Projected regional-scale changes in atmospheric stability condition for the
development of summertime convective precipitation in the Tokyo
metropolitan area under global warming

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Abstract:
This study examined regional-scale changes in stability conditions for the occurrence of summertime convective precipitation under global warming projected by global climate simulations. Precipitation events over the Kanto Plain on synoptically undisturbed days were specifically focused on. The outputs of the 20-km-resolution global model simulations for the present and a future warming climate were used for the analyses. It was shown that temperature and moisture content throughout the troposphere are expected to increase more in the rainy cases than in the August mean cases from the present climate to the future and that the moisture increase below the 700-hPa level is significantly enhanced. The effects of future warming result in the moisture increase favorably at the lower levels. Owing to the low-level moisture increase, some stability indices indicate a destabilizing tendency with a statistical significance. From the projected changes in the stability condition for precipitation occurrence, it is implied that the precipitation amount is considered to increase if a cumulonimbus cloud and its organized systems once develop. The degree of the destabilization of precipitation environments is projected to increase more significantly than that of non-precipitation environments, and therefore, the precipitation will be more intensified in a future climate.

KEYWORDS atmospheric stability; convection; precipitation; global warming; regional climate change

INTRODUCTION

Heavy precipitation events are one of the major disastrous natural phenomena. The events frequently occur during the development of synoptic-scale and mesoscale phenomena such as tropical cyclones, extra-tropical cyclones, and fronts. In addition, such extreme precipitation sometimes develops owing to rapidly developing cumulonimbus clouds under conditions without any significant effects from synoptic-scale and mesoscale disturbances. As stated in the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC), it is considered that the heavy precipitation events will become more frequent with the enhancement of global warming based not only on past observational evidence but also on future projections by numerical climate models (IPCC, 2007). Thus, it is anticipated that extreme precipitation events due to rapidly developing cumulonimbus clouds will frequently occur in a future warming climate.

Since those convective precipitation events are local-scale phenomena, the changes in precipitation characteristics projected in a future climate should be assessed at a regional scale. However, quantitative assessments of the changes of convective precipitation in climate change are very difficult owing to the limitation of the representation of the convective-scales in simulations by not only global circulation models (GCMs) but also regional climate models (RCMs). On the other hand, the atmospheric conditions that are formed before the development of precipitation events have a spatial scale with an order of magnitude larger than the scales of cumulonimbus clouds; therefore, the assessment of the changes in atmospheric conditions before the occurrence of precipitation events can be conducted by climate model simulations. Since the spatial scales of a cumulonimbus cloud and the resultant convective precipitation are generally on the order of 10 km, the atmospheric conditions for the occurrence of convective precipitation can be evaluated at regional scales on the order of 100 km or larger. This study examines the atmospheric stability conditions for the occurrence of precipitation events.

Under the ongoing research project named Innovative Program of Climate Change Projection for the 21st Century (so called the KAKUSHIN program, 2007–2012), atmospheric GCM (AGCM) simulations at a 20-km horizontal resolution are conducted to investigate the characteristics of tropical and extra-tropical cyclones, Asian monsoons, and the evolution of the Asian–Pacific atmospheric sector. However, quantitative assessments of the changes of precipitation characteristics, the changes in precipitation characteristics, the changes in climate model simulations. Since the spatial scales of a cumulonimbus cloud and the resultant convective precipitation are generally on the order of 10 km, the atmospheric conditions for the occurrence of convective precipitation can be evaluated at regional scales on the order of 100 km or larger. This study examines the atmospheric stability conditions for the occurrence of precipitation events.
the latitude (Thorne et al., 2010); therefore, a regional-scale assessment of the changes in midlatitudes should be conducted in various regions.

It is useful to focus on a specific region to investigate the changes of the atmospheric stability at a regional-scale in a future climate, because the ambient stability condition for convective precipitation widely differs from region to region and from season to season even over Japan (Chuda and Niino, 2005). The atmospheric stability over the Kanto Plain which includes the Tokyo metropolitan area, Japan in summer is suitable for this study, since a number of studies investigated the stability condition for summertime convective precipitation with the use of observational data (Yonetani, 1975; Taguchi et al., 2002; Kawano et al., 2004; Nomura and Takemi, 2011, hereafter referred to as NT11) and such observational evidence is a sound basis for future climate projection.

The present study investigates the changes of the stability conditions for the occurrence of summertime convective precipitation over the Kanto Plain in a future climate under global warming projected by the 20-km-mesh AGCM climate simulations. We choose the precipitation cases that occur under the condition without any significant influences due to synoptic-scale disturbances. We will refer to this condition as a synoptically undisturbed condition. The analyses presented here complements those conducted in Takemi et al. (2012) in the sense that this study specifically examines the ambient conditions before the development of convective precipitation. While the study of Takemi et al. (2012) examines the stability condition in synoptically undisturbed states both with and without afternoon precipitation, the present study focuses on rainy cases. This study also demonstrates that the high-resolution GCM outputs are useful in investigating atmospheric environmental conditions for the outbreak of extreme convective weather.

**DATA AND ANALYSIS METHOD**

**Data**

The data used for the present analyses are the gridded outputs from 20-km-resolution simulations with the use of an AGCM developed by Meteorological Research Institute (MRI), MRI-AGCM3.2S (Kusunoki et al., 2011). The simulated global warming climate is based on the assumption of the IPCC A1B emission scenario. The details of the model and the climate simulations can be found in Kusunoki et al. (2011). We use the data simulated for the present (corresponding to the period of 1980–2004) and the future climate (corresponding to the period of 2075–2099). The area of interest covers a region of 35.14°N–36.26°N and 138.94°E–140.25°E (Figure 1), a 100 km by 100 km area centered at the Tokyo central district, which is nearly identical to that in NT11. This analysis area covers most of the Kanto Plain, where the Tokyo metropolitan area extends. The size of the area is classified as a meso-γ-scale, which is regarded as an environment for cumulonimbus clouds over the Kanto Plain (NT11).

Although the basic performance of the MRI’s AGCM is validated against the observed climate (Mizuta et al., 2006, Kitoh et al., 2009), the representation of the synoptically undisturbed condition in the present-climate simulation needs to be evaluated. For this purpose, we use the upper-air observations by radiosondes at the Tateno station in Tsukuba during the period of 1976–2010. We also use the data of Automated Meteorological Data Acquisition System (AMeDAS) observations in order to extract synoptically undisturbed days during 1976–2010 by the same procedure with that in NT11.

**Analysis method**

In order to extract the synoptically undisturbed conditions from the GCM simulations, we impose the criteria against the GCM outputs at 0900 Japan Standard Time (JST) with the following steps: 1) to use the data for August to minimize the Baiu effects; 2) to extract days with 500-hPa winds of less than 10 m s⁻¹ and wind differences between the levels of 500 and 975 hPa of less than 8 m s⁻¹; and 3) to choose days with rainfall of less than 1 mm during 0000 to 1200 JST at all the grids in the analysis area. The condition of weak vertical shear and weak upper-level wind was compared with the method of NT11 and was shown to be useful in identifying the synoptically undisturbed condition (Takemi et al., 2012). The numbers of the synoptically undisturbed days are 182 for the present climate and 128 for the future climate.

Because this study is specifically interested in the condition with afternoon precipitation events, rainy days are further chosen from the days extracted through the three steps mentioned above. Precipitation amounts are computed from the hourly outputs of the AGCM simulations. Rainy days were defined as having total precipitation during the afternoon hours (i.e., 1200–0000 JST) of equal to or greater than 5 mm at any grid points in the analysis area (Takemi et al., 2012). After this final step to extract the rainy days, the numbers of the cases extracted are 58 for the present and 51 for the future.
Figure 2 shows the vertical profiles of temperature and water vapor mixing ratio averaged for the rainy days obtained by the present-climate simulation (at the Tateno grid point) and by the radiosonde observations. The agreement of the simulated results with the observations is quite favorable, although there are some noticeable differences of the simulations from the observations: underestimation (over-estimation) of temperature at low (upper) levels and overestimation (underestimation) of mixing ratio at low (upper) levels. Because of the overall agreement, we consider that the simulated data are useful in assessing the regional changes of the stability condition from the present climate to the future state under global warming.

To diagnose the atmospheric stability condition we examine the characteristics of some commonly used stability indices; i.e., Showalter stability index (SSI), lifted index (LI), K-index (KI), and total-totals index (TT). The definitions of these indices can be found in standard textbooks such as Bluestein (1993), but for the later discussion as well as the readers’ convenience the definitions of these indices are given as follows:

\[
SSI = T_{500} - T^{*}_{850-\text{sfc}},
\]

\[
LI = T_{500} - T^{*}_{850-\text{sfc}},
\]

\[
KI = T_{850} - T_{500} + Td_{500} - (T_{700} - Td_{700}),
\]

\[
TT = (T_{850} - T_{500}) + (Td_{850} - T_{500}),
\]

where \(T_p\) and \(Td\) are respectively temperature and dew-point temperature at the pressure level \(p\) (hPa), and \(T^{*}_{850-\text{sfc}}\) is the 500-hPa temperature that an air parcel acquires through adiabatically lifted from the 850-hPa (surface) level to the 500-hPa level. In calculating LI the 975-hPa level was regarded as the surface.

The atmosphere is diagnosed as more unstable with smaller SSI, smaller LI, larger KI, and larger TT. It was found in NT11 that SSI, LI, KI, and TT outperform the other stability parameters examined in their study and KI performs the best in distinguishing no-rain and rain events among all the parameters examined.

In the followings we will describe the differences of the stability condition between the present and the future climate simulated by the AGCM. The statistical significance of these differences is assessed by t-test statistic, \(T\), defined as:

\[
T = \left| x_A - x_B \right| \cdot \left( \frac{\sigma_A^2}{n_A} + \frac{\sigma_B^2}{n_B} \right)^{-\frac{1}{2}},
\]

where \(x_A\) and \(x_B\) are the mean values for category A (the number is \(n_A\)) and B (the number is \(n_B\)), respectively, and \(\sigma_A\) and \(\sigma_B\) are the standard deviations. The statistical significance with a confidence level of 95% is confirmed if \(T\) exceeds a specified threshold for the confidence level. This approach is useful in diagnosing the statistical significance of the differences of the stability parameters between no-rain and rainy days as demonstrated in NT11. In the analyses described in the next section, category A and B corresponds to the rainy cases in the present and the future climate, respectively.

**RESULTS**

In this section the differences of the stability condition for afternoon convective precipitation from the present climate to the future are demonstrated.

Figures 3a and 3b show the vertical distributions of the mean differences of temperature and water vapor mixing ratio, respectively, averaged over the analysis area and for the rainy days at 0900 JST between the present and the future climate. These differences are compared with those averaged for all the days in August. It is clearly demonstrated that the differences for the rainy days are about 1.5–2 times larger than those for all the August days, which indicates that the future changes of temperature and moisture for afternoon precipitation events are more enhanced than those for the overall mean atmospheric state. The atmosphere for the precipitation events is stabilized in terms of temperature lapse rate in the future climate (Figure 3a) while it is destabilized in terms of the increase in low-level moisture content (Figure 3b). These changes from the present to the future climate result in the increase of mean precipitable water from 48.6 to 53.8 (in kg m\(^{-2}\)) and the increase of convective available potential energy (CAPE) from 297 to 463 (in J kg\(^{-1}\)). This means that the destabilizing effect due to the moisture increase outweighs the stabilizing effect. From the analysis of t-test statistic, the differences for the rainy days between the present and the future state are statistically significant at all the levels (Figures 3c and 3d).

The differences in the stability indices are examined next. Figure 4 compares the frequency distributions of the stability indices in the simulated present climate and the future climate. In the future climate, the distributions of SSI, LI, and KI shift toward more unstable states. On the other hands, the changes in the distribution of TT is not consistent with the shifts in other indices. These shifts can also be identified in the changes of the mean values from the present to the future climate: decrease by 0.84, decrease by 0.41, and increase by 3.2 for SSI, LI, and KI (i.e., more unstable), respectively, but decrease by 1.0 for TT (i.e., more stable).

The differences of these mean values between the present and the future climate are statistically assessed by t-test.
The T values for SSI, LI, KI, and TT are 2.45, 2.16, 2.32, and 0.53, respectively. Because the threshold for the 95-% confidence level is $T = 1.96$, the differences of SSI, LI, and KI are statistically significant. The stability signature indicated by the TT difference is not statistically significant.

The statistical characteristics shown in Figure 4 can be understood by the vertical distributions of the changes in temperature and moisture shown in Figures 3a and 3b. The amount of the increase in moisture content is concentrated below the level of 700 hPa. Since the relative humidity at each height does not significantly change from the present climate to the future (Takemi et al., 2012), the increase in temperature as well as moisture content below the 700-hPa level leads to the increase in dew-point temperature. Therefore, KI increases owing to the increases in 850-hPa temperature and 850- and 700-hPa dew-point temperatures (see Equation (3)). SSI and LI decrease owing to the increase in low-level dew-point temperatures and hence the increase in adiabatically computed temperature at the 500-hPa level (see Equations (1) and (2)). The reason why there is no statistically significant change in TT is because TT only accounts the low-level moisture increases as the 850-hPa dew-point temperature and is more strongly influenced by the change in 500-hPa temperature than KI (see Equations (3) and (4)).

As investigated by Takemi et al. (2012) for synoptically undisturbed conditions in summer and by Kanada et al. (2010a) for precipitation events during the Baiu periods, temperature lapse rate is decreased and precipitable water and CAPE are increased from the present climate to the future. In addition to these changes, it is indicated that a tendency toward destabilization projected in the future climate clearly appears as the changes in some of the commonly used stability indices. Because the temperature lapse rate in the lower part of the troposphere is decreased (Figure 3a), the destabilization in the future climate seen in Figures 4a–4c is considered to be largely affected by the increase in the moisture content below the 700-hPa level.

The increase in moisture content from the present climate to the future is closely tied to the increase in temperature, since relative humidity does not significantly change throughout the troposphere. From the Clapeyron-Clausius relationship, the air with a higher temperature can include a larger amount of water vapor content, if relative humidity is unchanged. Therefore, it is easily understood that, as indicated in Figure 3b, the total amount of the moisture increase below the 700-hPa level is much larger than that above the 700-hPa level. In this way, the effects of future warming result in the moisture increase favorably at the lower levels.

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Figure 3. Vertical profiles of the mean differences of (a) temperature and (b) water vapor mixing ratio over the analysis area at 0900 JST between the future and the present climate in the rainy cases (solid line) and in all the cases in August (dotted line). Vertical distribution of the $T$ values for (c) the temperature difference and (d) the mixing ratio difference between the future and the present climate in the rainy cases. In (a) and (b) the positive differences indicate that the future case is larger than the present case, while in (c) and (d) the threshold of the statistical significance level ($T = 1.96$) is indicated by thin dotted lines.

Figure 4. The frequency distribution of (a) Showalter stability index, (b) lifted index, (c) K index, and (d) total-totals index in the present (dotted line) and the future climate (solid line) for the rainy cases. The $T$ values for the differences of the mean values between the future and the present climate are also shown in each panel.
CONCLUSIONS AND DISCUSSION

From the analyses of the outputs of the 20-km-mesh GCM simulations for the present climate (corresponds to the period of 1980–2004) and a future climate under global warming (corresponds to the period of 2075–2099), the changes of the stability conditions before the occurrence of precipitation in synoptically undisturbed settings in summer were assessed at a regional-scale. The environments on rainy days over the Kanto Plain were examined as a case study.

Temperature and water vapor mixing ratio throughout the troposphere are projected to increase more in the rainy cases than in the August mean cases from the present climate to the future. The temperature increase is larger at higher levels, while the moisture increase is larger at lower levels. These result in the decrease in temperature lapse rate and the increases in precipitable water and CAPE. Some stability indices, i.e., SSI, LI, and KI, indicate a destabilizing tendency with a statistical significance, because these indices take into account the increases in temperature and moisture below the 700-hPa level. These results are reflected from the simulated projection that future warming contributes to the increase in moisture favorably at low levels.

An implication for precipitation features under the synoptically undisturbed conditions in a future warming climate is discussed here from the viewpoint of stability condition. By conducting cloud-resolving simulations with idealized settings, Takemi (2007a, 2007b, 2010) examined the responses of precipitating convective systems to the vertical profiles of temperature and moisture in horizontally homogeneous environmental states with various wind shear profiles. It was found that the total precipitation amount generated by the systems increases with the increase in CAPE and precipitable water and noted that some stability indices such as KI well perform in delineating precipitation features. Weak shear conditions considered by his studies conform to the wind condition set in this study and the horizontally homogeneous states in his studies can be regarded as an idealized condition for the synoptically undisturbed state defined in this study. Therefore, the results by his studies should be used as an implication for this study. This is the basis of the discussion herein.

From the projected changes, revealed by this study, in the stability condition for precipitation occurrence as well as the results of Takemi (2007a, 2007b, 2010), the precipitation amount is considered to increase if a cumulonimbus cloud and its organized systems once develop. Although the stability condition for the precipitation events is more unstable than the normal condition even in the real climate (NT11), that condition in the projected future climate will be more favorable for the development of convective clouds. In other words, the degree of the destabilization of precipitation environments is projected to increase more significantly than that of non-precipitation environments, and therefore, the precipitation will be more intensified in a future climate.

The reason why the destabilization for the development of convective precipitation is more significant remains still unknown. Fundamental understandings for convective dynamics are required for revealing this unknown problem.

Finally, the usefulness of the high-resolution GCM outputs is emphasized here. In general the physically meaningful scales represented in numerical simulations are a couple of times larger than the computational resolution (Skamarock, 2004). Therefore, from the numerical aspect the scales larger than about 100 km are adequately represented in the current GCM. In other words, the high-resolution simulation outputs used here make it available to assess some aspects of regional-scale climate changes under global warming.

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