OFES2_NT.

(C) Temperature difference between OFES2 and OFES2_NT (OFES2 minus OFES2_NT).

3.1.2 Depth of Isopycnal

The temperature was investigated at a constant depth in the previous subsection. Here, we investigated the depth of isopycnals that represents the thermocline. The depth of isopycnals for 25.0, 25.5, and 26.0 kg/m³ represent the middle, lower, and near the bottom of the thermocline respectively.

Figure 3.1.2A shows the depth of 25.0 kg/m³ isopycnal for OFES2. Figure 3.1.2B shows the depth of 25.0 kg/m³ isopycnal for OFES2_NT. Both figures show that the overall depth is less than 200 m. So this isopycnal represents the water mass above 200m, which was examined in subsection 3.1.1. The depth tends to become deeper towards the west from the coasts of Chile/Peru to the coasts of Australia and the islands of Philippines. At the coasts of Chile/Peru, the depth is very shallow and is about 50 m. The depth is about 200 m on the eastern side of the Philippines. When comparing Figure 3.1.2A and 3.1.2B, the distribution of depth appears to be almost the same.

Figure 3.1.2C shows the difference between OFES2 and OFES2_NT. In the south of Sumatra, the Banda Sea, and near the Timor Strait, isopycnal depth becomes deeper by about 10 cm. On the eastern side of Australia from 160 °E to 110 °W, the isopycnal depths fluctuate and in particular, large changes occur at the area around 150 °W to 110 °W. At the western side of Chile/Peru, the difference is relatively small compared to other regions.

Figure 3.1.3A shows the depth of 25.5 kg/m³ isopycnal for OFES2. Figure 3.1.3B shows the depth of 25.5 kg/m³ isopycnal for OFES2_NT. This isopycnal also represents water mass around 200 m depth, which was examined in 3.1.1. In the Equatorial Pacific region, the depth is more than 200 m in the west and gradually becomes shallower towards the east. At the eastern equatorial Pacific and the seas around South America, the depth of isopycnal is relatively shallow and is about 100 m. The depth on the eastern side of Australia is deep, with about 250 m at the center of the southern Pacific (about 160 °W to 140 °W). The depth of the 200 m contours can be followed from the eastern side of the Philippines along the line of 10 °N to the North of Celebes Sea. In the Indonesian seas, the depth of isopycnal is about 140 m in the Banda Sea, the Timor Sea, and the Halmahera Sea. When compared with Figure 3.1.1, we find the depth of isopycnal with a similar spatial pattern as that of temperature.

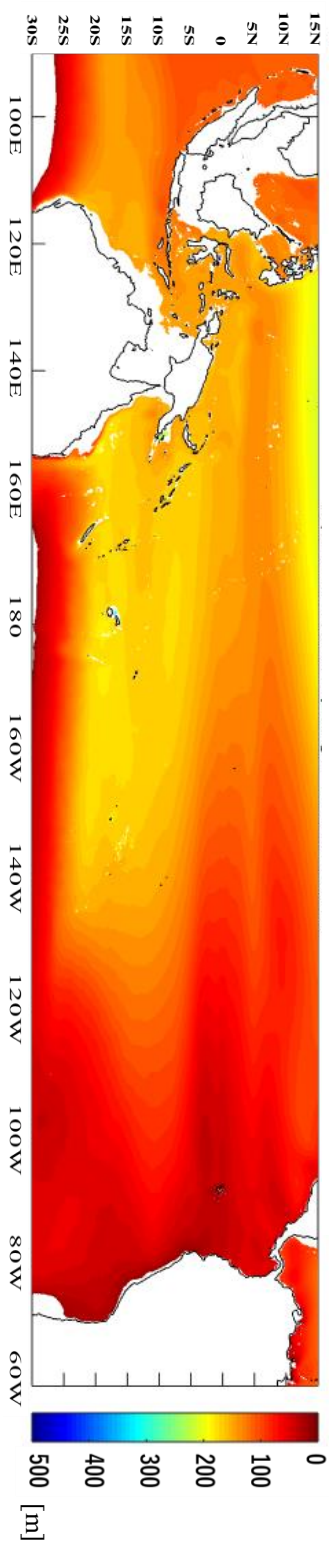
Figure 3.1.3C shows the difference between OFES2 and OFES2_NT. The depth tends to be deep from the equatorial Pacific to the 10 °S. In the subtropical regions around 20 °S, the variation is found at the eastern side of Australia and the western side of Chile where the isopycnal is shallow. In the Indonesian seas, the depths are about 10 m deeper along the ITF western route, from the Makassar Strait to the Timor Strait, and along the southern Sumatra Island. However, the depths in the Banda

Sea and Seram Sea, along the ITF eastern route, are found to become shallower.

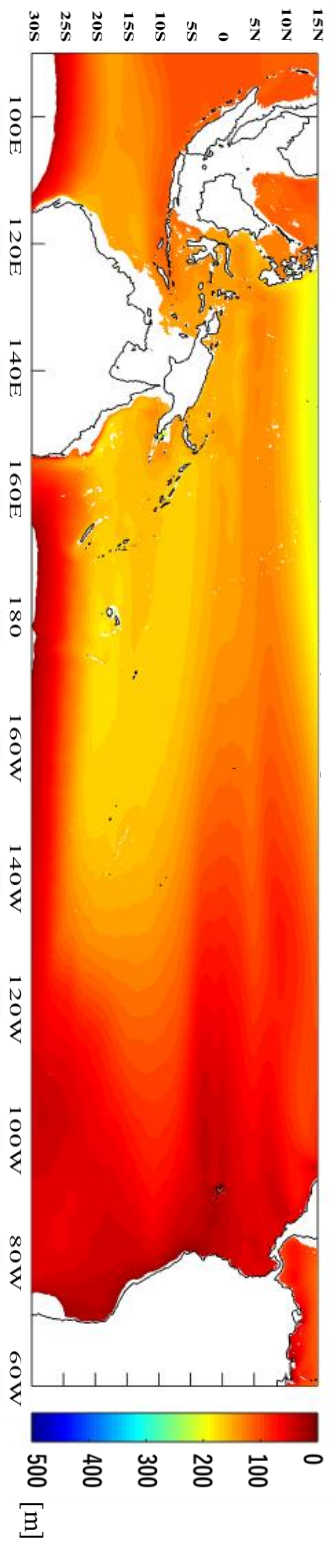
Figure 3.1.4A shows the depth of 26 kg/m^3 isopycnal for OFES2. Figure 3.1.4B show the depth of 26 kg/m^3 isopycnal for OFES2_NT. This isopycnal represents a deeper part of the thermocline and water mass around 200 m but below 25.5 kg/m^3 . The basic spatial distribution near the equatorial is similar to that of 25.5 kg/m^3 isopycnal (Figure 3.1.3A). On the east side of Australia, the isopycnal is deep, with about 350 m in the center of the South Pacific. The isopycnal is also deep to the east of the Philippines. In the Indonesian seas, the depth of isopycnal is about 200 m at the Makassar Strait, Halmahera sea and Banda sea. The 200 m depth contour is found to continue to the Indian ocean and its interior (15°S).

Figure 3.1.4C shows the difference in the depth of 26 kg/m^3 isopycnal between OFES2 and OFES2_NT. The decrease in depth extends over most areas of the domain except for only a few areas. In the Indonesian Seas, the isopycnal depth becomes deeper on the western route of the ITF, from the Makassar Strait, around Timor Strait, and south of the Sumatra Island. In the eastern route of ITF, such as the Halmahera Sea and Moluccan Sea, the isopycnal depth becomes about 15 m shallower. In the place same where a strong increase in temperature is found at the depth of 200 m (Figure 3.1.1C), the depth also becomes deeper with a maximum of about 20 m.

(A) Depth of isopycnal for density of 25.0 kg/m^3 for OFES2



(B) Depth of isopycnal for density of 25.0 kg/m^3 for OFES2_NT



(C) Difference of OFES2 and OFES2_NT

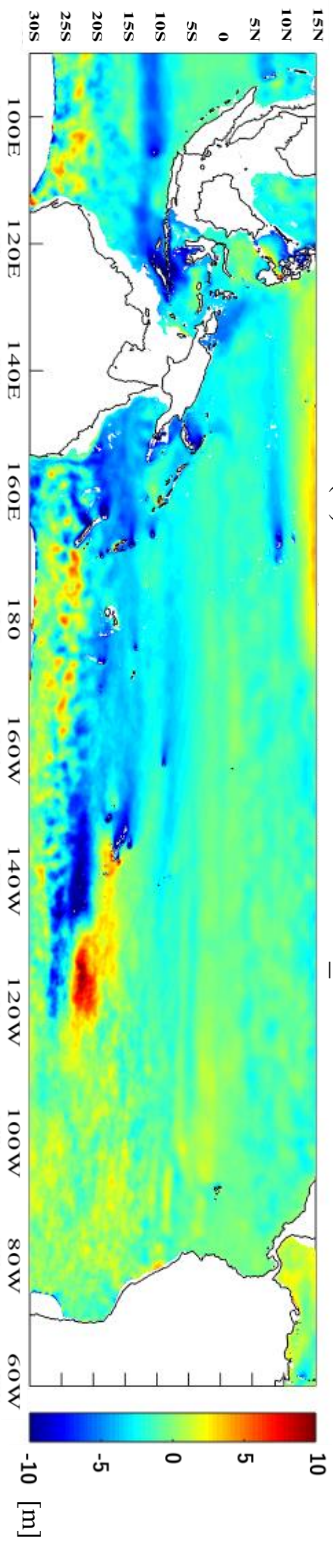
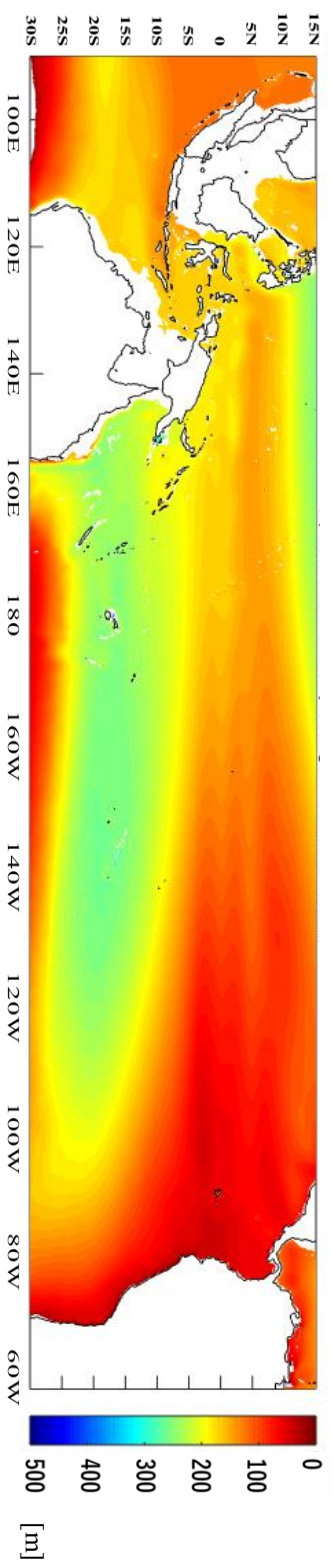


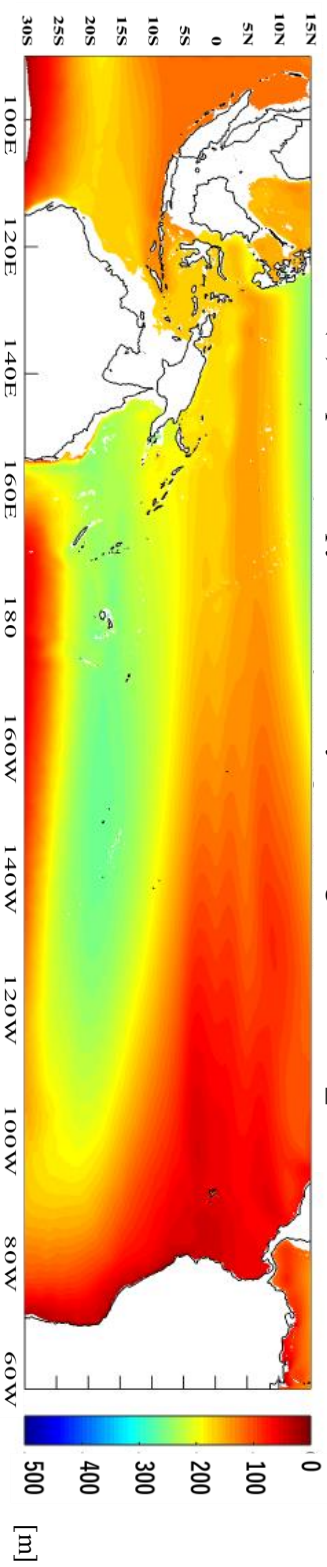
Fig 3.1.2 Depth of potential density 25.0 kg/m^3 in (A) OFES2 and (B)

OFES2_NT. (C) The difference in depth

(A) Depth of isopycnal for density of 25.5 kg/m^3 for OFES2



(B) Depth of isopycnal for density of 25.5 kg/m^3 for OFES2_NT



(C) Difference of OFES2 and OFES2_NT

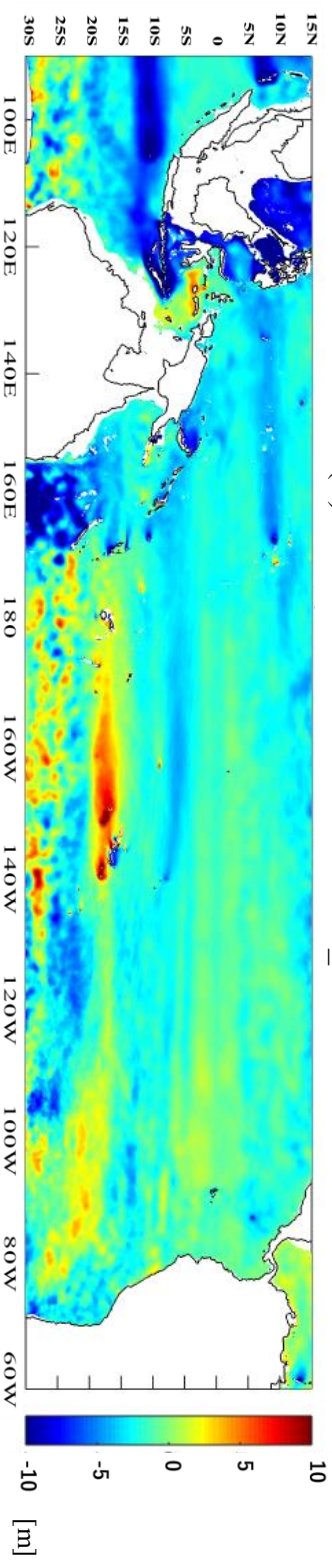
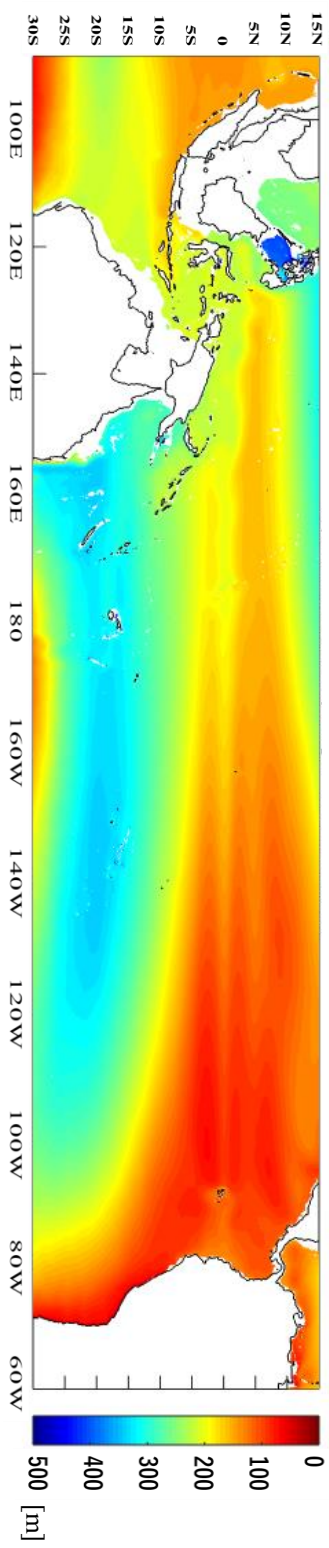


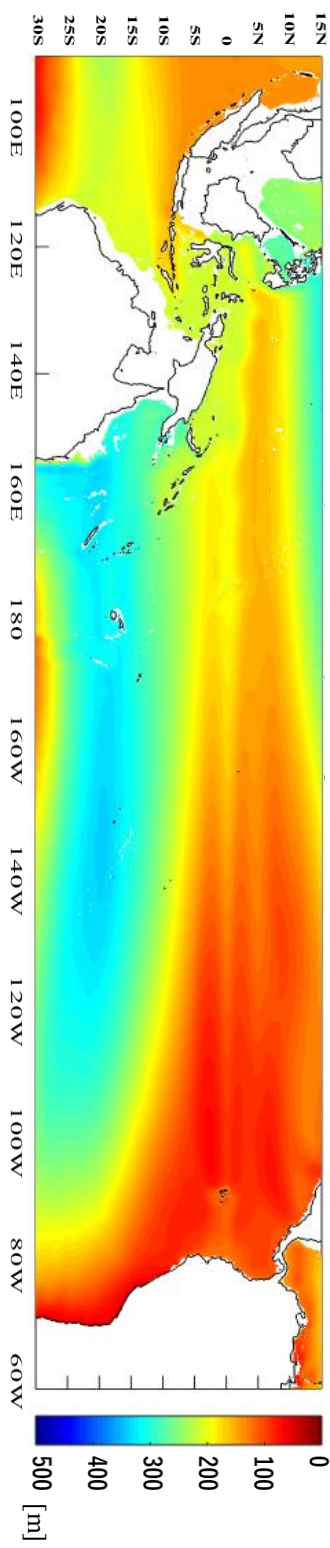
Fig 3.1.3 Depth of potential density 25.5 kg/m^3 in (A) OFES2 and (B) OFES2_NT.

(C) The difference of depth.

(A) Depth of isopycnal for density of 26.0 kg/m^3 for OFES2



(B) Depth of isopycnal for density of 26.0 kg/m^3 for OFES2_NT



(C) Difference of OFES2 and OFES2_NT

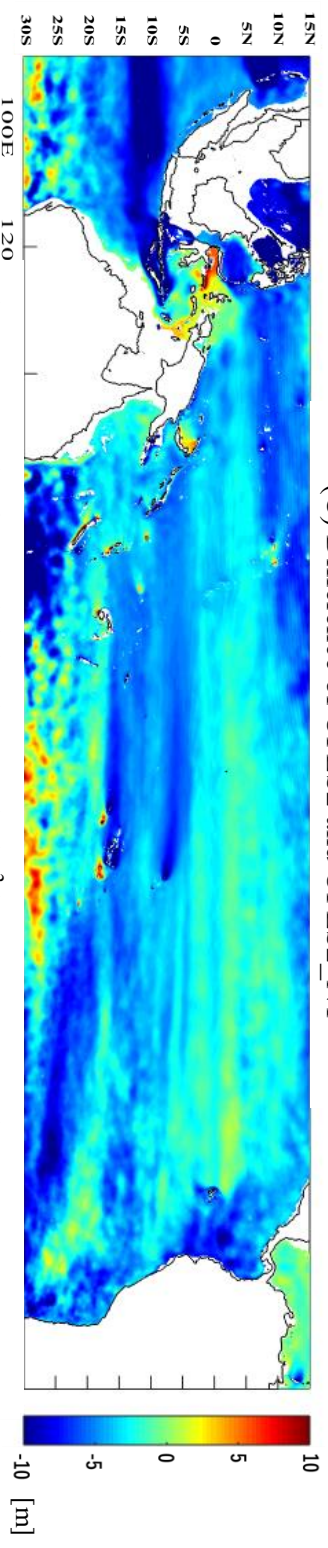


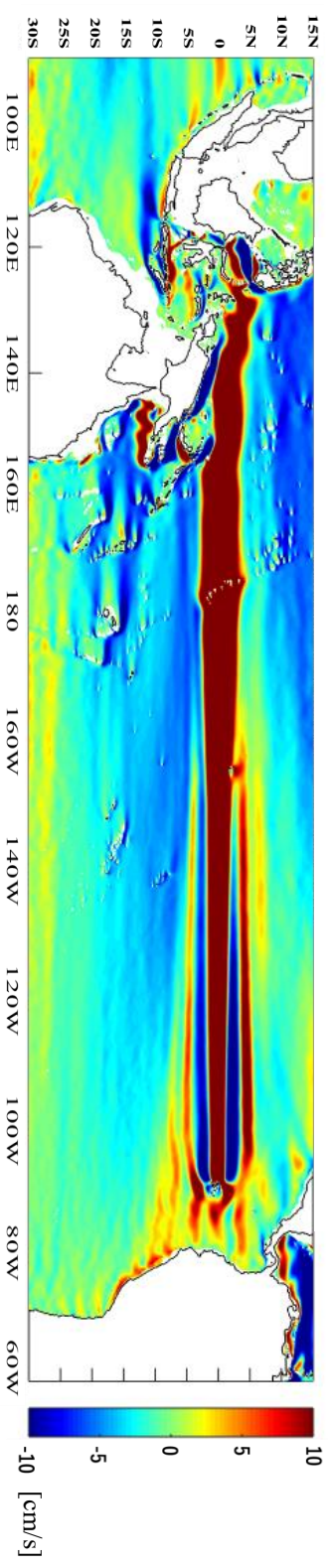
Fig 3.1.4 Depth of potential density 26.0 kg/m^3 in (A) OFES2 and (B) OFES2_NT. (C) The difference of depth.

3.1.3 Zonal Velocity

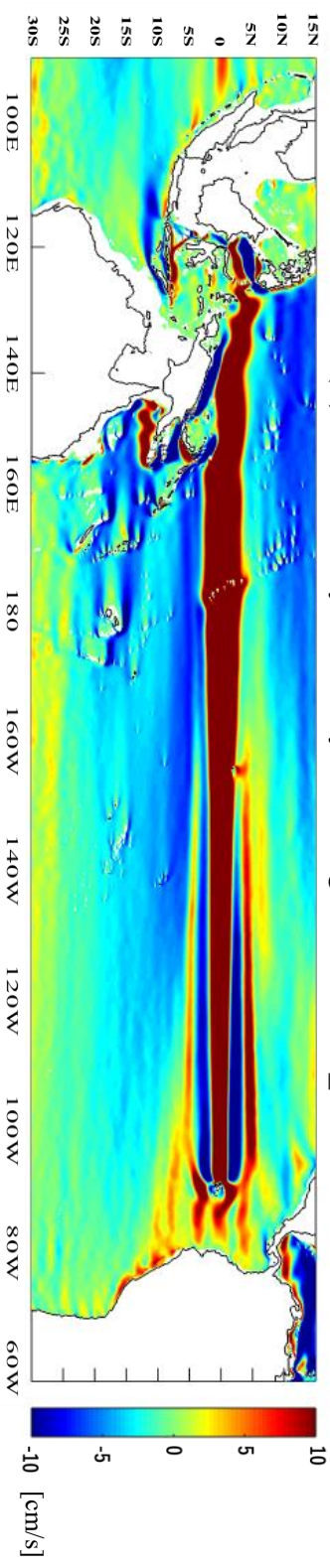
To investigate how the increase in temperature and decrease of isopycnal depth affect the flow field, we will investigate the zonal velocity next. Figure 3.1.5A shows the zonal velocity along the 26.0 kg/m^3 isopycnal for OFES2 and Figure 3.1.5B shows the zonal velocity along 26.0 kg/m^3 for OFES2_NT. A strong eastward flow is observed in zonal bands from near the Indonesian seas to the Galapagos Islands. This is the equatorial undercurrent. From the tropical zone to the subtropical zone, a westward flow is observed with a spatial distribution that spreads meridionally towards the west. The strong westward velocity located in the North Pacific near the Philippines is about 5 to 10 cm/s. It shows that the water mass of the North Pacific is entering the Indonesian Seas through this westward flow. Within the Indonesian Seas, there is a flow from the Makassar Strait to the Lombok Strait and to the Timor Strait through the Banda Sea that continues to the Indian Ocean. At the northern coast of the New Guinea island, there is a westward flow along the coast to the Halmahera Sea which enters the eastern route of the ITF. This flow plays a role of advecting the water in the South Pacific to the Indonesian Seas.

Figure 3.1.5C shows the difference between OFES2 and OFES2_NT. Changes occur with a narrow zonal structure. In the Equatorial Pacific, a westward flow of about 5 cm/s continue from the center of the Pacific to the entrance of the ITF. This means that the eastward flow becomes weaker on the equator and the Celebes Sea, located at the entrance of the Indonesian Seas for the ITF. In the Indonesian seas, a flow strengthens toward the west at the Seram Sea and the Lombok Strait, and toward the east at the Banda Sea. In the place where the temperature at the depth of 200 m strongly increased (Figure 3.1.1C) and the depth of 26.0 kg/m^3 isopycnal deepened (Figure 3.1.4C; 10°S , 140°W), the zonal velocity also changes. As the enlarged Figure 3.1.6B shows, the zonal velocity reverses at the eastern end of where temperature change occurred with a magnitude of about 0.6 cm/s. We are not aware of why such a phenomenon occurs yet.

(A) Zonal velocity for density of 26.0 kg/m^3 for OFES2



(B) Zonal velocity for density of 26.0 kg/m^3 for OFES2_NT



(C) Difference of OFES2 and OFES2_NT

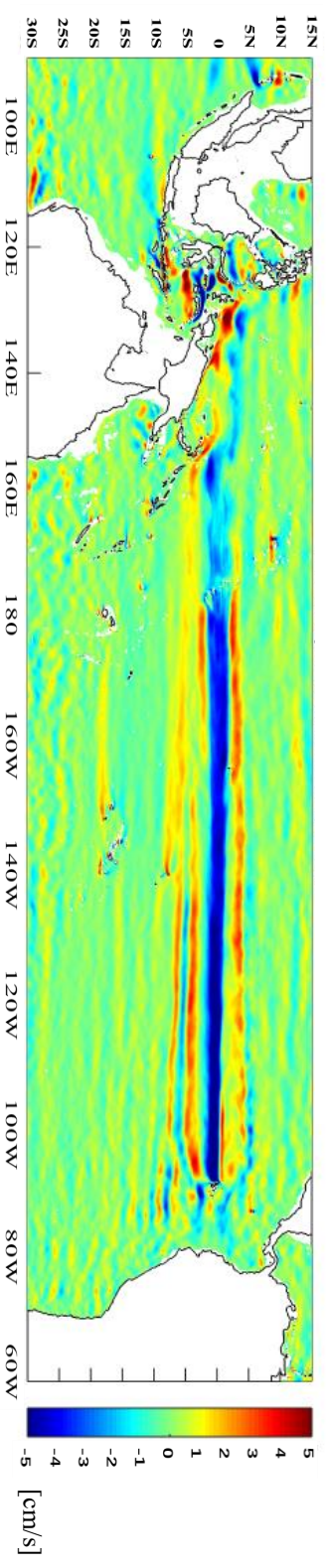


Fig 3.1.5 Zonal velocity along the depth of density 26.0 kg/m^3 in (A) OFES2 and (B)

OFES2_NT. (C) The difference in the zonal velocity.

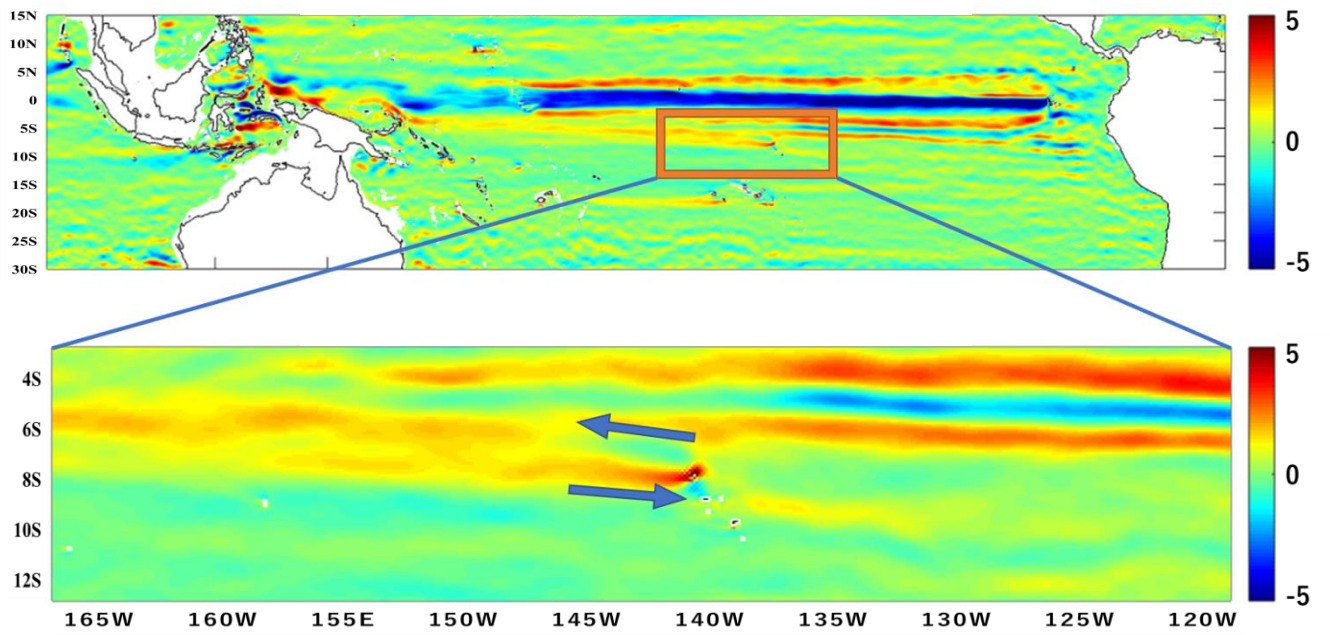


Fig 3.1.6 (A) The difference in the zonal velocity along density 26.0 kg/m^3 (same as Fig3.1.5C). (B) Enlarged view of where temperature increase occurred at 200 m.

3.2 Changes in ITF at the straits

We now examine the changes in the temperature, potential density, meridional velocity, and volume transport of the ITF at the entrance of the western and eastern routes. The western route of the ITF is through the Makassar Strait (115 °E -120 °E) and is known as the main route, where about 80% of the ITF transport is observed (Gordon, 2005). The eastern route of the ITF is through the straits around the Halmahera island (126 °E- 130 °E). We will first show the changes in water mass properties (temperature and potential density) and then the meridional velocity and volume transport.

3.2.1 The change in water mass property

Temperature and density on the west route (Makassar Strait, 2 °S, 115 °E-120 °E)

Figure 3.2.1A and 3.2.1B show vertical cross-section for temperature in the western route for OFES2 and OFES2_NT, respectively. The basic temperature profile for OFES2 and OFES2_NT are similar. The temperature is about 30 °C at the surface and drops sharply around 400 m and becomes about 5 °C around 1000 m. Figure 3.2.1C shows the difference between OFES2 and OFES2_NT, showing a temperature difference of less than 1 °C. Temperature decreases slightly from the surface to 150 m. The temperature then increases between 150 to 500 m with a maximum of 0.7 °C. Temperature also increases below 700 m, but it is about 0.2 °C and is weaker.

Figure 3.2.2A and 3.2.2B shows the temperature averaged horizontally across the strait for OFES2 and OFES2_NT, respectively. It confirms the abrupt temperature change down to 400 m and gradual change at further depth. Figure 3.2.2C shows the difference between OFES2 and OFES2_NT and confirms that the temperature increases at the depth between 150m and 500 m, and again below 600 m.

We now investigate changes in density at deeper depths, down to 2000 m. This depth is close to the bottom of the Makassar Strait at this latitude. Figure 3.2.3A and 3.2.3B show the distribution of potential density in the Makassar strait for OFES2 and OFES2_NT, respectively. The density of the Makassar Strait is about 21 kg/m³ at the surface and about 28 kg/m³ near the bottom. Potential density in the Makassar strait range decreased significantly from the surface to 400 m (which is roughly the pycnocline) and then become almost the same from 400 m to the bottom. These changes are similar to that of temperature.

Figure 3.2.4A and 3.2.4B show the potential density averaged across the strait. Like the horizontal average of temperature (Figure 3.2.2), potential density also changes from the surface to 400 m, but

hardly changes below. Density does not change much from 1000 m to 2000 m. The basic profiles of Figures 3.2.4A and 3.2.4B are similar.

Figure 3.2.3C and 3.2.4C show the difference between OFES2 and OFES2_NT. The density increases between 0 to 100 m with a maximum of 0.07 kg/m^3 and decreases between 200 to 500 m with a maximum of 0.09 kg/m^3 . Density increases slightly at around 600 m and then decreases at about 900 m. The difference becomes very small at further depths.

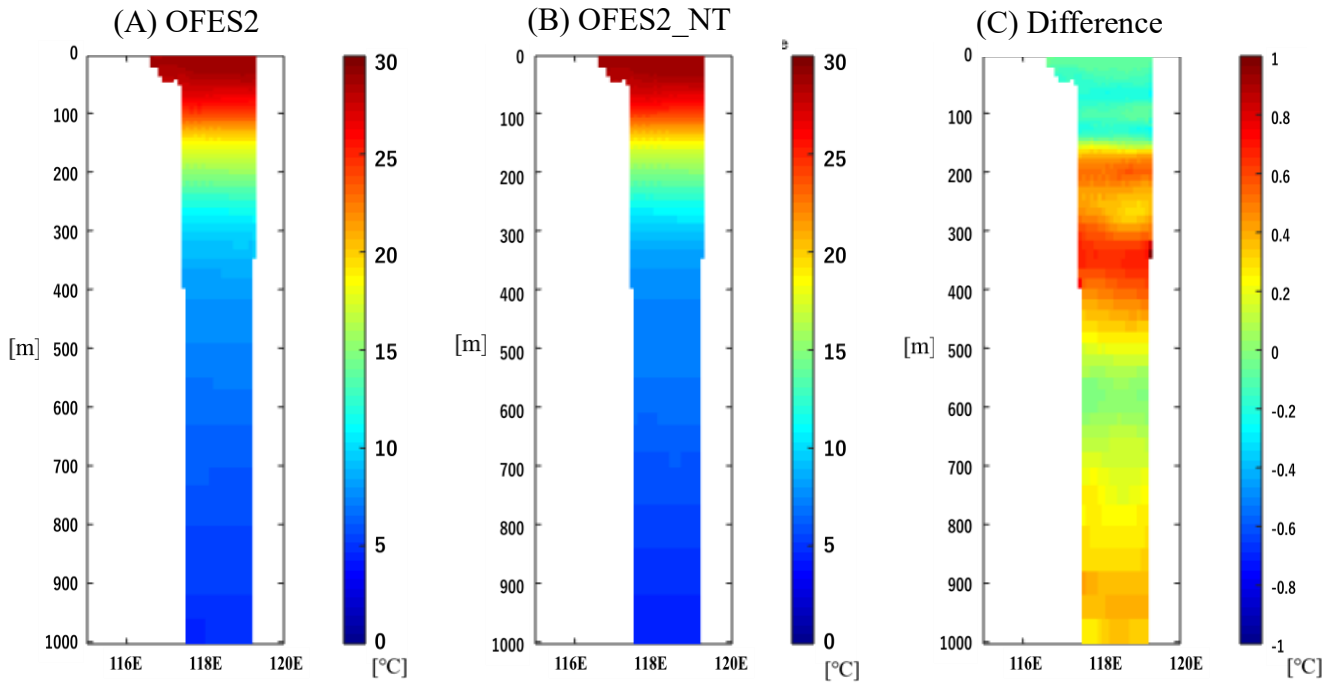


Fig 3.2.1 Temperature in the ITF western route in (A) OFES2 and (B) OFES2_NT. (C) The difference in temperature.

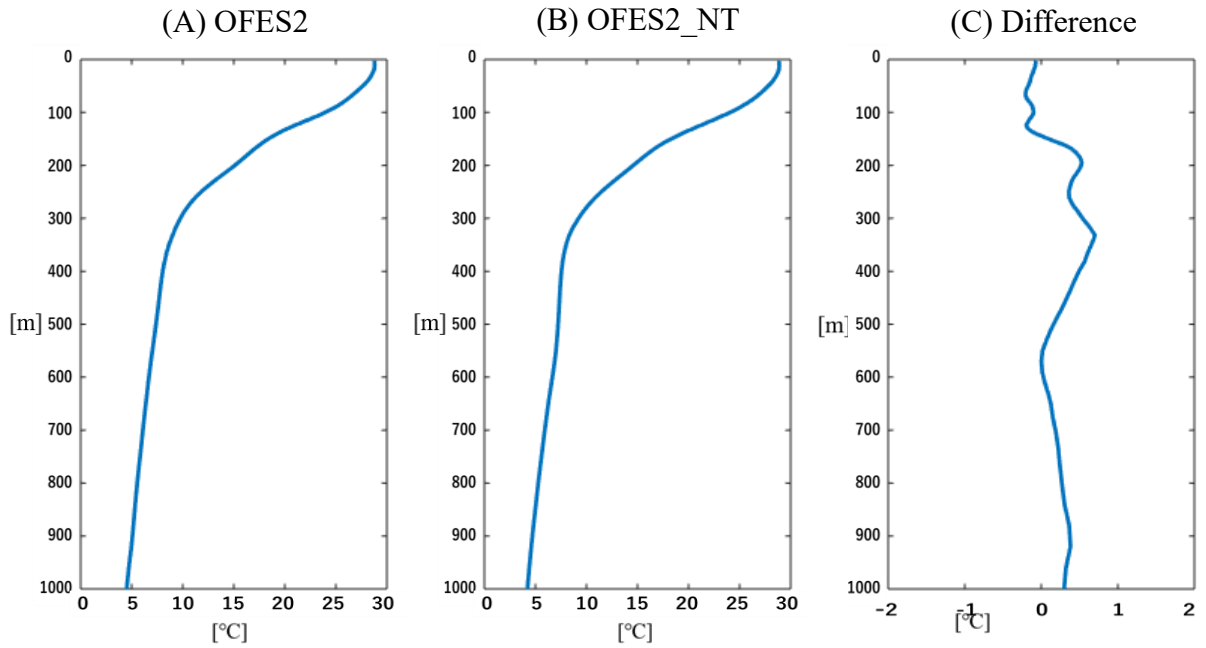


Fig 3.2.2 Horizontally averaged temperature in the ITF western route in (A) OFES2 and (B) OFES2_NT. (C) The difference in horizontally averaged temperature.

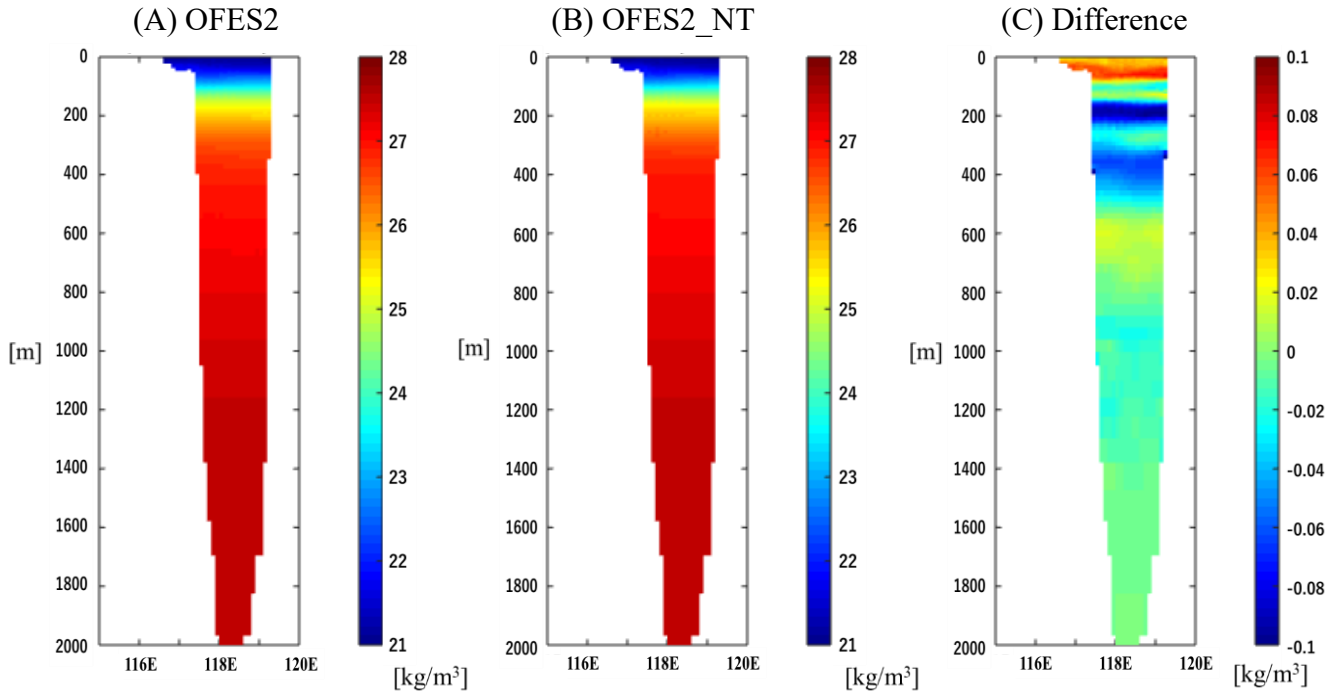


Fig 3.2.3 Potential density in the ITF western route in (A) OFES2 and (B) OFES2_NT. (C) The difference in potential density.

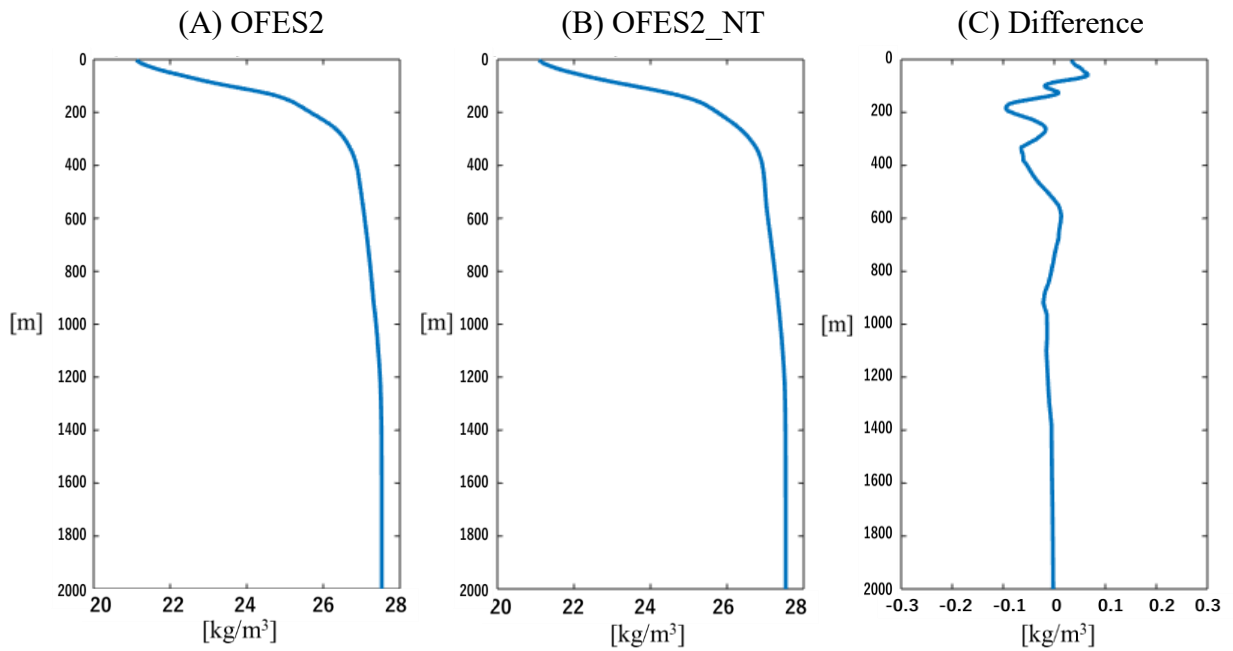


Fig 3.2.4 Horizontally averaged potential density in the ITF western route in (A) OFES2 and (B) OFES2_NT. (C) The difference in horizontally averaged density.

Temperature and potential density on the eastern route (the Equator, 120 °E – 135 °E)

The eastern route covers a wider distance than the western route, which includes the Moluccan sea and the Halmahera Sea (Figure 1.2). Figure 3.2.5A and 3.2.5B show the distribution of the temperature for OFES2 and OFES2_NT, respectively. The temperature of the surface layer is about 30 °C and becomes colder than 10 °C at depth deeper than 400 m. This vertical distribution is almost the same as that of the west route. When comparing the temperature of the Halmahera Sea with that of the Molucca Sea, the highest temperature is the same, but the lowest temperature at 1000 m depth is 7 °C in the Halmahera Sea and 4°C in the Molucca Sea. Deeper water of the Halmahera Sea is warmer than the Molucca Sea and the Makassar Strait (Figure 3.2.2). The temperature does not change much across the strait, which is the same as that in the Makassar Strait.

Figure 3.2.6A and 3.2.6B show horizontally averaged temperature for OFES2 and OFES2_NT, respectively. The temperature becomes uniform at depth and the depth of the thermocline is about the same as the western route (Figure 3.2.2A and B). The surface temperature of the eastern route is about 29 °C, which is higher than the surface temperature of the western route by about 1 °C.

Figures 3.2.5C and 3.2.6C show the difference of the temperature between OFES2 and OFES2_NT across the strait and the horizontally averaged temperature, respectively. Temperature decreases between 0 to 100 m. In the Molucca Sea (120 °E to 127 °E), temperature increases at the depth between 200 to 400 m with a maximum of about 3.0 °C. In the Halmahera Sea (128 °E to 130 °E), temperature decreases at the depth between 0 to 200 m, increase near 300 m, and again at deeper depths. The increase in temperature at depth deeper than 600 m is large with a maximum of about 2.3°C. Tidal mixing appears to affect the Halmahera Sea significantly compared to the Molucca Sea and the Makassar Strait. Horizontally averaged temperature decreases by about 0.8 °C at about 100 m, increases by about 0.7 °C at about 300 m, and increases again at depth.

The potential density in the eastern route is examined down to 2000 m next. The depth of the Molucca Sea is about 4000 m, which is deeper than the Makassar Strait of the western route but we will analyze the same depths as that of the Makassar Strait here (Figure 3.2.3).

Figure 3.2.7A and 3.2.7B show the potential density on the eastern route for OFES2 and OFES2_NT, respectively. Both show a similar profile with a density of about 21 kg/m³ in the surface layer and increases to 27-28 kg/m³ below 400 m. These basic changes in the vertical profile are the same as that found in the Makassar Strait. Figure 3.2.8A and 3.2.8B show the horizontally averaged

potential density across the eastern route. Pycnocline is located at depth of about 400 m. Just like Figure 3.2.7A and B, the basic vertical profiles of OFES2 and OFES2_NT are similar.

Figure 3.2.7C and 3.2.8C show the difference in potential density between OFES2 and OFES2_NT. Between 0 to 400 m, the potential density changes show a stripe pattern because the increase and decrease occur alternately. Such pattern is the same as that found in the western route. In the Moluccan Sea (123 °E to 127 °E), the difference of potential density is almost zero below 500 m, but in the Halmahera Sea (128 °E to 130 °E), a significant decrease in density occur with a maximum of about 0.34 kg m^{-3} . Changes in the temperature and potential density in the Halmahera Sea are quite different from the temperature and potential density changes found in the Makassar Strait (Figures 3.2.1 and 3.2.2).

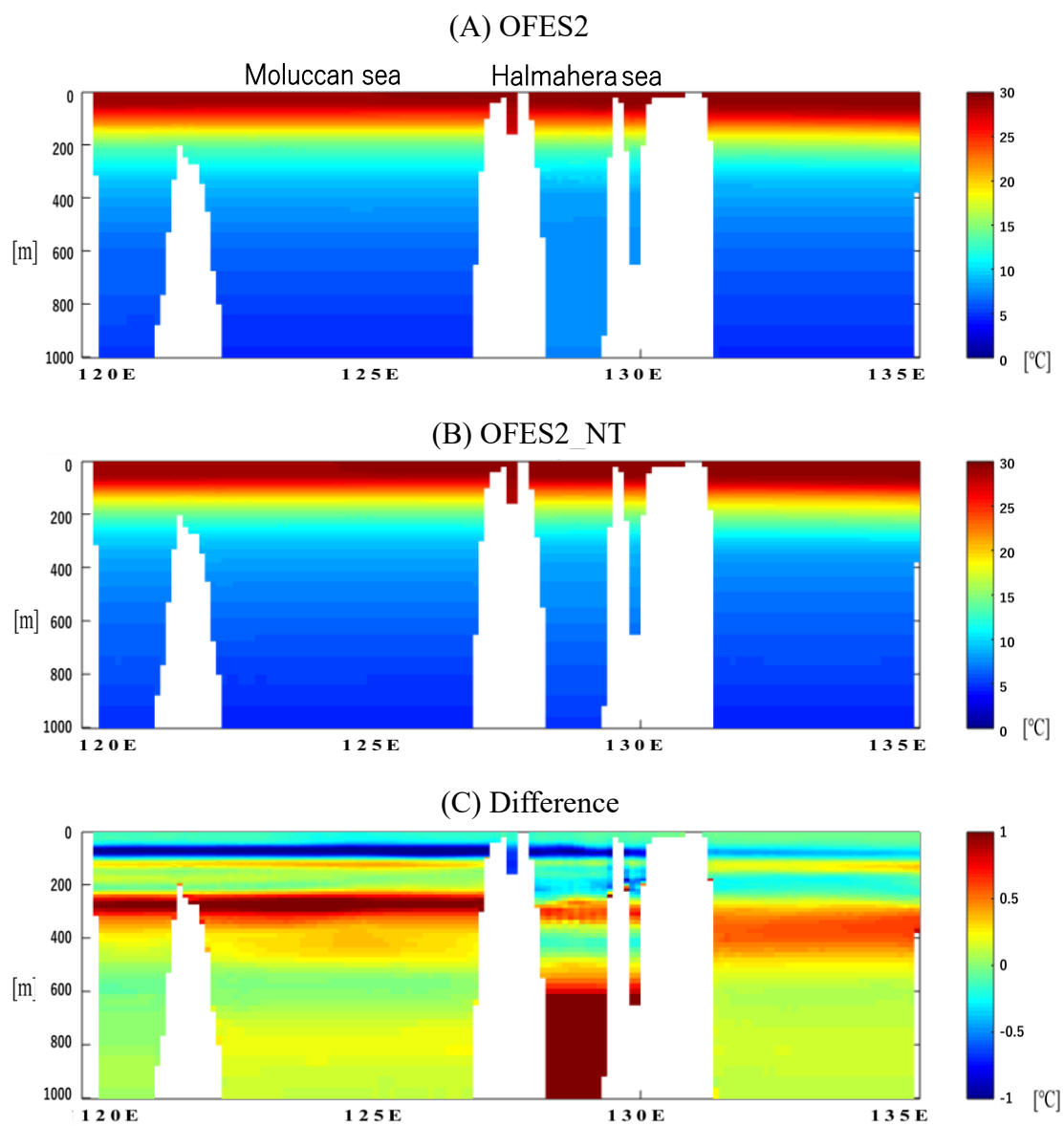


Fig 3.2.5 Temperature in the ITF eastern route in (A) OFES2 and (B) OFES2_NT.
(C) The difference in temperature.

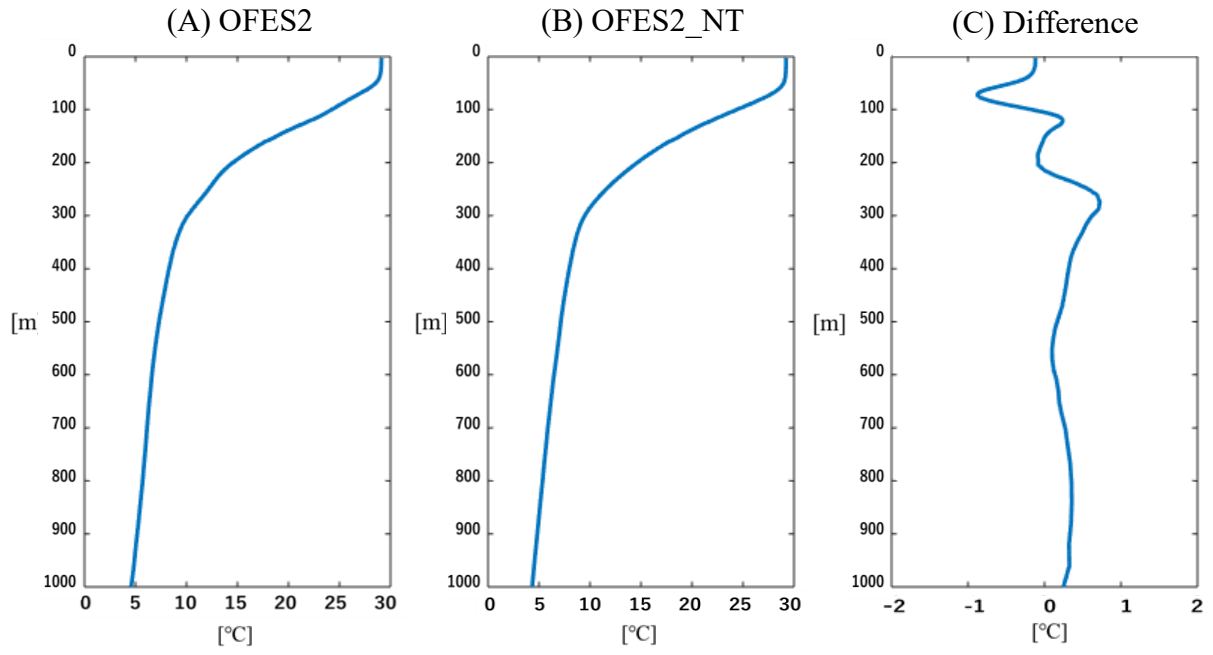


Fig 3.2.6 Horizontally average of the temperature in the ITF eastern route in (A) OFES2 and (B) OFES2_NT. (C) The difference in horizontal averaged temperature.

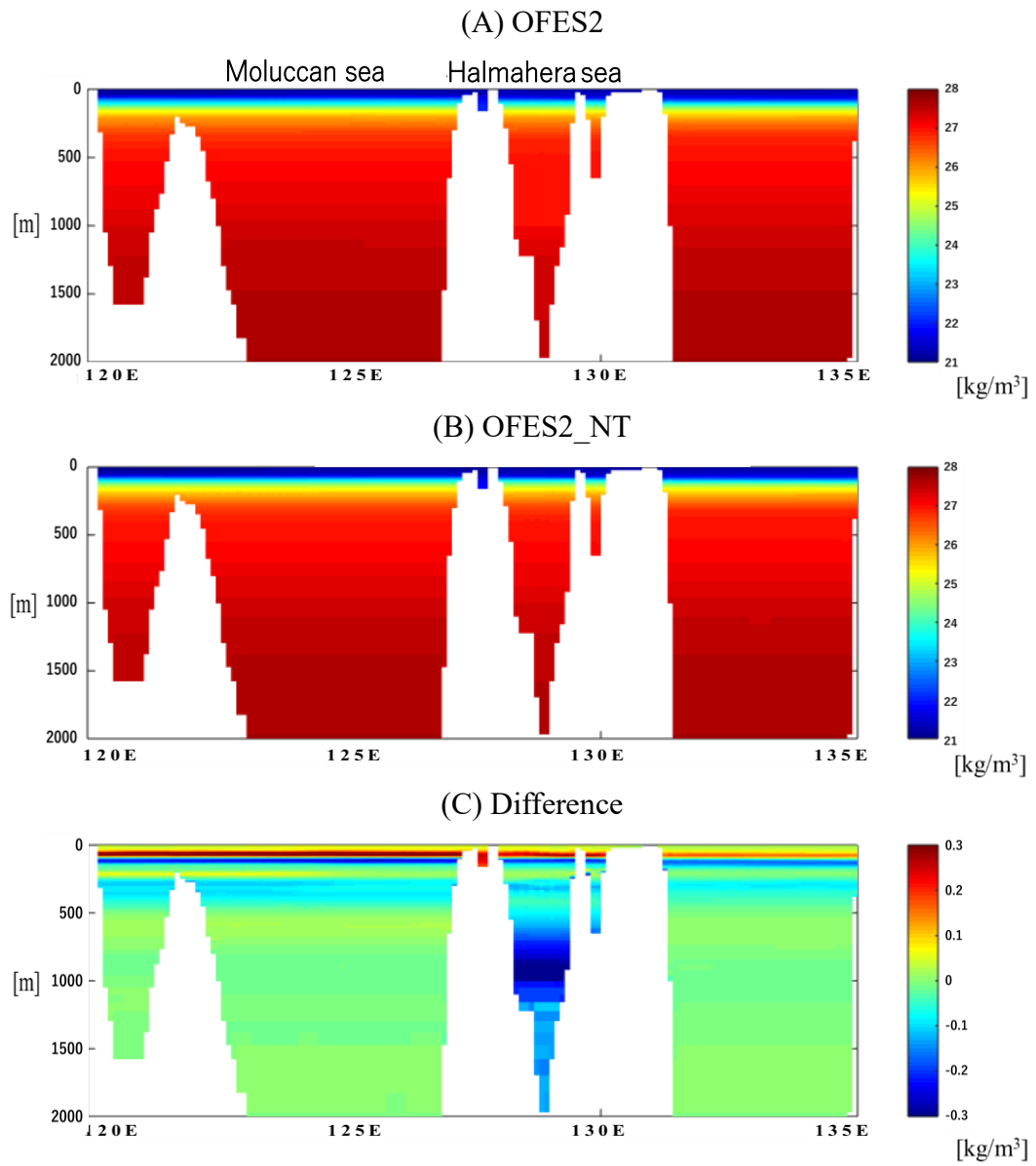


Fig 3.2.7 Potential density in the ITF eastern route in (A) OFES2 and (B) OFES2_NT. (C) The difference in potential density.

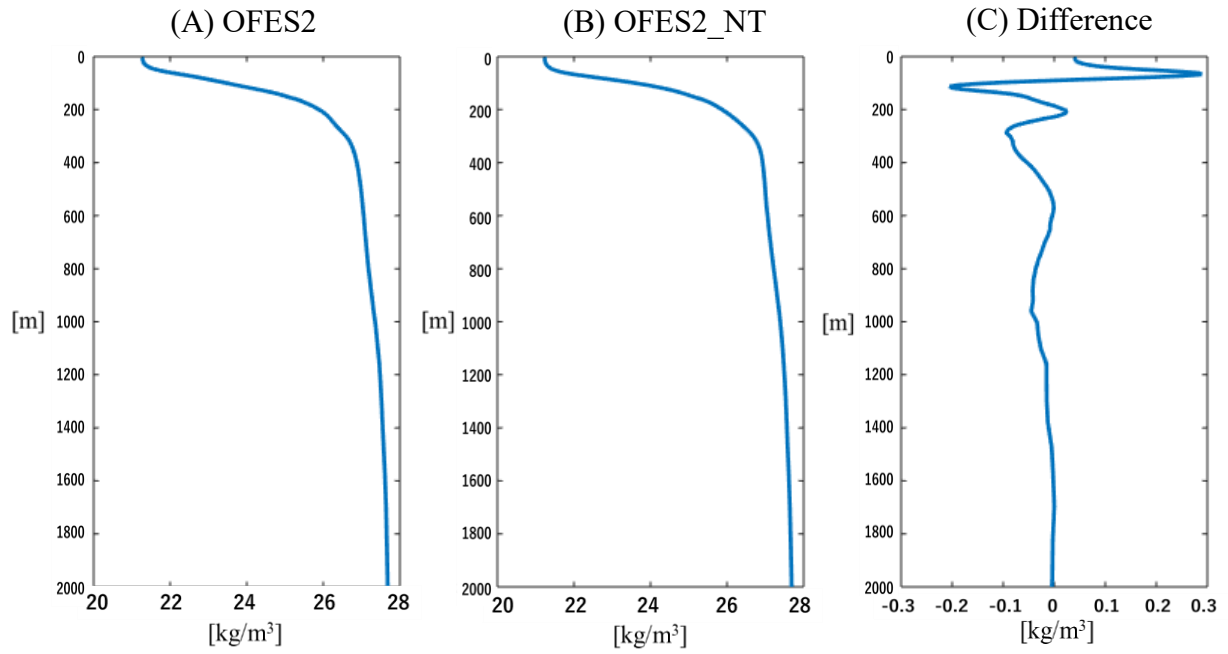


Fig 3.2.8 Horizontally average of the potential density in the ITF western route in (A) OFES2 and (B) OFES2_NT. (C) The difference in horizontal averaged potential density.

3.2.2 The change of Flow Field

We will now show the distribution and changes in the meridional velocity and the change in the volume transport of the ITF for OFES2 and OFES2_NT.

On the western route (Makassar Strait, 2 °S, 115 °E-120 °E)

Figures 3.2.9A and 3.2.9B show the meridional velocity at the western route from the surface to 1000 m across the Makassar Strait for OFES2 and OFES2_NT, respectively. A strong southward flow is found from the surface to about 600 m, which is the main core of the ITF. Northward flow is found in very limited locations. The southward flow has a maximum of about 60 cm/s close to the surface. Figures 3.2.10A and 3.2.10B show the horizontally averaged meridional velocity at the western route. Although it is not a smooth exponential profile like that of temperature and potential density (Figures 3.2.6 and 3.2.8), there is still a tendency to gradually become weak at depth. The average flow is strongest near the surface, with 26 cm/s, and the flow around the depth of 1000 m is less than 1 cm/s. When comparing Figures 3.2.10A and 3.2.10B, the decreasing trend near the depth of 300 m is somewhat abrupt for Figure 3.2.10B.

Figures 3.2.9C and 3.2.10C show difference of the meridional velocity between OFES2 and OFES2_NT. From the surface to 250 m, increase and decrease occur alternately. An increase in the southward flow occurs from 200 to 500 m and 800 to 900 m, with the highest increase in the southward flow of about 5.0 cm/s. A decrease in the southward flow is also found at the depth between 600 to 700 m. The magnitude of this enhancement in the southward flow matches with the increase in the ITF, which suggest that this feature is behind the enhanced flow from the Pacific to the Indonesia Seas due to tidal mixing.

Figures 3.2.11A and 3.2.11B show the meridional velocity in the Makassar strait at depths deeper than 1000 m for OFES2 and OFES2_NT, respectively. Although the magnitude is much weaker than above 1000 m, inflows and outflows exist at depths between 1000 to 2000 m in OFES2 whereas it is almost absent for OFES2_NT. The meridional velocity becomes almost zero and the velocity at the depth of 2000 m is 0.1 cm/s. Figures 3.2.12A and 3.2.12B show the horizontally averaged meridional velocity of the ITF across the Makassar Strait. Between 1000 m to 1400 m, the averaged velocity shows stronger inflow near 1000 m and again at 1400 m. The averaged velocity in OFES 2_NT is nearly zero.

Figures 3.2.11C and 3.2.12C show the difference in the meridional velocity between OFES2 and OFES2_NT. Below 600 m, the southward flow increases and decreases alternately down to 2000 m. Between 1000 and 2000 m, the southward ITF decreases near 1100 m but increases near 1300 m. The Makassar Strait is a place surrounded by the Borneo Island (western side of 118 °E), Swahili Island (eastern side of 119 °E) with abrupt changes in bottom topography. So there is a possibility that water mass in the deep layer is affected by the local tidal mixing.

The volume transport of ITF is estimated by integrating the meridional velocity in the strait

$$\text{volume transport} = \int v \Delta x \Delta z$$

where v is the meridional velocity, Δx is the horizontal resolution (about 10 km), and Δz is the thickness of each grid. Our estimate shows that the inflow of ITF on the wester route for OFES2 is 9.33 Sv, whereas that for OFES2_NT is 8.65 Sv. Therefore, the presence of tidal mixing enhances the ITF transport on the western route by about 0.68 Sv. This enhancement is mostly created by the enhanced flow between 300 to 500 m.

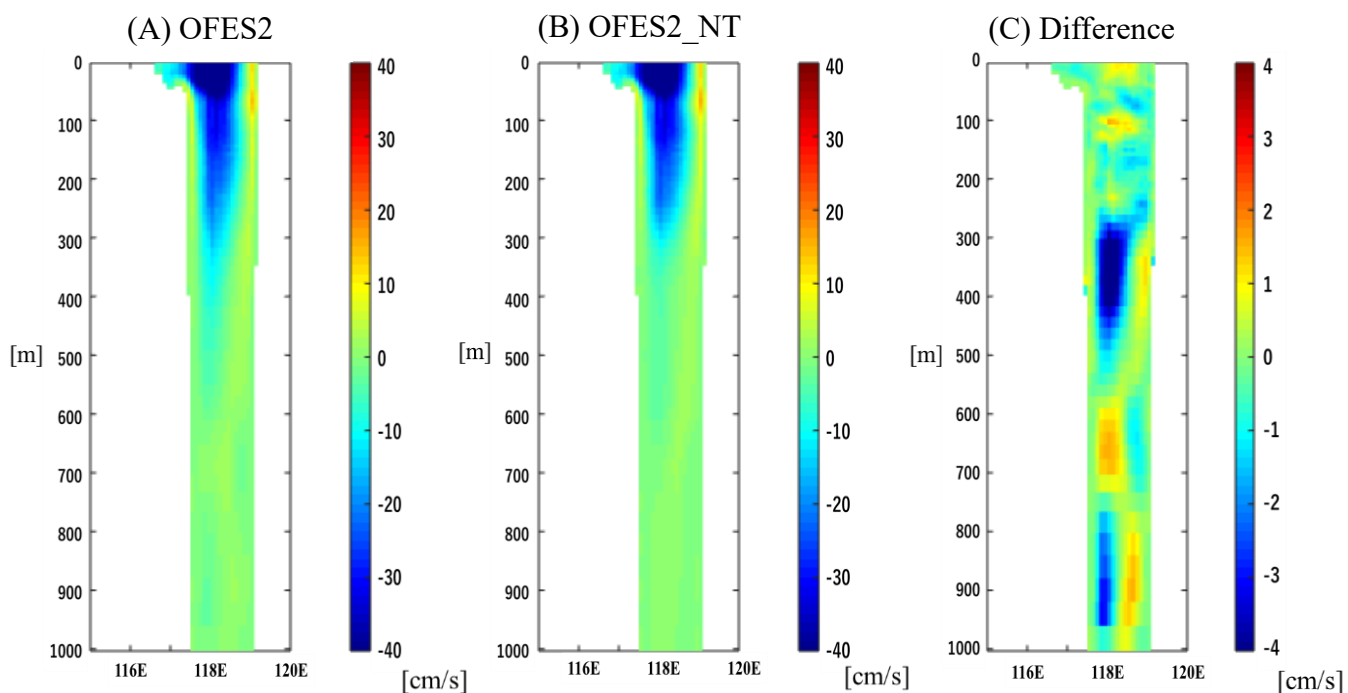


Fig 3.2.9 Meridional velocity in the ITF western route in (A) OFES2 and (B) OFES2_NT. (C) The difference in meridional velocity.

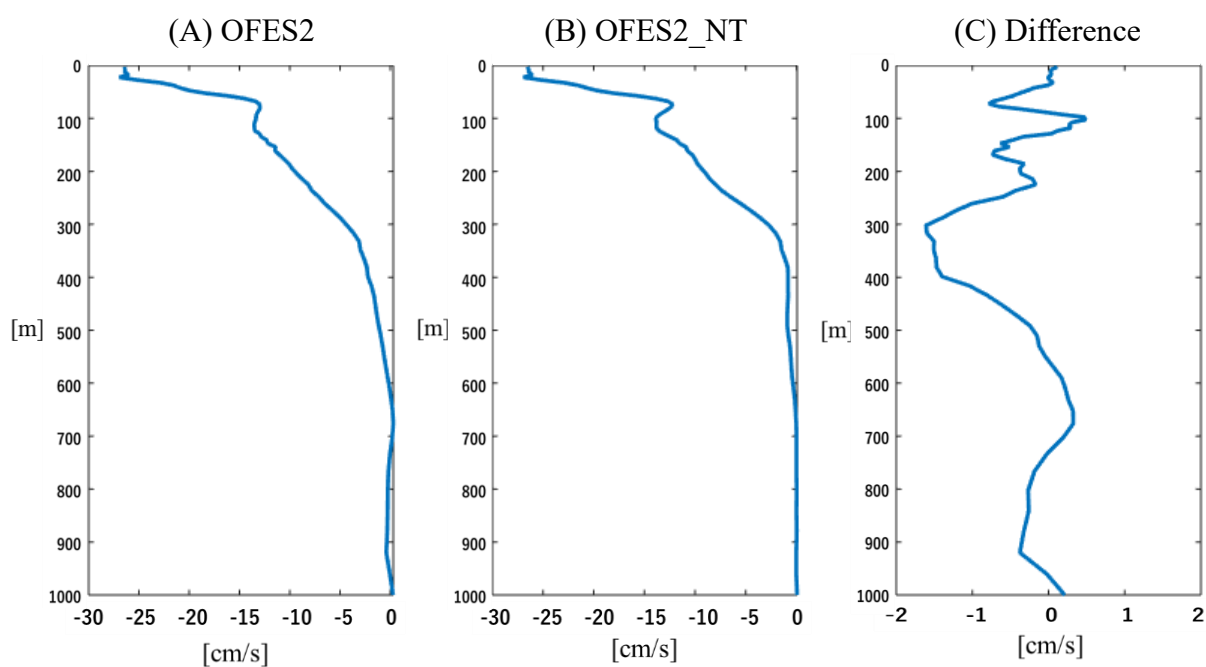


Fig 3.2.10 Horizontally averaged meridional velocity in (A) OFES2 and (B) OFES2_NT. (C) The difference in horizontally averaged meridional velocity.

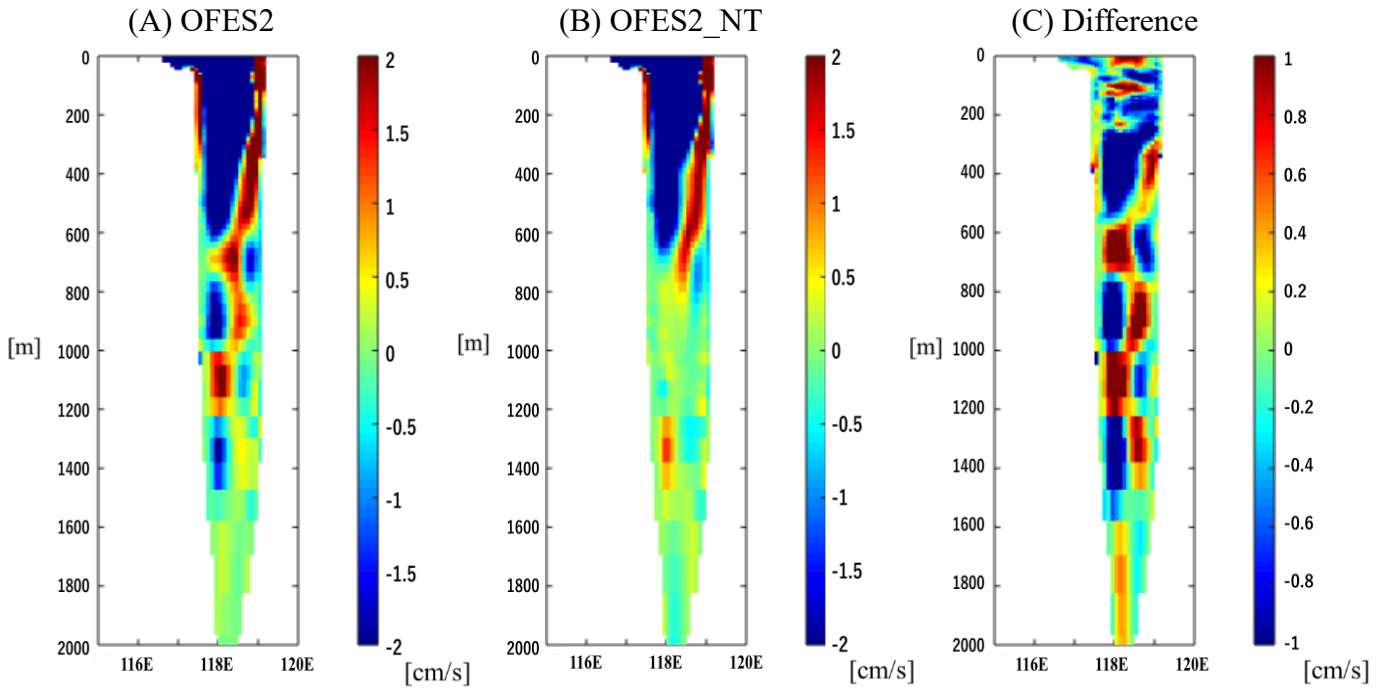


Fig 3.2.11 Meridional velocity in the western route in (A) OFES2 and (B) OFES2_NT. (C) The difference in meridional velocity.

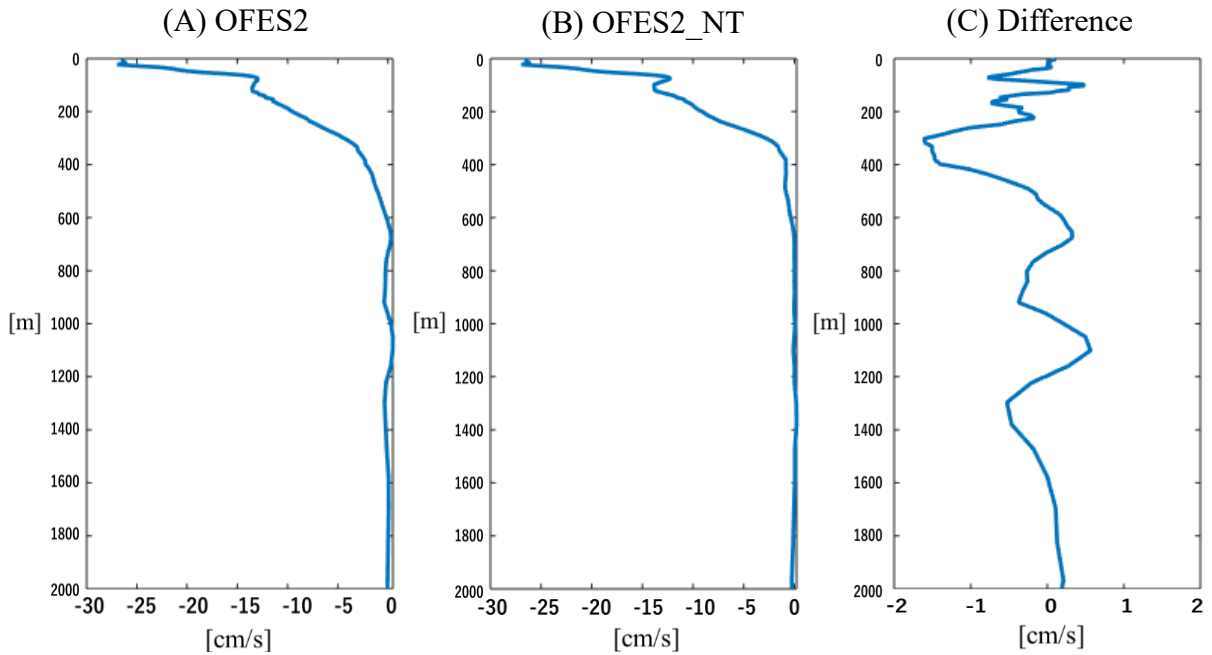


Fig 3.2.12 Horizontally averaged meridional velocity in the ITF western route in (A) OFES2 and (B) OFES2_NT. (C) The difference in horizontal averaged meridional velocity.

On the eastern route (the Equator, 120 °E – 135 °E)

Figures 3.2.13A and 3.2.13B show the meridional velocity across the equator along the eastern route for OFES2 and OFES2_NT, respectively. Comparison to Figures 3.2.9A and 3.2.9B show that the meridional velocity is weaker in the eastern route compared to the western route. The southward flow at the depth of 100 m in the Halmahera Sea (128 °E to 130 °E) is relatively strong compared to other places and this inflow is about 35 cm/s. The magnitude of this flow is about half compared with the maximum meridional velocity observed at the Makassar Strait (about 60 cm/s). The existence of an ocean current flowing into the Indonesia Seas through the Halmahera sea is known from past studies but is considered a weaker branch of the ITF (Gordon. 2005). Figures 3.2.14A and 3.2.14B show the horizontally averaged meridional velocity across 120 °E to 135 °E. Figure 3.2.14A shows many reversals of the averaged flow with depth with a maximum of about 2.0 cm/s. The magnitude of the signal gets smaller as the depth becomes deeper. It is found that on average, there is a northward velocity at the surface. In Figure 3.2.14B (OFES_NT), the alternating signal near the surface exist but the amplitude is smaller than Figure 3.2.14A (OFES2). Compared to the western route, the strength of the surface flow is weaker.

Figures 3.2.13C and 3.2.14C show the difference in the meridional velocity between OFES2 and OFES2_NT and its horizontal average, respectively. In the Molucca Sea (120 °E to 127 °E), the southward inflow increases at depths between 0 and 50 m and again around 200 m. The inflow enhances up to 7.0 cm/s. The changes in the meridional velocity also occur alternately with depth and the direction varies depending on the depth. In the Halmahera sea, changes in the meridional velocity also occur at depth. The magnitude of this signal is about 400 m where a northward flow of about 1.5 cm/s is found. The northward outflow is strengthened at depth around 100 m and from 200 to 350 m, while the southward inflow is strengthened at depth from 400 to 700 m.

Figure 3.2.15A and 3.2.15B show the meridional velocity on the eastern route at depth of deeper than 1000 m for OFES2 and OFES2_NT, respectively. In the Moluccan Sea, the southward inflow occurs strongly at the depth between 500 to 1700 m on the western side of 125 °E and the magnitude of this inflow is up to 3.0 cm/s. The northward outflow occurs on the eastern side of 125 °E. This seems to be creating an ocean current that is flowing in from the North Pacific but reverses and returns to the North Pacific. In the Halmahera Sea, an inflow occurs at the surface with about 2.5 cm/s and an outflow occurs underneath this inflow (Figure 3.2.15A). In the region from 131 °E to 135 °E, the outflow is strong at the surface, the inflow and outflow occur alternately at a depth deeper than 1000

m. Figures 3.2.16A and 3.2.16B show the horizontally averaged meridional velocity across 120 °E to 135 °E. In both figures, an alternating signal appears with a magnitude stronger than the western route.

Figures 3.2.15C and 3.2.16C show the difference between OFES2 and OFES2_NT and its horizontal average. The quantity of the change is smaller than the upper layer, but the direction and strength of meridional velocity are changed. In the Moluccan Sea, the difference in velocity appears alternately, and this pattern between the depth of 1000 to 1500 m is similar to that observed at the Makassar Strait (Figure 3.2.11C). The similar signal also appeared at the depth of 400 to 600 m in the Halmahera Sea (Figure 3.2.15C). the outflow is strengthened weakly from 1000 to 1200 m, the inflow is strengthened at depths between 1300 and 1700 m, but the difference is zero at 2000 m (Figure 3.2.16C).

The transport of the ITF on this eastern route is 3.70 Sv for OFES2 while that for OFES2_NT is 3.57 Sv. The transport of the ITF enhances on the eastern route by about 0.13 Sv. This is smaller than the ITF in the western route, suggesting that the large part of ITF change due to tidal mixing occur through the western route in the Makassar Strait. When estimate to transport on eastern route, we integrated the numbers from 120 to 131 °E include the Moluccan Sea and Halmahera Sea.

Finally, the total volume transport of ITF in the western route and eastern route for OFES2 is 13.03 Sv and that for OFES2_NT is 12.22 Sv. The enhanced transport is 0.81 Sv, which is slightly smaller than 0.88 Sv reported in Sasaki et al. 2018. The difference is likely due to the difference in the location of the straits used for the analysis but requires further analysis.

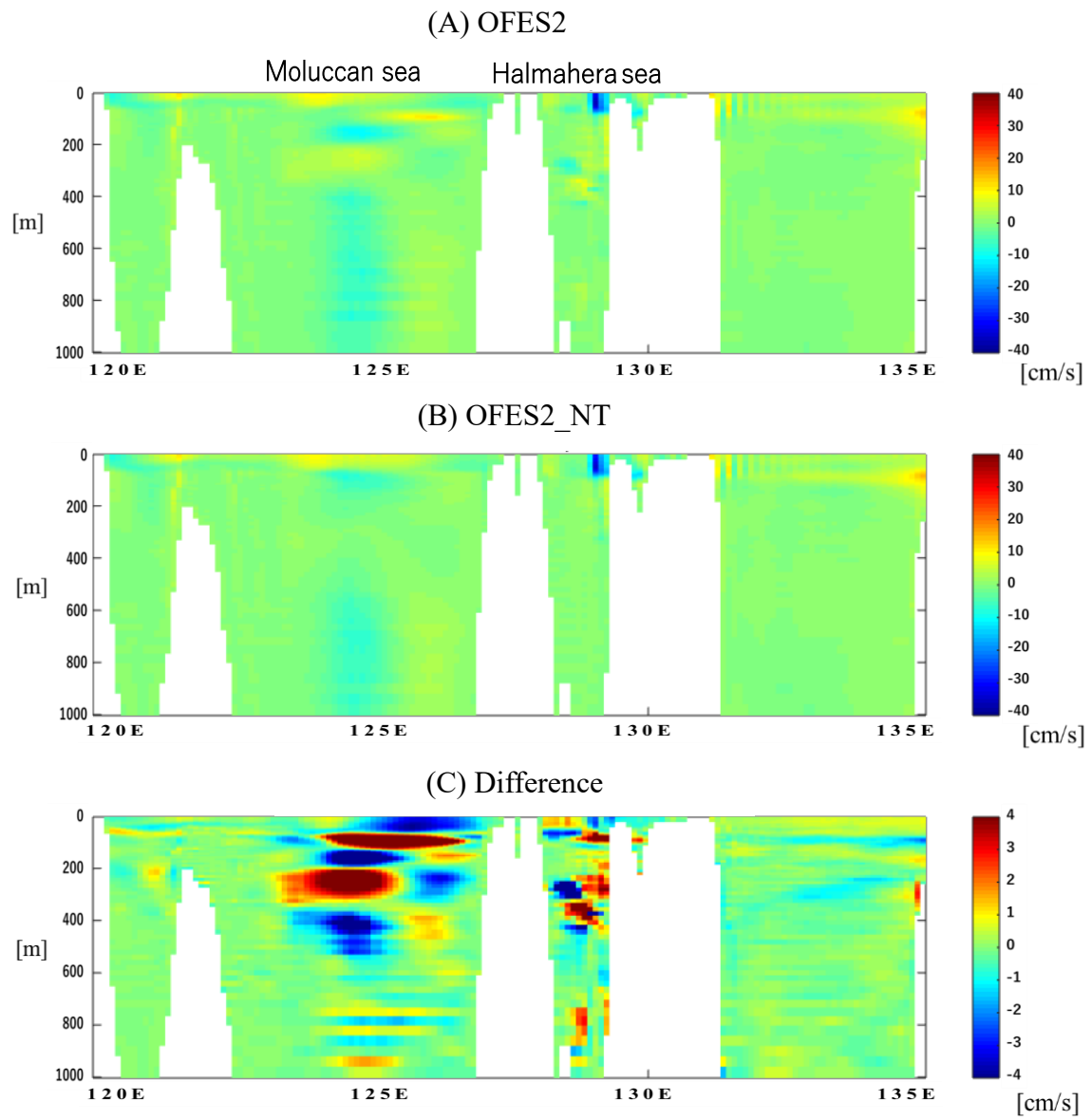


Fig 3.2.13 Meridional velocity in the ITF eastern route in (A) OFES2 and (B) OFES2_NT. (C) The difference in meridional velocity.

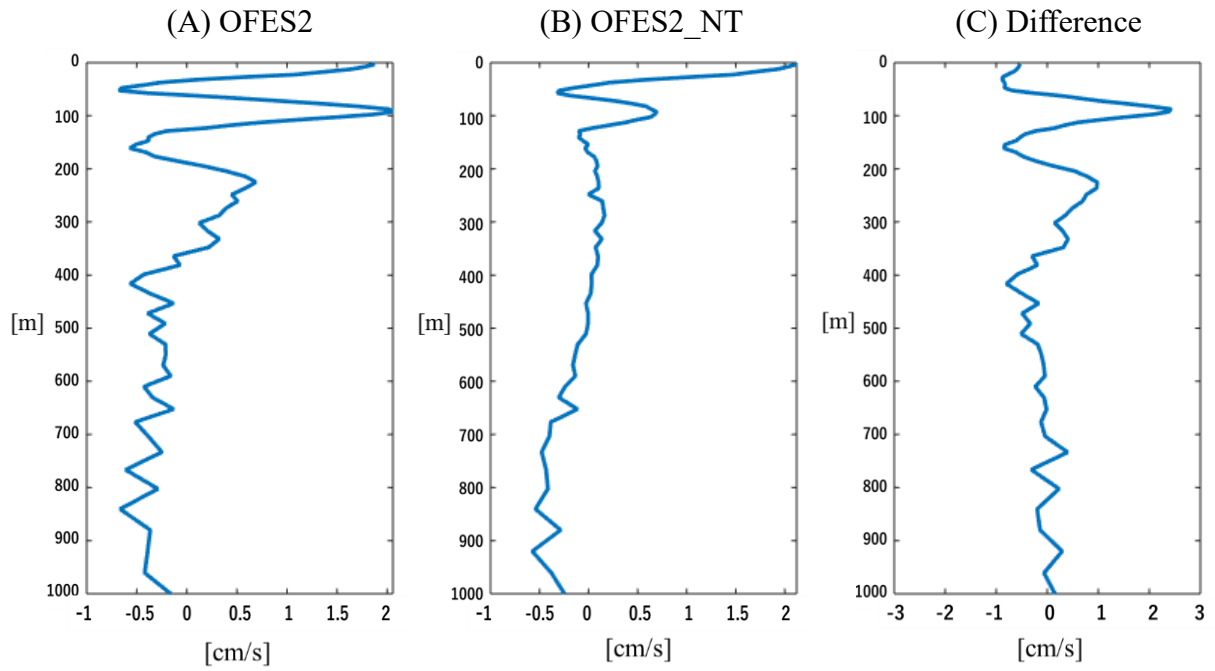


Fig 3.2.14 Horizontally averaged meridional velocity in the ITF eastern route in (A) OFES2 and (B) OFES2_NT. (C) The difference in horizontal averaged meridional velocity.

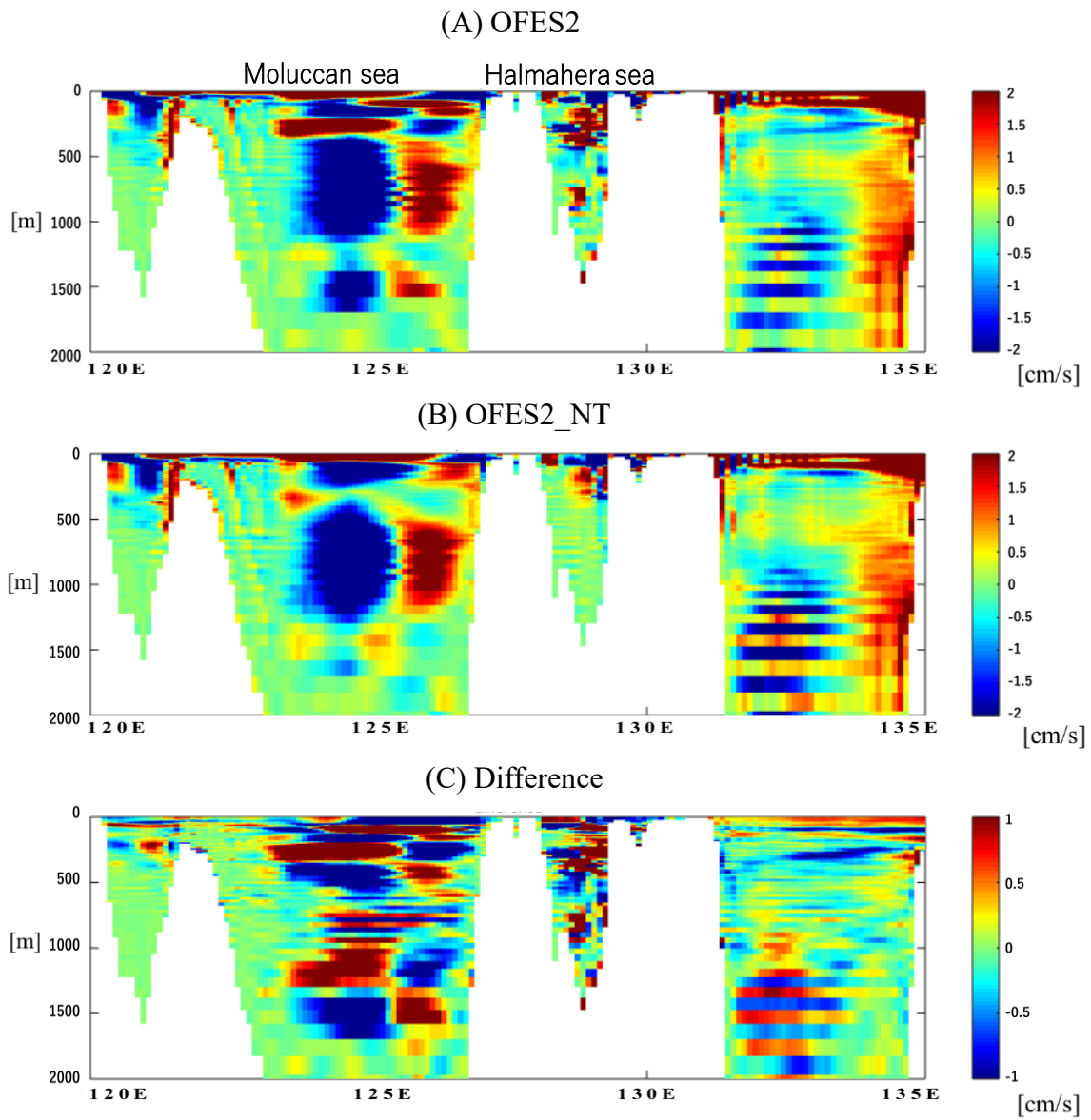


Fig 3.2.15 Meridional velocity in the eastern route in (A) OFES2 and (B) OFES2_NT.
(C) The difference in meridional velocity.

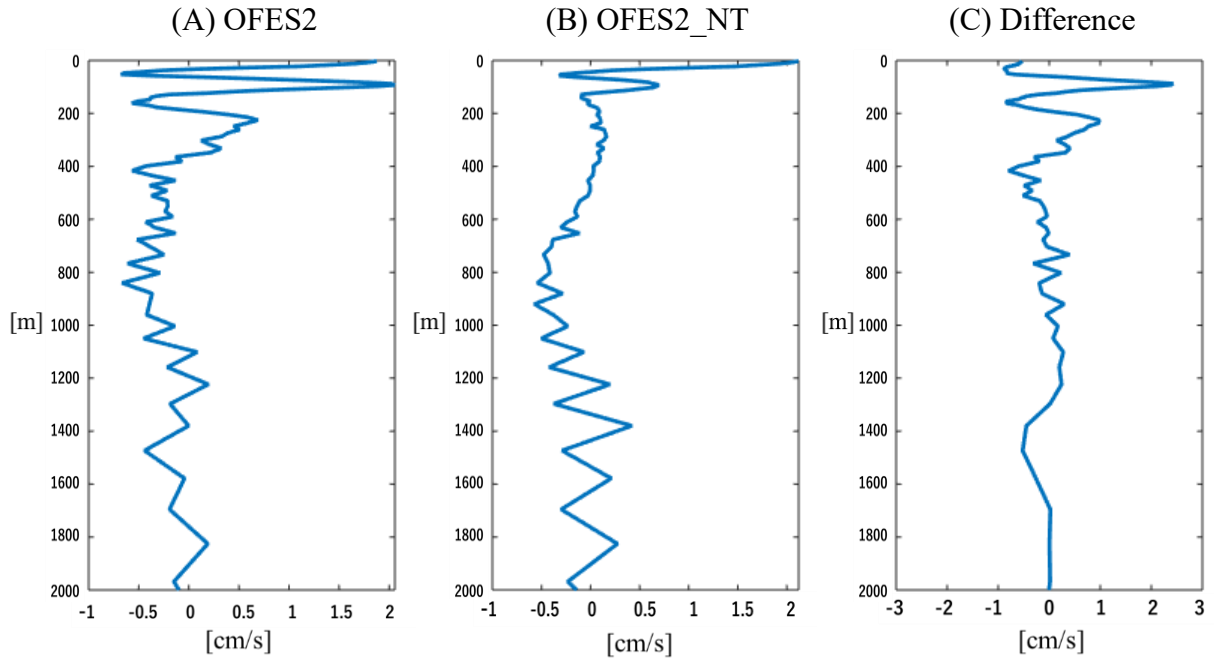


Fig 3.2.16 Horizontally averaged meridional velocity in the ITF eastern route in (A) OFES2 and (B) OFES2_NT. (C) The difference in horizontally averaged meridional velocity.

Chapter4 Summary and Conclusion

In this study, we investigated the impact of tidal mixing on the transport of the Indonesian Throughflow using two simulation results, OFES2 and OFES2_NT. These two simulations are based on a quasi-global ocean general circulation model with tidal mixing and without tidal mixing, respectively. Our goal was to clarify the causes of sea surface height increase in the Equatorial Pacific that induced the enhanced ITF transport.

We found that changes in the depth of the thermocline as an important factor for the SSH increase to occur. Basin-wide increase in the SSH is associated with a basin-wide deepening of thermocline depth. This change in thermocline depth is likely a result of tidal mixing that occurs locally over seamounts, which affects the density profile near the thermocline and creates a zonally elongated but basin-scale signal. We further found that the ITF transport increases around the thermocline in the western route of the ITF. Further work is needed to examine how the zonally elongated signal, created by tidal mixing, leads to a basin-wide signal over the entire Equatorial Pacific and its connection to the ITF at the western route.

The spatial difference from Equatorial Pacific to the Indonesian Seas

The temperature at 200 m depth from the Indonesian seas to the Equatorial Pacific showed that tidal mixing increases the temperature from the equator to near 10 °S. Temperature also increases at the western route of the ITF and near the Timor Sea. Strong temperature increase is further found on the east side of the New Guinea Island from 160 °W to the New Guinea island. We also investigated the distribution of isopycnal depth for 25.0, 25.5, and 26.0 kg/m³. The depth of these isopycnals tends to become deeper as the density above the isopycnal becomes lighter. In the case of 26.0 kg/m³, the isopycnal depth became deeper over a large area in the presence of tidal mixing where temperature increased. This results in an increase in sea surface height over the Equatorial Pacific. The zonal velocity along the isopycnal 26.0 kg/m³ showed that near the equator, the eastward zonal velocity decreases, which continues from the Galapagos islands to the entrance straits of the ITF at the Indonesian Seas. The zonal velocity also reverses from eastward to westward from where tidal mixing occurred and strong temperature increase occurred.

The change in the ITF at the strait

We also investigated how the water mass properties and meridional flow changes at the entrance straits of the ITF, the western route (Makassar Strait) and the eastern route (Moluccan Sea and Halmahera sea). In the western route, temperature decreases around the surface and increases strongly below. The difference of potential density appears in shallow depths, showing an increase at the depth near 100 m and a decrease at the depth of 200 to 500 m. An increasing/decreasing signal is found but this signal becomes weaker with depth. In the eastern route, temperature decreases and density increases between the depth of 0 to 100 m just like the western route. In the Moluccan Sea, changes in water mass properties are similar to the Makassar Strait rather than the Halmahera Sea.

We then investigated how the meridional velocity and the volume transport of ITF changes at the western and eastern routes. In the western route, the southward flow strengthens at depth of 300 to 500 m. The enhancement of the volume transport for the ITF is 0.68 Sv. In the eastern route, the magnitude of the flow is weaker than the western route but is relatively strong at the surface of the Halmahera Sea. The difference of meridional velocity is found on the same scale, but with changes in depths. The enhancement of the volume transport of the ITF on the eastern route is about 0.13 Sv, much weaker than the western route. The increase in the volume transport of the ITF for the west route represents more than 80% of the total 0.81 Sv volume transport increase, suggesting that changes in the velocity field at the western route as an important factor for the enhanced ITF transport to occur.

By comparing two simulation results, we clarified that changes in temperature and density have strong localized signal in the Pacific Ocean. Strong tidal mixing occurs over rough topography such as the seamount in the Pacific Ocean and possibly induces this local water temperature and density change and leads to changes in the zonal velocity. Although this signal was localized in space, the increase in sea surface height occurs over the entire equatorial Pacific. For future work, the mechanism that makes this localized signal to a basin scale signal is needed. The increase in sea surface height also increased the transport of the ITF. However, our study shows that the direction and strength of the meridional velocity vary with depth for both western and eastern routes. Although it is unclear which inflow was responsible for the increase in the eastern route, the enhanced flow between 300 and 500 m is the main cause for the enhanced transport in the western route.

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