ESTIMATION OF FUTURE REGIONAL-SCALE HEAVY RAINFALL CHANGE OVER JAPAN AND EAST ASIA UNDER THE GLOBAL CLIMATE CHANGE BY USING THE STATISTICAL DOWNSCALING METHOD

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ABSTRACT**:** To overcome poor spatial and physical problems of general circlulation models in the future climate projection, statistical downscaling methods (SDSMs) to convert large-scale circulation fields to local-scale climate factors using empirical relationships between large- and local-scale variables are effective. The purposes of this study are to develop the multiple regression-based SDSM method and to project future regional-scale heavy rainfall change over East Asia. An example is shown of the SDSM to the summer-time heavy rainfall over Japan with less than 10 km by 10 km horizontal scale. The SDSM-projection showed that summer-time rainfall magnitude increased around Hokuriku and Kyushu districts even though rainfall frequency decreased almost over Japan.

KEYWORDS: global climate change, heavy rainfall, Japan

1. INTRODUCTION

Severe flood disasters caused by heavy rainfall are likely to increase for recent years. The factors of increased heavy rainfall are often discussed directly associated with anthropogenic climate change (global warming). Japan Meteorological Agency (JMA, 2005) has just reported that daily rainfall in Japan has increasing tendency for last 100 years and it suggests the effect of global warming. The fact that heavy rainfall has been increasing, however, also has uncertainty meteorologically. Kanae et al. (2004) has investigated the variation of hourly and daily precipitation at Ote-machi, Tokyo for over 100 years. The result shows that short-time heavy rainfall that recorded annual maximum value has been increasing since 1970s, but the similar feature was also seen in 1940s. They also emphasize that it is not confident that recent increasing of heavy rainfall is related to the global warming or urbanized (heat island) phenomenon over capital area.

General circulation models (GCM) are advanced simulation tools for projecting future global warming in relation to the increased atmospheric greenhouse gases (GHGs). It is widely accepted that current GCMs are generally trustworthy for modeling large -scale atmospheric fields (circulation, pressure, wind fields, etc.). One of the major problems associated with the projection of the future climate, however, is that the achievable spatial resolution (around 200 km) is not suitable for investigation of the impact of climate on agriculture, hydrological and water resources, natural ecosystems, economies and human society. In addition, some GCM climate factors (precipitation, evaporation, soil moisture, runoff, etc., which are especially associated with water) depend upon subgrid-scale physical and hydrological processes. Parameterizations involving empirical methods of such factors are used to account for these subgrid-scale processes, but their reliability is questionable for simulating local climate conditions (IPCC, 2001). Heavy rainfall is quite local-scale phenomena, therefore, is very difficult even though GCM experiments are rapidly progressed.

To overcome these problems, there are two effective approaches. One is the use of regional climate models (RCMs) to translate large-scale GCM-derived information physically and dynamically to the local-scale climate. The other employs so called statistical downscaling methods (SDSMs) to convert the large-scale circulation fields (such as sea level pressure (SLP), geopotential height, and wind vector; termed “predictor” variables) to local-scale climate factors (such as temperature and precipitation; termed “predictand” variables) using the statistical or empirical relationships between the large- and local-scale variables. With SDSMs, therefore, it is possible to project from some GCM output factors to specific variables with higher resolution. The development of their application to future climate projection began in the early 1990s and has continued through the last decade primarily in Europe (e.g., Zorita and von Storch, 1999). An advantage of these statistical approaches is their simplicity, which is important for assessing climate impact and allows easy calculation and verification without high computational cost.

SDSMs can be classified as multiple regression techniques, weather pattern approaches, and stochastic weather generators (Wilby and Wigley, 1997). In these methods, a multiple regression technique is used to obtain the regression equations linking the large-scale circulation or airflow variables to the local-scale surface climate. The spatial pattern of the large-scale factors is set as an independent (predictor) variable, that is often not a grid point value but spatial anomaly pattern derived by canonical correlation analysis (CCA), and surface climate variables are set as subordinate (predictand) variable. Because CCA has the advantage that selected pairs of spatial patterns have optimal correlations and are independent, it is easy to recognize the physical relationships between predictor and predictand variables (Busuioc et al., 2001). Therefore, the combined method of the multiple regression and CCA is suitable for downscaling of future climate projection. This technique was first used by von Storch et al. (1993) then developed by Busuioc et al. (2001). The SDSM used here is similar to the method described in Zorita and von Storch (1999), but it has been modified to resolve a systematic difference between GCM and observed circulation fields and to easily calculate correlations of the GCM output with observed data.

The purposes of this study are to develop a multiple regression and CCA based SDSM to project future regional-scale heavy rainfall change over East Asia and to use the method to project future local-scale heavy rainfall change caused by the global warming. In this article, an example is shown of its application to summer-time precipitation change using a 10km by 10km horizontal scale over Japan.

2. DATA AND METHOD

2.1 Observational and GCM data

Observational (OBS) daily precipitation data of 120 stations were provided by JMA. Three indices, monthly amount, frequency and magnitude of rainfall explaining precipitation feature are used in this study. The frequency means the number of precipitation days with more than 1mm and the magnitude means the value of monthly amount divided by the precipitation days. Wind vector at 850hPa (UV850) of the U.S. National Center for Environmental Prediction (NCEP) reanalysis data (Kalnay et al., 1996) with a horizontal resolution of 2.5º by 2.5º were used as the large-scale predictor variable for 25–55ºN and 115–155ºE.

The Meteorological Research Institute (MRI) and JMA new spectral global atmosphere GCM (MJ98-AGCM: Kitoh et al., 2005) and an updated version of the Center for Climate System Research/National Institute for Environmental Studies (CCSR/NIES) global atmosphere GCM (CCSR/NIES-AGCM: Nozawa et al., 2001) were used as output examples of predictor variables. The atmospheric parts of the GCMs have a horizontal resolution of T42 (about lat. and long. 2.8º). Two 20-year control integrations were performed, one with a fixed concentration of CO_2 (CTL) and the other with a gradual increase in CO_2 in accordance with the IPCC-A2 scenario (GCO_2). Three elements, UV850 (predictor) and precipitation (predictand) were used in the CTL experiment. Only UV850 data were used in the GCO_2 experiment because GCM-derived precipitation may be less reliable, as discussed in Section 1.

2.2 SDSM method

We first consider the following multiple regression equation,

$$Y_{ij} = \sum_{m=1}^{p} a_{im} Z_{mj} + b_i \quad -(1)$$

where Y_{ij} indicates an OBS precipitation anomaly at the i_{th} target mesh in the j_{th} year; Z_{mj} are the UV850 anomaly patterns of the m_{th} component in the jth year derived from the CCA analysis between GCM-derived UV850 and OBS precipitation changes; a_{im} are partial regression coefficients at the i_{th} target mesh and the m_{th} component, which corresponds to a single regression coefficient associated with Z_{mj} to Y_{ij} because the time series of each CCA mode is temporally independent; and b_i are the intercepts at each i_{th} mesh.

UV850 anomaly patterns derived from CCA are given by the second of the following equations,

$$Z_{mj} = \sum_{k=1}^{q} h_{mk} X_{kj} \quad \rightarrow \quad Z'_{mj} = \sum_{k=1}^{q} h_{mk} X'_{kj}$$

where x_{kj} are GCM-originated grid point UV850 anomaly values at the k_{th} grid point in the j_{th} GCM year and h_{mk} are pattern coefficients of the m_{th} CCA at the k_{th} grid point. It is assumed that the UV850 spatial patterns or centers of action under increased GHGs are invariable, as in the CTL field; in other words, h_{mk} are common to CTL and GCO_2. The second equation above on UV850 pattern coefficients was suggested on the output of the GCO2 experiment, where x'_{kj} are UV850 anomaly values at the k_{th} grid point in the j_{th} GCM year under conditions with increased GHGs. Thus, Z_{mj} in Eq. (1) were replaced by the new UV850 spatial pattern Z'_{mj}, and new (projected) precipitation anomalies Y'_{ij} at each mesh were given similar to Eq. (1) where partial regression coefficients a_{im} and intercepts b_i are considered the same as in the CTL field.

3. PERFORMANCE OF GCM EXPERIMENT AND SDSM PROJECTION

Before we discuss future heavy rainfall changes by using the SDSM based on the large-scale output of GCMs, it is necessary to understand GCMs -originated climatological features of the GCMs used here. Figures 1b and 1c show the 20-year averaged monthly UV850, SLP and precipitation in July derived from the CTL experiments of the MJ98- and CCSR/NIES-AGCMs, respectively. Compared with the current observed fields (Fig. 1a) obtained from NCEP-Reanalysis and CPC Merged Analysis of Precipitation (CMAP), the North Pacific High and the southwest monsoon flow in MJ98- AGCM were both located more northward (Fig. 1b). The North Pacific High and monsoon flow in CCSR/NIES -AGCM were more intense than in OBS (Fig. 1a) and MJ98 (Fig. 1b). However, the GCM-originated large-scale climate yielded results similar to the actual climate compared with small-scale precipitation.

Next, we verify our SDSM method to predict regional-scale rainfall. Observed UV850 data for 1981-2000 was input to multiple regression equation (Section 2.2) and the reconstruction of rainfall amount was examined. Figure 2 shows the comparison of observed and SDSM-reconstructed rainfall amount of July at specific three point of Japan. Both rainfall amount were almost coincide each other. In the western and eastern parts of Japan, the reconstructed precipitation amount represented large amount of Baiu rainfall in 1993 and 1999. With the application of the rainfall amount of September, this method was also able to reproduce the historical heavy rainfall in September 1998 ('98 Kochi Disaster of Heavy Rainfall) at least monthly time-scale. Thus, our SDSM method can be used project future regional-scale precipitation features.

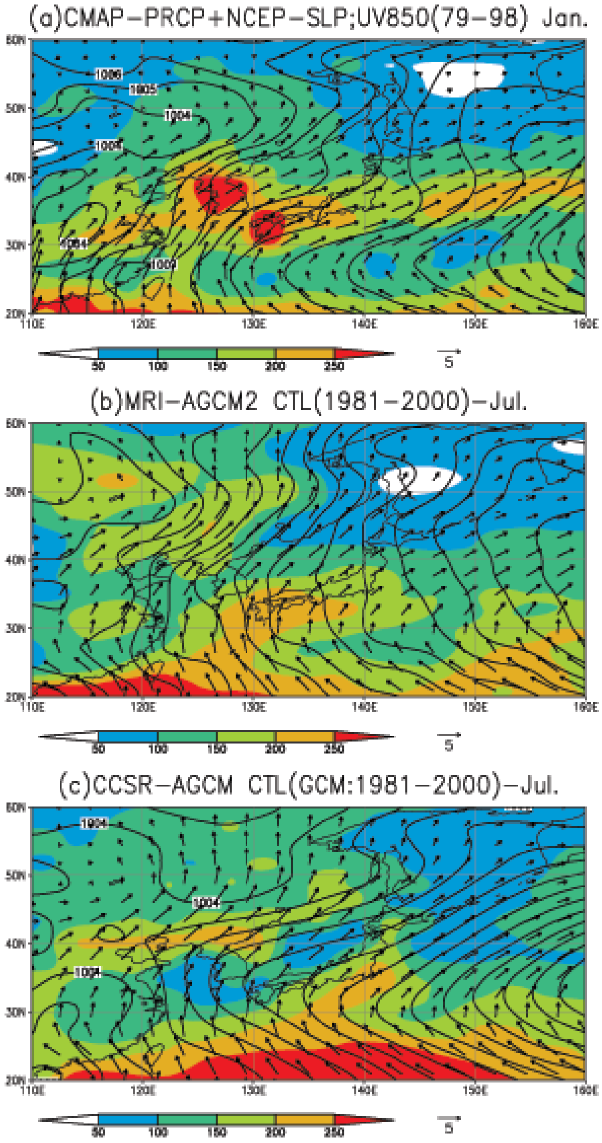

Fig.1 (a) Geographical distributions of observed monthly mean UV850 (vectors: m/s), SLP (isolines: hPa), and accumulated precipitation (shade: mm) for July (1979-1998) over East Asia; (b) same as (a) but for CTL (1981-2000) in MJ98-AGCM, (c) same as (b) but for CCSR-NIES AGCM.

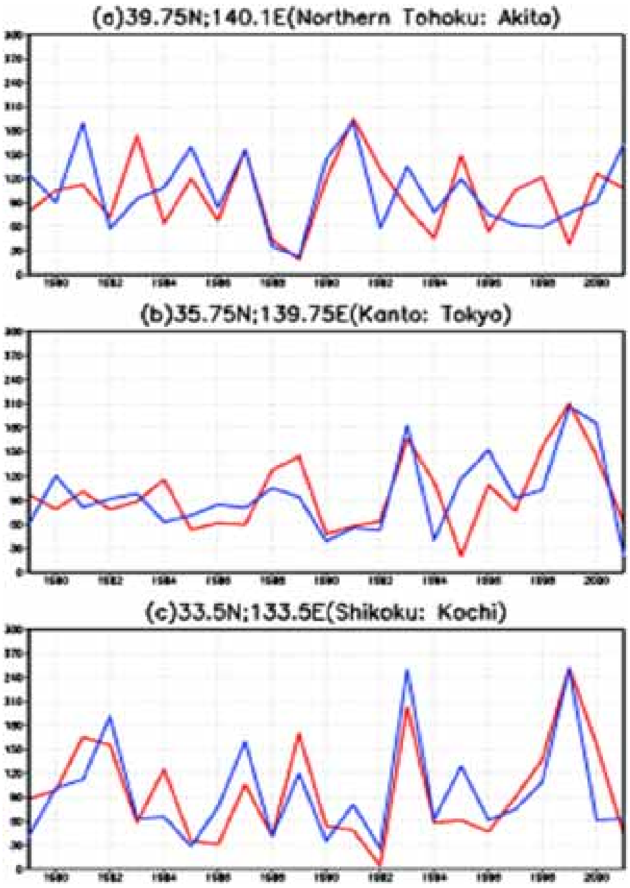

Fig. 2 Secular change of SDSM-reconstructed (red line) and observed (blue line) anomaly (percentage) of precipitation amount in July for 1979- 2002 relative to average of 1981-2000.

4. SDSM PROJECTION AND ITS COMPARISON TO GCM RESULT

At first, how did the GCMs themselves climate change in response to global warming? Figure 3 shows the output of the MJ98-GCO2 experiment for amount, frequency and magnitude of precipitation. The amount of precipitation increased to more than 115% of the normal value over the region from north

China to the Primorskiy district of Russia and the northern part of Japan. An area with below-normal precipitation amount was seen in the southern coastal area of Japan (Fig. 3a). The GCM -induced change of precipitation days was weaker than that of the amount and it showed the future rainfall frequency is slightly increasing over Kanto and Tohoku districts (Fig. 3b). Future change of the rainfall magnitude was also not significant relative to the change of amount and rainfall magnitude increased only on Hokkaido (Fig. 3c).

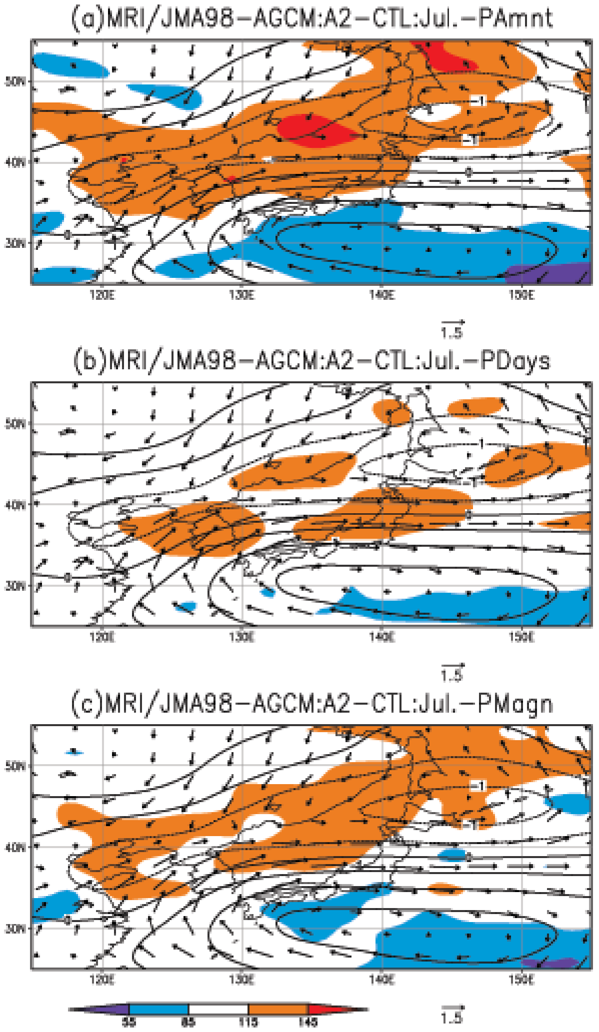

Fig. 3 Geographical distributions of mean UV850 (m/s), SLP (hPa) and the change (percentage) of (a) precipitation amount, (b) precipitation days and (c) precipitation magnitude in July derived from MJ98-AGCM GCO2 (2041-2060) compared to CTL (1981-2000).

How did the SDSM-applied future heavy rainfall change? Figure 4 shows the SDSM results by using the same UV850 anomaly originated from MJ98-GCO2. The ratio of future rainfall amount of July increased approximately 115% above normal in Hokkaido and the Sea of Japan coastal area, and in a part of it reached over 145% (Fig. 4a). The changing ratio of the amount, however, decreased to less than 85% in the Tokai and the southern part of Kyushu districts. This feature was similar to that of the MJ98-GCM. The future change of SDSM -projected precipitation days showed that rainfall frequency increased only in Hokkaido (Fig. 4b). It means that future increase of rainfall frequency over Hokkaido contributes to the increasing of amount, but this feature was slight different from GCM (Fig. 3b). On the contrary, the SDSM-projected rainfall magnitude partly increased at Tohoku and the northern part of Kinki and Kyushu districts (Fig. 4c). It suggests that Baiu front is intensified under the global warming condition and the risk of heavy rainfall and flood disaster have been rising in those areas. In GCM-originated projection, such a small -scale change of heavy rainfall was not clear (Fig. 3c), but this SDSM was successful to show future small-scale heavy rainfall change.

The same procedure was applied to the UV850 fields originated from CCSR/NIES-AGCM. The SDSM-projected rainfall amount increased to more than 115% over the northern and southern part of Japan and increased to more than 145% over a part of those areas (Fig. 5a). The SDSM-projected change of precipitation change showed features different from that of the amount. Rainfall frequency decreased over the Sea of Japan coastal area (excluding Hokkaido) (Fig. 5b) and rainfall magnitude showed that the heavy rainfall change increased more than 145% over the coastal area of the Pacific Ocean. Southeast wind anomaly oriented to the coastal area of Japan intensified for future period

(Fig. 5) The overall features of the regional distribution of rainfall change were different from those of GCM (Figure not shown).

5. DISCUSSION

Here, the reasons why summertime heavy rainfall increased are discussed. In July, Baiu front often brings heavy rainfall to Japan. Increasing tendency of rainfall magnitude over the Sea of Japan coastal areas were seen in SDSM projection in July (Fig. 4c). Therefore, heavy rainfall is likely to be associated with intensified Baiu front. On the contrary, intensified and more westward of the North Pacific High as shown in GCM projection (Fig. 3) is related to the decreasing tendency of rainfall over the Pacific coastal area (Fig. 4). RCM downscaling experiment of JMA showed, actually, that heavy rainfall more than 100 mm per day increases over the Sea of Japan coastal area of the West Japan (JMA, 2005).

An important result of this study is that the experimental SDSM discussed here could be used to project the future precipitation change in Japan not only on the amount but also on the frequency and magnitude. A merit of this statistical method is, in addition, that spatial downscaling is possible not

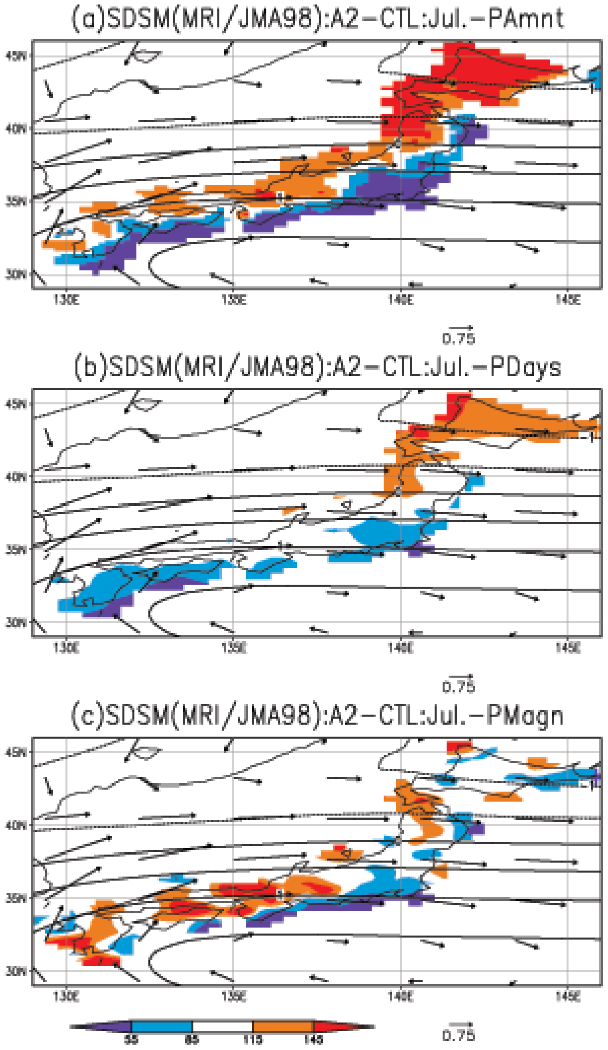

Fig. 4 Same as Fig. 3 but for SDSM applied precipitation (a) amount (b) days, and (c) magnitude (percentage) in July of MJ98-GCO2 (2041-2060) relative to OBS (1981-2000).

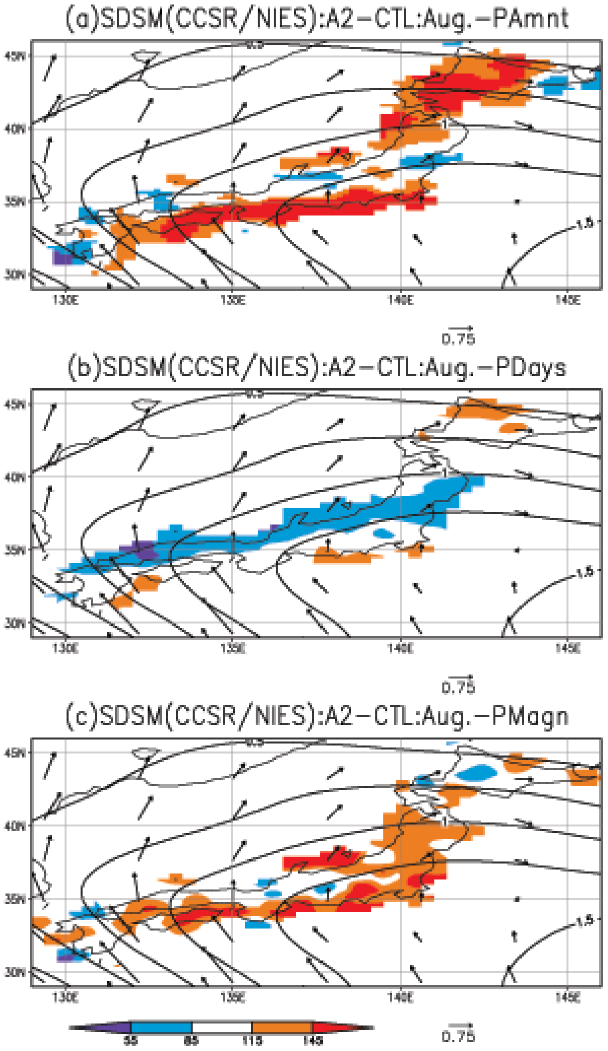

Fig. 5 Same as Fig. 4 but for August of CCSR/NIES-GCO2 (2041-2060) relative to OBS (1981-2000).

only with a 10km mesh but also with any spatial scale, for example 1 km or less, when a dataset with such a spatial scale exists. This is because one multiple regression equation is generated for each mesh, grid point, or station independently. In calculating the relationship between predictor and predictand variables, it is necessary, of course, to be careful in selecting the grid point or mesh of each variable when CCA is applied. The SDSM results of three precipitation elements are almost consistent each other even though we treat the three elements separately in this study. To consider short-term rainfall factors, however, it is actually better to apply an entire individual method such as weather pattern approaches or stochastic weather generators.

Generally speaking, land surfaces in the future will become wetter when globally averaged temperature and associated atmospheric moisture increases. In this study, there were some areas where total amount of rainfall was clearly decreased, so we might not resolve the question. One possibility to add the effect of temperature increase by global warming is to incorporate moisture flux and its convergence. Further analysis in this direction will be necessary to develop this statistical model.

6. SUMMARY

In this study, we have developed a multiple regression and CCA based SDSM to project future regional-scale heavy rainfall (amount, frequency and magnitude) change over Japan. We also use the method to project future local-scale heavy rainfall change caused by the increasing atmospheric concentrations of GHGs. SDSM-applied rainfall magnitude is increasing around Hokuriku and Kyushu districts even though rainfall frequency decreased almost over Japan. It is suggested, in addition, that increased heavy rainfall are associated with the intensified and more northward located Baiu front than usual in Hokuriku region.

To clarify above linkage, it is necessary to analyze climate system in GCM itself. Further study will also apply this SDSM to large-scale outputs from other GCMs and RCMs and extend the target area over East Asia including China and Korea. If the reliability of this method increases for projecting the future East Asian climate, it would also be possible to apply it to other mid-latitude regions, such as Europe and North America.

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