Summer Precipitation Changes in Northeast Asia from the AOGCM Global Warming Experiments

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(Manuscript received 31 May 2005, in final form 9 April 2008)

Abstract

In order to evaluate the model performance in simulating the Northeast Asian summer climate, and to investigate the effect of global warming on the summer climate over the Northeast Asian region, the multi-model ensemble of eight atmosphere-ocean coupled general circulation models in the historical (20C3M) and the scenarios (A2, A1B, B1) runs are analyzed, which is participating to the Intergovernmental Panel on Climate Change fourth Assessment Report (IPCC AR4). From comparison of the observation and the 20C3M experiment, it is found that the multi-model ensemble quite well simulates the Northeast Asian summer precipitation and circulation, especially in the first two empirical orthogonal function (EOF) modes and the associated regressed field. The first EOF mode represents the decaying phase of El Nino and Southern Oscillation (ENSO), which contributes to the development of the Philippines Sea anticyclone. The second one is associated with the fast transition of ENSO.

In future climate, the increase of the precipitation to 2099 at A2, and A1B simulation reaches 10% compared with the mean precipitation for 1961–1990 over the Northeast Asian region. After the stabilization of the greenhouse gas concentration in 2100, the precipitation is enhanced during 30 or 50 years more due to the inertia inherent in the climate system. From EOF analysis, it seems that the increased Northeast Asian summer precipitation due to global warming is contributed by the effect of the enhanced monsoon circulation in the decaying phase of El Nino rather than the mean linear increase of global climate or the circulation in the fast transitional period of ENSO.

1. Introduction

Numerous of impact assessments in global warming have been attempted so far. Min et al. (2004) tested the model performances and the sensitivity of projection results from all model ensemble (MME7) including four skillful model
ensemble (MME4) using SRES A2 and B2 scenario simulations with aerosol forcing. They found that MME4 displayed higher performance than MME7. The overall projection results from multi-model ensemble also showed that East Asia would experience warmer and wetter climate in the 21st century and both temperature and precipitation increases are larger over the continental area than the oceanic area. According to Lal and Harasawa (2001), the projected warming over Asia is higher during Northern Hemisphere winter than during summer from four skillful AOGCM simulations based on the Intergovernmental Panel on Climate Change (IPCC) IS92a scenario. The rise in surface air temperature is likely to be most pronounced over the North Asian region in all seasons. Atmosphere-ocean coupled general circulation models (AOGCMs) considered in their study simulate an enhanced hydrological cycle and an increase in annual precipitation over most of Asia. However, the inter-model differences in projections of precipitation are quite large even when averaged for the entire Asian continent suggesting rather limited confidence in the future projections of regional scale precipitation in AOGCM simulations.

Even though many effort in predicting the future climate due to the global warming, the process how the global warming influences on the climate is not sufficiently suggested yet. Therefore, this study tries to approach the dynamics of the effect of global warming as well as the phenomena, itself.

In order to evaluate the effect of global warming on the future climate and contribute to the IPCC fourth Assessment Report, many AOGCMs have produced the future climate simulation using the Special Report on Emissions Scenarios (SRES) of greenhouse gasses. In this study, the regional climate over the Northeast Asian region, which is defined as the areas including Korea, northeast China, and Japan is investigated using the output of the eight AOGCMs with aerosol forcing. Through the analyses of empirical orthogonal function (EOF) and the related regressed field, the simulated current climate and the observation in summer over the Northeast Asian region are compared to evaluate model performance to simulate the regional climate in Section 3. In Section 4, the simulated future climate change in emission scenario experiments for the period of 2001 to 2199 is analyzed to assess the influence of global warming on the Northeast Asian summer climate. The EOF and regression analysis will provide the possible mechanism for the enhanced precipitation over the Northeast Asian region due to the increased concentration of greenhouse gas. The results are summarized in Section 5.

2. Data and Model

We used the output of the eight AOGCMs for the IPCC fourth Assessment Report (AR4), which are provided by Program for Climate Model Diagnosis and Intercomparison (PCMDI). The resolution, greenhouse gas and aerosol forcing of the models used in this study are described in Table 1. We analyzed the multi-model ensemble field of the results in the eight models to reduce the uncertainty of an individual model (Giorgi and Mearns 2002; Lal and Harasawa 2001). The model data is available at the website https://esg.llnl.gov:8443, and the documentation of models and their simulations at the website http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php.

Among the scenarios of climate forcing recommended by IPCC, historical (20th century) experiment (20C3M), SRES A2 experiment, 750 ppm stabilization scenario (A1B), and 550 ppm stabilization scenario (B1) are used. The 20C3M initialized from a point early enough in the pre-industrial control run. This will enable us to subtract any residual drift in the control from all runs. SRES A2 experiment takes the end of the 20C3M run as its initial condition. 720 ppm stabilization experiment (SRES A1B) and 550 ppm stabilization experiment (SRES B1) initialized with conditions from the end of the 20C3M simulation and run to 2100, after which hold concentrations fixed at 720 ppm and 550 ppm respectively and continue run to 2200. The time series of the CO$_2$ concentration in each experiment is shown in Fig. 1. Documentation for this particular set of climate forcing factors may be found in Ammann et al. (2003) and Dai et al. (2001). We analyze the model results of 20C3M run from 1901 to 1999, A2 run for 2001 to 2099, and A1B and B1 runs for 2001 to 2199. The summer season in this study consists of the three-month period from June to August.

To compare the simulated climate with observation, the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) data (Xie and Arkin 1997) and the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP/NCAR) reanalysis data (Kalnay et al. 1996) are used. The CMAP data were derived by merging rain gauge observations, five different
The climatological monthly mean rainfall dataset was constructed for the 23-yr period from 1979 to 2001 with global coverage on 2.5° × 2.5° grids.

Table 1. Models used in this study

<table>
<thead>
<tr>
<th>Model</th>
<th>Atmospheric Resolution lon×lat (degree)</th>
<th>Oceanic Resolution lon×lat (grids)</th>
<th>Precipitation related scheme</th>
<th>Greenhouse gases and aerosol forcing</th>
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</thead>
<tbody>
<tr>
<td>CNRM-CM3 France</td>
<td>2.8125 × 2.8125 T63, L45</td>
<td>182 × 152 L31</td>
<td>• Statistical cloud scheme (Richard and Royer, 1993)</td>
<td>• Sulfate aerosol</td>
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<td></td>
<td></td>
<td></td>
<td>• Mass-flux convective scheme with Kuo-type (Bougeault, 1985)</td>
<td>• Direct effect only</td>
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<tr>
<td>ECHAM5/ MPI-OM Germany</td>
<td>1.875 × 1.875 T63, L31</td>
<td>240 × 120 L40</td>
<td>• Bulk cloud microphysics (Lohmann and Roeckner, 1996)</td>
<td>• CO₂, CH₄, N₂O, F11 (effective), F12</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>• Mass flux scheme for shallow, mid-level and deep convection</td>
<td>• Anthropogenic ozone (stratosphere only), and sulfate</td>
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<td></td>
<td></td>
<td></td>
<td>(Tiedtke, 1989)</td>
<td>• Direct and indirect effect</td>
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<tr>
<td>GFDL-CM2.0 USA</td>
<td>2.5 × 2 L24</td>
<td>360 × 200</td>
<td>• Cloud microphysics (Rotstyn, 1997) and macrophysics</td>
<td>• CO₂, CH₄, N₂O, 4CFC’s, ozone</td>
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<td></td>
<td></td>
<td></td>
<td>• Relaxed Arakawa–Schubert (Moorthi and Suarez, 1992)</td>
<td>• Tropospheric aerosols, volcanic aerosols</td>
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<td></td>
<td></td>
<td></td>
<td>• Direct effect only</td>
</tr>
<tr>
<td>INM-CM3.0 Russia</td>
<td>5 × 4 L21</td>
<td>144 × 84 L33</td>
<td>• Diagnostic calculation of cloud fraction</td>
<td>• CO₂, CH₄, N₂O</td>
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<td></td>
<td></td>
<td></td>
<td>• Deep and shallow convection (Betts, 1986)</td>
<td>• Sulfate and volcanic aerosols</td>
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<td></td>
<td></td>
<td></td>
<td>• Direct effect only</td>
</tr>
<tr>
<td>IPSL-CM4 France</td>
<td>3.75 × 2.5 L19</td>
<td>180 × 170</td>
<td>• Cloud scheme</td>
<td>• CO₂, CH₄, N₂O</td>
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<td></td>
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<td></td>
<td>• Moist convection</td>
<td>• Sulfate aerosol</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Direct and first indirect effect</td>
</tr>
<tr>
<td>MIROC3.2 (medres) Japan</td>
<td>2.8 × 2.8 T42, L20</td>
<td>256 × 192 L43</td>
<td>• Prognostic total water scheme (Le Treut and Li, 1991)</td>
<td>• CO₂, CH₄, N₂O, 13 halocarbons, ozone</td>
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<td></td>
<td></td>
<td>• Prognostic Arakawa-Schubert (Pan and Randall, 1998)</td>
<td>• Mineral dust, sea salt, sulfate, black carbon and organic</td>
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<td>• Volcanic aerosol</td>
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<td></td>
<td>• Direct and indirect effect</td>
</tr>
<tr>
<td>MRF-CGCM 2.3.2 Japan</td>
<td>2.8 × 2.8 T42, L30</td>
<td>144 × 111</td>
<td>• Diagnostic cloud</td>
<td>• CO₂, CH₄, N₂O, CFCs</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>• Prognostic Arakawa-Schubert (Pan and Randall, 1998)</td>
<td>• Sulfate aerosol</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>• Direct effect only</td>
</tr>
<tr>
<td>UKMO-HadCM3 UK</td>
<td>3.75 × 2.5 L19</td>
<td>288 × 144 L20</td>
<td>• Cloud physics (Smith, 1990)</td>
<td>• CO₂, ozone</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Convection</td>
<td>• Sulfate aerosol</td>
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<td></td>
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<td>• Direct and indirect forcing</td>
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</tbody>
</table>

Satellite estimates, and numerical-model outputs. The climatological monthly mean rainfall dataset was constructed for the 23-yr period from 1979 to 2001 with global coverage on 2.5° × 2.5° grids. The resolution of the NCEP reanalysis data used.

Fig. 1. The time series of CO₂ concentration used in 20C3M, A2, A1B, and B1 experiments.
in this study is 2.5° longitude by 2.5° latitude along with twelve pressure levels from 1000 hPa to 100 hPa. The observed SST data from 1979 to 2001 are those reconstructed at NCEP (Reynolds and Smith 1994). The horizontal resolution of SST data is 2° longitude by 2° latitude.

3. Simulated Northeast Asian summer climate in 20C3M experiment

3.1 EOF modes of precipitation

To assess the model performance in simulating the Northeast Asian summer monsoon, the observation and the ensemble average of eight AOGCMs in the historical simulation (20C3M) are compared. Because the SST in AOGCM is not prescribed, but predicted, the boundary forcing (SST forcing) is different from the observation. Therefore, the quantitative evaluation of summer precipitation in historical run is not easy. If the amount of summer precipitation over [30°N–50°N, 110°E–145°E] averaged from 1971 to 1999 in historical run and the observation is just compared, 4.8 mm/day in historical run is larger than 4.3 mm/day in the observation. But the variance of the precipitation in historical run is smaller than that in the observation.

For qualitative assessment, the EOF analysis using CMAP precipitation and the simulated precipitation in 20C3M run is performed over the Northeast Asian region [20°N–50°N, 100°E–150°E]. Figure 2 shows the first two EOF modes of precipitation in observation and simulation. The first and the second EOFs of the observation explain 28.38% and 19.10% of total variation, respectively. In 20C3M run, the first and the second one explain 20.34% and 12.47%, respectively. They are stabi-

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![Fig. 2. The first and the second EOFs of the CMAP summer (June to August) precipitation (left panel) for 1979 to 2001 and the simulated summer precipitation in 20C3M run (right panel) for 1901 to 1999.](image-url)
tically significant satisfying the North’s criteria (North et al. 1982). The first and the second EOF modes of the simulated precipitation are similar to those of the observation, but the variation patterns of the simulation are shifted southward compared to those of observation. The more general feature can be seen in the regressed precipitation field on the principal component (PC) time series of the EOFs in Fig. 3, in which the areas exceeding 90% significant level are shaded. The first EOF mode corresponds to the Northeast Asian monsoon rainfall band according to Lee et al. (2005), which showed that the first mode well represents the interannual variability of summer monsoon rain band and its structure. This rain band is negatively correlated with the rainfall over the western North Pacific around 20N as in Lau et al. (2000). In the second one, the variation over the area between 20N and 40N has a negative relationship with that of between 10N and 20N. The model results well simulate the variations over the Northeast Asian and the western North Pacific regions, but fail to simulate the variability over the Indian continental region and Indonesia. The possible reason of this failure will be suggested in the following.

In order to investigate the dynamical meaning of the first two EOF modes, the lag-correlations between the Northeast Asian summer precipita-

![Fig. 3](image-url)
tion associated with the EOFs and SST from the previous winter to the autumn are calculated. The precipitation associated with the EOFs is defined as the PC time series multiplied by the area-mean value of the eigenvector over the region $[30^\circ N-50^\circ N, 110^\circ E-145^\circ E]$, indicated by the small box in Fig. 2. This region has been chosen based on the one point correlation between the CMAP precipitation data in several grid points over East Asia and in the global area. The correlation map of the first EOF in observation indicates the decaying phase of ENSO (left panel in Fig. 4). ‘DJF’ in Fig. 4 means the previous winter, that is, December in the previous year (year-1), and January and February in the target year (year 0). The maximum variability exists over the tropical eastern Pacific in the previous winter and the variability becomes weaker from spring to autumn. The correlation field in 20C3M run also shows the decaying feature of ENSO and the opposite relationship of SSTs in between the tropical eastern and western Pacific (right panel in Fig. 4). That is, the negative correlations between the summer precipitation of the first EOF and SSTs from winter (DJF-) to summer (JJA) are shown in the western Pacific, whereas the positive correlations are shown in the central and eastern Pacific. In the case of the second EOF of observation, the positive variation over the tropical eastern Pacific becomes weaker in the previous winter and spring and the negative correlation gets stronger in the tropical central Pacific in summer and autumn (left panel in Fig. 5). This fast transition of ENSO signal is also seen in the model simulation, but the negative correlation is confined within the narrow region of the tropics and its maximum exists in the eastern Pacific, whereas the negative maximum of the observation exists in the central Pacific.

In spite of the some agreement between the

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**Fig. 4.** The lag-correlation between the SST and the PC time series of the first EOF in observation (left panel) and the 20C3M run (right panel). The first panel is for the previous winter, the second one for spring, the third one for summer, and the last one for autumn. The contour interval is 0.2 in observation and 0.1 in 20C3M run. The areas exceeding the 95% significant level are shaded.
observation and the model results, the correlation fields associated with the first two EOF could not capture the relationship between the Northeast Asian rainfall and the SST over the Indian Ocean and the South China Sea. For example, the multimodel ensemble misses the warming over the Indian Ocean in the previous winter and spring and the warming over the Bay of Bengal and the South China Sea in summer at the first EOF (Fig. 4), and the Indian Ocean Dipole (IOD) pattern in autumn at the second EOF (Fig. 5).

According to the power spectrum analysis, the first EOF modes of observation and historical simulation show a peak at 3–4 year. On the other hand, the second EOF of observation displays peaks at 5–6 and 3–4 years. Whereas EOF modes of simulation have rather shorter period of peaks at 2–3 years and 3–4 years compared to that of the EOF modes of observation. It may come from the failure in simulation of SST over the Indian Ocean and the South China Sea as mentioned in the previous paragraph. AOGCM has shown that the periods related to ENSO are 2–3 years and 3–5 years when the ocean dynamics is controlled by the tropical Pacific (Yeh et al. 2001). The three dominant periods of NINO3.4 index in observation, which is the averaged SST anomaly over [5S–5N, 170E–120W], are 3–4, 5–6, and 2–3 years. Furthermore, these three periods are well matched with the EOF modes of observation. The dominant periods of NINO3.4 index in simulation are 3–4 and 2–3 years and no peak is observed at 5–6 year like in the second EOF mode of simulation.

In summary, the first and the second EOFs of precipitation over the Northeast Asian region are related to the decaying of ENSO and the fast transition of ENSO respectively. Moreover the multi-model ensemble in 20C3M simulation well describes the summer precipitation pattern and this relationship between SST and the precipitation over the Northeast Asian region. Based on these results, the circulation pattern associated with the EOF modes will be discussed in the next section.

Fig. 5. Same as in Fig. 4 except for the second EOF.
3.2 Circulation pattern associated with EOF modes

Figure 6 shows the regressed zonal wind at 300 hPa and the regressed wind vector at 850 hPa on the PC time series of the first two EOFs in observation and 20C3M simulation. The regressed wind field on the first EOF of both observation and 20C3M is associated with the Philippines Sea anticyclone around 20N and the cyclonic circulation around 30N at 850 hPa (arrow), and the strengthening of westerly wind around 30N to 40N at 300 hPa (contour). The regions of convergence of wind at 850 hPa and the enhanced westerly wind at 300 hPa well correspond to the location of the rain band over the Northeast Asia. The simulated wind vector field of the first EOF is similar to the observed one.

The connection of the regressed precipitation pattern in Fig. 3, SST field in Fig. 4, and the wind field in Fig. 6 associated with the first EOF of the precipitation over the Northeast Asian region can be understood as follows. In Wang et al. (2000), the persistence of the Philippines Sea anticyclone is primarily attributed to a positive thermodynamic feedback between the anticyclone and the sea sur-

Fig. 6. The regressed zonal wind at 300 hPa (contour) and wind vector at 850 hPa (arrow) on the PC time series of (a) the first EOF and (b) the second EOF modes of observation, and (c) the first EOF and (d) the second EOF modes of 20C3M run. The contour intervals are 1 m sec\(^{-1}\) in (a) and (b), and 0.3 m sec\(^{-1}\) in (c) and (d). The areas exceeding the 95% significant level are shaded and only the wind vector exceeding 95% significant level is appeared.
face cooling over the western North Pacific in the presence of mean northeasterly trades during the mature phase of ENSO in the winter and the decaying phase in spring. In addition, the tropical eastern and central Pacific warming plays an essential role in the development of the western Pacific cooling and the intensification of the anticyclone by setting up a favorable condition for the anticyclone-SST interaction due to this cooling.

According to Lee et al. (2005), the development of strong anticyclone over the western North Pacific in summer of the decaying phase of El Niño induces the decreased precipitation, the increased insolation due to less cloud cover, and thus the surface temperature warming over the region. On the other hand, over the Northeast Asian region, the upward motion related to a cyclonic circulation is induced by a weakened local Hadley circulation. Also the moisture supplied by southwesterlies in the northeast flank of western North Pacific subtropical high, leads to enhanced precipitation and lower surface temperature over the Northeast Asia. The decreased temperature over the Northeast Asia and the increased temperature over the western North Pacific make the meridional temperature gradient between the two regions strengthened. Thus, the westerly wind over this region is strengthened by the thermal wind relationship. In summary, the Philippines sea anticyclone gets strengthened in the decaying phase of ENSO, and contributes to the enhanced precipitation over the Northeast Asia. These dynamical features are well simulated by the AOGCMs.

On the other hand, both observation and simulation show that the regressed wind field on the PC time series of the second EOF shows the cyclonic circulation over the Korean peninsula, Japan, and the East China Sea and the anticyclone in the southeastward of the cyclone at 850 hPa (lower panel in Fig. 6, denoted by arrow). This cyclonic circulation at lower-level is corresponding to the enhanced precipitation over the same region [20° N–40° N, 120°E–150°E] in the lower panel of Fig. 3.

Though there are some disagreement between the simulation and the observation, it can be said that the results of the multi-model ensemble quite well simulate the several dynamics of the Northeast Asian summer climate, especially related to the decaying phase and fast transition phase of ENSO. Therefore, analysis of the future climate change over Northeast Asia using the model outputs could be reliable at least in the view of those dynamics.

4. Future Northeast Asian summer climate

4.1 Precipitation change

Based on the comparison between the observation and the model results in 20C3M in the previous section, the future projection of climate change over the Northeast Asian region is evaluated using the multi-model ensemble of IPCC SRES A2, A1B, and B1 simulation. Figure 7 shows the ratio (%) of the summer precipitation change by the linear trend from 2001 to 2099 to mean precipitation from 1961 to 1990 in 20C3M run. The contour interval is 5% and the areas exceeding 10% are shaded.
trend from 2001 to 2099 to the mean precipitation from 1961 to 1990 in 20C3M run. The increase in the precipitation during 99 years at A2, and A1B simulation reaches 20% compared with the mean precipitation of the current climate over the Northeast Asian region. This enhanced precipitation due to global warming over this region well matches with the many previous studies (Lal and Harasawa 2001; IPCC 2001a; Min et al. 2004).

The time series of the ratio of ten-year mean precipitation change to the current climate over the Northeast Asian region [30°N–50°N, 110°E–145°E] describes the increasing trend of the precipitation, especially after 2050s (Fig. 8). Many researchers and IPCC report have said that there is a threshold of the concentration of greenhouse gases for influencing the climate due to the cooling effect of aerosols (IPCC 2001a). Before 2050 year, the precipitation over the Northeast Asia in A2 is even smaller than that in A1B or B1, because the concentration of aerosol in A2 is larger and then the cooling effect in A2 is also stronger than the others. However after 2050, the warming effect of greenhouse gases exceeds the cooling one, and the precipitation could have a large increasing trend.

The increase of precipitation in A2 and A1B scenarios is larger than that in B1 scenario after 2050s in Fig. 8. It means that if people try to reduce the emission of greenhouse gases, it could make the global warming slow and the increasing rate of precipitation over the Northeast Asian region reduced, because B1 scenario in Fig. 1 assumes the mitigation of emission of greenhouse gases. If done as in A2 or A1B, people living in the Northeast Asia would experience a large amount of summer rainfall in the future.

After the stabilization of the greenhouse gas concentration in 2100s, the precipitation is still enhanced for 30 or 50 years more due to the inertia inherent in the climate system (IPCC 2001b; Easterling et al. 2004), which may come from the long atmospheric lifetime of the greenhouse gases and the long memory and lag response of the ocean (Scheraga 1997). That is, though the concentration of greenhouse gases is stabilized, the radiation process related to greenhouse gases before stabilization is still going on for a long time due to the long lifetime of the gases. In addition, due to the long memory and lag response of ocean, the SST continues to be warm and the ocean still reacts to the previous effect of greenhouse gases after stabilization. So the influence of atmosphere and ocean interaction before stabilization of concentration can remain in the climate after.

The possibility of the influences of the global warming on the interannual variability of precipitation over the Northeast Asia could be found in Fig. 9. The standard deviation of precipitation, which is calculated after removing the linear trends, in scenario simulations is larger than that in historical simulation as it is expected. The interannual variation becomes larger, as the global warming is stronger. The large interannual variation means that the extreme events can be occurred easily. If the global warming is stronger, atmosphere and ocean can contain more energy, so they’ll be more unstable. Therefore the year-to-year variation will be larger than that in the present. After the stabilization of the greenhouse gas concentration, the

Fig. 8. The time series of the ten-year-mean precipitation ratio (%) to mean precipitation for 1961–1990 in 20C3M run. The ratio is averaged over the Northeast Asian region in A2, A1B, and B1 runs.
variability of precipitation still increases. The more analysis may be needed to understand the causes of this feature.

In order to investigate the mechanism of the enhanced precipitation over the Northeast Asia, the EOF analysis with the precipitation from 2001 to 2099 in scenario experiments is performed over the Northeast Asian region as in Fig. 2. The first three EOF modes explain about 20%, 10–15%, and 8–9% of the total variation, and they statistically satisfy the North's criteria (North et al. 1982). The time series of the precipitation associated with each EOF, which is calculated by multiplying the PC time series by the area-mean value of the eigenvector over the region [30°N–50°N, 110°E–145°E], has an increasing trend. The linear regression coefficients of precipitation by the first three EOF modes are shown in Fig. 10. For A2 and B1 run, the precipitation in the second EOF mode mainly contributes to the increasing precipitation over Northeast Asian region. In case of A1B simulation, the trend of the precipitation in the first EOF mode is also significant. The reason that the first mode of A1B is more dominant in the contributing to the increase of precipitation over the Northeast Asia, is unclear and needs more investigation continuously. The precipitation by the linear trend of the three EOF modes explains about 85% of the enhanced precipitation due to the global warming over the Northeast Asian region. The dynamical meaning of the first three EOF modes will be addressed in the following section.

4.2 The regressed field

The regressed precipitation and the regressed wind field on the first three EOF modes in A1B simulation are presented in Fig. 11 and Fig. 12. The regressed fields in A2 and B1 simulation are very similar to that in A1B run, so only the results of A1B experiment are presented. The regressed precipitation associated with the first EOF mode shows that the precipitation increases in most of the area over the East Asia. The regressed wind field in Fig. 12a indicates that the first mode is related to the weakening of westerly wind at 300 hPa over the Korean peninsula due to the weakening of the meridional temperature gradient. The weakening of the meridional temperature gradient can be found in Fig. 13, which is the linear regression coefficient map of surface temperature in summer of A1B simulation. As it is well known, the surface temperature is more increased in continent than in ocean. Therefore the weakening of the meridional temperature gradient is large in the eastern part of the continent including the Northeast Asia, where continent and ocean are located in north-south direction. And then the westerly at the upper-level around 30°N over the Northeast Asia is weakened by thermal wind relationship.

The regressed surface temperature on the first EOF mode (not shown here) well corresponds to the linear regression coefficient map (Fig. 13). Therefore, the first EOF mode seems to be associated with the mean linear trend of global warming. This mode contributes to the increase of precipitation over the Northeast Asian region in A1B simulation, but not so much in A2 and B1 experiments.
Fig. 11. The regressed precipitation field on the PC time series of (a) the first, (b) the second, and (c) the third EOF modes in A1B scenario simulation. The contour interval is $1 \times 10^{-6}$ kg m$^{-2}$ sec$^{-1}$, and the positive-valued areas are shaded.

Fig. 12. The regressed zonal wind at 300 hPa (contour) and wind vector at 850 hPa (arrow) on the PC time series of (a) the first, (b) the second, and (c) the third EOF modes in A1B simulation. The contour interval is 0.2 m sec$^{-1}$ and the areas exceeding 95% significant level are shaded.

Fig. 11. The regressed precipitation field on the PC time series of (a) the first, (b) the second, and (c) the third EOF modes in A1B scenario simulation. The contour interval is $1 \times 10^{-6}$ kg m$^{-2}$ sec$^{-1}$, and the positive-valued areas are shaded.
The precipitation pattern in the second mode of A1B simulation (Fig. 11b) is similar to the pattern in the first mode in 20C3M run in Fig. 3c. One of the positive maximum precipitation centers is located at the southeast of Korea-Japan region in both historical and future projection simulations. This second mode shows the well structured Philippine Sea anticyclone around 20N, cyclonic circulation around 40N at lower-level (850 hPa), and the enhanced westerly wind at upper-level over Korea-Japan region as in the observation and 20C3M run. The regressed SST on the second EOF mode is shown in Fig. 14. The linear trend of SST (Fig. 13) is removed from total SST field in this calculation. Though the regression analysis is applied after removing the linear trend of SST, the decaying phase of ENSO associated with the second mode is robust.

From investigating the regressed fields, it is found that the second EOF mode in future simulation, which is responsible for the increased precipitation over the Northeast Asia in all three scenario experiments (Fig. 10), is identical to the first EOF mode in historical run. That is, the increased Northeast Asian summer precipitation due to global warming is associated with the decaying phase of El Niño. However there is no significant change of El Niño SST pattern between the first EOF of historical run (Fig. 4 right panel) and the second EOF of A1B run (Fig. 14). Instead, as in Fig. 10 the second EOFs of the future run have an increasing trend, that is, the decaying phase of El Niño can be occurred more frequently as global warming may provide the favorable condition to occur El Niño like SST warming. Because there is much rain over the Northeast Asia in the decaying phase of El Niño, summer precipitation over this area will become increased according to frequent El Niño event due to global warming.

The precipitation pattern related to the third EOF mode in Fig. 11c is somewhat different from that of 20C3M simulation of Fig. 3d, but the center of the positive maximum variation is located at the Korean Peninsula and the center of the negative one is at the southeast of the Korea-Japan region as in historical run. This mode does not contribute to the increase of precipitation over the Northeast Asia and the regressed SST field does not have significant signals (not shown here).

5. Conclusion

In order to evaluate the model performance in simulating the Northeast Asian summer climate, and to investigate the effect of global warming on the summer climate over the Northeast Asian region, the multi-model ensemble of eight atmosphere-ocean coupled general circulation models in the historical (20C3M) and the scenarios (A2, A1B, and B1) runs are analyzed. From comparison
of the observation and the 20C3M experiment, it is found that the multi-model ensemble quite well simulates the Northeast Asian summer precipitation and circulation, especially in the first two EOF modes and the associated regressed field. The first EOF mode represents the decaying phase of ENSO, which contributes to the development of the Philippine Sea anticyclone. The second one is associated with the fast transition of ENSO. The circulation pattern related to the first two EOF modes in observation and the model is well corresponding to the patterns in the decaying and developing phases of ENSO respectively with Wu et al. (2003)’s result. However there are some disagreements between the observation and the simulation, for example, variation patterns of the simulation are shifted southward compared to those of the observation, and the model cannot simulate the variation over the Indian continental region and Indonesia.

In future climate, the increase of the precipitation to 2099 at A2, and A1B simulation reaches 10% compared with the mean precipitation for 1961–1990 over the Northeast Asian region. After the stabilization of the greenhouse gas concentration in 2100, the precipitation is enhanced during 30 or 50 years more due to the inertia inherent in the climate system. From EOF analysis, it seems that the increased Northeast Asian summer precipitation due to global warming is contributed by the effect of the enhanced monsoon circulation in the decaying phase of El Niño rather than the mean linear increase of global climate or the circulation in the fast transition period of ENSO.

The reason that the second mode associated with the decaying phase of ENSO becomes important in the increase of precipitation over the Northeast Asia due to global warming is not revealed. According to Moon et al. (2004), as the vertical stratification of ocean enhances at the upper levels after the late 1970s due to increase of temperature within the thermocline in the tropical Pacific, the variability of higher-order baroclinic mode contributes to current anomalies and surface pressure significantly increases in the region. Because the higher-order baroclinic mode of ocean has the low frequency, an increase of the dominant period of the ENSO variability after the late 1970s can be thought to the result from the enhanced contribution of higher-order mode. That is, global warming can enhance the period of ENSO. Their research supports the fact that as the slow decaying mode, that is the second EOF mode in the future of the global warming experiments, is stronger due to global warming, the precipitation over the Northeast Asia increases in this study. However, in spite of the increase of SST over the tropics due to global warming, there is no evidence that the period of ENSO becomes long. Timmerman et al. (1999) also argued that the response of ENSO to greenhouse warming in a coupled model generally does not show increased period or amplitude despite in presence of increased stratification of ocean.

Fig. 14. The regressed surface temperature, which is removed linear trend, on the second EOF mode in A1B simulation. The contour interval is 0.05 K, and the areas exceeding 95% significant level are shaded.
Therefore, this needs further investigation.

In order to get the best result, instead of using all models, it needs the process that the higher-performance models are chosen by statistical and dynamical analysis, for example Taylor diagram and EOF analyses, which is so-called superensemble method (Krishnamurti et al. 2000). According to Min et al. (2004), the inter-model variability (noise) in precipitation changes is as large as that of ensemble mean (signal), whereas noise is smaller than signal in the projection of temperature changes. Therefore, it should also check the uncertainty of the simulated future climate originating from different initial conditions, characteristic biases of an individual model, and the difference among different models (IPCC 2001b).

Acknowledgement

This study is supported by a project “The application of regional climate change scenario for the National Climate Change Report” (metri-2008-B-5) funded by METRI. We acknowledge the international modeling groups for providing their data for analysis, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) for collecting and archiving the model data, the JSC/CLIVAR Working Group on Coupled Modeling (WGCM) and their Coupled Model Intercomparison Project (CMIP) and Climate Simulation Panel for organizing the model data analysis activity, and the IPCC WG1 TSU for technical support. The IPCC Data Archive at Lawrence Livermore National Laboratory is supported by the Office of Science, U.S. Department of Energy.

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