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RESEARCH ON SEA LEVEL RISE DUE TO GLOBAL WARMING IN THE NORTHWESTERN PACIFIC USING A NON-BOUSSINESQ NUMERICAL MODEL

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ABSTRACT: To study the seawater volume change due to the warming of the oceans, this work adapts the Modular Ocean Model Version 4 (MOM4) oceanic general circulation model, which does not consider the Boussinesq approximation, to regional model. Simulation data of Climate Model 2.1 (CM2.1), the Hadley Center Coupled Climate Model 3 (HADCM3), and the Model for Interdisciplinary Research on Climate 3.2 (MIROC3.2), provided by the Intergovernmental Panel on Climate Change (IPCC), were used as initial and boundary values, and the Special Report on Emissions Scenarios (SRES) A1B and B1 were selected as the global warming scenarios. The Northwestern Pacific region, which includes Korea, was selected as the study area, and the Yellow Sea, which has a complex coastline, was expressed in detail by increasing the resolution. The average values of the results for the three experiments include a temperature/sea level increase of approximately 3 °C/35 cm from 2000 to 2100 in SRES A1B, and approximately 2 °C /27 cm in SRES B1. The East Sea experienced a larger change owing to the steric effect and showed a larger influence resulting from density changes as the temperature of the Tsushima Warm Current, which passes through the Korea Strait, increased. The result of the study that directly considered the steric effect predicted a higher sea level rise than that of indirect computation because the indirectly computed dynamic height was eliminated; sea level rise in a shallow area cannot be computed, and the unchanged volume serves as undersea pressure. Moreover, the Kuroshio Current, which is a major current in the Northwestern Pacific, showed a decrease in transport as global warming progressed. Despite the differences between models, a decrease of 4–5 SV in transport was observed for 2100; however, there was no notable change in the transport of the Tsushima Warm Current.

Keywords: Steric, Boussinesq approximation, MOM4 model, sea level rise, Kuroshio transport, Tsushima Warm Current transport

INTRODUCTION

Many numerical models are used to predict climatic changes such as global warming and sea level rise in the Northwestern Pacific region; the Modular Ocean Model Version 4 (MOM4), an oceanic general circulation model, is used to obtain regionally detailed predictions. Numerical models specific to oceanography are used to predict water temperature, salinity, change in current, and sea level rise. However, because most models use the Boussinesq approximation, sea level change cannot be considered in calculating the volume change of the entire ocean. The Boussinesq approximation ignores density changes by assuming that the change in density over time is very insignificant compared with average density. Therefore, sea level change, which is closely related to density change, can only be computed by examining prediction results of general oceanic models. MOM4 was used in this research because it incorporates a non-Boussinesq system to resolve this issue.

After creating the model, the initial and boundary fields of the Special Report on Emissions Scenarios (SRES) A1B and B1 from the global data of CM2.1, which was submitted to the Intergovernmental Panel on Climate Change (IPCC), were extracted, and the simulation was repeated. The data from CM2.1 have a resolution of 1° and are composed of 50 layers.

NUMERICAL MODEL DEVELOPMENT

Regional Ocean Circulation Model

To predict realistically the sea level changes due to global warming, the changes due to heat expansion must be simulated, and ocean volume change due to the movement of sea ice and melting of land ice must be considered. Therefore, the ocean model must be a non-Boussinesq fluid model that can consider density changes, and the sea surface should be considered as a free surface. The resolution of the model must be sufficiently high to enable predictions at a regional level, and parallel optimization is required for tens to hundreds of years of simulation.

Because previous oceanic circulation models assumed

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the sea surface as to be a rigid lid, wind stress, in addition to heat and salt transfer, were established on the basis of observation data or climatic information and atmospheric models. These models also permitted lengthy time gaps in the computation. Such conditions do not allow the computation of sea level changes, making it impossible to predict the sea level rise caused by global warming. Therefore, the development of an oceanic circulation model with a free surface is essential, and recent models attempt to address this problem.

In this study, we developed a regional oceanic circulation model for a detailed prediction of sea level change in the waters near the Northwestern Pacific by using MOM4. Because MOM4 is an oceanic global circulation model, we adapted it to a regional scale as the Regional Modular Ocean Model (ReMOM). The horizontal resolution of this model is set at 0.2° intervals to realistically express the shallow Yellow Sea and the width of the Korea Strait. This model consists of 34 perpendicular layers

Initial Value and Boundary Data

IPCC prediction results of CM2.1, HADCM3, and MIROC3.2H models were used as initial and boundary fields in the simulation. Only results that were highly reliable and well verified were selected.

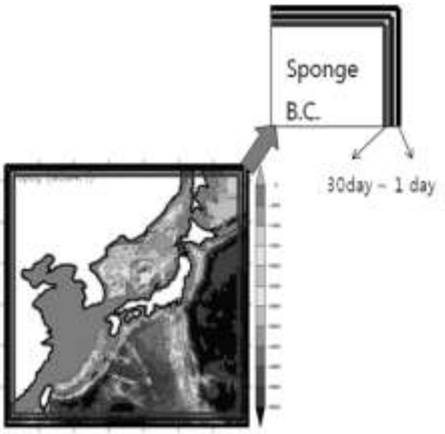

Figure 1. Sponge and lateral boundary conditions

Wind stress, sea surface temperature, and salinity are given as boundary values in the form of sponge boundary for data applied to the sea surface layer, while only temperature and salinity were given for the lateral boundary. To minimize the boundary effect of the sponge boundary, the damping time was expanded to 30 days for the interior and was gradually reduced toward the exterior such that 1 day was set in the outermost area (Figure 1).

Scenarios and Simulation Procedures

Although a total of 40 different SRES have been developed by the IPCC, the Geophysical Fluid Dynamics Laboratory (GFDL) provides results in six major SRES categorized into B1, A1T, B2, A1B, A2, and A1F1. These divisions are based on the levels of increasing greenhouse gas concentration, assuming that the CO_2 concentrations in Earth’s atmosphere will increase to 600, 700, 800, 850, 1250, and 1550 ppm in 2100.

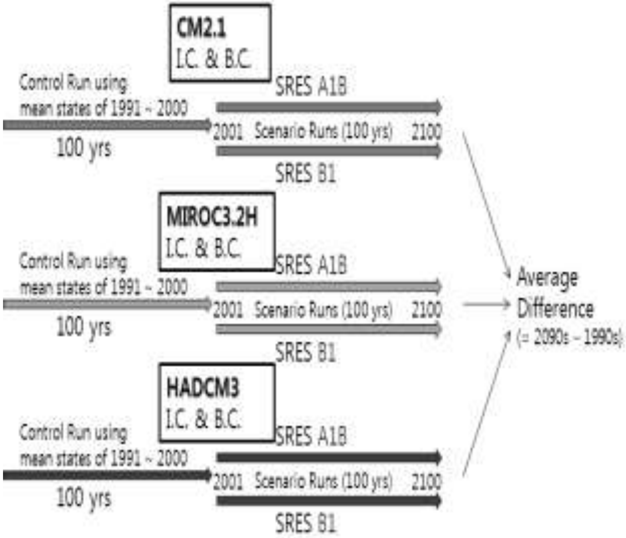

Figure 2. A diagrammatic representation of the simulation procedure in this study

Scenarios A1B and B1 were used in this study. Scenario A1 assumes an extremely rapid growth of the world economy, a global population that will peak in the middle of this century, and the rapid introduction of new and more efficient technology. Scenario A1 has three categories depending on the explained direction of technological change, which can be divided into A1T (non-fossil energy resource), A1B (balance between resources), and A1F1 (fossil intensive).

Scenario B1 has the same global population as A1 but is set to have a more rapidly changing economic structure toward a service- and information-based economy. Thus, B1 shows the lowest CO_2 concentration among the scenarios.

The present initial field of 2000 is required to predict sea level rise with future climatic scenarios. To create the initial field, a stabilizing simulation of 100 years was run with the 10-year average of 1991–2000 from CM2.1’s global result as the boundary value. Afterward, a 100-year simulation was run for each scenario by using their respective boundary values. The results for the final decade (2090–2100) and those for 2000 were then compared and analyzed (Figure2).

Results and Analysis

Comparison of the boundary value (CM2.1) and sea level rise in ReMOM (A1B)

For the 100-year time series data of CM2.1 and ReMOM (Figure 5), the temperature rose only ~2 °C. Conversely, significant differences were observed in sea level rise, with increases of 10 cm for CM2.1 and 30 cm for ReMOM.

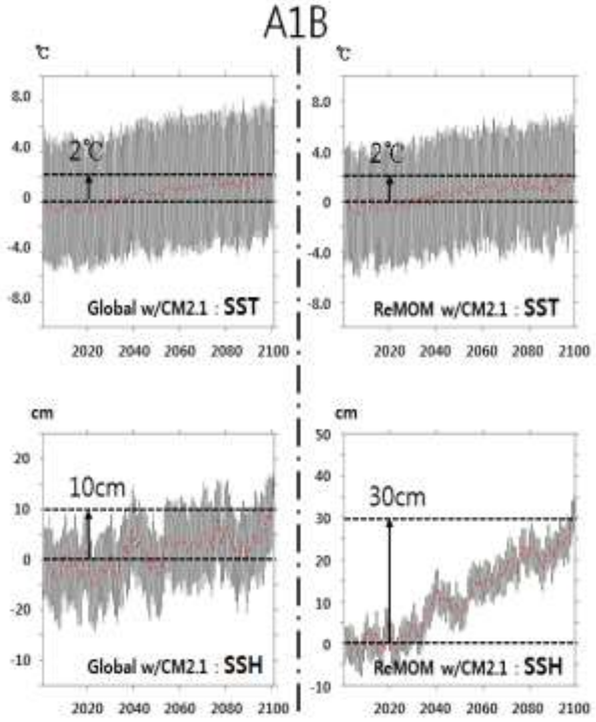

Figure 3. Time series analysis of sea level and temperature changes in the northwestern Pacific. A comparison of Climate Model 2.1 (CM2.1) results used as a boundary value model and the Special Report on Emissions Scenarios (SRES) A1B of the Regional Modular Ocean Model (ReMOM) is indicated.

These differences, more than twofold, are believed to have resulted from direct consideration of sea level changes due to density differences and the prediction of rising sea levels in narrow waters, which were enabled by the difference in resolution.

Generally, data for future sea level increases provided by the IPCC showed no global change in seawater volume and could only consider regional change because they used a Boussinesq model. Therefore, to overcome this issue, previous studies by the IPCC were recalculated, and analyzed changes in volume due to density changes were extracted from simulation results by considering the temperature changes. By using a non-Boussinesq model that eliminates such shortcomings, a more realistic simulation was possible by directly considering seawater volume changes caused by temperature fluctuations in the model and by enabling interaction with currents.

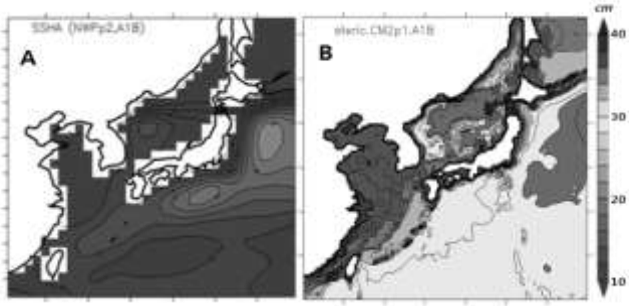

Figure 4. Comparison of sea level changes in the northwestern Pacific. A shows sea level changes in 2100 for Climate Model 2.1 (CM2.1), and B shows sea level changes in 2100 for the Regional Modular Ocean Model (ReMOM) with CM.2.1.

Figure 6 shows the sea level changes obtained by indirectly calculating the outcome of the CM2.1 global model provided by the IPCC from a dynamic height (A) and the result of ReMOM, which used a non-Boussinesq model(B); the sea level change is larger in ReMOM than in the indirect calculation.

3.2 Boundary Value Comparison of SRES A1B, B1

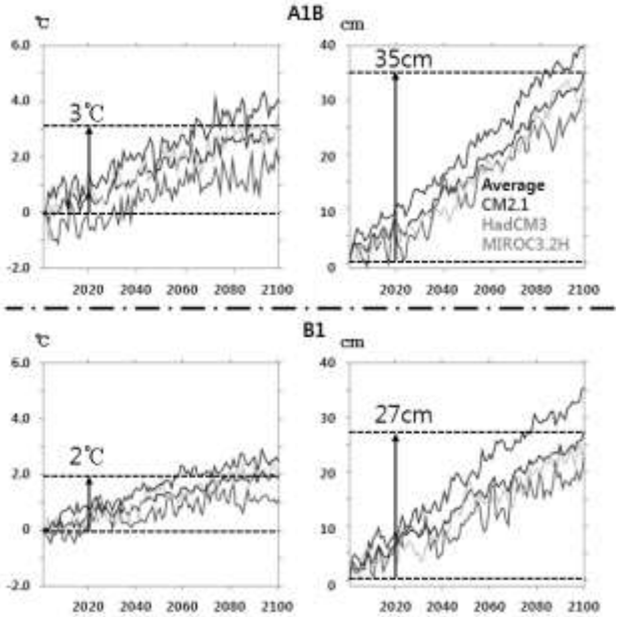

Figure 5. Time series data for the models and their average. Sea levels in A1B/B1 rose by approximately 30/18 cm for Climate Model 2.1 (CM2.1), 33/25 cm for Hadley Center Coupled Climate Model 3 (HADCM3), and 40/33 cm for the Model for Interdisciplinary Research on Climate 3.2H (MIROC3.2H).

The average value the three models indicates that sea surface temperature in the northwestern Pacific near the Korean waters rose by approximately 3 °C and 2 °C for A1B and B1, respectively. The sea level increase was approximately 35 cm and 27 cm for A1B and B1, respectively. The respective small and large differences occurred because the speed in which sea level changes due to temperature changes of a stratified ocean is slow. A longer period of time is required for a temperature increase to raise the sea level. Tsutsui et al. (2007) determined that sea levels will continue to rise after 2300, even after increases in greenhouse gases stop in 2100.

3.3 Steric

The steric effect, which is defined as volume change due to heat expansion, is limited in the shallow Yellow Sea but has a huge effect in the deep East Sea.

Image B in Figure 4 shows that most parts of the East Sea and the northwestern Pacific, which are deep, are significantly influenced by the steric effect. Steric hindrance represents density changes due to changes in volume, and the magnitude of these density changes depends on water temperature and salinity. Sufficient water depth is required to cause changes in steric hindrance. Because the East Sea and the Pacific Ocean are sufficiently deep, steric hindrance has a huge impact.

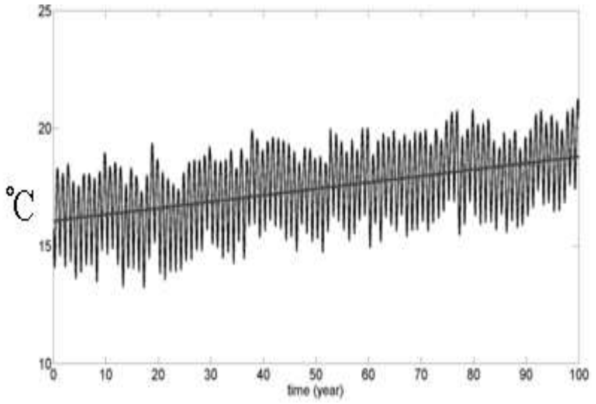

Figure 6. Temperature changes in the Tsushima Warm Current, which passes through the Korea Strait (SRES A1B).

Figure 9 shows time series data indicating temperature changes in the Tsushima Warm Current, which reveals that the temperature of the warm current entering along the Korea Strait increases. On the contrary, in the case of the Yellow Sea, the steric hindrance cannot be sufficiently applied because the water depth at the deepest point is approximately 80 m, and average depth is approximately 44 m.

3.4 Transport Change

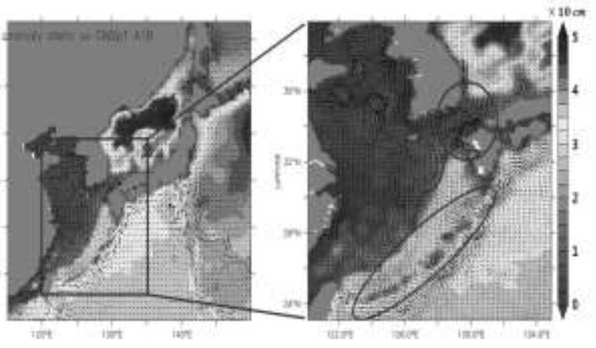

Figure 7. Transport changes due to sea level increases.

The right-hand image in Figure 7 is a magnified section within the left-hand image. The contour represents the range of sea level, and the arrows represent flow velocity changes. The flow velocity of the Kuroshio Current apparently decreases, while that of the Tsushima Warm Current, which passes through the Korea Strait, increases. The Tsushima Warm Current's transport increase is attributed to an influx from the Kuroshio Current through continental shelves.

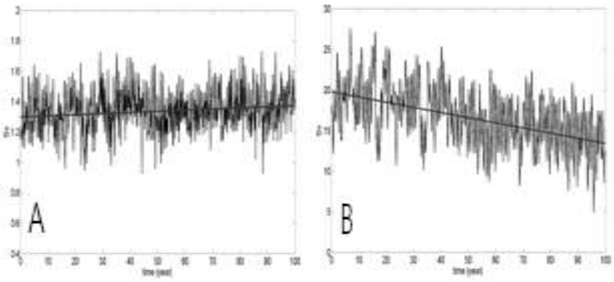

Figure 8. A shows the transport change in the Tsushima Warm Current, which passes the Korea Strait; B shows the change in the Kuroshio Current.

Figure 8 shows a time series of SRES A1B current transport change in CM2.1, in which the Kuroshio transport decreases by 4–5 Sv. Although the Tsushima Warm Current transport increases by 0.1–0.2 Sv, this value is much smaller than the decrease in the Kuroshio Current transport.

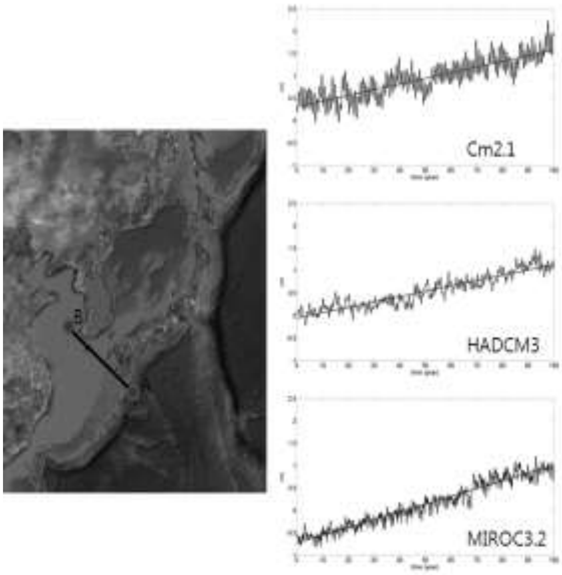

Figure 9. Differences in sea level change at Point A and Point B. The sea level increase rate of Point A is higher than that of Point B.

One reason for the change in transport that passes through continental shelves is sea level change (Toba et al., 1982; Ohshima, 1994; Tsujino et al., 2008). Because the magnitude of sea level change at Point A is larger than that at Point B, an increase in continental shelf penetration occurs. The time series data in Figure 9 show that the difference between sea levels at points A and B increased with the passage of time.

In selecting Points A and B in Figure 10, we chose two points that were perpendicular to the flow of the current that passes the Korea Strait because it is a geostrophic current. In addition, the distance that can influence the flow of the current was considered.

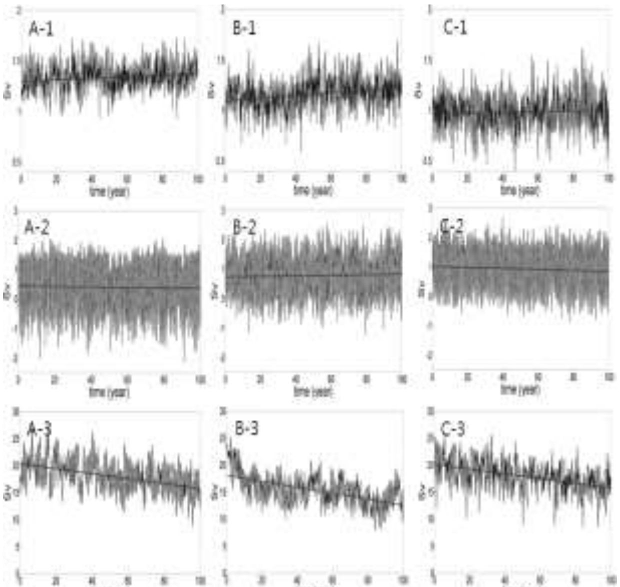

Figure 10. Major changes in current shown for each model. A represents Climate Model 2.1 (CM2.1); B, Hadley Center Coupled Climate Model 3 (HADCM3); and C, Model for Interdisciplinary Research on Climate 3.2H (MIROC3.2H). The number 1 represents the transport of the Tsushima Warm Current that passes through the Korea Strait; 2, the Taiwan Warm Current; and 3, the Kuroshio Current transports.

The transport changes in the three models show a similar tendency (Figure 10). The most pronounced result is the decrease of the Kuroshio Current transport. All models show a decrease of 4–5 Sv.

On the contrary, the Tsushima Warm Current transportincreased slightly by 0.1–0.4 Sv. The Taiwan Warm Current did not display a clear tendency. The HADCM3 model showed an increased, while other models showed a decrease.

However, the changes in the Tsushima Warm Current and the Taiwan Warm Current were minimal compared to the amount of decrease in the Kuroshio Current. Even after considering that the transport of the Kuroshio Current is larger than that of the other currents, the changes in the Tsushima Warm Current and the Taiwan Warm Current can be regarded as small.

Figure 11 Transport change tendency for each model.

	CM2.1	HADCM3	MIROC3.2H
Tsushima Warm Current	Increase	Increase	Increase
Taiwan Warm Current	Decrease	Increase	Decrease
Kuroshio Current	Decrease	Decrease	Decrease

Results and Summary

Sea level increases are occurring worldwide, and huge regional differences have been observed (Landerer et al., 2007; Yin et al., 2009). To examine this phenomenon, we developed a regional ocean circulation model known as ReMOM based on MOM4, an oceanic general circulation model, to conduct a detailed prediction of sea level change in the northwestern Pacific. Because ReMOM simulates sea level change by directly considering heat expansion, or the steric effect, a more realistic prediction was possible.

The initial and boundary fields used in the prediction simulation were obtained from CM2.1, and results from SRES A1B and B1 were chosen among the model's IPCC prediction results. The initial field was simulated for 100 years with the average result of the decade during 1991–2000 in the global result used as the boundary value. Simulations for 100 years were then conducted by using the boundary values of each scenario, and the difference between the results for the final decade (2090–2100) and those for 2000 were compared and analyzed.

In the case of the CM2.1 model, which was used as boundary value, the increase of sea level in 2100 was simulated at 12 cm. In the case of ReMOM, sea level rose by 28 cm. The two models showed the same temperature increase of 3 °C. This result is attributed to sea level changes due to density differences were directly considered, and the resolution difference enabled prediction of sea level rise in narrow waters.

The steric effect has a larger influence on the East Sea because the warm current flowing through the Korea Strait is increasing, and the current itself experienced a temperature increase because of global warming. Moreover, the steric effect is substantial in the East Sea and in the northwestern Pacific, which are deep.

The Kuroshio Current, which is a major current in the northwestern Pacific, showed a decrease in transport with the progression on global warming. Although differences were apparent among models, 4–5 V of transport was reduced in 2100. However, no significant changes were detected in the transport of the Tsushima Warm Current, which passes through the Korea Strait.

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