Response of North Pacific Ocean Circulation in a Kuroshio-Resolving Ocean Model to an Arctic Oscillation (AO)-Like Change in Northern Hemisphere Atmospheric Circulation Due to Greenhouse-Gas Forcing

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Abstract

Time-slice experiments are performed using a high-resolution North Pacific ocean general circulation model (NPOGCM) resolving the strong currents near Japan, such as the Kuroshio and the Oyashio, to investigate the effect of global warming on the North Pacific ocean circulation. The NPOGCM is forced by heat, momentum, and fresh-water fluxes obtained from a global warming projection using a global climate model (MRI-CGCM2.2).

The annual mean sea-level pressure trend exhibits an annular pattern similar to the positive phase of the Arctic Oscillation in a global warming projection by MRI-CGCM2.2 based on the Intergovernmental Panel on Climate Change (IPCC) SRES A2 emission scenario. Associated with this trend, the anticyclonic atmospheric circulation is intensified over the mid-latitude North-Pacific, leading to a northward shift of the oceanic subtropical wind-driven gyre boundary, where extensions of the Kuroshio exist in MRI-CGCM2.2.

Under these forcing changes, NPOGCM projects that in the future climate warm core eddies are more frequently pinched off from the Kuroshio off the eastern coast of Japan, leading to an annual mean SST rise over 5 K at its maximum, compared with the present climate. The projected annual mean sea-level rise ranges from 12 to 18 cm along the coasts of Japan, and about 40 cm over the ocean east of Japan.

1. Introduction

The Arctic Oscillation (AO) is a leading mode of atmospheric low-frequency variability in the extratropical Northern Hemisphere, characterized by annular modes involving seesaws in air mass between the Arctic region and surrounding zonal rings in mid-latitudes (Thompson and Wallace 1998). It is closely related to the North Atlantic Oscillation (NAO; van Loon and Rogers 1978; Hurrell 1995), characterized by north-south dipole in surface pressure over the North Atlantic Ocean. The positive index of the AO/NAO corresponds to the low-pressure anomaly in high-latitudes, the high-pressure anomaly in mid-latitudes, and the strong westerly winds between them. By changing wind system and thus hemispheric-scale surface atmospheric conditions with low-frequencies, the AO/NAO has a large effect on long-term climatic and oceanic variabilities in the whole extratropical Northern Hemisphere (e.g., Timmermann et al. 1998; Overland et al. 1999; Yasunaka and Hanawa 2002).

Some recent studies suggested that the AO/NAO might also have effects on climatic and oceanic conditions around Japan, especially in the northern part of Japan. Xie et al. (1999) showed that quasi-decadal time scale tempera-
ture anomalies over Siberia associated with the NAO affect surface air temperature over northern Japan. They further showed that the Aleutian low and the Sea Surface Temperature (SST) around the subarctic front in the North Pacific vary synchronously with the quasi-decadal NAO in recent decades. Minobe et al. (2004) and Minobe and Nakamura (2004) showed that the quasi-decadal variabilities of subsurface temperature in the marginal seas around northern Japan (the Japan Sea and the Okhotsk Sea, respectively) are likely to be caused by the quasi-decadal AO/NAO via the east Asian winter monsoon, which is closely associated with the northern part of the Siberian high (and thus with the AO/NAO).

Although the oceanic conditions along the Pacific coast of Japan, characterized by strong western boundary currents such as the Kurishio and the Oyashio, are important in forming the present climate conditions of Japan, there is little information about the effect of the AO on them in contrast to that of El Niño Southern Oscillation (ENSO) (e.g., Ishi and Hanawa 2005). This is mainly because the effect of ENSO on the sea level pressure (SLP) field of the mid-latitude North Pacific Ocean is too strong to extract a pure effect of the AO from anomalies in SLP and ocean circulations of the mid-latitude North Pacific in the present climate.

Most climate change projection experiments for global warming using a Coupled Atmosphere-Ocean General Circulation Model (CGCM) show that the spatial anomaly response patterns to the greenhouse-gas forcing resemble anomaly patterns of the natural variability, such as the AO and ENSO (e.g., Yamaguchi and Noda 2006). Indeed, it is reported that the trend of the positive phase of the AO has been predominant for over 30 years (Thompson and Wallace 1998, 2000; Limpasuvan and Hartman 1999). Shindel et al. (1999, 2002) discussed relations between global warming and the frequent appearance of the positive phase of the AO. They claimed further that the AO signal was captured only in climate models that include a realistic stratosphere. It is reported that El Niño-like pattern will prevail in a future warmer climate (IPCC 2001). As shown in Fig. 1 and discussed later in Section 3.1, our MRI-CGCM version 2.2 (hereafter referred to as MRI-CGCM2.2) exhibits a stronger positive AO-like signal than the ENSO-like one in the SLP field. Thus it may be possible that the positive AO-like signal dominates over the ENSO-like signal in the extratropical North Pacific in a global warming climate.

An interesting question is, therefore, how the positive AO-like response to the greenhouse-gas forcing influences the oceanic conditions around Japan. As is well known, the oceanic currents around Japan are driven by wind-stress fields over the mid-latitude North Pacific Ocean. The wind-stress field is characterized by the mid-latitude westerly, whose strength and position are strongly influenced by the Aleutian low. Since the SLP has a positive anomaly over the mid-latitude North Pacific in the positive phase of the AO, the Aleutian low is expected to become weak, and the mid-latitude westerly is expected to be shifted northward in a warmer climate with a positive AO-like trend. This is opposite to the response to ENSO that is expected to induce a negative SLP anomaly in the mid-latitude eastern North Pacific. Whether the mid-latitude SLP response results in a positive or a negative anomaly is different among CGCMs (Yamaguchi and Noda 2006). Given the uncertainties of future climate projections by CGCMs, it is meaningful to investigate detailed effects of the positive AO-like trend on the oceanic conditions around Japan by using a specific CGCM showing a typical AO-like response in the mid-latitude North Pacific.

The purpose of this study is thus to analyze the positive AO-like signal found in a global warming projection, and to investigate how the positive AO-like signal affects the oceanic conditions around Japan in a warmer climate. In order to realistically simulate strong currents such as the Kuroshio, the Oyashio, and the Tsushima warm current, which are important in forming the climate conditions of Japan, we use a high-resolution North-Pacific Ocean general circulation model (hereafter referred to as NPOGCM). The NPOGCM is forced by a surface atmospheric condition obtained by the MRI-CGCM2.2. It is noted that these currents have not been properly simulated by conventional CGCMs so far because of insufficient resolutions. Because the NPOGCM requires too much computational resource for a continuous
integration from the present to a global warming climate, a time-slice experiment is performed as described in the next section.

This paper is organized as follows. Section 2 describes the models and the experimental design. Results of the CGCM and NPOGCM experiments are presented in section 3, and section 4 presents discussion and concluding remarks.

2. Model description and experimental design

The MRI-CGCM2.2 (an updated version of the MRI-CGCM2, Yukimoto et al. 2001) is used for a global warming projection due to a greenhouse-gas forcing based on the Intergovernmental Panel on Climate Change (IPCC) SRES A2 emission scenario (IPCC 2000). The atmospheric component is a spectral general circulation model, with a triangular truncation at horizontal wave number 42 (approximately 280 km grid-spacing), and with 30 vertical levels. The oceanic component is a grid model with a horizontal resolution of 2.5° longitude by 2° latitude north/south from 12°N/S, and with 23 vertical levels. It has varying latitude increments between 12°N and 12°S, with 0.5° increment at the Equator. Effective climate sensitivity of the atmospheric component of this model is estimated to be about 2.5 K under the doubling CO2 equilibrium (corresponding to the radiative forcing of 3.7 W/m²) experiment, with a global atmospheric model coupled to a mixed layer ocean model (isothermal 50 m depth slab) (Yukimoto and Noda 2002). First, we performed a historical simulation from 1850 to 2000 followed by a future (warmer) climate projection into 2100 based on the SRES A2 scenario.

Next, using this historical and future projection simulation as an external forcing, two time-slice experiments are performed for the 30 years from 1981 to 2010 for the present climate, and for the 40 years from 2041 to 2080 for a future (warmer) climate, using the NPOGCM (see the conceptual view in Fig. 2).
The present climate run is started from an oceanic state obtained by integrating the model for twenty years from a state of rest, with climatological temperature and salinity of the World Ocean Atlas 1994 (Levitus and Boyer 1994; Levitus et al. 1994; hereafter WOA94), using a climatological forcing (an average from 1981 to 2010) from the CGCM. The future climate run is started from a final state of the present climate simulation (the end of 2010). The last 20-year data of each run is analyzed (conceptual view in Fig. 2).

Physical factors to drive the NPOGCM are wind stress (momentum flux), heat flux, fresh water flux (precipitation and evaporation), and longwave radiation and shortwave radiation, which were supplied monthly from the CGCM. This ocean model has a domain from 15°S to 65°N, and 100°E to 75°W in the Pacific Ocean, with a horizontal resolution of 1/4° (longitude) by 1/6° (latitude) and 48 vertical levels, falling under the category of eddy-permitting ocean models. Its vertical increment varies from 3 m near the surface to 250 m below 2000 m depth. The open boundaries of the domain are replaced by vertical walls, i.e., there is no inflow/outflow at the boundary, and the non-slip boundary condition is specified at all boundaries. At the southern boundary, temperature and salinity are nudged to the monthly climatology from the WOA94 to give basic density stratification for the whole domain. The current domain setting is adopted because the upper layer oceanic circulation in the North Pacific is almost closed within the North Pacific in terms of heat as well as mass (McCreary and Lu 1994; Talley 2003). It could be safely assumed that the deep stratification in the South Pacific Ocean will not be changed by the global warming significantly enough to affect the remote upper layer circulation in the North Pacific within 100 years from now, on the basis of the results from MRI-CGCM2.2.

In the following, the physical processes of the model are briefly introduced. Readers should refer to the document of the Meteorological Research Institute, Community Ocean Model (MRI.COM) (Ishikawa et al. 2005) for more detail. The bulk formula to calculate surface fluxes is based on that of Large and Pond (1982). Although sea-surface salinity changes according to evaporation and precipitation, a nudging to the climate values of WOA94 is applied to prevent model drift. The ocean mixed layer is described by the turbulent closure model (level 2.5) of Mellor and Yamada (1974). A special finite-difference scheme is devised for momentum advection on bottom relief in the ocean model (Ishizaki and Motoi 1999). Horizontal friction and diffusion to free ocean water are expressed in bi-harmonic formula with constant values of $1.0 \times 10^{18}$ cm$^4$ s$^{-1}$ and $1.0 \times 10^{17}$ cm$^4$ s$^{-1}$, respectively. Bottom friction is calculated with the formula proposed by Weatherly (1972). Sea ice is formulated based on thermodynamics by Mellor and Kantha (1989) and elastic-viscous-plastic dynamics by Hunke and Dukowicz (1997, 2002). Basic performances of the high-resolution North-Pacific OGCM can be seen in Ishizaki and Motoi (1999) and Tsujino and Yasuda (2004).

3. Results

3.1 Responses to the global warming in CGCM experiments

The MRI-CGCM2.2 shows an increase of the globally averaged surface air temperature by about 0.9°C from 1850 to the present, and an
increase by about 1.9°C from the present to 2080, on the basis of the SRES A2 scenario (Fig. 2). This is well within the range spanned by the projections performed by many institutions based on this scenario (see Fig. 9.6a of IPCC 2001).

As is shown in Fig. 1a, a strengthening of the positive phase of the first EOF mode of the annual mean Northern Hemisphere SLP (twenty-year low-pass filtered) starts around 1990. And consequently we can observe in Fig. 1b a 110-year trend (from 1990 to 2100) with a spatial pattern similar to that of the positive phase of the AO, that is, an annular pattern with a decreasing SLP trend in the Arctic region and an increasing SLP trend in the mid-latitudes.

To investigate the dominant mode of the atmospheric circulation that drives the ocean currents of the mid-latitude North Pacific, an EOF analysis was conducted for SLP covering the North Pacific (from 60°E to 60°W, and from 30°S to 75°N). Here the tropical region is included to compare influences of the AO and the ENSO signal on the mid-latitude atmosphere. Figure 3 illustrates a spatial pattern and a time-varying amplitude of the first two EOF modes of the annual mean SLP of the global warming projection using the CGCM (from 2000 to 2100). The first and second EOF mode explains 28.4% and 15.8% of the total variance, respectively. The first EOF represents the AO with the low-pressure in high-latitudes, and the high pressure in mid-latitudes. There are only weak signals in the equatorial region. Time varying amplitude includes energetic short timescale variability, but there is a positive trend in it. This indicates that the positive phase of the AO is strengthening. The second EOF represents the El Niño-like pattern, with the low-pressure in the eastern equatorial Pacific, the high-pressure in the mid-latitude western Pacific, and the low-pressure in the mid- to high-latitude eastern Pacific, which is similar to the so-called Pacific-North American (PNA) pattern. There is also a positive trend in the time varying amplitude, indicating that the climate becomes El Niño-like in the global warming.

Responses of the mid-latitude SLP to these two kinds of trend are generally opposite. High-pressure anomalies occur for the positive AO-like trend, and low-pressure anomalies occur for the El Niño-like trend. In the current projection, the positive AO-like trend dominates over the El Niño-like trend, yielding an intensified anti-cyclonic atmospheric circulation over the mid-latitude North Pacific with an evolution of the global warming (Fig. 1). This results in the strengthening and the
The response of the North Pacific ocean circulation to this change is presented in the next subsection.

The global mean sea-level rise of the CGCM due to thermal expansion of sea water is 10 cm during the 70 years from 2000 to 2070. See the Appendix for details of the calculation methods. Church et al. (1991) obtained a similar result. They projected a 10 cm sea-level rise that is caused by thermal expansion for a global mean 1.5°C SST rise in the 60 years from 1990 to 2050. More recent results from CGCM experiments are summarized in IPCC (2001). It should be noted, however, that these estimates do not include effects of melting of continental and/or mountain glaciers.

3.2 North Pacific ocean circulation in time-slice experiments

First we look at results of the present climate simulation (long-term mean oceanic state) around Japan, focusing on the representation of the Kuroshio. Figure 4 compares the Sverdrup stream functions, calculated using the wind stress field by the present climate CGCM simulation, and by the NCEP/DOE re-analysis (Kanamitsu et al. 2002). The Sverdrup stream function is the expected linear dynamic response of ocean circulation to the wind stress forcing. The CGCM (Fig. 4a) reproduces basic climatological features of the wind stress field of the re-analysis (Fig. 4b). The maximum transport of the subtropical gyre is a little more than 40 Sv for both of them. But the extension of the Kuroshio of the CGCM Sverdrup stream function is broad and shifted somewhat northward, compared with the re-analysis Sverdrup stream function. This is due to the northward shift of the mid-latitude westerly in the CGCM.

Figure 5 compares computed and observed sea-surface height (SSH; left) and SST (right). The NPOGCM successfully simulates the path of the Kuroshio, with the straight and the meandering path south of Japan and the separation off the eastern coast of Japan (Fig. 5b). It also simulates sharp fronts that compose extensions of the Kuroshio and the Oyashio in the offshore region east of Japan. The correspondence of the NPOGCM SSH with the observed one (Fig. 5c) is clearly superior to that of the CGCM SSH (Fig. 5a). The NPOGCM SST (Fig. 5e) presents sharp fronts, indicating the presence of strong currents. They are not represented in the CGCM (Fig. 5d). Contours of 25°C are located at 26° to 27°N for both models and observation. Contours of 10°C are located southeast of Hokkaido Island for both NPOGCM and observation, while they are shifted a little northward in the CGCM because of the weaker Oyashio. Overall, the computed SST distribution of the NPOGCM corresponds very well to the observation in the Pacific Ocean. Strictly speaking, the Kuroshio Extension is simulated to be at a little northern latitude as compared with observation. This is partly caused by the wind stress forcing from the CGCM that tends to induce a northward located Kuroshio Extension as a linear response (Fig. 4a). This might also be due to a still insufficient resolution of the OGCM to reproduce meso-scale oceanic processes, such as eddies and boundary currents.

Figure 6 presents the differences of atmospheric forcing between the present climate run and the global warming run for the mid-latitude North Pacific. Here differences of thirty-year North data (from 1981 to 2010 for the present climate, and from 2051 to 2080 for the global warming climate) are presented.
The difference in SLP at mid-latitudes (Fig. 6a) is characterized by a high pressure in the eastern Pacific. This reflects the strengthening of the positive phase of the AO in the global warming climate. The difference in the Sverdrup stream functions (Fig. 6b) shows the northward shift and strengthening of the clockwise subtropical gyre in the offshore region east of Japan. The difference in the surface air temperature (Fig. 6c) is positive over the Pacific, and a strong warming signal is found east of Hokkaido centered at (42°N, 150°E). This strong warming signal east of Hokkaido is also related to the weakening of the Aleutian low associated with the positive AO-like change, as shown by Yamaguchi and Noda (2006). It is also influenced by a positive temperature anomaly over Siberia, which is advected by the mean westerlies to northern Japan.

Figure 7 depicts results of the global warming projection by the NPOGCM. In the future (warmer) climate, the Kuroshio tends to take meandering paths south of Japan. Warm core eddies that are pinched off from the Kuroshio tend to appear more frequently off the eastern coast of Japan, leading to the SST rise over 5°C at its maximum there. The projected sea-level rise for the 70 years from 2000 to 2070 is estimated to be 12–18 cm at the grid points around Japan and 40 cm or more around the center of warm-core eddies off the eastern coast of Japan. The rise was calculated using a linear combination of the global-mean thermal expansion calculated from the CGCM result (10 cm,
as mentioned before), and the SSH difference between time slices (2061–2080 minus 1991–2010) from the NPOGCM result (see appendix for details). The intense SST and sea-level rises east of Japan suggest the northward extension of the subtropical gyre. The northward shift of the boundary between the wind-driven oceanic subtropical and subpolar gyres, where extensions of the Kuroshio exist, is just what is expected from the change in the atmospheric fields shown in Fig. 6. There is a clear correspondence between the Sverdrup stream function difference in Fig. 6b and the SSH difference in Fig. 7b.

The intense SST rise east of Japan seems to be also forced by the surface air temperature rise over this region as shown in Fig. 6c. Though the precise quantification is difficult at this stage, 2°C out of 5°C rise in SST might be explained by the direct forcing from the air mass above, since the warming by at least 2°C is found in Siberia and seems to be advected by the mean westerly to northern Japan (Fig. 6).

Comparison of the projections between the NPOGCM (Fig. 7) and the CGCM (Fig. 8) reveals that qualitative features of them are similar. The SST changes of both runs basically correspond to that of the surface atmospheric temperature change in Fig. 6 except for the region off the eastern coast of Japan (40°N, 143°E) in the NPOGCM, where a significant SST rise is found. But the features of SSH changes are generally enhanced in the NPOGCM with a significant sea-level rise in the region off the eastern coast of Japan. The large SSH change between global warming and the present climate in the offshore region east of Japan of the NPOGCM is attributed to the successful reproduction of the offshore sharp fronts in the NPOGCM. Since the gradients of SSH across the fronts are large, subtle shifts in position and changes in strength of the fronts result in large differences in SSH. The large difference in SSH change between the NPOGCM (Fig. 7b) and the CGCM (Fig. 8b) off the eastern coast of Japan around (40°N, 143°E) is caused by the successful representation of the separation of the Kuroshio in the present climate NPOGCM. Since the Kuroshio of the CGCM overshoots both in the present climate and in the global warming climate, the differences in both SSH and SST are not significant off the eastern coast of Japan in the CGCM. Since the Kuroshio of the NPOGCM separates from the eastern coast of Japan in the present climate, the frequent appearance of warm core eddies in the global warming climate results in the significant rise in both SSH and SST off the eastern coast of Japan in the NPOGCM.

Figure 9 (right) illustrates temporal variations of upper-layer water temperature change averaged at each depth over the northwestern Pacific (20° to 50°N and 120°E to 180°) from 2041 to 2080. The figure on the left indicates the vertical profile of temperature in the initial stage of the second time-slice run for the future (warmer) climate of the model. It can be seen that major changes are confined to the upper 300 m. This is because the mixed layer reaches this level in late winter every year. We can also see that this variation in water tempera-
Fig. 7. Results of the global warming projection by the NPOGCM. (a) Averaged sea-level (in cm) in the warming period (from 2061 to 2080) and (b) its difference from the present climate. (c) Averaged SST (in °C) in the warming period (from 2061 to 2080) and (d) its difference from the present climate. Areas with sea-level rise greater than 15 cm are shaded in (b) and areas with SST rise greater than 2°C are shaded in (d). The CI is 10 cm for (a), 2.5 cm for (b), and 1°C for (c, d).

Fig. 8. Results of the global warming projection by the CGCM. (a) Averaged sea-level (in cm) in the warming period (from 2061 to 2080) and (b) its difference from the present climate. (c) Averaged SST (in °C) in the warming period (from 2061 to 2080) and (d) its difference from the present climate. Areas with SST rise greater than 2°C are shaded in (d). The CI is 10 cm for (a), 1 cm for (b), and 1°C for (c, d).
ture came from a warming-trend like variation superimposed on a decadal variation signal. This horizontally averaged temperature rise in the surface mixed layer is a little less than 1°C.

4. Discussion and concluding remarks

Global-warming-induced changes in ocean circulation around Japan are projected by integrating a high-resolution North-Pacific OGCM driven by momentum, heat, and water flux data from a global warming projection using the MRI-CGCM2.2, based on the IPCC SRES A2 scenario. We have found a trend in the future climate projection that both a cyclonic circulation over the Arctic region and an anticyclonic circulation in the mid-latitude North Pacific and North Atlantic regions are intensified. The resultant anomaly field is similar to that at the positive phase of the AO, inducing a northward shift of the peak of the basic westerly jet in the lower troposphere.

In accordance to these changes in circulation, the clockwise Sverdrup mass transport intensifies in mid-latitudes but reduces in high-latitudes and in the region south of Japan. Therefore the boundary between subtropical and sub-polar oceanic gyres shifts northward in a warmer climate. Specifically, the Kuroshio tends to flow further northward, and the Oyashio becomes weaker. Accordingly, warm-core oceanic eddies pinched off from the Kuroshio move northward off the east coast of Tohoku and Hokkaido region in the northern part of Japan, leading to an SST rise over 5°C at its maximum, and the Kuroshio meanders along the southern coast of Japan more frequently than in the present climate. It should be noted that some portion of the 5°C rise of SST off the eastern coast of Japan is due to the direct forcing from the overlying warm atmosphere, which is also related to the positive AO-like trend (Yamaguchi and Noda 2006).

Though both the frequent occurrences of the warm core eddy off the eastern coast of Japan and the meandering tendency of the Kuroshio along the southern coast of Japan are nonlinear processes, they might be to some extent related to a linear response of the SSH to the change in wind stress fields over the mid-latitude North Pacific. By linear response, we mean that signals of wind-stress curl change in the North Pacific basin are carried westward by lower vertical mode Rossy waves to the Pacific side of Japan along the latitudinal lines (Kawabe 2000, 2001; Yasuda and Sakurai 2006). If the SSH responds linearly to the change in wind stress field (Fig. 6b), SSH off the eastern coast of Japan becomes high. Indeed, major sea level rise is found for a latitude band between 35° and 50°N from the eastern...
offshore to the eastern coast of Japan (Fig. 7b). This high SSH environment allows the existence of warm core eddies with high SSH off the eastern coast of Japan. Similarly, we speculate that, since the relatively minor rise of SSH is expected along the southern coast of Japan as a linear response to changes in wind stress curl field (Fig. 6b), this relatively low SSH environment might allow the existence of the stable large meander path of the Kuroshio along the southern coast of Japan that brings about a cold core eddy with low SSH to the southern coast of Japan. Indeed, a minor sea level rise less than 15 cm is found for a latitude range between 25° and 35°N from the eastern offshore to the southern coast of Japan, especially along 30–32°N (Fig. 7b). Note, however, that this qualitative correspondence between the low SSH caused by the meander of the Kuroshio and the low SSH caused by the linear response to wind stress forcing found in the current experiment, is apparently inconsistent with the study by Kurogi and Akitomo (2003). Though more thorough sensitivity studies are needed to resolve these issues, they are left for future studies.

This kind of long-term response of extensions of the Kuroshio to long-term changes in the wind stress field has been discussed in relation to Pacific Decadal Variability (Seager et al. 2001; Schneider et al. 2002). A signal of a shift of the gyre boundary is carried by baroclinic Rossby waves to the western North Pacific, resulting in a change in position and strength of the extensions of the Kuroshio, and a change in SST there some years later. It should be noted here that a group of Center for Climate System Research, University of Tokyo (CCSR), National Institute for Environmental Studies (NIES), and Frontier Research Center for Global Change (FRCGC) projected the oceanic circulation change using a global high-resolution coupled model in somewhat different way (Sakamoto et al. 2005). In their projection the Kuroshio and its extensions do not extend northward but intensify with their positions almost unchanged. This difference in the behavior of the Kuroshio and its extensions might be attributed to a difference in atmospheric circulation. They argue that the response of the atmospheric circulation in the mid-latitude North Pacific is more strongly affected by the El Niño-like trend, which is contrary to the current simulation. Detailed comparisons of results from different models will be necessary to further understand the response of the atmosphere-ocean system to global warming.

The projected sea-level rise for the 70 years from 2000 to 2070 in the NPOGCM ranges from 12 to 18 cm along the coasts of Japan, and about 40 cm off the eastern coast of Japan associated with the northward shift of the gyre boundary and frequent appearance of warm core eddies (Fig. 7b). The sea-level rise around Japan in the CGCM is 11–12 cm (Fig. 8b), lower than that of the NPOGCM. But both are higher than the global mean sea-level rise of 10 cm. According to Liu et al. (1999), the average SSH around an island can be derived as the mean SSH of the baroclinic Rossby long waves coming to the eastern coast of the island. Generally these long Rossby waves are excited by wind forcing over the eastern basin, but local features such as eddies and warm water advection near the coasts may modify SSH along the coast. In the current projection, increase of the mean SSH along the eastern coast of Japan can be almost explained if the linear response to wind forcing is taken into account. The mean Sverdrup transport anomaly along the eastern coast of Japan is positive, that is, an anti-cyclonic circulation with a positive anomaly of SSH is induced in the global warming climate as shown in Fig. 6b. This explains the above-average sea-level rise around the coasts of Japan in the CGCM. In the NPOGCM, frequent appearance of warm-core eddies off the eastern coast of Japan may result in a larger sea-level rise around Japan. An advection of warmer water by the Kuroshio in the global warming climate may also result in a sea-level rise. Effects of local warming by the overlying atmosphere to sea-level rise around Japan seem to be minor because the large rise of the surface air temperature in the CGCM is confined in the region east of Hokkaido (Fig. 6c). Since this study is not a process-oriented study, we cannot at this stage distinguish these effects. But from the above discussions we may say that a global warming projection should be performed with high-resolution models to assess detailed changes of oceanic states around Japan in the global warming climate. Though somewhat higher resolution would be needed.
to simulate the Kuroshio and its extensions more precisely, we believe that qualitative features of the response of the oceanic circulation in this simulation will not be changed in higher resolution models.

It should also be noted that NPOGCM exhibits some bias in SST in the Japan Sea, with the computed SST being a few degrees higher than the observed, although the NPOGCM reasonably simulates the annual mean mass transport of the Tsushima warm current. Actually, it is estimated to be 2.64 Sv by Takikawa et al. (2005) using observations, while the NPOGCM yielded 2.79 Sv for the present climate (1991 to 2010) and 3.16 Sv for the future (warmer) climate (2061 to 2080). Since the geostrophic balance holds between the current speed along the Tsushima Strait and the pressure gradient across the Strait as revealed by Takikawa and Yoon (2005), a higher sea-level rise around Japan than that of global average mentioned earlier results in this increase of the Tsushima current transport in the future climate. At the present stage, we have found a similar SST bias in the Japan Sea in a fully coupled atmosphere-ocean regional climate model (Murazaki et al. 2005; Sasaki et al. 2006).

Finally, we mention the effect of the global warming on “Yamase”, which is a cold wind that blows over Hokkaido and Tohoku regions in the northern part of Japan in early summer, and often damages agriculture in the Tohoku district. Because of an atmospheric circulation change due to global warming in the Northern Hemisphere, a large increase in SST by several degrees is projected in the future climate over the ocean east of Hokkaido and Tohoku. This SST rise might weaken “Yamase”, because the cold air might be warmed. However, we need to investigate the variations and trends of the Okhotsk Sea anti-cyclone from which Yamase originates. This issue remains to be studied in the future.

The ultimate goal of our project study is to predict regional climate change over Japan and North-east Asia, which have complex distributions of land, sea and surrounding ocean-current. The present study is the first step to fulfill the goal. As the next step, we have developed a regionally full-coupled high-resolution (about 20 km horizontal grid spacing) atmosphere-NPOGCM. Results from a time-slice experiment with the regional coupled model will be presented in other papers (Murazaki et al. 2005; Sasaki et al. 2006).

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Appendix

Diagnosis of sea-level changes including thermal expansion

In this appendix, the method of estimating absolute sea level change that includes the effect of thermal expansion is briefly described. Basic idea is the same as that of Church et al. (1991). Here the vertical integration is performed from the sea surface to the bottom, not assuming “a depth of no motion” as in Church et al. (1991).

Since the commonly employed Boussinesq approximations are also used in the current OGCM, the total volume rather than the total mass of the sea water is conserved during model integrations. This means that we should diagnostically calculate the steric sea level change (the sea level change due to thermal expansion) to study global sea level change due to net heating of the ocean.

The global mean increase in the steric sea level $\Delta h$ is calculated by the following area averaging:

$$\Delta h = \frac{1}{A} \int_{\text{sea}} \int a^2 (h_{gw}(\theta, \psi) - h_{pre}(\theta, \psi)) \cos \theta d\theta d\psi,$$

$$A = \int_{\text{sea}} a^2 \cos \theta d\theta d\psi,$$
where $A$ is the total area of the ocean, $a = 6370$ km is the Earth’s radius, $\theta$ is latitude, $\psi$ is longitude, and $h_{gw}$ and $h_{pre}$ are local steric sea levels in the global warming climate and the present climate, respectively. The local steric sea levels are obtained by vertically integrating specific volume anomaly ($\delta$) from the bottom to the surface:

$$h(\theta, \psi) = \rho_0 \int_{-H(\theta, \psi)}^{0} \delta(\theta, \psi, z) \, dz,$$

where $\rho_0 = 1000$ kg/m$^3$ is a constant reference density of sea water, $H(\theta, \psi)$ is the local sea depth. Specific volume anomaly ($\delta$) is defined by

$$\delta(\theta, \psi, z) = \rho^{-1}(S(\theta, \psi, z), T(\theta, \psi, z), p(\theta, \psi, z)) - \rho^{-1}(35.0, 0.0, p(\theta, \psi, z)),$$

where $\rho$ is the density of sea water as a function of salinity ($S$), temperature ($T$) and pressure ($p$).

In estimating the non-Boussinesq sea level in the global warming, we assume that the local sea level elevation induced purely by density change is rapidly distributed over the globe with a speed of the barotropic gravity waves. Thus, using a spatially uniform global mean steric sea level increase ($\Delta h$) and the local sea level ($\eta_{ogcm}(\theta, \psi)$) from OGCM that uses the Boussinesq approximation, the non-Boussinesq sea level in the global warming ($\eta_{gw}(\theta, \psi)$) is obtained as

$$\eta_{gw}(\theta, \psi) = \eta_{ogcm}(\theta, \psi) + \Delta h.$$

This sea level estimation, the Boussinesq dynamics corrected by a spatially uniform, time-dependent factor calculated from volume-averaged density change, almost reproduces the sea level variations obtained using an OGCM where the Boussinesq approximations are relaxed (Mellor and Ezer 1995).

The global warming projection of this study with CGCM yields global mean sea level rise of $\Delta h = 10$ cm from 2000 to 2070. This is added to the local time-mean sea level of the future time-slice of the NPOGCM to represent the future sea level change relative to the present state.

References


Yamaguchi, K. and A. Noda, 2006: Global warming