Statistical and dynamical consistency of ocean current through the East Asian straits

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January 2017
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A Dissertation
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Doctor of Science

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ABSTRACT

The measured volume transport at the Korea/Tsushima, Tsugaru, and Soya/La Perouse Straits remains quantitatively inconsistent. Even though the outgoing volume transport through the Tsugaru and Soya/La Perouse Straits are subtly different, data assimilation models provide a self-consistent estimate. Especially, all assimilated results of the Tsugaru transport are significantly overestimated than the observed data. In this study, we used the multiple linear regression and ridge regression of multi-model super ensemble (MMSE) methods to find statistically and physically consistent values of transport at the channel connecting East/Japan Sea using four different data assimilation models. The latest data assimilation models fail to clearly explain the variation of transport flow through the major straits in the East/Japan Sea. This has been especially true in the case of the Tsugaru Strait, where all previous modeled results overestimate volume transport. This study attempts to establish the principal reasons for this failure and seeks to elucidate the missing dynamics.

The MMSE outperformed all the single models by reducing uncertainties, especially the multicollinearity problem with the ridge regression. However, the regression constants turned out to be inconsistent with each other when MMSE was applied separately to each strait. Thus the MMSE for a connected system was performed to find common constants for these straits. The estimation of this MMSE was found to be similar to the MMSE result of sea level difference (SLD). The estimated mean transport (2.42 Sv) was smaller than the data measured at the
Korea/Tsushima Strait, but the data measured at Tsugaru Strait (1.63 Sv) was larger than the observed data. The MMSE results of transport and SLD also suggested that the standard deviation (STD) of the Korea/Tsushima Strait is larger than the STD of the observation, whereas the STDs were almost identical to that observed for the Tsugaru and Soya/La Perouse Straits. The similarity between MMSE results confirms the reliability of the present MMSE estimation.

Nonetheless, the reason for overestimation of all the simulated results in comparison to the observed data even after consolidation of the TG transport remains unclear. The causes of throughflows in the straits were using an unstructured model that takes advantage of the finite volume method.

Modeled throughflow clearly depends on grid resolution, and the flow of the Tsugaru Strait, in particular, is more sensitive to spatial resolution than the other two straits, the Korea/Tsushima and Soya/La Perouse Straits. Simulated volume transport through the Tsugaru Strait in our high resolution experiment was less than that in the low resolution experiment due to the effect of form drag. Outflow through the Soya Soya/La Perouse Strait was affected by choking the Tsugaru Strait, while the outflow of the Tsushima Strait remained relatively unchanged.

The outflow partitioning of low resolution experiment shows that 90.4% of the total inflow transport flows out of the East/Japan Sea through the Tsugaru Strait and 9.6% through the Soya/La Perouse Strait. On the other hand, outflow transports in the high resolution experiment indicated 78.5% through the Tsugaru Strait and 21.5% through the Soya/La Perouse Strait. The outflow values from the high-resolution experiment seems more realistic than that of low resolution experiment due to the effect
of form drag. Additional experiments with modified topography also confirmed that the form drag has a significant impact on flow in the Tsugaru Strait. The results indicate that the throughflow of the Tsugaru Strait was impacted by topography features such as the bump in its western slope.
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CHAPTER I: General introduction

The East/Japan Sea (EJS) is a semi-enclosed deep marginal sea surrounded by East Asian continent and Japanese Islands. The EJS is connected with the Northwestern Pacific through shallow straits of Korea/Tsushima (KT), Tsugaru (TG), Soya/La Perouse (SP), Tatar, and Kanmon. The volume of transport through Tartar and Kanmon Straits is usually negligible. The Tsushima Warm Current inflow through the KT Strait branches out to the North Pacific through the TG Strait and partly to the Sea of Okhotsk through the SP and Tartar Straits. The TG and SP Straits are shorter in length and narrower in width than the KT Strait. The deepest TG Strait is characterized by a topographic feature, which are relatively precipitous and steep compared to slopes corresponding to the KT and the SP Straits.

Reliable estimates of the volume transports through the KT, TG and SP Straits have recently been reported. Many observational studies in the EJS arose during the late 1990s. The Research Institute for Applied Mechanics (RIAM) of Kyushu University has been carrying out a long-term acoustic Doppler current profilers (ADCPs) observation since February 1997 using a ferryboat, Camellia, along a track in the KT Strait. Estimation of the KT transport from the ferryboat observation was about 2.6 Sv (1Sv=10^6 m^3/s) (Fukudome et al.2010). Monitoring the volume transport through the KT Strait is also being done through observation using a cable voltage measurement since March 1998. Kim et al. (2004) found that voltage has a good linear relationship with the transport estimated from these datasets. KT transports were also observed by other short-term studies. KT transport volume estimated from hydrographic data using
a geostrophic calculation show a broad annual mean of 0.5–4.2 Sv and a seasonal variation of 0.7–4.6 Sv. The number of observed datasets of the TG and SP Straits is relatively smaller than that of the KT Strait. The volume transport through the TG Strait estimated using ADCP data was 1.5 Sv, while the data was measured only 22 times during 1993-1999 (Nishida et al., 2003). The TG transport estimated from a direct and continuous measurement using the vessel-mounted ADCP during November 1999 to March 2000 ranged from 1.1 to 2.1 Sv (Ito et al., 2003). The volume transport through the SP Strait varied in the range of 0.5–1.5 Sv. The annual transport of the SP Strait estimated using bottom-mounted ADCP and HF radar was 0.62–0.67 Sv from September 2006 to July 2008 and 0.94–1.04 Sv during 2004–2005 (Fukamachi et al. 2010). These estimates of the transport through the major straits in the EJS vary widely depending on the method and time of observation. Consequently, the observed data have been inconsistent. Moreover, due to the insufficiency of long-term and simultaneously observed data for the three straits, it has been difficult to propose the inflow and outflow systems for the EJS until now.

On the other hand, volume transports through EJS estimated by different organizations using numerical ocean models have at least provided self-consistent values. These results show similar seasonal variation and inter-annual change. However, annual means and ranges of seasonal variations of volume transports at three channels show a significant quantitative difference. Numerical model results suggested a variety of outflow partitioning into the TG and SP Straits. Chu et al. (2001a) assumed that 75% of the total inflow transport flows out of the EJS through the TG Strait, and 25% through the SP Strait. Similarly, Bang et al. (1996) also presumed similar values of 80% inflow through TG strait and 20% through SP Strait. Chu et al. (2001b)
suggested that transport through the TG and SP straits estimated using the U.S. Navy Generalized Digital Environmental Model with variational P-vector method are 61 and 39%, respectively.

All simulated results were overestimated comparing to the observed data, one of which is about twice as large as the observations in the TG Strait. The question regarding volume transport, overestimation and huge discrepancies in the measured and modeled transports in the TG Strait remains unanswered. Until now, there have been studies concerning the volume transport of these straits for investigating only individual straits (Fukudome et al., 2010; Iino et al., 2009; Fukamachi et al., 2010). Even though considering the interconnected effects from three straits, the important dynamics focused on the straits could not be proposed.

In order to solve these discrepancies in observed data and to make optimal estimations, it is essential that an approach that takes the model uncertainties into account is needed. Thus I have considered the multi-model ensemble approach in the first part of this study to examine the channel transports in the EJS. Here, four different data assimilation models were used to estimate the transport at these straits more accurately. Later, I also attempt to use the unstructured grid, and then try to elucidate important factors contributing to the mechanism of transport for the interconnected three straits in the EJS.

This thesis is divided into two major parts. The methods and results of MM(S)E are described in Chapter 2. Numerical experiments to explain the MM(S)E results are demonstrated in Chapter 3. General introduction and conclusions are given in Chapter 1 and 4, respectively.
CHAPTER II: Multi-model ensemble

2.1. Introduction

The EJS is a semi-enclosed deep marginal sea surrounded by Korea, Russia, and Japan. It is nearly isolated from the Pacific Ocean, except for the surface through flow. The water balance of EJS is determined mainly by inflow and outflow through the Korea/Tsushima (KT), Tsugaru (TG), Soya/La Perouse (SP), Tatar, and Kanmon Straits connecting it to the East China Sea, Pacific Ocean and Sea of Okhotsk. The Tsushima warm current inflow through the KT Strait mostly exits to the North Pacific through the TG Strait and partly to the Sea of Okhotsk through the SP and Tartar straits. The TG and SP Straits are shorter and narrower compared with the KT Strait. The Tartar Strait also communicates with the Okhotsk Sea and EJS, although the corresponding volume transport is negligible (0.01 Sv; Yanagi 2002). As the Kanmon Strait is very narrow and shallow, its volume transport is also negligible. Seasonally, the transports at the KT and SP Straits are typically large in summer–autumn and small in winter, whereas the seasonal variation of the TG Strait is relatively small. The volume transport through the SP Strait has an annual range about twice that of the TG Strait, and the former has an annual mean volume transport of about half that of the latter (Seung et al. 2012).

The water mass entering the KT Strait should be basically balanced by the mass flowing out through the TG and SP Straits. However, this budget of observed data is inconsistent in the EJS system. Previous studies estimated seasonal and annual variations of volume transport through these straits using acoustic Doppler current
profiler (ADCP) and high-frequency (HF) radar. The annual range of volume transport through the KT Strait varied widely from 0.5 Sv to 4.2 Sv, and the seasonal variation of volume transport had a broad range of 0.7 to 4.6 Sv (Chang et al. 2004). The transport through the KT Strait has been measured by long-term ADCP using the ferry boat of the Research Institute for Applied Mechanics (RIAM) of Kyushu University since 1997 (Fig. 2.1). This estimation of the KT transport was about 2.6 Sv (Fukudome et al. 2010). Other studies have also estimated the volume transport through the KT Strait. Teague et al. (2002) proposed 2.7 Sv between May 1999 and March 2003 using 12 bottom-mounted ADCPs, and Isobe (1994) obtained an annually averaged volume transport of 2.3 Sv. The maximum transport reported by Fukudome et al. (2010) was greater by approximately 0.37 Sv and the minimum transport was slightly greater than the estimation of Teague et al. (2002).

Previous studies suggested seasonal and interannual variations of transport through the TG Strait (Toba et al. 1982; Ito et al. 2003) with an annual mean of about 1.5 Sv. Nishida et al. (2003) also showed that the monthly mean transport through the TG Strait was 1.5 Sv by using ADCP only 22 times during 1993–1999. Ito et al. (2003) suggested that the volume transport from a direct and continuous measurement from November 1999 to March 2000 using the vessel-mounted ADCP decreased from 2.1 Sv on November 4 to 1.1 Sv on January 24 and March 15. The four-month mean value was 1.5 Sv, which was in the same range as the previous studies.

Volume transport through the SP Strait was varied in the range of 0.5–1.5 Sv. The annual transport of the SP Strait was estimated to be 0.62–0.67 Sv from September 2006 to July 2008 and 0.94–1.04 Sv during 2004–2005 using bottom-mounted ADCP
and HF radar. The difference between the two periods may be attributable to interannual variability of the SP current transport and/or the different measurement locations (Fukamachi et al. 2010). Matsuyama et al. (2006) suggested that the volume transport from other measurements was about 1.2–1.3 Sv in August, 1998 and 1.5 Sv in July, 2000. This discrepancy in the observed transports for the three straits may arise from a variety of sources such as observation periods, measurement devices and exploiting methods from measurement data of ADCP or HF radar to volume transports.

On the other hand, ocean models at least provide a self-consistent budget despite subtle differences among the models. These estimations are able to simulate the volume transport of these straits. The amplitudes and phases of simulations are usually comparable to observations despite being virtual values. In recent years, ocean models including data assimilation have been estimated in this region by several organizations. These reanalyses can be more accurate than simulation without assimilation. Nevertheless, the estimated results have subtly different features depending on the model. There are many reasons for the discrepancies among the models: the different physical process parameterization schemes, initial condition, and data assimilation.

Numerical model studies also suggested outflow partitioning in the EJS circulation using model results. Chu et al. (2001a) assumed that 75% of the total inflow transport flows out of the EJS through the TG Strait, and 25% through the SP Strait. Bang et al. (1996) presumed to be similar in the ratio as 80%, 20%, respectively. Chu et al. (2001b) suggested that the ratio of the TG and SP transports is 0.61, 0.39 using the U.S. Navy Generalized Digital Environmental Model with variational P-vector method.
Furthermore, the observed transport through the TG Strait is about 70% of the average of several estimates through the KT Strait. This ratio between volume transports through the KT and TG Straits is the first time estimated based upon concurrent observational data taken in the two straits (Na et al. 2009). The ratio between outgoing volume transports through the TG and SP Straits is 7:3, which is very close to the ratio suggested by Ohshima (1994), who applied the theory derived by Toulany and Garrett (1984) to understand the flow dynamics through the straits in the EJS. However, this ratio is based on relatively short observed time series.

To solve these discrepancies in observed data and to make optimal estimations, an approach that takes account of model uncertainties was needed; this approach has generally been considered to be the ‘multi-model ensemble.’ The multi-model ensemble is generally easily identified as a simple multi-model ensemble (for convenience, MME). This simple multi-model ensemble is obtained by assigning equal weights to each of the models (Peng et al. 2002). To use this method, there should be a sufficiently high ensemble number due to the removal of unexpected or unexplained ensembles in a preprocessing stage. However, it is difficult to abandon the poor ensembles given the small number of ensemble members or reanalyses of models. A more sophisticated approach for the multi-model ensemble seeks optimal multi-model ensemble predictions by obtaining different weights using multiple linear regression, a technique known as the multi-model super ensemble (for convenience, MMSE) developed by Krishnamurti et al. (1999a and 1999b).

The MMSE has been used in the field of atmospheric science to examine uncertainties in models, but it has been underused in the field of oceanography to date.
The following studies are based on its application to the atmospheric sciences. Krishnamurti et al. (2000) demonstrated that a multi-model ensemble outperforms all individual models for hurricane track and intensity forecasts. This multi-model ensemble was based on linear multiple regression of the different models against observations to determine statistical weights for each model. Hagendorn et al. (2005) also showed that the MMSE concept could improve single-model ensemble predictions and consistently estimate more accurately than estimation from any individual model.

Previous studies have indicated that the MM(S)E arising from a combination of multi-models with similar skill outperforms forecasts from individual models. Ideally, the models used should be as independent of each other as possible. As stated above, the volume transports of three straits from assimilated ocean models are similar despite subtle differences. The similar assimilation can also lead to a problem when at least one of the models is not entirely independent from the rest. That is, one of the input models in MMSE might include a certain small error by linear combination with the other ensemble members. This collinearity problem among the models is known as ‘multicollinearity.’

Peña and Van den Dool (2008) assessed the performance of several consolidation methods that were divided into constrained and unconstrained multi-model ensemble forecast systems to predict monthly SST in the deep tropical Pacific. When multicollinearity existed in the models, ridging regression of the constrained consolidation methods was used to determine the optimal weight.

This study attempts to optimally combine the volume transports of the EJS system by using the MME/MMSE approach. In addition to the one of MMSE
approaches, ridge regression was used to solve the multicollinearity among the assimilation models. The ridge regression approach has rarely been used in the ocean sciences.

The objectives of this chapter are twofold. First, we explore the importance of consolidation of four different data assimilation models in developing physical conservation transports in the EJS system. Here, we work to reduce the uncertainties of consolidation models applied for MM(S)E compared with the estimation of single models. Second, we compare various consolidation methods, particularly multiple linear regression and ridge regression. The multiple linear regression was based on the least squares method. The ridge regression is more complicated compared to the ordinary least squares method.

The sea level difference (SLD) not only across but also along a strait can be used to estimate the volume transport through the strait. The SLD with cross-channel is primarily in geostrophic balance, and the along SLD between the two oceans connected through the shallow strait is related to hydraulic controlled (Garrett and Petrie 1981; Csanady 1982). In the KT Strait, Lyu and Kim (2003) showed that a strong linear relationship exists between the transport and the SLD, using cross-strait hydrographic sections to remove baroclinic effects. Takikawa et al. (2005) demonstrated that the relations between the surface current velocities and the SLDs across the eastern and western channels in the KT Strait are approximately in geostrophic balance. The current entering the EJS may be regarded as being balanced with the outgoing transport to the Northwest Pacific. Previous studies have shown that the flow of the KT Strait is related to the SLD between the EJS and the East China Sea.
(ECS) (Ohshima 1994; Toba et al. 1982). Additionally, the other straits are also linked to the SLD between the basin and the Pacific (Hata 1973; Ito et al. 2003; Ohshima 1994). According to Nishida et al. (2003), the volume transport of the TG Current is related to the SLD between Fukaura and Hakodate.

Considering these strong relationships between the volume transport and the SLDs, this study carries out the MM(S)E using these SLDs and the results compared with the MM(S)E result with transport. We examined the similarity between the two different estimation MM(S)E results to clarify the stability of solutions.

The chapter is organized as follows. The data used in the study are described in Section 2.2. Section 2.3 outlines the theoretical foundation of consolidation methods. Section 2.4 describes the MM(S)E results. Section 2.5 verifies the MM(S)E result, and Section 2.6 discusses and summarizes the results.
Figure 2.1 (a) Bathymetry showing the locations of the three straits of the East/Japan Sea (EJS), KT, TG, and SP refer to the Korea/Tsushima, Tsugaru and Soya/La Perouse Straits, respectively. Depths are in meters. Detailed information for each strait is shown in the enlarged maps (b) and (c). The shaded box indicates averaging areas for SLD calculation. (b) The track line (solid line) of a ferry boat (Camellia) between Busan and Hakata (cross marks). (c) The locations of the tide-gauge stations at Fukaura and Hakodate (cross marks), locations of the bottom-mounted ADCP measurement (northerly solid line), radar data grid points (triangles), ADCP location (cross), and radar section (southerly solid line).
2.2. Data description

The data used in this study consisted of volume transport and SLD data in three straits, the KT, TG, and SP Straits. The volume transport data comprised four different ocean models and observed data as ensembles to conduct the MM(S)E. Additionally, the SLD was considered as an independent variable for comparison with the MM(S)E result using transport data.

2.2.1. Measurement data

Measurement data have the role of explained variables in MMSE. As mentioned above, the observed data have inconsistency of budget, despite the fact that they were observed directly. Figure 2.2 summarizes the periods of the measurement data. A five-year overall period in the measurement data was determined based on the greatest overlap duration, and the volume transport was used to calculate a monthly average from January 2003 to December 2007.

In the KT Strait, the Research Institute for Applied Mechanics (RIAM) of Kyushu University has carried out long-term current measurements using a vessel-mounted ADCP between Hakata and Busan since February 1997 (Fukudome et al. 2010). The frequency of this ADCP data collection has been doubled from 6 or 7 to 12 or 14 times per week in accordance to the replacement of vessel in July 2004 (Fig. 2.2). However, there are several chances of errors in the observation data. The estimation of the volume transport ADCP measurement data has mechanical and process limitations. The ship-mounted ADCP is unable to measure the velocity near the bottom of the vessel. The data within the range of 15% of the total depth from the seafloor also cannot
be measured. Thus, the surface and bottom velocities are obtained by extrapolating the values at the shallowest and at the deepest depths of reliable measurements (Takikawa et al. 2005). The margin of error caused by these limitations maybe almost ± 0.2 Sv assuming the error order of 0.1 m/s. In addition, the sampling intervals (the time between two successive cruises) vary from point to point through the ferry track. This problem may cause complicated tidal aliasing errors. Especially the S1 and S2 constituents possibly suffer from the infinite aliasing period at 12-hour measurement interval.

ADCP traverse observation cruise at the west mouth of the TG Strait was carried out seasonally for 22 times from 1993 to 1999. The relationship of the daily mean between volume transport and the SLD based upon the measured data is given by the linear equation by performing a regression analysis (Nishida et al. 2003).

\[ Q = 0.0271\Delta\eta + 0.933 \] (2.1)

Where Q is the estimated volume transport of the TG Strait, and \( \Delta\eta \) is the SLD between Fukaura and Hakodate (Fig. 2.1). In order to estimate the alternative transport, the TG transport is predicted by the regression model using the SLD data, which are provided by the Japan Oceanographic Data Center (JODC), at the same tidal stations for the MM(S)E period from 2003 to 2007. The predicted TG transport from the SLD includes considerable uncertainty, and the disagreement on the observed period between the regression analysis period and the predict period may also lead to substantial error.
The volume transport of the SP Strait was estimated during 2004 to 2008 using the combination of ADCP and HF radar data (Fukamachi et al. 2010) (Fig. 2.2). Compared with the data of the KT or TG Strait, the accuracy of data at the SP Strait may be the lowest since the HF radar system obtained only surface current information. Although the vertical structure was estimated with the assistance of ADCP data, the ADCP deployment site was downstream of the SP Strait and outside the ocean-radar coverage, and just one ADCP was deployed for one year.

The inconsistency of the observed data, which is defined as the incoming transport minus outgoing one, is 0.37 Sv at the annual mean. The water mass budget in the observed transports may be unbalanced due to the variety of error sources explained above. In addition, the unbalanced mass budget might be inevitable in non-synchronized observations. These are the reasons why I consider that the observed volume transports in these three straits of the EJS remain inconsistent (Fig. 2.3).

### 2.2.2. Model reanalyses

The four different ocean data assimilation models used in this study, together with descriptions of their characteristics, are listed in Table 2.1. The reanalysis data from these models have represented similar patterns of seasonal variation with small differences, as discussed later. The ensembles of the MM(S)E comprised four members: the Data assimilation Research of the East Asian Marine System (DREAMS); the Meteorological Research Institute Multivariate Ocean Variational Estimation System/Meteorological Research Institute Community Ocean Model (MOVE/MRI.COM, or for convenience MOVE); the Japan Coastal Ocean
Predictability Experiment (JCOPE); and the HYbrid Coordinate Ocean Model (HYCOM). These members are from RIAM of Kyushu University, the Japan Meteorological Agency (JMA), the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), and the Center for Ocean-Atmospheric Prediction Studies (COAPS), respectively. All models provide realistic data assimilation estimates. Table 2.1 summarizes the main model components and their data assimilation strategies. The Multi-variate Optimal Interpolation (MVOI) of data assimilation, which is taken into account in HYCOM, seems to be difficult to satisfy dynamical consistency such as the mass balance, considering the OI is more empirical method compared to near-optimal 3D, 4D-Var or KF. The period of analysis was 2003–2007, which was selected to match the configurations duration of the observed data (when all of the outputs coincide). All systems use different data assimilation method.

2.2.3. Sea level data

The sea level data were used to examine the validity of the MM(S)E with volume transport data. The SLD data used consisted of two types, satellite altimeter data and tide gauge data. The sea level anomalies (SLA) measured by satellite altimeter, which were from Jason-1, Envisat, and GFO (plus available Topex/Poseidon and ERS-1/2 altimeters), were obtained from the Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO) (available at http://www.aviso.oceanobs.com/). AVISO has been distributing two types of altimeter data, near real-time data and delayed-time data, worldwide since 1992. The near real-time type data provide operational applications for directly usable high-quality altimeter data, but the delayed
time products are more precise than the near real-time products due to their consistency. The spatial type is also divided into gridded and along-track products. The along-track product with delayed-time type data was used in this study.

The SLA used for the five years from 2003 to 2007 were also averaged into monthly bins and then averaged in space. The monthly SLA of the EJS was calculated simply by averaging over the basin, with the exception of a 5-km band along the coastline. The averaged data represent an area that includes the ECS, east of TG (ETG), and the Sea of Okhotsk (SOK) regions, which are shaded in panels (b) and (c) of Fig. 2.1. The number of SLA data changed according to the time and spatial types. The number of data in each area is expressed as time series in Fig. 2.4. Data of the SOK region are not available during February–March 2003 due to the presence of sea ice.
<table>
<thead>
<tr>
<th>System Name</th>
<th>DREAMS_B</th>
<th>MOVE/MRLCOM</th>
<th>JCOPE2</th>
<th>HYCOM+NCODA Global</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ocean model</td>
<td>RIAMOM</td>
<td>MRI.COM</td>
<td>Modified POMgcs</td>
<td>HYCOM</td>
</tr>
<tr>
<td>Domain</td>
<td>NW Pacific</td>
<td>NW Pacific</td>
<td>NW Pacific</td>
<td>Global</td>
</tr>
<tr>
<td>Horizontal Grid</td>
<td>1/4 °×1/5 °</td>
<td>1/10 °×1/10 °</td>
<td>1/12°×1/12°</td>
<td>1/12°×1/12°  Orthogonal curvilinear</td>
</tr>
<tr>
<td>Vertical layers</td>
<td>z-coordinate 38 layers</td>
<td>Sigma-z hybrid coordinate 50 layers</td>
<td>Modified s-coordinate 45 layers</td>
<td>Hybrid coordinate (isopycnal/s/z) 32 layers</td>
</tr>
<tr>
<td>Nesting strategy</td>
<td>One-way nesting</td>
<td>One-way nesting</td>
<td>One-way nesting</td>
<td>One-way nesting</td>
</tr>
<tr>
<td>Atmospheric forcing</td>
<td>JRA-25 reanalysis; the GPV/GSM meteorological data</td>
<td>JMA's operational atmospheric analysis; Results of climate forecasting model</td>
<td>6-hourly NCEP Global Forecast System or NCEP/NCAR reanalys</td>
<td>NOGAPS; 3-hourly forcing QuikSCAT correction</td>
</tr>
<tr>
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<td>AVISO</td>
<td>Jason + Envisat</td>
<td>NRL/SSC</td>
<td>Cooper-Haines projection</td>
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<tr>
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<td>MGDSS</td>
<td>NAVOCEANO</td>
<td>Satellite</td>
</tr>
<tr>
<td>SST</td>
<td>MGDSS</td>
<td>NRL/SSC</td>
<td>NAVOCEANO</td>
<td>Satellite</td>
</tr>
<tr>
<td>In situ T,S</td>
<td>ARGO floats (T,S)</td>
<td>ARGO, Ship</td>
<td>XBTs, ARGO</td>
<td></td>
</tr>
<tr>
<td>Data assimilation scheme</td>
<td>RoKF 3DVAR with vertical coupled TS-EOF modes</td>
<td>3DVAR with vertical coupled TS-EOF models</td>
<td>3DVAR with vertical coupled TS-EOF models</td>
<td>NCODA MVOI scheme</td>
</tr>
<tr>
<td>Agency / Institution</td>
<td>RIAM Kyushu University</td>
<td>JMA JAMSTEC</td>
<td>Naval Research Laboratory</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.1 Overview of models contributing to the multi-model ensemble
Figure 2.2 Monthly volume transports through the Korea/Tsushima (green), Tsugaru (blue), and Soya/La Perouse (red) Straits calculated from the observed data (cross) and DREAMS simulation (square). The bar at the bottom represents discrepancies between the transport entering the Korea/Tsushima Strait and transport outgoing through the Tsugaru and Soya/La Perouse Straits for measurement data (light gray) and DREAMS reanalysis (dark gray).
<table>
<thead>
<tr>
<th>Names of strait</th>
<th>Period</th>
<th>Data type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Korea / Tsushima</td>
<td>1993-1997</td>
<td>Vessel-mounted ADCP</td>
</tr>
<tr>
<td></td>
<td>1998-2005</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2006-2012</td>
<td></td>
</tr>
<tr>
<td>Tsugaru</td>
<td>1993-2001</td>
<td>Bottom-mounted ADCP</td>
</tr>
<tr>
<td></td>
<td>2002-2005</td>
<td>Sea level</td>
</tr>
<tr>
<td>Soya / La Perouse</td>
<td>1993-1997</td>
<td>Bottom-mounted ADCP and HF radar</td>
</tr>
<tr>
<td></td>
<td>1998-2001</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 2.3** Period and type of observed data in the major straits of the East/Japan Sea. The hatched area indicates a discontinuous period through the Tsugaru Strait.
Figure 2.4 Numbers of monthly satellite altimeter data from January 2003 to December 2007 for the East China Sea (ECS), east of Tsugaru (ETG), Sea of Okhotsk.
2.3. Methods

2.3.1. Simple multi model ensemble (EW)

A model averaging is widely used for MME. This simple MME is obtained by assigning equal weights (EW) to each of the models (Peng et al. 2002). To use this method, there should be a sufficiently high ensemble number due to the removal of unexpected or unexplained ensembles in a preprocessing stage.

2.3.2. Multiple linear regression (MLR)

A regression analysis is a statistical process for estimating the relationships between variables. Multiple linear regression (MLR), a term first used by Pearson (1908), attempts to describe the distribution of a dependent variable with the aid of a number of independent variables and to model the relationship between the dependent variable and one or more independent variables by fitting a linear equation to observed data.

The dependent variables are sometimes called regressands, or explained variables, whereas the independent variables are called regressors, or explanatory variables. Ideally, the models used should be as independent of each other as is possible so that their errors are small.

The MLR is based on a least squares method, which means that the overall solution minimizes the sum of the squares of the differences between observed and predicted values from the results of each equation. The MLR expresses the value of a
dependent variable as a linear function of one or more independent variables and an error term:

\[ y(i) = \beta_0 + \beta_1 x_1(i) + \beta_2 x_2(i) + \cdots + \beta_p x_p(i) + \varepsilon(i) \]  
(2.2)

where \( y_j(i) \) is the \( i \)th observation of the dependent variable and \( x_j(i) \) is the \( i \)th experiment on the \( j \)th independent variable, \( i=1,2,\ldots,n \) and \( j=1,2,\ldots,p \). The values \( \beta_j \) represent parameters to be estimated, and \( \varepsilon(i) \) is the \( i \)th independent identically distributed normal error. Written over again in matrix form, one obtains

\[ y = X\beta + \varepsilon \]  
(2.3)

The method of ordinary least squares (OLS) for finding the values of the coefficients of the regression line is to minimize the sum of the squared vertical distance between the observed value and predicted value:

\[ \min_{\hat{\beta}} \| \varepsilon \| = \min_{\hat{\beta}} \| y - X\hat{\beta} \| \text{ where } \| \varepsilon \| = \sum_i \varepsilon_i^2 \]  
(2.4)

In which solving for \( \beta \) yields
\[ \hat{\beta} = (X^TX)^{-1}X^TY \] (2.5)

\( \hat{\beta} \) is extrapolated under several assumptions. Above all of these assumptions, independent variables should not be correlated with each other. The models used should ideally be as independent of each other as possible so that their errors are small, although the monthly means of volume transport from the reanalyses are related to each other. In the KT Strait, the MOVE model is closely related to the DREAMS and JCOPE models, with correlation coefficients of 0.93 and 0.94, respectively. In addition to this, it is likely to be the same as that of the high correlation in other straits.

Similar models can also lead to problems when at least one of the models is not entirely independent of the others. The independent variables might be based on a presumption that one of the variables should be independent of the others. Alternatively, to say that two or more independent variables are independent means that the occurrence of one does not affect the probability of the others.

If collinearity exists among the independent variables, the result of the independent variables used is not appropriate for statistics. That is, one of the input models in MMSE might include a certain small error by a linear combination with the other ensemble members. This problem is known as “multicollinearity” in statistics. Multicollinearity refers to the presence of highly or moderately intercorrelated predictor variables in ensemble members, and its effect is to invalidate some of the basic assumptions of the estimation of MLR.
To solve the harmful effects of the multicollinearity problem, spurious exogenous variables are dropped or ridge regression is used. It was difficult to drop spurious variables due to the paucity of ensemble members in this study, so another approach, the “ridge regression method” (Hoerl and Robert Kennard 1970), was used to solve this effect.

2.3.3. Ridge regression (RR)

When multicollinearity exists in the model, it has several negative effects on the estimation result. First, the regression coefficients of individual models may change radically with the removal or addition of a predictor variable in the equation. Accordingly, the sequence of the weights can be switched. Second, the variance of the regression coefficients might be inflated even though the overall regression equation has good ability.

The variance inflation factor (VIF) is used as an indicator of multicollinearity in a matrix of predictor variables, that is, to determine how much the variance of an estimated regression coefficient is increased because of collinearity. Computationally, it is defined as

\[ VIF_i = \frac{1}{1 - R_i^2} \]  

(2.6)
where $R_i^2$ is the coefficient of determination, which is a number that indicates how well the data fit a statistical model. Values of VIF that exceed 10 are often regarded as indicating multicollinearity, and values higher than 2.5 may be cause for concern.

When multicollinearity occurs, the $X^T X$ matrix of the OLS estimator has a determinant that is close to zero, which makes it “ill-conditioned” so that the matrix cannot be inverted. If the OLS estimate was applied in the present condition in which ensemble members are correlated with each other, the estimates would be unbiased but their variances would be large, so the estimates may be far from the true value. There is the case, however, for which the “best linear unbiased estimator (BLUE)” is not necessarily the “best” estimator.

One approach to this is to use an estimator that is no longer unbiased, but has considerably less variance than the new least-squares estimator. A new way of doing this is Ridge regression (RR), also known as Tikhonov regularization. RR seeks a solution for analyzing multiple regression data that suffer from multicollinearity and it is a multiple linear regression with an additional penalty term to constrain the size of the squared weights in the minimization of the sum of the squared errors.

The RR estimate, $\hat{\beta}$ is defined as

$$\hat{\beta}_{\text{ridge}} = (X^T X + kI)^{-1} X^T Y, \quad k \geq 0$$ (2.7)
where I denote the identity matrix and $k$ is a positive scalar parameter. A small positive value of $k$ improves the conditioning of the problem and reduces the variance of the estimates. Although biased, the reduced variance of ridge estimates often results in a smaller mean square error when compared to least-squares estimates.

In this RR, the selection of $k$ is important. Hoerl and Kennard (1970) proposed a method for selecting the correct value of $k$, which is the ridge trace by an iterative process. Typically, $k$ begins with 0 and then runs through an increasing short interval. When the $k$ value increases, the ridge coefficients begin tending toward zero, and a value is chosen when the ridge coefficients stabilize. Hoerl et al. (1975) attempted to determine the optimal value for $k$ by use of the harmonic mean, and the solution is given by

$$k = \frac{p\sigma^2}{\hat{\beta}^T\hat{\beta}}$$

where $p$ is the number of ensembles and $\sigma^2$ is the residual mean square.

However, when multicollinearity in the independent variables is extreme; i.e., the independent variables are almost perfectly correlated, we would probably prefer to delete one or more independent variables before using the ridge approach as “stepwise regression”. However, the number of ensemble members in this study was only four, so this method was not available. The two consolidation methods, as stated above, were
thus applied with the four different ocean models and the observed data to obtain more accurate transports in the EJS system and the results of MLR and RR were evaluated for deterministic skill assessment.
2.4. Results of Multi-model ensemble

We attempted to conduct MM(S)E using the reanalyses from four different ocean models and the observed data to obtain more accurate data for volume transport at these straits. In Sections 4.1 and 4.2, we discuss in detail comparisons of results between individual and consolidation models, which are MLR and RR. Section 4.3 describes common coefficients to enhance physical conservation.

2.4.1. Comparison of single-model and multi-model ensemble

Figure 2.5 shows the seasonal variation of transports in the KT Strait using the reanalyses from the four single models and ADCP observation. The results of individual models have quantitatively different, although they show a similar tendency such as seasonal cycle. The MOVE reanalysis has the largest amplitude among the model results, which is almost twice larger than the variation range of JOCPE output. The root mean square differences (RMSDs) between the observed data and the reanalyses of individual models vary widely in the range 0.10–0.28 Sv for the seasonal variation.

Comparisons of the monthly averaged transports through the KT, TG, and SP Straits from 2003 to 2007 between the observed data and the four model reanalyses are shown in Fig. 2.6 (a), (b), and (c), respectively. The fluctuations of the observed volume transport in these straits are dominated by seasonal effects, and the range of seasonal variation differs from year to year. Each model reanalysis shows a similar tendency and also broadly resembles the observation. Nevertheless, some differences arise among the models, such as the amplitude and bias of transport. An apparent discrepancy is that all
reanalyses from individual models for the TG Strait are overestimated in comparison with the observation (Fig. 2.6 (b)).

Figure 2.7 (a)–(c) shows the five-year mean transports from 2003 to 2007 in these straits using the observed data and the model reanalyses. The five-year mean transports of the MOVE reanalysis tend to be larger than the observation in all straits. The long-term mean transport of DREAMS has the smallest difference from the ADCP observations in the KT Strait. The five-year mean of HYCOM, which also has a relatively small difference, well represents observation in the TG and SP Straits among the individual models. Particularly, overestimations of the modeled transports are manifested in the annual means through the TG Strait, with the largest gap of 0.79 Sv in the JCOPE reanalysis.

The MM(S)E using the observed data and four assimilation model results are expected to decrease these discrepancies. The five-year mean transports of the consolidation models are similar to the measured transport, although all reanalyses from the single models strongly overestimated the volume transport in the TG Strait (Fig. 2.7 (b)). The time-mean of the MMSE estimates can be calibrated to the dependent variable despite the fact that all independent variables are strongly biased. This suggests that the MMSE can be much closer to the dependent variable with the combination of ‘poor’ ensembles in contrast with MME.

To provide a detailed comparison of the single model reanalyses and the MM(S)E estimates, three important statistics are represented by diagrams developed by Taylor (2001) in Fig. 2.7 (d)–(f). The Taylor diagram enables visualization of the standard deviation (STD) of the model and observation patterns ($\sigma_m$, $\sigma_o$), the
correlation coefficient (R), and the RMSD (E) between the two fields simultaneously in a two-dimensional space by a polar coordinate system. These statistical measures are normalized to the observed STD. The normalized STD and normalized squared difference can be written as

\[ \hat{\sigma} = \frac{\sigma_m}{\sigma_o} \]

\[ \hat{E}^2 = \left( \frac{E}{\sigma_o} \right)^2 \]  

(2.9)  

(2.10)

We understand easily that each ensemble point quantifies how closely related the modeled field and observed field (represented as “reference” field) are on the basis of the three normalized statistics. The cosine of the angle of the model point from the horizontal axis of the Taylor diagram indicates the correlation between the observation and the model. The correlation coefficients between the observed data and the MMSE estimates are higher than those between the observed data and the individual models. For instance, the correlation coefficients between the observed data and the results of the individual models (DREAMS, MOVE, JCOPE, and HYCOM) for the TG Strait are 0.602, 0.835, 0.487, and 0.525, respectively (Fig. 2.7 (e)), but the MLR and RR of consolidation models have higher correlations with the observed data of about 0.856. However, the correlation coefficient of EW is lower than that of single model as MOVE. The radial distances from the origin (0, 0) to the ensemble points in the Taylor diagram are proportional to the normalized STD. The STDs (\( \hat{\sigma} \)) of the MMSE estimates
are close to unity, similar to the normalized observed data, although each model has a standoff point from the observation in the TG Strait. This indicates that the MMSE is able to estimate the anomaly component of the observation data, although the MOVE and HYCOM points stray significantly from unity. Thus, the MMSE can estimate not only time-mean transport but also the anomaly component. The linear distance between the reference lying on the horizontal axis and the point of the independent variable in the Taylor diagram is proportional to the RMSD. In the TG Strait, all models were remote from the observation, but the MM(S)E result is close to the reference (1, 0). In general, the normalized statistics of the MM(S)E estimates display the variability of volume transport more realistically than the individual models, although all ensemble members are not very close to the reference. The MM(S)E estimates are closer to the reference than any individual model. These statistics of MMSE also expose thoughtful regression coefficients, as discussed later.

The MM(S)E estimates are not very different for the other two straits. For the KT Strait, the normalized RMSDs (\( \bar{E} \)) of the MM(S)E estimates are slightly smaller than those of any modeled point, and these RMSDs are pretty similar to the RMSD of HYCOM (Fig. 2.7 (d)). It is important to note that the present MM(S)E analyses successfully eliminate the outlier effect of the MOVE, resulting in the minimum RMSD for the KT Strait.

However, the normalized RMSDs (\( \bar{E} \)) and STDs (\( \bar{\sigma} \)) of all of the single models and the MM(S)E estimates are almost identical in the SP Strait. The normalized STDs of the reanalyses from the models range from 0.585 to 0.828. After the MM(S)E was performed, the STDs of the consolidation models were about 0.665. The STDs of the
estimates for MM(S)E remain underestimated in the SP Strait. This is considered to be a limitation of the MM(S)E, which is an unsatisfactory result, because all estimates of the individual models are too similar in the Taylor diagram (Fig. 2.7 (f)). The inconclusive result is caused by collinearity among the independent variables, as discussed in the next section.

2.4.2. Evaluation of multi model ensemble methods

First, the results of EW are compared with the MM(S)E estimations. The mean transport from EW tends towards what four reanalyses overestimate or underestimate because the measured data dose not considered (Fig. 2.7 (a-c)). Furthermore, the statistic results represented the variation of volume transports also is located far away from reference and in the middle of the four assimilation results (Fig 2.7 (d-f)). Especially, the MME results of the TG Strait among three straits, are relatively large difference with other consolidation results as MMSE. It is related that unsuitable ensemble member is influence on the EW results due to having identical weights of the four reanalyses. Judging from these results, it is clear that the MME estimates underperform the MMSE estimates.

The consolidation results of other straits show that the MME has almost the same ability as MMSE. It indicates that the KT and SP throughflow can simulate than that of the TG Strait. Especially, the volume transports of the SP Strait from the assimilated ocean models were similar (Fig. 2.7 (f)). First of all, we examined how much multicollinearity exists within the independent variables. The VIFs were calculated to check the multicollinearity among the independent variables. The VIF of
MOVE tended to be high in all straits (Table 2.2), which means that this ensemble is widely correlated with the other ensembles.

The reanalyses of all models indicate strong VIF in the SP Strait but weak VIF in the TG Strait. In other words, the reanalyses from all models have many similarities, such as the variability and tendencies of the transport in the SP Strait, but these are independent of each other in the TG Strait.

Table 2.3 shows the equations obtained from the MMSE analyses for the MLR and RR for each strait. The equation used MME (EW) is not shown here because the weights are identical as 0.25 and the intercept coefficient is null. If the regression coefficients of each consolidation model are arranged in descending order, the corresponding sequences of both the MLR and RR are almost identical (with the exception of the regression coefficients of JCOPE and HYCOM for the SP Strait). For the KT Strait, the regression coefficients of HYCOM are the largest and those of JCOPE are the smallest among the single models for both consolidation models. The similarities in the sequence of the regression coefficients between the two combination models indicate that both MMSE results are reliable for statistics.

The residual terms, ε, in the equations are almost zero in the obtained regressions for both MLR and RR (not shown in Table 2.3). The small difference between the observed and the MMSE estimates means that the MMSE is able to estimate the observed data.

Many similarities exist, but we also find some discrepancies between the two MMSE estimates. The regression coefficients are quantitatively different depending on
the consolidation method. Furthermore, the correlation coefficients between the observation and the MLR estimates (0.894, 0.856, and 0.682) are slightly higher than those of the RR estimates (0.893, 0.855, and 0.666) for the KT, TG, and SP Straits, respectively. The error terms $\epsilon$ of the MLR estimates are also slightly smaller than those of the RR estimates. Although it seems that the MLR estimates outperformed the RR results, this assumption is incorrect. If the OLS estimator finds the regression coefficient of one of the independent variables, the others are considered constant numbers. In other words, the OLS estimator finds the estimation with minimized differences between the observation and the corresponding variable without considering collinearity within the independent variables.

There is evidence that the RR considers multicollinearity in the models in the comparison with the MLR. The most remarkable improvement is the relaxing of abnormal weights. A significant difference between the MLR and RR estimates is seen in the SP Strait. This difference comes from the multicollinearity of the dependent variables. It is exposed in the VIF for the SP Strait, which was larger than those of the other straits. On the other hand, both the MLR and RR results are almost identical for the TG Strait. These results are also related to the smallest VIF for the TG Strait. In a similar vein, the decrease in the variation of the regression coefficients is greater when conducting RR than when conducting MLR for all straits.

The intercept coefficient $\beta_0$ in the regression equations indicates the amount by which the observation differs from the simulated fields. In other words, it also contributes to the bias of the MMSE model. If the independent variables are independent of each other and at least one of the explanatory variables can explain the
explained variable, the intercept coefficient should be close to zero in the MMSE. The intercept coefficients of the RR analysis are smaller than those of the MLR for all straits, although all intercept coefficients are far from zero (Table 2.3).

Although the applied results were almost identical as shown in Figs. 2.6 and 2.7, the present analysis demonstrates that the ridge estimator finds proper regression coefficients by relaxing multicollinearity problems compared with the least squares estimator. For these reasons, it is clear that the RR estimates outperform the MLR estimates.

However, some unsolved problems remain. The intercept coefficients $\beta_0$ in the regression equations are not close to zero but have significant positive values (Table 2.3). This means that all single models include errors as large as $\beta_0$ and/or that the observed data as the dependent variable have the problem of inconsistency of the mass balance.

Figure 2.8 shows the differences between the transport entering the EJS and the transport flowing out through the TG and SP Straits from the observation data, the four model reanalyses, and the MM(S)E estimates. The MME results conserve the mass budgets due to only combination of assimilation results and measured data not considered. However, neither of the MMSE estimates solves the inconsistency problem of the unbalanced budget, which is in common with the observation.

Although the single-model ensembles at least provide a self-consistent budget, the MMSEs do not satisfy physical conservation due to incomplete combinations of the multiple models. These problems are exposed by the total of the weights in the
regression equations (Table 2.3). In particular, for the TG Strait, the total of the weights is relatively small due to the overestimation of the four models in the TG Strait.

According to these results, the estimates of the MM(S)E performed well statistically, but MMSE did not satisfy the physical conservation of volume transport. In addition, the estimated coefficients are scattered among the solutions, indicating the need for unified weights.

2.4.3. Unified estimation

To unify the coefficients for all of the straits, the MM(S)E was conducted for a connected system without dividing the three straits. Thus, the ensemble size was increased by about threefold (Fig. 2.9). Although the number of ensembles is ideally 180 (monthly mean for five years for the three straits), the number of ensemble members used was actually 140 because of missing data for the SP Strait (Fig. 2.2). The present MM(S)E was carried out based on the same method as the previous MM(S)E. As stated above, the MMSE (MLR and RR) can estimate accurately than MME (EW), above all, the RR of estimates outperformed the MLR estimates in solving the multicollinearity problem. Hereafter, we perform only RR analysis on the connected system and give the new term “UR (Ridge regression applied to the unified system)” to distinguish from previous RR estimates.

Figure 2.9 shows the monthly averaged transports of the observed data, the four reanalyses from the ocean models, and the UR estimate from 2003 to 2007 for each strait. The MM(S)E estimate considering a connected system tends to catch up with the
observed data, such as was shown in the RR result (Fig. 2.6). However, a difference exists between the previous and present MM(S)E estimations despite use of the same method. The significant difference is that the transport through the TG Strait of the MMSE estimation with the UR is larger than that of the RR by 0.16 Sv. In addition, the volume transports through the other straits of the UR results are also changed. These changes indicate that the UR considers not only the volume transport corresponding to the strait but also the transports of other straits, improving the balance between incoming and outgoing transport compared with RR.

Figure 2.10 (a) depicts the five-year mean volume transport from 2003 to 2007 through the major straits in the EJS system. The five-year mean transport of the MMSE result is remarkably similar to that of the observed data, although all of the assimilated model results are overestimated. The JCOPE model has the largest volume transport among the models, and the HYCOM model is fairly similar to the observation.

The correlation coefficient ($R$), normalized STD ($\tilde{\sigma}$), and RMSD ($\tilde{E}$) between the observation and the MMSE result and the estimations from the models are represented by the Taylor diagram in Fig. 2.10 (b). The MMSE point is much closer to the reference than any individual model point. The correlation coefficient of the MMSE result is 0.97, whereas the correlation coefficients between observation and the individual models (DREAMS, MOVE, JCOPE, and HYCOM) are 0.90, 0.92, 0.82, and 0.90, respectively. Thus, the MMSE result also has the highest correlation coefficient with the observed data. The normalized STD is slightly smaller than unity, and the DREAMS and HYCOM points also show normalized STD less than unity. According
to the three statistics in Fig. 2.10, the consolidation model most resembles the observation. The resulting equation for the MMSE is

$$y_{\text{Transport}} \approx -0.053 + 0.503 \ x_{\text{DREAMS}} + 0.503 \ x_{\text{MOVE}} - 0.352 \ x_{\text{JCOPE}} + 0.301 \ x_{\text{HYCOM}}$$  \hspace{1cm} (2.11)

where the intercept coefficient shown as the first term is -0.053. It means that the all model has a bias as the amount of the intercept coefficient. Moreover, the residual is almost zero although not shown in Eq. (2.11). This error term also contributes to the bias of MMSE model. The mean squared error (MSE) as variance of the errors is 0.08 Sv$^2$. The MSE suggests that the MMSE models could estimate the volume transport of the EJS compared with single models (Fig. 2.7 (d-f)). If the regression coefficients of the four models are arranged in the sequence of weights, DREAMS and MOVE, HYCOM, and JCOPE is obtained. The sequence of the regression coefficient is exposed by the three normalized statistics and the five mean transports of the four models (Fig. 2.10). The DREAMS and MOVE models, which have the large regression coefficient, are very near unity in the normalized STD and have the highest correlation with the reference. On the other hand, the JCOPE model point is farther away from the reference in the Taylor diagram, and the five-year mean also shows the largest difference between the line indicating the observed mean transport.

Compared with the previous regression equations (RR), which are expressed in Table 2.3, we find a significant improvement in the present equation (UR) as Eq. (2.11).
First, the remarkable change, of course, is the common regression coefficients that can be applied to any strait. Second, the sum of the weights approaches unity. The total weights of the RR result were 1.268, 0.903, and 1.205 at the KT, TG, and SP Straits, respectively, but that of the UR is 0.930. If the total weight is larger or smaller than unity, it indicates that the independent variables tend to be underestimated or overestimated from the reference. The total weight of the UR result is close to unity, thus water mass balance is well established by the present condition. Third, the residuals approach zero. The residuals of the RR result were far from zero, 0.429, 0.283, and 0.189 for the KT, TG, and SP Straits, respectively, whereas the residuals of the UR result are almost zero. This means that the present combination model is able to estimate the observed data statistically. Moreover, the correlation coefficients between the UR and the observed data are higher than those of the RR. The correlation coefficients between the present MMSE estimates of 0.939, 0.871, and 0.914 are higher than those of the previous estimates of 0.893, 0.855, and 0.666 for the KT, TG, and SP Straits, respectively. Judging from these analyses, it is clear that the UR estimates for the present condition outperform the former RR estimates because the combination model with the present condition satisfies not only physical conservation but also the statistical condition.

Figure 2.11 shows the seasonal variations of volume transport with the MMSE estimates compared with observed data for the three straits to interpret the consolidation model. The KT transport of the UR estimate is smaller than the observation, except during summer. The volume transports of UR and the observed data tend to be relatively similar for the SP Strait. However, the UR estimate of TG transport is overestimated compared with the observed data.
The annual mean transports and the seasonal variability of the observed data and the consolidation estimate are quantified in Table 2.4. The mean transport of the obtained model for the KT Strait tends to be smaller than the measurement data by about 0.17 Sv, whereas the mean transport of the consolidation model through the TG Strait shows the opposite tendency with an overestimation of about 0.16 Sv. The annual transport of the SP Strait is slightly smaller than the observed data. Compared with the RR estimates applied to the single system, they show similar trends with UR estimate for the present condition in all straits. Although the difference of the MMSE estimates between unified and single cases for the KT Strait is relatively larger than other straits. The difference is almost 0.15 Sv, and it shows in winter – spring. On the other hand, the STDs of \( y_{\text{transport}} \) are almost identical to the observed, except for the KT Strait. In the KT Strait, the STD of the UR estimate (\( y_{\text{transport}} \)) presents a marked contrast to that of the observed data, differing by about 0.13 Sv. These analyses indicate that the mean and seasonal variation of the observed volume transport is overestimated in the KT Strait, whereas the observed mean transport of the TG Strait is underestimated. The consolidation and observed results have almost identical mean and seasonal variation of volume transport through the SP Strait.

The inconsistency of the combination model and the observed data is shown in Fig. 2.12. The inconsistency of the observed data is quite large, about 0.33 Sv, but the budget inconsistency of the \( y_{\text{transport}} \) is relatively small. This demonstrates that the UR estimate is balanced with respect to the incoming transport at the KT Strait and the outgoing transport through the TG and SP Straits.

40
Figure 2.5 Comparison of seasonal variation of volume transport from reanalysis from the four ocean models (square marks with colored curves) and ADCP observation (cross marks with gray curve) by month averaged from 2003 to 2007 through the Korea/Tsushima Strait.
Figure 2.6 Monthly averaged transport through the Korea/Tsushima (a), Tsugaru (b), and Soya/La Perouse (c) Straits from January 2003 to December 2007. The observed data, reanalyses of models, and multi-model ensemble estimates are represented by the gray cross mark, colored square mark, and black circle mark, respectively. The consolidation models are consisted of multiple linear regression (closed circle) and ridge regression (open circle).
Figure 2.7 (upper) Five-year mean of volume transport through the Korea/Tsushima (a), Tsugaru (b), and Soya/La Perouse (c) Straits. The line is same as the observation value. (lower) Statistical analysis using a Taylor diagram for the volume transports of the Korea/Tsushima (d), Tsugaru (e), and Soya/La Perouse (f) Straits. The reference at the bottom indicates the observation in each strait. The radial distance from the origin is proportional to the normalized standard deviation. The RMS difference between the model and reference field is proportional to their centered distance apart. The correlation between the two fields is given by the azimuthal position of the model field.
Table 2.2 VIFs of individual model transports through the Korea/Tsushima, Tsugaru, and Soya/La Perouse Straits

<table>
<thead>
<tr>
<th>The predictors</th>
<th>DREAMS</th>
<th>MOVE</th>
<th>JCOPE</th>
<th>HYCOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Korea/Tsushima</td>
<td>8.146</td>
<td>13.755</td>
<td>9.046</td>
<td>6.963</td>
</tr>
<tr>
<td>Tsugaru</td>
<td>1.740</td>
<td>2.627</td>
<td>2.744</td>
<td>3.249</td>
</tr>
<tr>
<td>Soya/La Perouse</td>
<td>11.378</td>
<td>19.523</td>
<td>17.131</td>
<td>16.955</td>
</tr>
</tbody>
</table>
Table 2.3 Regression coefficients of multi-model ensembles for the Korea/Tsushima, Tsugaru, and Soya/La Perouse Straits

\[ y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 \]

<table>
<thead>
<tr>
<th>Model</th>
<th>y_Korea/Tsushima</th>
<th>y_Tsugaru</th>
<th>y_Soya/La Peroue</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Multiple Linear Regression</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DREAMS</td>
<td>0.546</td>
<td>0.327</td>
<td>0.290</td>
</tr>
<tr>
<td>MOVE</td>
<td>+ 0.109</td>
<td>+ 0.211</td>
<td>- 0.849</td>
</tr>
<tr>
<td>JCOPE</td>
<td>+ 0.147</td>
<td>+ 0.604</td>
<td>- 0.406</td>
</tr>
<tr>
<td>HYCOM</td>
<td>+ 0.021</td>
<td>- 0.087</td>
<td>+ 1.544</td>
</tr>
<tr>
<td>TOTAL</td>
<td>+ 0.527</td>
<td>- 0.126</td>
<td>+ 0.853</td>
</tr>
<tr>
<td></td>
<td>0.804</td>
<td>0.602</td>
<td>1.142</td>
</tr>
<tr>
<td><strong>Ridge Regression</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DREAMS</td>
<td>0.429</td>
<td>0.283</td>
<td>0.189</td>
</tr>
<tr>
<td>MOVE</td>
<td>+ 0.153</td>
<td>+ 0.213</td>
<td>- 0.182</td>
</tr>
<tr>
<td>JCOPE</td>
<td>+ 0.144</td>
<td>+ 0.567</td>
<td>+ 0.099</td>
</tr>
<tr>
<td>HYCOM</td>
<td>+ 0.114</td>
<td>- 0.052</td>
<td>+ 0.758</td>
</tr>
<tr>
<td>TOTAL</td>
<td>+ 0.427</td>
<td>- 0.108</td>
<td>+ 0.341</td>
</tr>
<tr>
<td></td>
<td>0.840</td>
<td>0.620</td>
<td>1.016</td>
</tr>
</tbody>
</table>
Figure 2.8 Differences between the volume transport entering the East/Japan Sea (green) and the outgoing transport though the Tsugaru (blue) and Soya/La Perouse (red) Straits for measured data, reanalyses from the four models, and consolidated estimations.
Figure 2.9 Monthly averaged transport through the major straits. The x-axis includes each strait and period. The period differs according to the measurement data of each strait. The observed data, reanalyses of the models, and ridge regression performance are represented by the gray cross mark, colored square mark, and black circle mark, respectively.
Figure 2.10 (a) Five-year mean of volume transport. The line is the same as the observation value. (b) Statistical analysis using the Taylor diagram for the volume transports considered in the connected system.
Figure 2.11 Monthly volume transport of the observed data (cross mark), consolidation estimates with transport (circle mark), and sea level difference (diamond mark) in the Korea/Tsushima (green), Tsugaru (blue), and Soya/La Perouse (red) Straits from 2003 to 2007. The light shading denotes the 90% confidence interval of measured transports.
Table 2.4 Annual mean and standard deviation of measurement data and multi-model ensembles for the Korea/Tsushima, Tsugaru, and Soya/La Perouse Straits from 2003 to 2007

<table>
<thead>
<tr>
<th>Names of strait</th>
<th>OBS</th>
<th>$y_{\text{Transport}}$</th>
<th>$y_{\text{SLD}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Korea/Tsushima</td>
<td>2.60</td>
<td>2.43</td>
<td>2.45</td>
</tr>
<tr>
<td>Tsugaru</td>
<td>1.47</td>
<td>1.63</td>
<td>1.77</td>
</tr>
<tr>
<td>Soya/La Perouse</td>
<td>0.80</td>
<td>0.74</td>
<td>0.68</td>
</tr>
<tr>
<td><strong>STD</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Korea/Tsushima</td>
<td>0.36</td>
<td>0.49</td>
<td>0.42</td>
</tr>
<tr>
<td>Tsugaru</td>
<td>0.13</td>
<td>0.14</td>
<td>0.13</td>
</tr>
<tr>
<td>Soya/La Perouse</td>
<td>0.30</td>
<td>0.33</td>
<td>0.30</td>
</tr>
</tbody>
</table>
Figure 2.12 Differences between the transport entering through the Korea/Tsushima Strait (green) and the outgoing transport at the Tsugaru (blue) and Soya/La Perouse (red) Straits for observed data and multi-model ensemble estimations.
2.5. Validation of Multi-model ensemble

So far, the MMSE estimates have been obtained based on transport data. The aim of this section is to verify the previous UR result by using the independent variable SLD. Furthermore, we predict the seasonal variation of volume transport with the obtained regression equations from volume transport and SLD data after three years to validate the MMSE results.

2.5.1. Multi-model ensemble with altimeter data

If another variable that is related to the original variable derives the same result, the methodology could ensure the validity of the original result. Numerous studies have shown that the variation of volume transport is closely related to the SLD between two oceans connected by shallow straits. Thus, the along-strait SLD from the satellite altimeter, which is related to the variation of transport, was considered as an independent variable.

Although the observed transport data considered a connected system have missing data for 40 months, the altimeter SLD data provide an almost continuous record (Figs. 2.3 and 2.4). The same number of ensembles of each strait may be attributed to the fair MMSE estimation of seasonal variation equally weighted to the three straits.

The monthly averaged SLDs of the altimeter data and four modeled results in the KT, TG, and SP Straits are shown in Figure 2.13. The HYCOM reanalysis shows
relatively large fluctuations, whereas the JCOPE result shows moderate change. Each reanalysis represents the seasonal cycle in the KT and SP Straits, but the seasonal variation of the TG Strait is smaller than that of the other straits.

Comparing the AVISO data with the MMSE conducted using SLD, the MMSE estimate better tracks the AVISO data as the dependent variable compared with any individual model. This evidence is shown in the Taylor diagram of Fig. 2.14. The RMS of the MMSE (in detail UR) is smaller than that of any single model result. The MMSE also has the highest correlation with the AVISO data (reference) compared with the four-modeled points. Although the normalized STD of the MOVE model is the nearest to unity, 1.004, the MMSE point is also close to unity.

These normalized statistics are reflected in the regression coefficients of the regression equation. The resulting regression equation using SLD data is

\[
y_{SLD} \approx 0.000 + 0.069 x_{DREAMS} + 0.464 x_{MOVE} + 0.142 x_{JCOPE} + 0.228 x_{HYCOM}
\]

(2.12)

The shorter the distance between the model point and the reference in the Taylor diagram, the larger the regression coefficient gained in the regression equation. The MOVE model point has the shortest distance from the reference among the model points. Accordingly, the regression coefficient of the MOVE is the largest among the
individual models. The regression coefficient of the DREAMS model is the smallest among the models because the DREAMS point is farthest from the reference.

In the MMSE equation with SLD, the intercept coefficient is near zero, and the sum of the regression coefficients is almost unity, about 0.903. As described in Section 4.3, this indicates that the MMSE result satisfies not only mass conservation but also the statistical condition.

Figure 2.11 shows the seasonal variation of the volume transport with the observed data and the consolidation model for the equation obtained in Eq. (2.12) using the transport of the four assimilation models. The applied transports for the consolidated MMSE result tend to be smaller than the measured data in the KT Strait, except during summer, whereas those of the TG Strait are larger than the observed data.

The annual mean transport and the STD of the observed data and the estimates of the applied consolidation equations are summarized in Table 2.4. The mean transport of the applied MMSE result is smaller than the observed data in the KT Strait but larger than the observed data in the TG Strait. In the SP Strait, the mean transport of the consolidation model is smaller than the observed data, but this difference, 0.12 Sv, is relatively small.

In comparison with the STD of the observed data, the MMSE result has larger STD than the observed data by about 0.06 Sv in the KT Strait. For the other straits, the MMSE result and the observed data have almost identical STD. This indicates that the linear equation to calculate the transport of the TG Strait is able to estimate the seasonal variation of volume transport.
The consolidation models applied in Eq. (2.11) and Eq. (2.12) show similar tendencies of annual mean transport and STD. The mean transports of both combination models are smaller than the observed data for the KT Strait but larger than the observed data for the TG Strait. The resemblance between the two MMSE results is shown by the STD. The similarity of the two consolidation models enhances the reliability of the MMSE estimation.

The inconsistency between incoming transport and outgoing transport is shown in Fig. 2.12. The inconsistency in the budget of the UR_{SLD} is smaller than that of the observed data, which indicates that the mass balance is maintained in the MMSE result of SLD. As shown in the MMSE estimation results, the inconsistency of observed data originated from the transports of the KT and TG Straits.

### 2.5.2. Prediction

For additional validation of the MMSE results, we attempted to predict the volume transport after the three years from 2008 to 2010. The prediction was carried out using transport data from the four different models with the obtained the regression equations.

Figure 2.15 shows the seasonal variation of the volume transports through the KT, TG, and SP Straits from the observed data and the prediction. The observed data for the KT and TG Straits were available during a set period, but observed data of the SP current transport were unavailable (Fig. 2.2).
There seem to be similar seasonal tendencies between the predictions and the observed data for the KT and TG Straits. However, the predictions are quantitatively dissimilar to the observed data. The predictions for the KT Strait tend to be smaller than the measurement data, whereas those of the TG Strait are larger than the observed data.

Table 2.5 summarizes the annual mean transports and the STDs of the observations and predictions in the three straits. The mean transports of the predictions in the KT Strait are smaller than the ADCP observation by 0.34 Sv, while those of TG Strait are larger than the observation by about 0.20 Sv. The difference between the observed data and the prediction is twofold that between the observed data and the MMSE estimate for the KT Strait, whereas the differences between the observed data and both the prediction and the MMSE estimate are generally comparable. The STDs of the volume transports also show the same tendencies as the MMSE estimates. The STDs of the predictions in the KT Strait show relatively large differences between the observed data compared with the other straits. Hence, the predictions are also underpinned by the MMSE results.

The unavailable data of the observed SP transport can be estimated by the difference in transport between the KT and TG Straits of the MMSE result because mass conservation is guaranteed in the predictions.

Previous studies have shown that the volume transport is related to the across-strait SLD. We compared the SLD during the set periods of the MMSE and prediction. The monthly SLDs across the KT and TG Straits during 2003–2007 (the MMSE period) and 2008–2010 (the prediction period) are shown in Fig. 2.16. The SLDs of the two separate periods are very similar, which suggests that the volume transports of the
MMSE and prediction periods should also be similar. The TG observed transports in the two separate periods are almost identical quantitatively, but the observed value for the KT Strait from 2008–2010 is larger by 0.14 Sv compared with that in the MMSE period of 2003–2007. It may be that the observed transport from 2008 to 2010 is more overestimated (particularly for 2008) than in the MMSE period of 2003–2007. This result implies that the long-term ADCP data in the KT Strait include some error, thus there is a need to verify the observation in not only the current period but also in previous or subsequent periods.
Table 2.5 Annual mean and standard deviation of measurement data and predictions for the Korea/Tushima, Tsugaru, and Soya/La Perouse Straits from 2008 to 2010

<table>
<thead>
<tr>
<th>Names of strait</th>
<th>OBS</th>
<th>y_{Transport}</th>
<th>y_{SLD}</th>
</tr>
</thead>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>2.40</td>
<td>2.42</td>
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<td>1.68</td>
<td>1.70</td>
</tr>
<tr>
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<td>.</td>
<td>0.72</td>
<td>0.72</td>
</tr>
<tr>
<td><strong>STD</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>0.37</td>
<td>0.42</td>
<td>0.41</td>
</tr>
<tr>
<td>Tsugaru</td>
<td>0.14</td>
<td>0.13</td>
<td>0.12</td>
</tr>
<tr>
<td>Soya/La Perouse</td>
<td>.</td>
<td>0.28</td>
<td>0.28</td>
</tr>
</tbody>
</table>
Figure 2.13 Monthly sea level difference at the major straits in the East/Japan Sea. Satellite altimeter data, reanalyses from the four models, and ridge regression performance are represented by the gray cross mark, colored square mark, and black diamond mark, respectively.
Figure 2.14 Same as the lower panel of Fig. 2.10, but for sea level difference instead of volume transport.
Figure 2.15 Monthly averaged transport through the Korea/Tsushima (green), Tsugaru (blue), and Soya/La Perouse (red) Straits from 2008 to 2010. Measured volume transport is represented by the cross mark. The prediction results represented by the circle-mark curve indicate the application with equation (1) with transport, and the diamond-mark curve indicates the application with regression equation (2.2) with SLD. The light shading denotes the 90% confidence interval of observed transports.
Figure 2.16 Comparison of the monthly sea level differences in 2003 to 2007 (red cross) and 2008 to 2010 (blue cross) across the Korea/Tsushima (a) and Tsugaru (b) Straits.
2.6. Conclusions

The goal of this study was to estimate the transports of the KT, TG, and SP Straits for physically consistent circulation in the EJS using the MM(S)E approach. The MM(S)E arising from a combination of multi-models outperformed the reanalyses from the individual models by considering model uncertainties. In particular, the MME estimates was less accurate the MMSE estimates. Above all, the ridge estimator overcame the problem of multicollinearity compared with the OLS estimator.

The MMSE equation, which satisfied the physical and statistical conditions of these straits, was obtained using the transport data. To validate this MMSE estimate, the MMSE was carried out with SLD, which was related to transport, as the independent variable.

Comparing the two regression equations for the transport and SLD data, the estimates of MMSE with SLD were found to be similar to the MMSE results with transport data. The MOVE model was allocated the highest weight, whereas the JCOPE model had small regression coefficients in both of the consolidation models. This result demonstrated that the MOVE model can simulate the flow system of the EJS compared with the other models. The DREAMS model had the strong weight in the regression equation for the transport data, even with relatively coarse horizontal grid resolution.

The MMSE estimate indicated that the volume transport was smaller than the measurement data at the KT Strait, but was larger than the observed data at the TG Strait. The optimal transports considering mass conservation for 2003 to 2007 were 2.42, 1.63, and 0.74 Sv for the KT, TG, and SP Straits, respectively. The MMSE results also suggested that STD in the KT Strait was larger than observed, whereas the
estimated results were almost the same as the ones observed in the TG and SP Straits. The MMSE estimates for SLD data and prediction were also found to be similar to the original case with transport. These similarities enhanced the reliability of the MMSE estimates for transport data.

Since the insufficiency of the long-term and simultaneous observational data in straits, it had been difficult to propose the inflow and outflow systems of the EJS until now. Even though, the ratio of the model reanalyses data, which was sufficient for the conservation of mass budget, was different depending on the model. The outflow partitioning of four reanalyses showed that 75%, 69%, 82% and 73% of the total inflow transport flows out of the EJS through the TG Strait, and 25%, 31%, 18% and 27% through the SP Strait in DREAMS, MOVE, JCOPE and HYCOM, respectively. According the MMSE result, the ratio of the outflow through the TG Strait versus SP Strait is 0.68:0.32. This ratio is relatively close to Na et al. (2009).

These results suggest the need to modify the observed transport data in the three straits to estimate physically consistent transport in the EJS system. In the case of the KT Strait, the measured transport has been calculated from current data obtained from the vessel-mounted ADCP. When the KT current was observed on the cruise, the sampling error of time intervals or spatial points and cruising speed might have affected the accuracy of the dataset. In addition, programming errors from missing data and the calculation process need to be considered.

For the TG Strait, the similarity between the MMSE result and the observed data indicates that seasonal variation in volume transport can be simulated with the along-strait SLD. The equation used to estimate the observed transport of the TG Strait
was $Q = 0.0271 \Delta \eta + 0.9333$ (Nishida et al. 2003). The linear equation was based on the ADCP data observed from 1993 to 1999. Nevertheless, this equation was able to estimate the seasonal variation in the volume transport of the TG Strait in other periods, whereas the mean transport of MMSE estimate had been underestimated compared with any single model results, at least in 2003 to 2010. This indicates that the estimation equation is necessary to consider the interannual variability, that is, the need exists to increase the term of the y-intercept in this equation.

Although these MMSE results were consistent with mass conservation in the EJS circulation, this study does not explain why the TG transports from all model reanalyses have a large gap within the observed data. The dynamic mechanism that overestimated the volume transport of the TG strait will be investigated in a next chapter. Overall, this paper suggests that the volume transports of the KT, TG, and SP Straits are physically consistent.
CHAPTER III: Numerical experiments

3.1. Introduction

Due to its exclusive role in the exchange of water between two seas, channel flow is an essential regulator of various oceanographic properties. The pathways and mechanisms of this exchange through the channel and their variability are important factors influencing the continual circulation of the ocean.

In reality, multiple channels are often linked to a basin and the open ocean. Indeed, the throughflow of the East Asian straits has a large impact on circulation in the EJS, the Pacific Ocean and the East China Sea. The Tsushima Warm Current flows into the EJS through the KT Strait from the East China Sea. The water mass inflow through the KT Strait exits to the North Pacific through the Kanmon and TG Straits and to the Sea of Okhotsk through the SP and Tartar Straits (Fig. 3.1 (a)). The Tsushima Warm Current (TWC), which delivers warmth and salt from the south, transports heat through the KT Strait into the EJS. The TWC is also responsible for heat loss to the atmosphere in the EJS, and salt carried by the TWC can play a significant role in deep water formation off Vladivostok (Seung and Yoon, 1995; Hirose et al., 1996).

To balance inflow and outflow, volume transport through the KT Strait inlet should account for the sum of the outflow through the TG and SP Straits. The observed transport in these three straits has recently been reported, not only as measured by acoustic Doppler current profilers (ADCPs) and HF (High frequency) radar, but also estimated from hydrographic data using a geostrophic calculation (Iino et al., 2009;
Fukudome et al., 2010; Fukamachi et al., 2010). Estimates of the transport through the major straits in the EJS vary widely with respect to the annual mean, a function of the insufficiency of the long-term and simultaneously-measured data and the limitations of observation. Consequently, the observed data have an inconsistency problem for mass conservation.

On the other hand, volume transport estimates based on numerical ocean models at least provide a self-consistent budget. The circulations of EJS have been simulated using numerical models with data assimilation by many organizations (Usui et al., 2006; Miyazawa et al., 2009; Hirose et al., 2013). The results show similar seasonal variation and inter-annual change; however, the ratio of the outflowing volume transports shows significant differences. For example, reanalysis of the outflow partitioning from four ocean data assimilation models—DREAMS, MOVE, JCOPE and HYCOM—showed that almost three quarters of the total inflow transport flows out of the EJS through the TG Strait and about one-quarter through the SP Strait for the period 2003–2007.

In Chapter 2, we suggested optimal volume transports which could solve the inconsistency problems in the observed data and numerical modeling results using a multi-model ensemble. The outflow partitioning assumed that, for the total inflow KT transport, 68% of the outflow was through the TG Strait and 32% was through the SP Strait. The estimated mean transport (2.43 Sv) was smaller than the measurement data (2.59 Sv) in the KT Strait, but the calibrated transport of the TG Strait (1.63 Sv) was larger than the observed data (1.47 Sv). The SP transport estimated by using the multi-
model ensemble (0.80 Sv) was roughly the same as the combined HF radar and ADCP data (0.74 Sv).

Among the three straits, the TG transport value showed the largest discrepancy between the observed data and multi-model ensemble results. As for the biases of the modeled and observed transports relative to the multi-model ensemble for the three straits, all simulated results for the TG transport were overestimated when compared to both the observed data and the results of the multi-model ensemble (Fig. 3.2). The reanalysis of JCOPE produced the largest difference among the four analyses as 0.79 Sv, or almost half the volume transport in the TG Strait.

Based on the previous studies, there remain two unanswered questions regarding the volume transports through the three straits. Specifically,

1) Why is it that all model transport through the TG Strait overestimate the optimal estimates of the multi-model ensemble?

2) What are the dominant factors determining the partitioning of outflow?

In this chapter, we attempt to answer these questions using the unstructured grid, finite-volume method that overcomes the common limitations of existing finite element models. Moreover, we seek to elucidate the important factors contributing to the mechanism for the three interconnected straits in the EJS.

Toulany and Garrett (1984) proposed a frictional parameter, a measure that determines whether flow is "geostrophically controlled" or "frictionally controlled." When the frictional parameter is equal to or greater than unity, the sea level difference
along the strait becomes significant and the volume flux is more affected by frictional control than geostrophic balance. Estimated frictional parameters that are close to zero (0.11, 0.16 and 0.10 m/s in the KT, TG and SP Straits, respectively) imply that the flows are mainly geostrophically controlled in the three straits (Ohshima, 1994). However, according to Iino et al. (2009), the value of the frictional parameter was estimated to be 1.3 m/s in the TG Strait (vs. 0.16, above) using a two-dimensional model with simple step/sill topography. The difference here is a linear bottom friction coefficient as large as one order of magnitude. Frictional control is mainly shown in the TG Strait, resulting not only from bottom friction but also the effect of the local sill topographies. This implies that the passage-flow motion of the TG Strait has an impact on form drag caused by topographically forced waves. Yang et al. (2013) suggested that the volume transport of the KT Strait is largely controlled by the barrier effect, which includes the form drag associated with bottom pressure torque, the generation of cross-isobathic flow by horizontal friction, and the northward shifting of the force arising in the inflow and outflow channels. The result indicates that bottom pressure torque (or form drag) is a dominant factor in the balance of the depth-integrated vorticity budget and that it produces a significant reduction in the KT transport.

Numerous studies that focus on an individual strait or consider only a barotropic mode without regard to baroclinic effects have been undertaken (Iino et al., 2009; Fukudome et al., 2010; Fukamachi et al., 2010; Seung et al., 2012). The major straits of the EJS have a steep topography and irregular geometry. To simulate accurately a complex geometry and bottom bathymetry, the model used should be provided with an adequately high resolution. The basin scale OGCMs (Ocean Global Circulation Models) have had difficulty simulating the interaction between a basin and
connecting straits due to resolution as low as 1/5°~1/15°. Even though some models have adopted a higher resolution, their coverage regions are restricted so that they are unable to include the effects of inter-connected straits.

The unstructured grid, finite-volume method is appropriate for the effective simulation of a system with a steep and complex topography and coastline. This method employing triangular elements is a good alternative to the existing ocean models employing structured grids and combines the advantage of finite-element methods for geometric flexibility and finite-difference methods for simple code structure and computational efficiency (Huang et al., 2008). The geometric flexibility allows a smaller computational load than in finite difference models striving to achieve the same horizontal resolution. Representative of this type of model is the unstructured-grid Finite-Volume Coastal Ocean Model (hereafter, FVCOM), which was originally designed for regional, coastal and estuarine regions with complex irregular geometry. The flexibility of the triangular grid allows the user to design with multiple scales: higher resolution over steep bottom topography and a complicated coastline, and coarser resolution over an open sea and an interior along a basin. Previous numerical studies taking into account the finite volume method have improved their finite element models in straits; however, they have rarely involved the EJS region. Chen et al. (2009) demonstrated that the harmonic constituents of sea surface elevation and currents using a spherical coordinate version of the unstructured grid 3-D FVCOM agreed well with corresponding observational results, particularly in the narrow straits of the Canadian Archipelago. Aoki et al. (2007) showed that a nested model with FVCOM together with the structured finite-difference Princeton Ocean Model (POM) for the KT Strait was more accurate than a model in which the FVCOM was replaced by a high-resolution
POM for Fukuoka Bay in Japan. Taking advantage of the geometric flexibility of the unstructured triangular grid of the FVCOM, we try to simulate more realistic conditions in order to find important factors contributing to the volume transports through the three straits.

This chapter is organized as follows: In Section 3.2, model configuration and the data used in the study are described; Section 3.3 covers the simulated results; Section 3.4 describes the dynamics of throughflow in the EJS; Section 3.5 discusses and summarizes results.
Figure 3.1. Unstructured model domain (a) showing the locations of the three straits of the East/Japan Sea. KT, TG, and SP refer to the Korea/Tsushima, Tsugaru and Soya/La Perouse Straits, respectively. Enlarged views of the white shading boxes for the KT Strait (lower) and TG and SP (upper) Straits. Bathymetry from JTOPO30 in outflow region as the Tsugaru and Soya/La Perouse Straits (b) and inflow region as the Korea/Tsushima strait (e). Model domain around outlet region as (c) and (d) and inlet region as (f) and (g) for Exp. L and Exp. H, respectively.
Figure 3.2 Seasonal variation for bias of modeled and observed transports relative to the multi-model ensemble in transport through the Korea/Tsushima (a), Tsugaru (b), and Soya/La Perouse (c) Straits from January 2003 to December 2007. The zero line is same as the estimates of multi-model ensemble. The reanalyses of ocean models and observed data are represented by the four colored square marks and gray cross mark, respectively.
3.2. Model description and experiment design

3.2.1. Control experiment

FVCOM (finite volume coastal ocean model) is a prognostic, unstructured grid, finite-volume, free-surface, 3-D primitive equation coastal ocean circulation model (Chen et al., 2009). FVCOM has a numerical simplicity and computational efficiency compared with the finite element and finite difference methods. The remarkable difference between FVCOM and other ocean models is its use of the finite-volume method that discretizes the integral form of the governing equations and numerically solves them by flux calculation over an unstructured triangular grid. This approach has the merit of geometric flexibility; the curving cells provide for a grid that follows the coast better than a grid that uses square grid cells. Thus, this model is capable of simulating multi-scale resolution, which can be enhanced according to the desired object of focus.

The numerical experiments in this study are conducted using an FVCOM based on the MPI parallel environment with the modified Mellor and Yamada level 2.5 (MY-2.5) and Smagorinsky turbulent closure schemes for vertical and horizontal mixing, respectively, and a generalized terrain-following coordinate to match bottom topography (Smagorinsky, 1963; Mellor and Yamada, 1982; Galperin et al., 1988). A nondimensional Smagorinsky constant 0.2 is used, and horizontal and vertical prandtl numbers are set to 1.0.

The applied domain covers the North Pacific region (112.5°E–74.84°W, 18.47°N–62.46°N) shown in Fig. 3.3. It is configured with unstructured triangular grids, which consist of 33,988 nodes and 65,941 elements. Resolution varies from 10
km to 15 km near the straits in accordance with the resolution of the basin scale OGCMs, while for the Russian and Chinese coastlines, and the deep ocean basins, the resolution is roughly 20 km to 200 km. The model is formulated with a solid boundary condition, which is set far from the three straits so as not to have a direct influence on circulation in the EJS. Vertically, depth is divided into 17 uniform sigma layers. The layer number is enough to simulate the throughflow of the three straits due to the sigma coordinate. The minimum water depth in the model was artificially made to be 10 m at the shoreline. The Mamiya and Tartar straits were closed, since the corresponding volume transports are negligible quantities.

The bathymetric data is taken from two sources. The JTOPO30 topography on a 1/120° grid was obtained from the Marine Information Research Center, Japan Hydrographic Center. It covers the EJS, the East China Sea and part of the Northwest Pacific, as shown in Figure 3.3 (a). The rest of the data are depths from the ETOPO05 (1/12°), which was provided by the National Geophysical Data. The topography is interpolated to each grid separately.

The model is forced by an idealized wind stress. The batch of idealized wind field is composed in such a way that the zonal component is a sinusoidal curve of latitudes and the meridional component is set to null. Idealized wind flow lines for a westerly wind with a maximum value of 0.24 Pa toward the east are shown in Fig. 3.3 (b). This is time-independent based on an annual reliable wind stress curl data set.

The initial fields are derived from stratification using a climatological annual mean provided by the World Ocean Atlas 2009 (WOA09). The temperature and salinity
(T-S) profile is horizontally and vertically changed from the sea surface to 5500m (Fig. 3.3 (c-d)). The flow field is initially set quiescent.

### 3.2.2. Simulation experiments pursued

We first seek to evaluate how closely the bottom boundary simulates the real topography in the existing basin scale OGCM, as DREAMS, MOVE, JCOPE, and HYCOM. The spatial resolution of DREAMS is 1/4°~1/5°; for the others, the resolution twice that. It is our belief that the horizontal resolutions of these models may be insufficient to represent the relatively narrow and steep topography around the straits. We examine the bottom boundaries of the existing OGCM near the narrowest TG Strait (Fig. 3.4). Compared to the JTOPO30, their bottom boundaries are unable to capture the topographic features (Fig. 3.1 (b)).

Similarly, most OGCM have insufficient horizontal resolution to simulate flow through a narrow strait. Sensitivity experiments are performed with high resolutions near the three straits to determine whether the simulated flow is dependent on horizontal resolution. The setup for the additional experiments is identical to the control run, except for the spatial resolution. The resolution of this experiment varies from 1-2 km (∼10 times higher than the density of the control run) near the strait; resolutions for the rest of the region are the same as in the control run (Fig. 3.1).

The control experiment using coarse resolution in all straits will be referred to as Exp. L, while the sensitivity experiment using a fine scale in all straits will be
designated as Exp. H. Fig. 3.1 shows the domain and topography for the two experiments. Other sensitivity experiments are described in Table 1; details are provided later in the paper, where they are to be applied.
Table 3.1 Descriptions of numerical experiments

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<th>S2</th>
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Figure 3.3 (a) Zonal component of idealized wind stress on surface for numerical simulations. Wind forcing is a sinusoidal curve of latitudes and meridional component is set to null. Unit is Pa. (b) Bottom topography from combination of ETPO05 and JTOPO30. Red box covers JTOPO30, while coverage of blue box has ETPO05. Depths are in meters. Stratification of (c) temperature and (d) salinity at surface in initial conditions for numerical simulations. These fields are provided from WOA09 and use climatological annual mean.
3.3. Simulation results

3.3.1. Impact on the horizontal resolution

Sea surface elevations simulated in Exps. L and H, averaged over days 150 to 350, are shown the Figure 3.5 (a) and 3.5 (b), respectively. (Simulated flow fields reach a quasi-steady state in about 150 days, and we discuss later) The sea surface elevations in the two experiments follow almost an identical pattern. The main features of both sets of results show a lower sea surface level in the northern part of the North Pacific, with a higher value in the southern part. Sea surface elevation is associated with geostrophic surface circulation. Both experiments were able to simulate the extension and separation point of the Kuroshio current as a western boundary current. In addition, the results also represented other ocean currents: The North Pacific, California, Oyashio and Alaska currents. These features are in good agreement with the known general circulation pattern.

To give a closer look at the two experiments, the sea surface elevations around major straits of the EJS are enlarged in Fig. 3.6. The spatial gradients across straits are almost identical for Exps. L and H, although the spatial mean of the sea level elevation simulated in Exp. L is higher than that in Exp. H. However, the sea surface elevations around the TG Strait reveal significant differences between the two experiments. The high sea surface elevation of the southern part is extended to the outlet region in Exp. L, while the sea surface elevation of Exp. H near the outlet shows a different pattern, with a high sea surface elevation along the Japanese coast alongside a low elevation in the north-western Pacific. This difference might be related to the southern outlet of the SP Strait around 144-144.5°E, 43.9-44.5°N. There is an increasing trend for sea surface elevation in Exp. L, while that feature is not present in Exp. H. Based on these sea
surface elevation results, it seems clear that the modeled throughflows of the three straits are affected by the horizontal resolution. In particular, the TG Strait is the most sensitive of the three straits. Thus, we would expect that there would be large differences between the two experiments around the TG Strait.

To satisfactorily draw a comparison between the results of Exp. L and Exp. H, the barotropic component velocities of the TG Strait are shown in Fig. 3.7. The velocity fields are also averaged over days 150 to 350. The general direction of current motion for Exp. L is similar to that of Exp. H, whereas the velocity in Exp. H shows large fluctuations along the central streamline as compared to Exp. L. Especially, the TG current field of Exp. H shows clear separation into a relatively strong current in the central part and a weak current near the lateral boundary. It is widely known that eddies have been observed along the northern and southern sidewalls of the TG Strait (Conlon, 1981). The eddies show near both the north and south lateral boundaries in Exp. H, while the current field of Exp. L is unable to capture any eddy motion at the northern boundary. As shown by the sea surface elevations, the flow pattern near the outlet in Exp. H also differs from that in Exp. L. In the Exp. H results, a relatively small eddy appears adjacent to the Japan coastline, with a relatively large eddy building next to it. The impact of horizontal resolution is also found in the other straits (not shown here), although the differences between the two experiments is smaller here than in the case of the TG Strait. Based on these results, the simulated results of Exp. H are more realistic than those of Exp. L.

Generally, it takes longer computation time for basin-scale and global general circulation models to reach a steady state. An additional approach is employed to test
whether this model have actually stabilized by extending periods based on the control experiment, and it is maintained by nudging the initial temperature and salinity with a time scale every 350 days. Fig. 3.8 shows the variation volume transports through the three straits over 1950 days. The volume transports are almost the same after 150 days per each period. It is clear that the system becomes stabilized, therefore subsequent analysis will be evaluated on 150 to 350 days.

In order to examine more closely the differences between the two experiments in the three straits, volume transports are depicted in Fig. 3.9 (a). The simulated results can be sustained in steady-state conditions from the 150th day. The volume transports in the KT Strait have quite similar trends in both experiments. The average volume transport from day 150 to day 350 is 2.49 in Exp. L and 2.31 Sv in Exp. H. This indicates that the resolution used in the existing model is sufficient to simulate the KT Strait throughflow. The volume transport in Exp. L is larger than that in Exp. H for the TG Strait, whereas the estimated transport for the SP Strait shows the opposite tendency. The mean transport values in Exp. L, averaged for the period from day 150 to day 350, are 2.33 Sv through the TG Strait and 0.25 Sv through the SP Strait, while in Exp. H they are 1.76 Sv and 0.48 Sv, respectively. Thus the volume transports through the TG and SP Straits clearly depend on the grid resolution.

The ratios of outflow transport for the TG and SP Straits in Exps. L and H are depicted in Fig. 3.9 (b). The outflow partitioning of the low resolution experiment shows that 90.4% of the total inflow transport flows out of the EJS through the TG Strait, while the remaining 9.6% flows out through the SP Strait. On the other hand, outflow transports in the high resolution experiment indicated that 78.5% of the inflow
transport flows out through the TG Strait, with 21.5% flowing out through the SP Strait (Table 2). It implies that the flows in the TG and SP Straits are more sensitive to the spatial resolution than is the flow in the KT Strait.

3.3.2. Sensitivity experiments

The impact of the resolution on the three channel transports is verified as indicated in the previous results. However, it remains uncertain as to which of the straits controls the outflow partitioning ratio in Exp. L and Exp. H. A partial area with high resolution was inserted into the control run for Exp. L in order to find out which strait is most affected by the spatial resolution and to determine which channel flow would control the outflow partitioning ratio. The validated experiments consisted of three conditions and were designated Exp. S1, Exp. S2, and Exp. S3 (Table 3.1). The letter S indicates that the experiment is a sensitivity experiment and the number 1, 2, or 3 identifies the strait to which the high resolution is applied. For instance, Exp. S1 is the case in which high resolution is used for the KT Strait (strait 1) and the low resolutions are used for the TG Strait (strait 2) and the SP Strait (strait 3).

Comparisons of the volume transports through the KT, TG, and SP Straits for Exps. S1, S2, and S3 are shown in Fig. 3.10. The resulting transports in Exp. S1 and Exp. S3 show qualitatively analogous results in all straits. In Exp. S1, the ratio of the outgoing volume transports is 91.4% for the TG Strait, 8.6% for the SP Strait; in Exp. S3, the ratios are 88.6% (TG) and 11.4% (SP). The ratios of the outflowing transports from Exps. S1 and S3 are also close to those in Exp. L (90.4% and 9.6%). (Table 3.2.)
On the other hand, the volume transports in Exp. S2 are significantly different from those in Exps. S1 and S3. The inflowing and outflowing transports are lower compared to those in the other experiments. Moreover, the ratio of outgoing volume transports is 80.3% for the TG Strait and 19.7% for the SP Strait, which is similar to Exp. H results, where the volume transport ratio is 78.5% for the TG Strait and 21.5% for the SP Strait. (Table 3.2.)

These results imply that the modeled current of the TG Strait is greatly dependent on the spatial resolution among the three straits and that, most of all, the difference in the outflow partitioning ratio between Exp. L and Exp. H results from the resolution of the TG Strait. In addition, the water budgets entering the EJS produced in Exp. S2 and Exp. H decrease, while the transport of the SP Strait increases in comparison with other experiments. This indicates that the horizontal resolution through the channel affects not only the corresponding strait but also the other straits; that is, one strait flow is dependent on the flows of the others.
Figure 3.4 Bottom boundaries for existing ocean models DREAMS (a), MOVE (b), JCOPE (c) and HYCOM (d). Unit is meter.
Figure 3.5 Sea surface elevations averaged from day 150 to day 350 in Exp. L (top) and Exp. H (bottom). Unit is meter.
Figure 3.6 Sea surface elevations around the Tsugaru and Soya/La Perouse Straits (top) and the Korea/Tsushima Strait (bottom) in averaged from day 150 to day 350 in Exp. L (a and c) and Exp. H (b and d). Unit is meter.
Figure 3.7 Barotropic component of velocities around the Tsugaru Strait averaged from day 150 to day 350 in Exp. L (a) and Exp. H (b).
Figure 3.8 Daily transport through the Korea/Tsushima (green), Tsugaru (blue), and Soya/La Perouse (red) Straits resulted from Exp. L.
Figure 3.9 (a) Daily transport through the Korea/Tsushima (green), Tsugaru (blue), and Soya/La Perouse (red) Straits. Volume transport in Exp. L is represented by the dashed line; Exp. H is represented by the solid curve. (b) Ratios of outflowing transports for the Tsugaru (blue), and Soya/La Perouse (red) Straits produced in Exp. L and Exp. H.
Figure 3.10 Differences between the transport entering through the Korea/Tsushima Strait (green) and the outgoing transport at the Tsugaru (blue) and Soya/La Perouse (red) Straits for estimations from control and sensitive experiments.
Table 3.2 Outflowing portioning of numerical experiments.

<table>
<thead>
<tr>
<th>Experiment Label</th>
<th>L</th>
<th>H</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>LM</th>
<th>HS</th>
<th>LU</th>
<th>LD</th>
</tr>
</thead>
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<td>SP</td>
<td>9.6</td>
<td>21.5</td>
<td>8.6</td>
<td>19.7</td>
<td>11.4</td>
<td>23.8</td>
<td>7.4</td>
<td>22.7</td>
<td>6.7</td>
</tr>
</tbody>
</table>
3.4. Impact of topography on through flow in the Tsugaru Strait

3.4.1. Simulated experiment on modified topography

The importance of resolution was tested in the previous five experiments. The TG Strait throughflow was especially affected by the horizontal resolution in comparison to that of the other straits. In general, the results with fine resolution tend to be more realistic than with low resolution. The effect of horizontal resolution is directly associated with how close the bottom boundary is to the actual topography. Therefore, we carried out two additional experiments with topographical modifications around the TG Strait in order to examine whether the bottom topography features could control the ratio of outflow transports. In these experiments, the features of topography are emphasized/eliminated in the TG Strait while resolution is maintained. Conditions for the other straits are consistent with those in the control run. Comparisons of the bottom boundary are presented in Fig. 3.11. In one version of the experiment, topography is added to the actual sills and bumps in the bottom boundary, while maintaining low resolution in the TG Strait. In the other, we use artificially smoothed topography such as gradual bumps, with high resolution in the TG Strait. We will refer to these new experiments as LM and HS (M indicates modified topography in the TG Strait; S indicates smoothed topography in the TG Strait). (Table 3.1.)

The time-mean volume transports through the three straits in Exp. LM and Exp. HS are depicted in Fig. 3.10. The respective averaged transports of Exp. LM averaged over days 150 to 350 are 2.31 Sv (KT), 1.64 Sv (TG) and 0.51 Sv (SP). The inflowing and outflowing transport in Exp. LM consistently show quantitative similarity to the results in Exp. H and Exp. S2. The ratio also tends to show a similar
trend to that shown in Exp. H. As presented in Table 3.2, 76.2% of the inflow transport flows out through the TG Strait, whereas 23.8% flows out through the SP Strait. Thus the outflow partitioning of Exp. LM bears a certain similarity to that in Exps. H and S2. This indicates that the effect of modified topography has the same efficacy as high resolution, which supports the conclusion that it is the accuracy of the topography feature near the TG Strait that is important, rather than fine resolution.

On the other hand, the volume transports of Exp. HS are 2.71 Sv (KT), 2.47 Sv (TG) and 0.20 Sv (SP). (Fig. 3.10). These results have much in common with the results of Exp. L. With respect to the ratios of outflowing transports in the previous experiments, the Exp. LM results are analogous to those in Exp. H and Exp. S2. This affirms that flow is sensitive to the topography in the TG Strait. Moreover, it is seen that the water budget through the TG Strait is changed by topography, causing the SP transport to also fluctuate to conserve water mass. The modified bottom boundary significantly affects the interaction between bottom topography and flow through the TG Strait, as well as the use of high resolution. This implies that the flows through the TG Strait are impacted by topography structures such as bumps or sharp slopes.

Judging from these results, the exchange water mass between the EJS and the North Pacific Ocean can be accurately simulated with low resolution only if the bottom boundary has appropriate features, as in Exp. LM. This suggests that the existing models can accurately simulate the TG throughflow if their bottom boundary layers capture the exact topographic features with low resolution.
3.4.2. Impact of topographically induced drags

As mentioned earlier in the introduction, the frictional parameter in the TG Strait showed opposite results to those of previous studies (Iino et al., 2009; Ohshima, 1994). Consequently, we attempt to confirm whether the frictional parameter differs for the topographic features of this study.

The dynamics on a given traverse and longitudinal direction between two oceans connected through a shallow strait are controlled by a geostrophic and hydraulic control. This is expressed as

\[ fU = -g \frac{\partial \eta_y}{\partial y} \]  
\[ g \frac{\partial \eta_x}{\partial x} + \frac{rU}{h} = 0 \]

where \( f \) is a Coriolis parameter and \( U \) is the meridional component of velocity; \( g \) is gravity acceleration; \( \eta_x \) and \( \eta_y \) indicate sea surface elevations across and along the strait; \( r \) is a bottom linear friction coefficient; and \( h \) represents the bottom depth. Following to Toulany and Garrett (1984), we define the frictional parameter, \( Fr \), as

\[ Fr = \frac{r}{fh} \cdot \frac{L}{W} \]
where $L$ is the length and $W$ is the width of the strait. In our study, the Coriolis parameter and the depth, length and width of the TG Strait are almost identical in all experiments. This means that the frictional parameter, $Fr$, is controlled by the bottom linear friction coefficient, $r$.

We compare the bottom linear friction coefficients for Exps. H and HS, which have steep and gradual topographies, using Eq. (3.2). The SLDs along the strait, $\frac{\partial n_s}{\partial x}$, are estimated as 9.76 cm and 0.38 cm in Exps. H and HS, respectively. We found that the SLD when steep topography is involved is larger than in cases involving relatively gradual topography. The u-velocities are slightly different in the two experiments: 0.18 m/s (H) and 0.17 m/s (HS). Calculating the bottom friction coefficients in the two experiments gives $4.30 \times 10^{-3}$ m/s for Exp. H and $3.22 \times 10^{-3}$ m/s for Exp. HS. (The bottom friction coefficient, $r$, determines the degree to which the friction force disturbs the flow system.) These results suggest that the more realistic bottom boundary is subject to roughly four times the bottom friction as the artificial (smoothed) bottom boundary.

Indeed, the outflow partitioning through the TG Strait in Exp. H (78.5%) is smaller than in Exp. HS (92.6%). (Table 3.2). This confirms that topographic features such as bumps and valleys play an important role in choking the flow through the TG Strait. This bottom roughness typically influences overflow product distribution, which is associated with enhanced mixing, drag and dissipation. These processes result in a drag force imparted on the flows. The frictional stress imposed by the bottom friction coefficient decomposes into friction and form drag. These drags can be calculated in
order to determine which of the two drag factors lead the bottom friction of the flow through the TG Strait.

Friction drag (skin drag) is generated by the viscous shear stress acting tangentially to the body and associated with dissipative losses in the bottom boundary layer. It can be determined as

\[
\frac{D_{\text{friction}}}{w} = - \int_{x_u}^{x_d} \rho \nu^2 \, dx'
\]  

(3.4)

where \(\nu\) is the friction velocity and \(\rho\) denotes water density. The along-track coordinate is \(x'\), indicating the angle to the along-channel direction. The drag is integrated from \(x_u\) (upstream) to \(x_d\) (downstream) along the bump as shown in Fig. 3.12. The friction velocity can be determined from

\[
\nu = (\kappa \nu^2 z)^{1/3}
\]  

(3.5)

\[
-\overline{u'w'} \frac{\partial U}{\partial z} = \varepsilon
\]  

(3.6)

where \(-\overline{u'w'}\) is the same as the vertical Reynolds stress; \(\kappa\) is 0.4, using von Ka´rma´n’s constant. The \(\nu^2\) can be estimated directly as the bed stress over the bank.
Contrary to the friction drag, which exerts itself only in the bottom boundary layer, form drag leads to mixing and turbulence over the water column and results in eddies and internal waves that carry energy away from the bottom topography. Form drag arises when currents create drag on a body moving through a fluid as a result of the shape of the body. It is related to the pressure drop across the strait and is generated by normal stress (mostly pressure) acting on a body. The along-channel component of form drag is

\[
\frac{D_{\text{form}}}{w} = - \int_{x_u}^{x_d} P_{\text{bot}} \frac{dh}{dx'} dx'
\]

(3.7)

Its value is determined by integrating the bottom pressure anomaly, \( P_{\text{bot}} \), and topography slope, \( \frac{dh}{dx'} \) over the bank. A detailed derivation from the momentum equation can be found in McCabe et al. (2006). These drags are negative because it removes momentum from the flow.

When calculating the form drag, the bottom pressure anomaly, \( P_{\text{bot}} \) is used because the total pressure is dominated by the static pressure related with the depth and background stratification. So we express only the terms that contributed to form drag in Eq. (3.8).
\[ P_{\text{bot}} = \rho_0 g \eta' + g \int_{\eta}^{\eta} \rho'(x,y,z) dz \] (3.8)

The density is divided into the three parts, \( \rho = \rho_0 + \bar{\rho}(z) + \rho'(x,y,z) \), where \( \rho_0 \) is a constant background density, \( \bar{\rho}(z) \) is a background stratification, and \( \rho'(x,y,z) \) is a remaining perturbation. The sea surface height can be broken into two parts, \( \eta = \bar{\eta} + \eta'(x,y) \). Here, \( \bar{\eta} \) is a spatial averaged sea surface elevation, and \( \eta'(x,y) \) is the sea surface anomaly. The first term of Eq. (3.8) accounts for local perturbations of the sea surface and it indicates the external pressure. The second term accounts for vertical displacement of isopycnals, it related to the internal pressure. The sum of internal and external pressures is generally called the dynamic pressure anomaly. Here, the use of terms, internal and external pressure, are used to emphasize deformation of isopycnals and sea surface perturbations. They are not equivalent to baroclinic and barotropic pressures.

The form drag is integrated from \( x_u \) and \( x_d \), where the bottom depth is identical. Because of the surface incline and the isopycnal deflection, the bottom pressure would be higher on the upstream relative to the downstream, leading to the form drag. The reference level from a link between \( x_u \) and \( x_d \) is set as 220–250 m. We develop three lines for calculation of the drags which are determined according to surface velocity magnitude of flow as marked in Fig. 3.11. The three lines are arranged from north to south, then intervals between lines tend to be proportional to the width of channel.

The components of frictional and pressure drags in Exps. H and HS using an along-track coordinates the TG Strait are demonstrated in Fig. 3.13. The results of
bottom density averaged in the middle line are almost identical in Exp. H and Exp. HS. In the north and south lines, the bottom density from $x_u$ and $x_d$ have differences between Exp. H and Exp. HS, however the amount is small. The bottom stress values have relatively large differences between Exps. H and HS compared to the water density.

Form drag is defined as the integral of the bottom pressure anomaly times the bottom slope (Fig. 3.13). The dynamic bottom pressure anomaly has significant differences between upstream and downstream in Exp. H, whereas that of Exp. HS remains little changed along the channel. The dynamic bottom pressure anomaly is composed of the external and internal pressures. The external pressure is dominant for the dynamic pressure in both of the experiments rather than the internal pressure. It means that the deformation of the sea surface elevation field is larger than the pressure perturbation due to the deformation of isopycnals. The dynamic bottom pressure anomaly of Exp. H has a large fluctuation along the channel compared to that of Exp. HS. The topographic slope of Exp. H also relatively large, especially on the western slope, compared with Exp. HS.

Fig. 3.14 shows the bottom boundaries, surface u-velocity and magnitude of frictional and pressure drags in Exps. H and HS using along-track coordinates in the TG Strait. The bottom boundaries of Exp. H in three lines have more complex bottom boundary compared to the that of Exp. HS. The surface u-velocities of Exp.H have large fluctuation, whereas the results of the Exp. HS keep constant along channel. The surface u-velocities of Exp.H tend to accelerate in inlet region even though having large drags. It might be related with the wide width of the inlet region.
The friction drags of Exp. HS are slightly larger than that of Exp. H in the middle bump region among the three lines. Friction drags tend to follow the same pattern as topography roughness in both experiments. More remarkable differences are in the form drags in Exps. H and HS. The form drag in the more realistic topography is larger than in the smoothed topography. The form drag in Exp. H with sharp slopes of bumps shows a fluctuating trend along the strait, with a magnitude that is higher than in Exp. L. The difference between the two experiments shows in the upstream and downstream regions. Especially, the results of Exp. H are more than 10 times larger than that of Exp. HS in the western slope in the three lines. In the middle bump region, the form drags of the two cases have a negligible quantity. This indicates that the topographical features especially, the western slope, is more important in simulating the flow of the TG strait as compared to other regions.

To make an intuitive estimate of flow drag, accumulated friction and pressure drags show in Fig. 3.15. The accumulated drag is integrated along-track coordinates and also involve whole width of the TG Strait. The accumulated form drag has a large gradient in western and eastern slope, while the accumulated skin drag increases with the distance of channel in in Exp. H. The total drag is 6.84×10^7 N, which is composed of the skin drag (2.61×10^7 N) and the form drag (4.23×10^7 N).

In Exp. HS, the total drag increases in direct proportion to the distance and its value is 2.08×10^7 N. The throughflow of the TG Strait is rarely affected by form drag (0.35×10^7 N), whereas it is clearly impacted by friction drag (1.73×10^7 N) in Exp. HS.

The dominance of form drag over friction drag was evident in comparison between Exps. H and HS. This indicates that the throughflow of the TG Strait having
real topography is affected by not only frictional drag (38.1%), but also form drag (61.9%). The magnitude of form drag in Exp. H is larger by one order than the form drag in Exp. HS. Given that form drag is determined by topography features, our results show that the topographically-induced form drag also controls the TG throughflow as well as friction drag.

The force exert on the flow can be compared to the dynamical terms in the friction control. The total drag is also estimated as the areal average of the pressure gradients (Eq. 3.2). The SLDs along the strait, \( \frac{\partial \eta_x}{\partial x} \), are estimated as 9.76 cm and 3.85 cm in Exps. H and HS, respectively. Integrated over bump area, the total force over the strait are \( 1.95 \times 10^7 \) N, \( 0.77 \times 10^7 \) N in Exps. H and HS respectively. This results are approximately the estimation of total drag as summation of skin drag and form drag.

To verify that throughflow in the TG Strait is controlled by form drag, we carried out additional experiments. The form drag in Exps. H and HS showed significant differences near the upstream region along the TG channel (Fig. 3.14). So we design new experiments as Exps. LU and LD (Table 1). The letters U and D indicate that the modified region as the upstream and downstream, respectively. The partial area of bottom boundary in the TG strait is modified based on the Exps. L and S2. The modification in Exp. LU is that steep of bottom boundary around the inlet region as Exp. LM and the bottom boundary near the outlet region is applied to smoothing topography like as Exp. L. The bottom boundary of Exp. LD is more realistic topography around the downstream area, while the rest area is identical with that of Exp. L.
The volume transports in the additional experiments are 2.02 Sv (KT), 1.48 Sv (TG) and 0.43 Sv (SP). The outflow partitioning through the TG Strait (77.3%) and the SP Strait (22.7%) also bears a certain similarity to the partitioning in Exps. H and S2. On the other hand, the results of Exp. LD are similar with that of Exps. L and HS. These additional experiments confirm that form drag is an important factor in the throughflow of the TG Strait, especially on the western slope.

One interpretation of these findings is that the bottom friction coefficient in cases having steep topography is roughly 1.5 times larger than in cases involving smooth topography. This result supports the estimated drags. However, a large friction coefficient is rarely related to frictional drag. Rather it is caused primarily by form drag on features of the bottom topography.

We also considered the effect of possible form drag from the lateral boundary of the TG Strait, which has a weaving coastline and narrow channel. The coastline in Exp. HS is more realistic than that in Exp. L as the coastline changes with resolution. The bottom boundaries in the two experiments are identical. To ascertain possible lateral boundary effects, the volume transports produced in Exps. HS and L are compared in Fig. 3.10. Their similar values indicate that form drag arising from the lateral boundary has little influence.
Figure 3.11 Surface velocity magnitude (a-b), sea surface elevations (c-d) and bottom boundary depths (e-f) in the Tsugaru Strait averaged from day 150 to day 350 for numerical experiment as H (left) and HS (right). Three lines are arranged from north to south, designated as line 1 (triangle marks), line 2 (cross marks) and line 3 (inverted triangle marks) in Exp. H (red) and Exp. HS (blue).
Figure 3.12 Schematic vertical sectional view of flow with bump. $x_u$ and $x_d$ indicate the longitude point of upstream and downstream along the bump. The dash lines denote the isopycnal.
Figure 3.13 Friction drag is controlled by density (a) and bed stress magnitude (b), and form drag is effected by dynamic bottom pressure anomaly which is composed of external and internal pressures (c) and topography slope (d). These component along-track three coordinates (1-3) in the Tsugaru Strait averaged from day 150 to day 350 for numerical experiment as H (red) and HS (blue).
Figure 3.14 Bottom boundaries (a) of Exps. H (red) and HS (blue) in three line (1-3). The vertical dashed lines indicate $x_u$ and $x_d$ in two experiments, and the reference level from a link between $x_u$ and $x_d$ is set as 220–250 m. Surface u-velocity (b) Friction drags (c), form drags (d) and along the Tsugaru Strait averaged from day 150 to day 350 for Exps. H and HS.
Figure 3.15 Accumulated drags along-track coordinate in the Tsugaru Strait of Exps. H (red) and HS (blue). Total drag (black line) is composed of friction drag (square mark) and form drag (circle mark). (left-upper) Ratio of friction and skin drags.
3.5. Summary and discussion

Existing structured models fail to clearly explain the dynamics of transport flow through major straits in the East/Japan Sea. This study attempted to establish the major explanatory factors and elucidate the missing dynamics. The mechanism responsible for the throughflows of the straits was investigated using an unstructured model. We addressed to answer two questions.

1) Why is it that all model transport through the TG Strait overestimate the optimal estimates of the multi-model ensemble?

We began to address the question by confirming that the common problem among numerous OGCMs for simulation of the throughflow in EJS is an insufficient horizontal resolution to simulate flow through a narrow strait. As a consequence, sensitivity experiments were performed with high resolutions near the three major straits. The experiments found that the modeled throughflow of these major straits clearly depends on grid resolution. The flow of the TG Strait was especially sensitive to the spatial resolution. Outflow through the SP Strait was adjusted by choking the flow of TG Strait, while that of the KT Strait remained relatively unchanged. The outflow ratio in the high resolution experiment changed according to the spatial resolution. The outflow partitioning of the low resolution experiment showed that 90.4% of the total inflow transport flows out of the EJS through the TG Strait, with the remaining 9.6% flowing through the SP Strait. On the other hand, outflow transports in the high resolution experiment indicated an outflow of 78.5% through the TG Strait and 21.5% through the SP Strait. The results of additional experiments which modified the bottom boundary while maintaining low resolution, coincided with those using high
resolution. These results implied that flow through the TG Strait is impacted by the topography structure, especially on the western slope. The reason that all modeled transport through the TG Strait has been overestimated is that the bottom boundaries in the models were not properly reproduced. If the bottom boundaries accurately capture topographic features while maintaining low resolution, the overestimation problem will be solved.

2) What are the dominant factors determining the partitioning of outflow?

One of the main factors dominant the partitioning of outflow was revealed in this study. As mentioned above, outflow partitioning changed with changes in the topographic features of the TG Strait. In the experiments with a more realistic bottom boundary, the bottom friction coefficient was almost 1.5 times larger than in the experiments involving the smoothed bottom boundary. Friction stress was modeled by the presence of obstacles such as bumps and valleys. However, the “effective friction” was hardly attributed to the frictional drag. Rather, it was related to form drag. Form drag was significantly larger than friction drag. The form drag varied with the bottom pressure and the bottom topographic slope.

Fig 3.16 shows that schematics of flows over two bumps, as steep (a) and gradual (b) topographies. The sea surface slope as a gradient of $\eta$ means that the pressure (weight of the water) above a position on the bottom is larger on east side of the bump than the other. At the same time, deformation of the density structure also creates a difference in pressure. These external and internal pressure anomalies contribute to the form drag. The magnitude of form drag is depending on the gradient of topographic slope. The pressure anomaly of steep topography (a) has larger
difference between upstream and downstream compared with that of the gradual (b) topography. The pressure difference means that a net force is exerted by the flow on the bank. In turn, form drag interrupts and decelerate flow, which reduces transport. This was true in the TG Strait. The volume transport of SP Strait also changed in accordance with the size of the TG flow.

The numerical results complement previous studies. We compare the bottom boundary around the TG Strait for four OGCMs: DREAMS, MOVE, JCOPE and HYCOM (Fig. 3.4). All the models, except for DREAMS, reproduced the eastern topographic feature. DREAMS and JCOPE rarely capture the topographic features in the upstream region. Comparing the volume transports of the four models, the volume transport of the TG Strait is related most closely to its western topographic features (Fig. 3.4). In the western region of the TG Strait, the bottom boundary of HYCOM is closest to the actual topography among the four models (Fig. 3.1). The volume transport of HYCOM is smallest among the four models, in accordance with its superior ability to reproduce the western topographic features.

Iino et al., (2009) also has suggested that form drag impacted the passage-flow motion of the TG Strait using a two-dimensional model. However, when their experiment involving barotropic conditions was carried out, the outflow partitioning was excessively affected by the spatial resolution, and, consequently, the volume transports of the TG and SP Straits showed abnormal amounts. The study suggests that the baroclinic effect is also important to the throughflow of the EJS. In addition, it suggests that the capture of topographic features is likely to be important where multiple
channels link a basin to open ocean, as, for instance, in the case of the Indonesian Throughflow.

Overall, this study found that the topographic features of the TG Strait were an important dynamics affecting the outflowing ratio in the EJS. Moreover, it found that TG throughflow was controlled by topographically induced drags—primarily form drag rather than friction drag. Finally, this study presented a solution for the inconsistency of modeled TG transports and raised the issue of dynamical consistency of the ocean current through the major straits of the EJS.
Figure 3.16 Schematics vertical sectional view of flow with bumps having complex (a) and smooth (b) topographic slopes.
CHAPTER IV: General conclusions

Finally, we have arrived at the statistically and dynamically consistent estimation of volume transports through the East Asian straits using MM(S)E and unstructured modeling approaches.

The MM(S)E arising from a combination of multi-models outperformed the reanalyses from the individual models by considering model uncertainties. In particular, the MME estimates was less accurate than the MMSE estimates. Above all, the ridge estimator overcame the problem of multicollinearity compared with the OLS estimator. The MMSE equation, which satisfies the physical and statistical conditions of these straits, was obtained using the transport data. To validate this MMSE estimate, the MMSE was carried out with SLD, which was related to transport, as the independent variable. Comparing the two regression equations for the transport and SLD data, the estimates of MMSE with SLD were found to be similar to the MMSE results with transport data. The MOVE model was allocated the highest weight, whereas the JCOPE model had small regression coefficients in both of the consolidation models. This result demonstrated that the MOVE model can simulate the flow system of the EJS compared with the other models. The DREAMS model had the strong weight in the regression equation for the transport data, even with relatively coarse horizontal grid resolution.

The MMSE estimate indicated that the volume transport was smaller than the measurement data at the KT Strait, but was larger than the observed data at the TG Strait. The optimal transports considering mass conservation for 2003 to 2007 were 2.42, 1.63, and 0.74 Sv for the KT, TG, and SP Straits, respectively. The MMSE results
also suggested that STD in the KT Strait was larger than observed, whereas the estimated results were almost the same as the ones observed in the TG and SP Straits. The MMSE estimates for SLD data and prediction were also found to be similar to the original case with transport. These similarities enhanced the reliability of the MMSE estimates for transport data.

Since the insufficiency of the long-term and simultaneous observational data in straits, it had been difficult to propose the inflow and outflow systems of the EJS until now. Even though, the ratio of the model reanalyses data, which was sufficient for the conservation of mass budget, was different depending on the model. The outflow partitioning of four reanalyses showed that 75%, 69%, 82% and 73% of the total inflow transport flows out of the EJS through the TG Strait, and 25%, 31%, 18% and 27% through the SP Strait in DREAMS, MOVE, JCOPE and HYCOM, respectively. According the MMSE result, the ratio of the outflow through the TG Strait versus SP Strait is 0.68:0.32. This ratio is relatively close to Na et al. (2009).

The numerical study found that throughflow of major straits certainly depends on the grid resolution, especially, the flow of the TG Strait was more sensitive to the spatial resolution than that of the other two straits. The outflow through the SP Strait was also adjusted by choking of TG Strait, while that of the KT Strait remains relatively unchanged.

The outflow partitioning of low resolution experiment showed that 90.4% of the total inflow transport flows out of the EJS through the TG Strait and 9.6% through the SP Strait. On the other hand, outflow transports in the high resolution experiment indicated 78.5% through the TG Strait and 21.5% through the SP Strait. The outflow
values from the high resolution experiment seemed more realistic than that of low resolution experiment due to the effect of form drag.

Additional experiments with modified bottom boundary also supported that the form drag had a significant impact on flow in the TG Strait. The results of Exp. LM, which combined with the high resolution around the TG Strait and the low resolution in other straits, were analogous to that of Exp. H. These results implied that the current of the TG Strait was greatly dependent on the spatial resolution and the difference between Exps. L and H attributed the resolution of the TG Strait.

Furthermore, inflowing and outflowing transport in Exp. LM consistently showed quantitative similarity to the results in Exp. H and Exp. S2. It was implied that the flows through the TG Strait was impacted by a topography structure such as topographic slope. In addition, it supported that how accurate topography feature near the TG Strait was important and the existing models also can accurately simulate the TG throughflow if their bottom boundary layers were caught topographic features with kept the low resolution.

As shown the estimation of bottom friction coefficients, the friction stress was modeled by the presence of obstacles such as bumps and valleys. However, the “effective friction” was hardly attributed to the frictional drag. Rather, it was related to form drag. Form drag was significantly larger than friction drag in Exp. H. Form drag interrupts and can decelerate flow, which reduces transport.

In addition, the water budgets entering the EJS resulted in Exps. LM and H decreased, while the transport of the SP Strait increased comparisons with other
experiments. This indicated that the horizontal resolution through the channel affected not only the corresponding strait but also the other straits; that was, one strait flow was dependent on the flows of the others.

The numerical study also complemented the MM(S)E results. The reason of that the transports through TG Strait resulted in MMSE was smaller than that of the four individual models can be explained dynamically by the form drag from the complexity of bottom boundary layer, especially in the western slope. This study also came up with a solution for the existing model having the overestimated problem. The solution was imposing the large friction parameter or modification of the bottom boundary layer in the TG Strait.

Overall, this study suggested that the volume transports of the KT, TG, and SP Straits were statistically and dynamically consistent. The MMSE proposed that the estimated results were consistent with the mass conservation. In addition, the numerical modeling explained that TG throughflow was controlled by topographically induced drags, not by the friction drag but also mostly form drag. This results also presented the solution for the inconsistency of the TG transports, thereby, it also raised that the dynamical consistency of ocean current through the East Asian straits.
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