筑波大学陸域環境研究センター報告　No.7　59 ～ 69　（2006）

モンゴルにおける環境変化診断のための 領域気候シミュレーション

Regional Climate Simulations to Diagnose Environmental Changes in Mongolia

佐藤　友徳 *・木村　富士男 **

Tomonori SATO* and Fujio KIMURA**

Abstract

Arid/semi - arid region in Northeast Asia has been suffering from climate change due to the global warming. Cold season temperature has been rapidly increasing in recent years, especially during the cold season. Dynamical downscaling using a regional climate model is one of the methods to evaluate the regional - scale climate change with high resolution. In this study, numerical experiments were carried out in order to reproduce past and future regional climate condition in Mongolia for the use of environmental studies in RAISE project (Sugita, 2002). A modified version of the Regional Atmospheric Modeling System developed at Terrestrial Environment Research Center, University of Tsukuba (TERC - RAMS) was adopted to simulate hydrometeorological condition with 30 km horizontal resolution. Spatio - temporal features in ten - year integration for 1994 - 2003 were compared with local observations obtained during RAISE (The Rangelands Atmosphere - hydrosphere - biosphere Interaction Study Experiment in northeastern Asia; Sugita, 2002) project. Seasonal changes of temperature and precipitation were well reproduced in the TERC - RAMS although cold - season temperature and precipitation were overestimated.

Downscale experiments nested within the global warming test runs of general circulation model for 2071 - 2080 period indicated the possible climate change in Northeast Asia including Mongolia. One - hour interval dataset of model variables in both recent and future climate integrations will be provided to the research community. Variety of impact assessment such as on agricultural production, ground water, and carbon cycle can be possible by the use of this dataset.

*　日本学術振興会特別研究員・東京大学気候システム研究センター

**　筑波大学生命環境科学研究科

Ⅰ Introduction

Mongolia is a landlocked and elevated country on the Mongolian Plateau in Northeast Asia. The western part of the country contains very complex topography with major mountain ranges of Altai and Khangai Mts. while relatively gentle topography occupies the eastern part. Vegetation cover also changes drastically. Southern Mongolia is arid area where vegetation is hardly seen in Gobi desert. But northern part of Mongolia is covered by grassland and forest being connected to Taiga forest in Siberia. Thus, Mongolian territory exhibits a transition of vegetation. During winter, snow accumulates in northern part. In general, transition zones of vegetation or snow cover are likely to show vulnerability against the external forcing such as global-scale climate change. Furthermore, most of local people rely their water on river and groundwater. After the global change, shortage of available water may occur if precipitation is decreased, or evaporation is increased. Additionally, abundant grass in Mongolian steppe has maintained traditional pasturage for a long time. If the land degradation extends, and if it causes the shortage of grass in Mongolia, their grazing activity becomes difficult to continue in the future.

In order to assess future changes of water resources or vegetation product, projection of the climate change with high spatial resolution is necessary. In the RAISE (The Rangelands Atmosphere-hydrosphere-biosphere Interaction Study Experiment in northeastern Asia ; Sugita, 2002) project, changes of atmosphere-hydrosphere-biosphere interactions have been studied using three physical models, regional climate model, distributed hydrological model, and terrestrial carbon cycle model. Atmospheric condition under the global warming due to increasing greenhouse gases emission is evaluated by the use of regional climate model and general circulation model products.

Sato *et al.* (2006) proposed a new downscaling method using regional climate model which makes possible to enhance simulation skills reproducing the past climate by using reanalysis data as well as the general circulation model products. Since their interest was only for the precipitation during summertime, year-round validation of meteorological variables is the target of this study. The evaluations compose of two integrations, the recent climate runs and the future climate runs. This paper validates, at first, the ability to reproduce recent climate by the regional climate model, and second, reports the changes of meteorological variables simulated by the model. Section Ⅱ describes the regional climate model and experimental design. Comparisons of meteorological variables between recent climate simulation and observation are addressed in section Ⅲ. Future changes of precipitation and temperature are described in section Ⅳ.

Ⅱ Method

2.1. model description

The Regional Atmospheric Modeling System (RAMS; Pielke *et al.*, 1992), which was originally developed at Colorado State University, is adopted in this study. The physical schemes in RAMS has been modified and replaced at Terrestrial Environment Research Center (TERC) to improve the predictability in regional climate simulation (hereinafter TERC-RAMS). Detail of configuration of TERC-RAMS for the RAISE project was described in Sato *et al.* (2006). Arakawa-Schubert type convective parameterization (Arakawa and Schubert, 1974) and microphysics parameterization (Walko *et al.*, 1995) are used to calculate precipitation in the model. Formation of the subgrid scale cumulus near the top of the convective boundary layer, which affects the surface radiation balance, is parameterized by grid mean relative humidity. The concentration of carbon dioxide is assumed to be constant in all experiments by the TERC-RAMS experiments. The TERC-RAMS has two grid systems for two-level two-way nesting. The coarse grid system is centered on the Tibetan Plateau with a 150 km horizontal resolution covering an area of 12,000 × 9,000 km. The fine grid system covers the whole of Mongolia with a 30 km resolution. Both coarse and fine grid systems contain 30 vertical layers in a terrain following coordinate system. The thicknesses of the vertical layers vary from 110 m, at the lowest layer, to 800 m in the upper layers. The top of the model atmosphere is 17,500 m. Surface conditions in the TERC-RAMS domains are given by a global land cover characterization dataset provided by the U. S. geological survey (Loveland *et al.*, 2000), which is based on satellite observations by an Advanced Very High Resolution Radiometer (AVHRR). The TERC-RAMS uses distributions of the Leaf Area Index (LAI), the vegetation albedo, the roughness height, and other parameters of vegetation determined in the Biosphere-Atmosphere Transfer Scheme (BATS; Dickinson *et al.*, 1986). The soil texture is assumed uniformly as sandy clay loam type with saturated volumetric soil water content of 0.42. The TERC-RAMS does not contain snow model. Initial soil moisture for numerical integration in coarse and fine grid systems are firstly computed by one-month integration of TERC-RAMS starting from homogeneous soil moisture condition.

Meteorological variables in the coarse grid system are nudged to the forcing dataset with the time coefficient of 10 minutes in six grids from the lateral boundaries. The inner part of the domain is also nudged very weakly with the coefficient of four days. For the ten-year calculations of both recent and future climate runs, time-slice experiment is performed in which each integration covers 35-day period initialized by the forcing dataset.

We use two forcing datasets for each of the recent climate run and the future climate run which are mentioned in section 2.2. and 2.3. After section Ⅲ, the results in the fine grid system are mainly presented and discussed, since the target of this study is regional climate validation and prediction in Mongolia.

2.2. Recent climate run

Meteorological variables, such as wind speed, temperature, humidity, and geopotential height, in the coarse grid system are nudged to the NCEP/NCAR reanalysis (Kalnay *et al.*, 1996). The NCEP/NCAR reanalysis is produced by the model incorporating surface and upper air observations in the world, which can be regarded as the representative of the recent climate. By use of the six-hourly reanalysis, recent climate run prognoses meteorological variables from March of 1994 through February of 2004. Variables at each of 30 km resolution grids are archived with one-hour interval.

The results from recent climate run are tested by comparing with the observational data in Mongolia. Three-hour-interval meteorological elements from 1993 through 2004 are provided by Institute of Meteorology and Hydrology (IMH), Mongolia. Sensible and latent heat flux and 4-component radiation data at both of KBU site (108.78E, 47.28N) and Forest site (108.65E, 48.35N) are also used to validate the TERC-RAMS simulations.

2.3. Future climate run

A new forcing dataset were made for the future climate run using 6-hourly product of SRES-A2 (Nakicenovic and Swart, 2000) scenario run by MRICGCM2 (Yukimoto *et al.*, 2001). The procedure to make the forcing dataset for TERC-RAMS is as followings.

$$A(x, y, z, t)=N(x, y, z, t)+G'(x, y, z, m) \quad (1)$$

where A is meteorological variables, such as wind speed, temperature, humidity, geopotential height, and Sea Surface Temperature (SST) in the new forcing dataset. N represents the atmospheric variables in NCEP/NCAR reanalysis and sea surface temperature provided by Reynolds *et al.* (2002) from 1993 through 2004. Both A and N are in six-hour interval. G' is the perturbation term defined as the changes of monthly-mean variables in each month evaluated by MRICGCM2. G' can be calculated as

$$G'(x, y, z, m)=\overline{GF}(x, y, z, m) - \overline{GR}(x, y, z, m), m=1,2,...,12 \quad (2)$$

where $\overline{GF}$ and $\overline{GR}$ are ten-year-mean of monthly-means of variables during 2071-2080 and 1991-2000, respectively.

Biases induced by GCM are much reduced by using the new forcing dataset instead of some limitations in downscaled future climate. We evaluate the changes of meteorological variables under the global warming, which are addressed in section IV, as the difference between recent climate run and future climate run. Recently, very similar approach to reduce GCM bias was attempted by Misra and Kanamitsu (2004). Advantages and disadvantages of this method to apply to global warming studies were discussed in Sato *et al.* (2006).

III Comparison with observations

3.1. Temperature

Figure 1a and 1e shows winter (December-January-February) temperature. Temperature in TERC-RAMS tends to show higher value than observations. The largest bias is found over central and northwest regions where Khangai and Altai mountains are located. Around these two regions, temperature in TERC-RAMS is about 5 K higher than observations. This is mainly attributed to the fact that current version of TERC-RAMS does not explicitly simulate accumulation and melting of snow. Another reason relates to the method of comparison between the observation and the model. Usually numerical models use digital elevation maps comprised of mean elevation in the grid box. On the other hand, local observation sites are usually located at city or village rather than high place like mountain top. Therefore, the elevations of the local observation site and the neighboring model grid are basically different, in particular, near mountains. At worst, this effect causes the difference of elevation more than 500 m in the

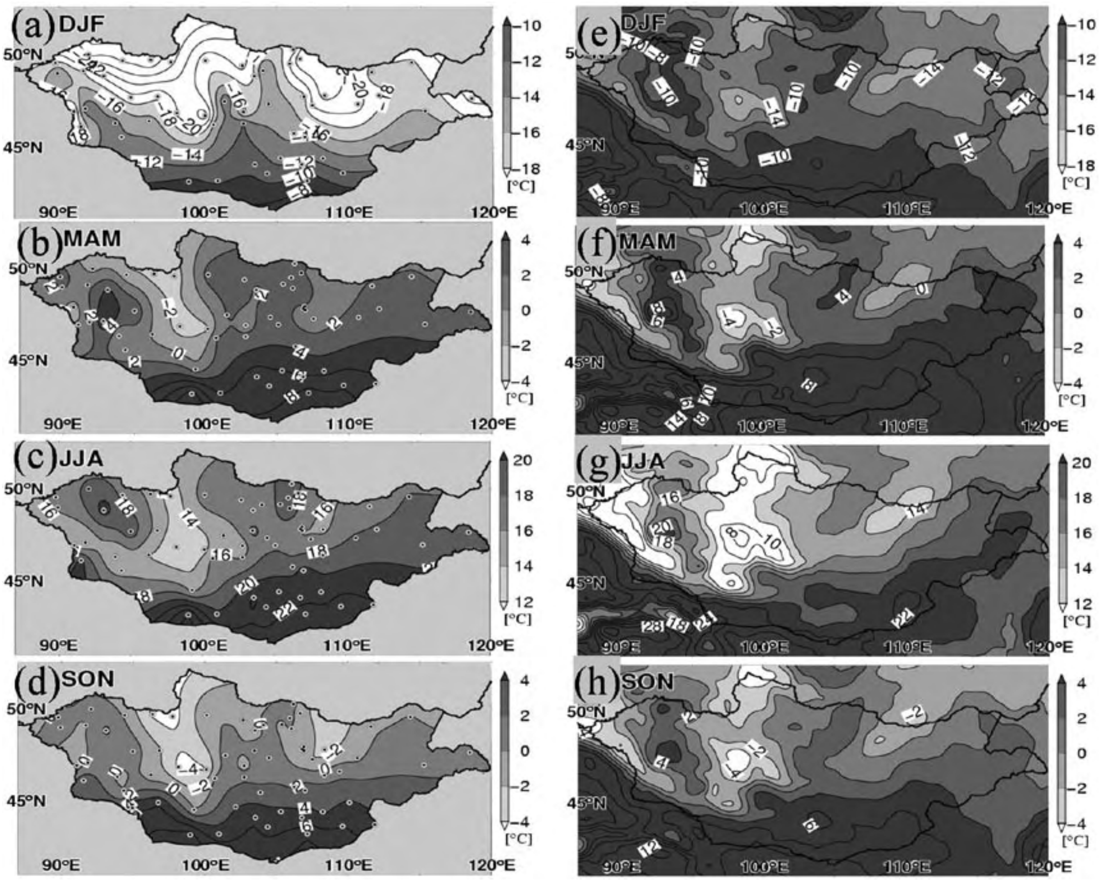

Fig.1 Ten-year-mean temperature distribution from the (left) observation and (right) model. (a) and (e) December-January-February. (b) and (f) March-April-May. (c) and (g) June-July-August. (d) and (h) September-October-November. Shades and contour intervals are different with seasons.

mountainous area. During the cold season, due to cold land surface, stratification near ground surface becomes very stable. Therefore, warm bias in the model is the most significant in winter. In spring (March-April-May), TERC-RAMS simulates seasonal mean temperature and its distribution very well (Figs. 1b and 1f). In summer (June-July-August), the model shows slightly lower temperature around mountainous regions (Figs. 1c and 1g). In autumn (September-October-November), temperature distribution is very well reproduced (Figs. 1d and 1h). Since wintertime temperature is higher in the model, annual range of temperature is lower in the model than the observations (Fig. 2).

Figure 3 shows seasonal/intraseasonal variations of temperature at six representative stations. The model excellently captures intraseasonal variations which are mainly caused by the passage of cyclones and fronts. However, December-January-February temperature is overestimated except for stations in southern Mongolia. At Muren and Khovd, simulated temperatures during the summer are lower than observations. Cumulus over the mountain may be formed too frequent intercepting solar radiation

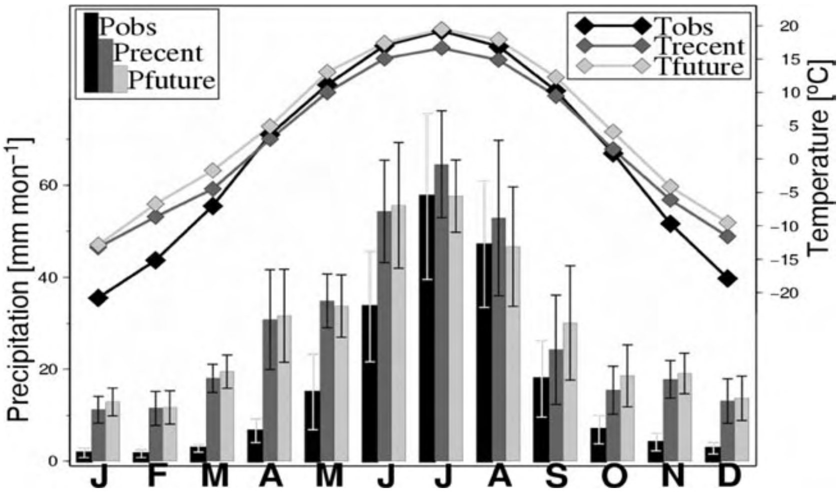

Fig.2 Ten-year-mean seasonal variations of temperature (lines) and precipitation (bars). Black lines and bars represent observation. Dark and light shaded lines and bars represent model results from recent climate experiment and future climate experiment, respectively. Error bars indicate standard deviation.

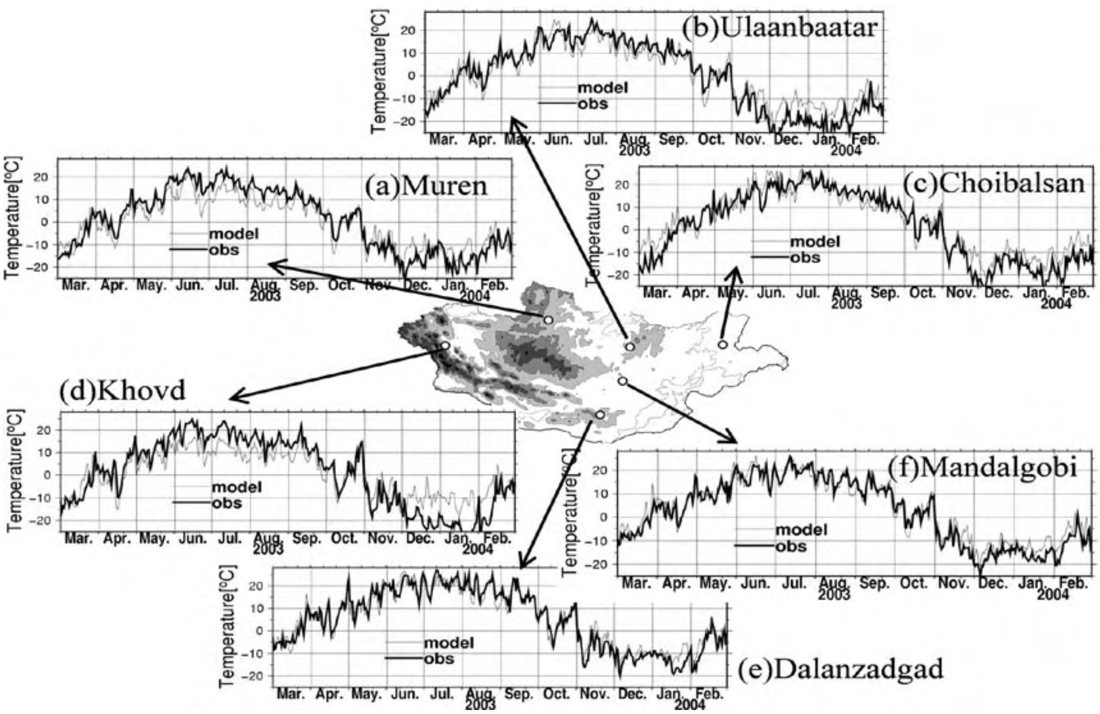

Fig.3 Intraseasonal variations of daily mean temperature from observation (thick line) and model (thin line) at representative stations in Mongolia. Periods are from March 2003 through February 2004. (a) Muren (100.15℃E 49.65℃N, 1288 m). (b) Ulaanbaatar (106.87℃E 47.92℃N, 1306 m) (c) Choibalsan (114.52℃E 48.07℃N, 759 m) (d) Khovd (91.65℃E 48.02℃N, 1405 m) (e) Dalanzadgad (104.42 ℃E 43.58℃N, 1462 m) (f) Mandalgobi (106.27℃E 45.75℃N, 1393 m).

around these two stations.

3.2. Flux and radiation

Sensible and latent heat flux and radiation at KBU and Forest site are compared with those from model using nearest grid point value. Figure 4 represents seasonal change of net radiation at two sites. From early summer to autumn, net radiation from TERC-RAMS is in good agreement with the observation. During the cold season, simulated net radiation shows larger amount than that observed. This is because the model does not contain snow processes; thus, surface albedo tends to be smaller. Seasonal change of sensible heat is well reproduced by the model albeit too large amount in June. Seasonal change of latent heat is also well reproduced. The model tends to overestimate latent heat flux in April, which might be related with large amount of precipitation in this season as addressed in the next section.

3.3. Precipitation

Figure 5 shows the comparison of precipitation. Precipitation in the model tends to overestimate in all seasons. Especially, over the mountain, simulated precipitation exceeds twice of observations in spring, autumn, and winter, although the model captures regional distribution, i.e., less precipitation in southern part, and seasonal cycle. Such overestimation except for summer can be also attributed to the absent of snow in the model which results to absorb more solar energy at the surface owing to the lower surface albedo. Heated surface is useful to organize or intensify the precipitation systems;

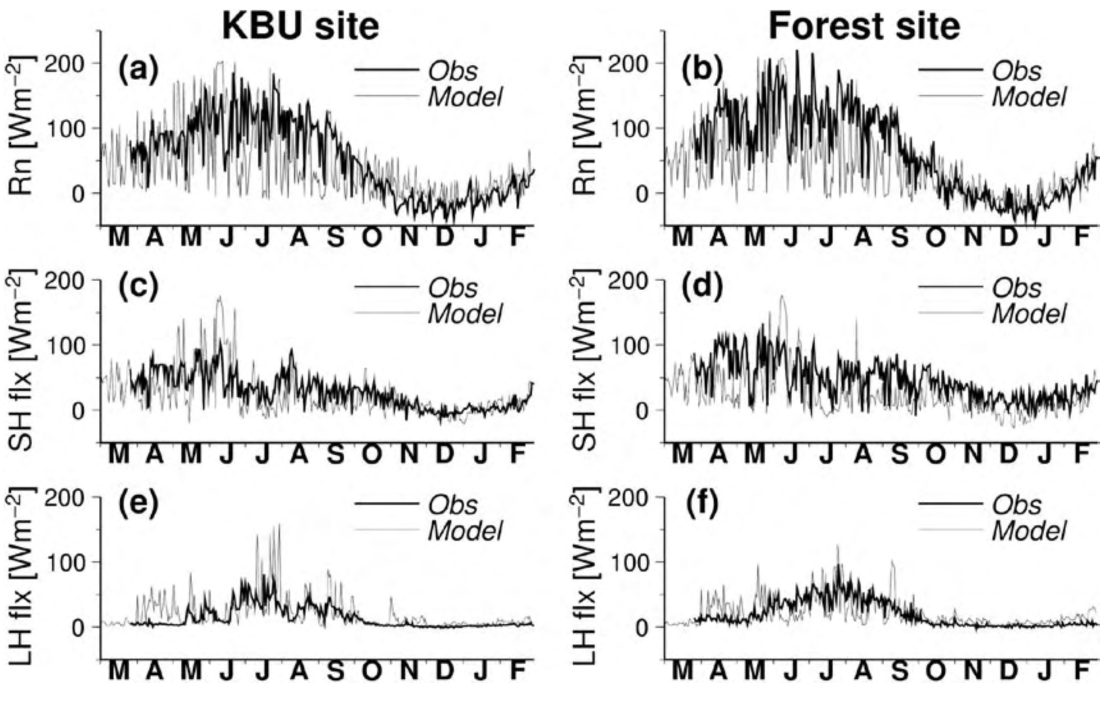

Fig.4 Intraseasonal variations of (top) daily mean net radiation, (middle) daily mean sensible heat flux, and (bottom) daily mean latent heat flux at KBU site (108.78°E 47.28°N) and Forest site (108.65°E 48.35°N). Thick lines from observation and thin lines from model.

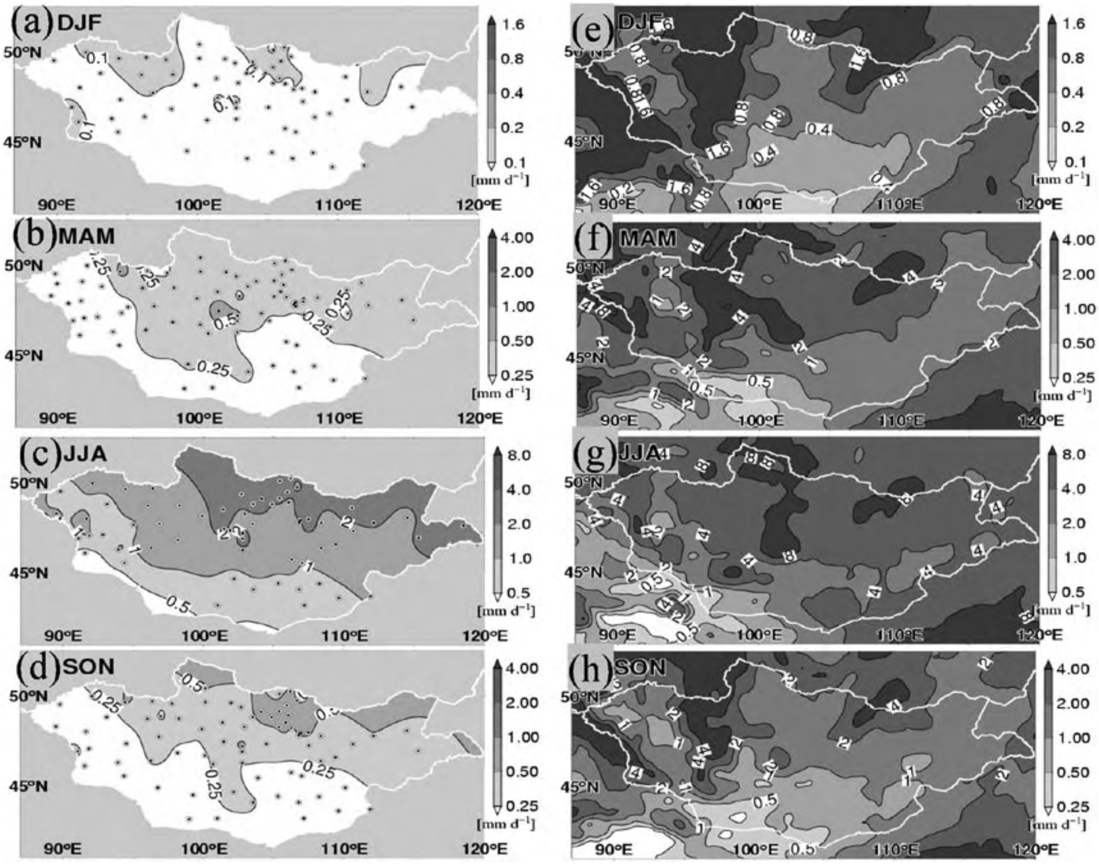

Fig.5 Ten-year-mean rainfall distribution from the (left) observation and (right) model. (a) and (e) December-January-February. (b) and (f) March-April-May. (c) and (g) June-July-August. (d) and (h) September-October-November. Shades and contour intervals are different with seasons.

thus, it causes too much precipitation in the model. On the other hand, observed precipitation during winter might be too small possibly due to the problem in snowfall collection by rain gauges.

In Mongolia, more than half portion of annual precipitation falls during the warm season. As seen in Fig.2, the TERC-RAMS well reproduce the warm season rainfall. Interannual variation of warm season rainfall is also well reproduced in the model (no figure). Additionally, probability density distribution of daily rainfall intensity is very well simulated in the model. More detail description on the warm season rainfall can be found in Sato *et al.* (2006).

Ⅳ Future changes

In general, changes of meteorological elements estimated by TERC-RAMS are strongly dependent on the choice of the forcing GCM, greenhouse gas emission scenarios, and the period of analysis. In this section, evaluated changes by downscaling experiment using A2 scenario run of MRICGCM2 is addressed.

4.1. Temperature

Increase of air temperature due to the global warming is more drastic in the high-latitude region. Northern Eurasia including Mongolia is one of the regions expecting largest increase of air temperature (Houghton *et al.*, 2001). Usually, the increment of air temperature in wintertime is known to be larger than that in summertime. In TERC-RAMS, the increment is larger in autumn and summer rather than winter and spring (Fig. 6). In summer, increase of mean temperature exceeds 2 K in whole Mongolia while it is less than 1 K in winter. Monthly mean temperature shows higher in all seasons after the global warming as seen in Fig. 2. Therefore, annual mean temperature, on average, rises 2-3 K in Mongolia. In our evaluation, annual range of temperature does not change largely. But, when snow processes at the surface can be treated appropriately, the annual range will be decreased significantly after the global warming owing to more severe temperature rise during winter.

4.2. Precipitation

Change of precipitation under the global warming is very complex; and thus, it has been difficult to estimate. By TERC-RAMS, precipitation change in winter and autumn shows slight increase compared to the recent years (Fig. 7). On the other hand, precipitation decreases in spring and summer. Most prominently, in summer, precipitation decreases almost entire Mongolia, especially around mountain. The change of annual mean precipitation shows decrease in central Mongolia where Khangai Mountain located and increase in western and southeastern Mongolia. Decrease of warm season rainfall is a serious concern for river water and ground water management. Natural vegetation growth might be also affected by shortage of available water. Changes of rainfall intensity and interannual variability in summer are addressed in Sato *et al.* (2006).

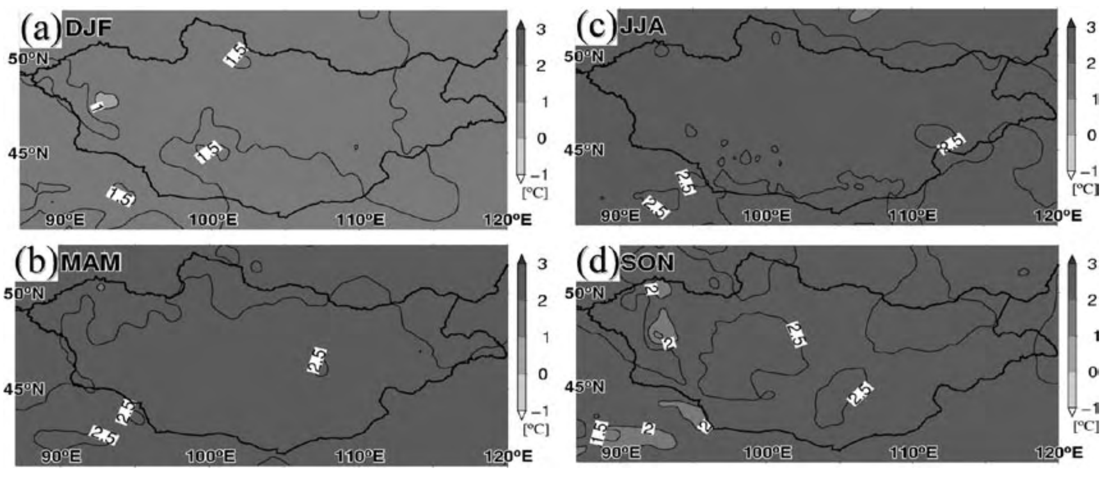

Fig.6 Difference of seasonal mean temperature between future climate experiment and recent climate experiment. (a) December-January-February. (b) March-April-May. (c) June-July-August. (d) September-October-November.

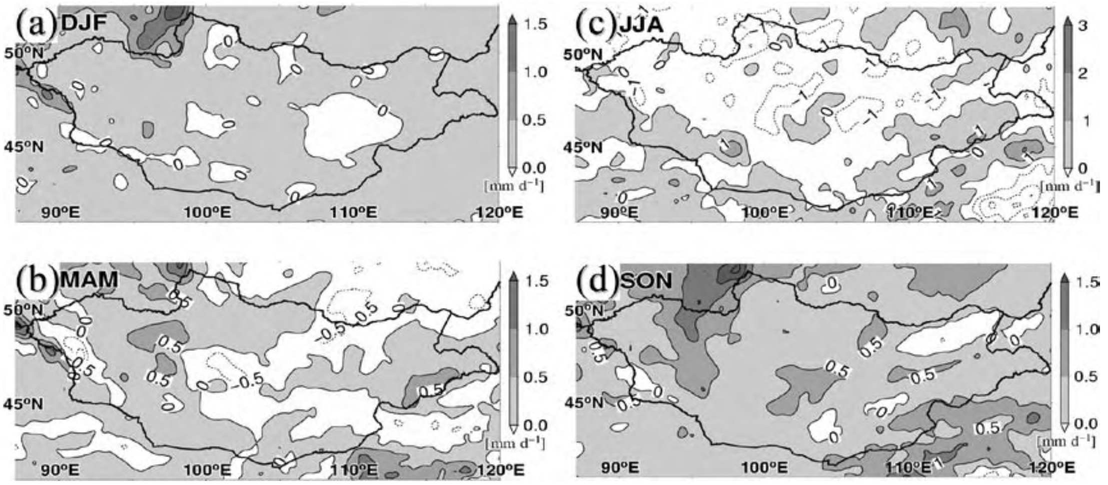

Fig.7 Difference of seasonal mean precipitation between future climate experiment and recent climate experiment. (a) December-January-February. (b) March-April-May. (c) June-July-August. (d) September-October-November.

V Conclusion

Numerical experiments are carried out in order to reproduce regional climate condition in Mongolia for the evaluation of environmental changes in RAISE project. Spatio-temporal features of meteorological elements in ten-year integration for 1994-2003 are compared with local observations obtained during RAISE. Seasonal changes of temperature and precipitation are well simulated in the TERC-RAMS although cold-season temperature and precipitation tend to be overestimated. These results indicate that the snow model should be included in the TERC-RAMS for the evaluation of winter season climate. During warm season, the model well reproduces the meteorological elements in Mongolian region. The TERC-RAMS well captures seasonal/intraseasonal variation of temperature and rainfall distributions.

Downscale experiments using global warming test runs by general circulation model for 2071-2080 period indicate the possible climate change in Northeast Asia including Mongolia. Temperature rises in the entire Mongolia in all seasons after the global warming. Warm season precipitation decreases, especially in central Mongolia where sources of the major rivers are located.

One-hour interval dataset of meteorological elements in both recent and future climate runs are planned to distribute to the research community. Variety of impact assessment or researches such as on agricultural production, ground water, and carbon cycle can be possible using this dataset.

References

Arakawa, A. and Schubert, W. H. (1974): Interaction of a cumulus cloud ensemble with the large-scale environment, Part I. *J. Atmos. Sci.*, **31**, 674-701.

Dickinson, R. E., Henderson-Sellers, A., Kennedy,

P. J. and Wilson, M. F. (1986): Biosphere Atmosphere Transfer Scheme (BATS) for the NCAR Community Climate Model. *NCAR Technical Note NCAR/TN275+STR*, 69p.

Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, K. and Johnson, C. A. (2001): *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881p.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Leetmaa, A., Reynolds, B., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Jenne, R. and Joseph, D. (1996): The NCEP/NCAR 40-Year Reanalysis Project, *Bull. Amer. Meteor. Soc.*, **77**, 437-472.

Loveland, T. R., Reed, B. C., Brown, J. F., Ohlen, D. O., Zhu, J., Yang, L. and Merchant, J. W. (2000): Development of a global land cover characteristics database and IGBP DISCover from 1-km AVHRR Data: *Int. J. Remote Sens.*, **21**, 1303-1330.

Misra, V. and Kanamitsu, M. (2004): Anomaly nesting: A methodology to downscale seasonal climate simulations from AGCMs, *J. Climate*, **17**, 3249-3262.

Nakicenovic, N. and Swart, R. (2000): *Special Report on Emissions Scenarios : A Special Report of Working group III of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 599p.

Pielke, R. A., Cotton, W. R., Walko, R. L., Tremback, C. J., Lyons, W. A., Grasso, L. D., Nicholls, M. E., Moran, M. D., Wesley, D. A., Lee, T. J. and Copeland, J. H. (1992): A comprehensive meteorological modeling system RAMS, *Meteor. Atmos. Phys.*, **49**, 69-91.

Reynolds, R. W., Rayner, N. A., Smith, T. M., Stokes, D. C. and Wang, W. (2002): An improved in situ and satellite SST analysis for climate. *J. Climate*, **15**, 1609-1625.

Sato, T., Kimura, F. and Kitoh, A. (2006): Projection of global warming onto regional precipitation over Mongolia using a regional climate model. *J. Hydrol.*, in press.

Sugita, M. (2002): The rangelands atmosphere-hydrosphere-biosphere interaction study experiment in northeastern Asia, *Bulletin of the Terrestrial Environment Research Center*, **3**, 147-156.

Walko, R. L., Cotton, W. R., Meyers, M. P. and Harrington, J. Y. (1995): New RAMS cloud microphysics parameterization. Part 1: The single-moment scheme, *Atmos. Res.*, **38**, 29-62.

Yukimoto, S., Noda, A., Kitoh, A., Sugi, M., Kitamura, Y., Hosaka, M., Shibata, K., Maeda, S. and Uchiyama, T. (2001): The new Meteorological Research Institute coupled GCM (MRI-CGCM2). - Model climate and variability -. *Pap. Meteor. Geophys.*, **51**, 47-88.

（2006 年 5 月 31 日受付，2006 年 9 月 6 日受理）