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Environmental Stability for Convective Precipitation Under Global Warming

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1. Introduction

Severe convective weather induces various types of local-scale meteorological disasters, e.g., torrential rain, flush flooding, tornadoes, and damaging winds, which have significant impacts on our societal environments. Such convective weather is caused mostly by atmospheric deep convection that accompanies cumulonimbus clouds. With the explosive development and extension of densely populated, metropolitan areas worldwide, vulnerability of such areas to extreme convective weather is rapidly increasing. Therefore, accurate short-term forecasting and reliable long-term projections of extreme convective weather are critically important for the prevention and mitigation of induced disasters.

As far as precipitation is concerned, cumulonimbus clouds primarily spawn extreme precipitation events. In a future climate under global warming, it is anticipated that convective weather including extreme precipitation is more prevalent and more intensified in various regions of the world. Previous studies indicated that extreme events producing heavy rainfall are projected to increase in a global warming climate (Kimoto et al., 2005; Kamiguchi et al., 2006). In the Fourth Assessment Report (AR4) from the Intergovernmental Panel on Climate Change (IPCC) (2007), it is summarized that under future global warming the intensity of precipitation events is projected to increase particularly in tropical and high latitude areas. Furthermore, the IPCC report says that in the warming climate the precipitation extremes are more enhanced than the precipitation means in most tropical and mid-/high-latitude areas. However, such future projections on precipitation characteristics are based on the numerical experiments by general circulation models (GCMs) that have horizontal resolutions of much coarser than the scales of individual cumulonimbus clouds, which means that the convective precipitation is not explicitly resolved but only represented by a parameterized way. Characteristics of extreme precipitation events due to deep convection under global warming, therefore, require further investigations in order to gain deeper understandings of convective precipitation under global warming.

Even if we are not concerned with the long-term changes of convective precipitation but the short-term forecasts, we are still far from accurately predicting the times and locations of the occurrence of convective precipitation. Such difficulty in predicting the behaviour of cumulonimbus clouds not only in climatic timescales but also in daily-weather timescales is due to the chaotic nature and randomness of convection development. In this sense, quantitative evaluations of convective precipitation become harder if the area of interest is smaller. On the other hand, we need regional-scale evaluations of convective precipitation not only in weather forecasting but also in climate projections. At this time we are facing critical challenges in dealing with the quantitative evaluations of convective precipitation at regional scales not only in short timescales but also in long-range climate timescales. In contrast, the horizontal scales of the environments for the development of deep convective clouds are in general an order of magnitude larger than the scales of individual deep clouds. The environmental conditions for convective weather have been widely investigated in the literature (Bluestein, 1993; Emanuel, 1994; Cotton et al., 2011) and are relatively tractable owing to their longer timescales and larger spatial-scales than convective clouds themselves. Therefore, in this study we deal with the environmental conditions for deep convection rather than consider deep convection itself.

Since deep convection develops under unstably stratified conditions, the vertical stability of the stratified atmosphere plays a critical role in determining the development of deep convection. Therefore, in order to understand how and to what degree cumulonimbus clouds develop, it is important to obtain the information on the stability of the atmosphere that is the environment for such deep convection. The environmental conditions for the occurrence of cumulonimbus clouds have been investigated by a large number of studies in the atmospheric science community, which can be found in standard meteorological textbooks (e.g., Bluestein, 1993; Emanuel, 1994; Cotton et al., 2011), and it is widely understood that the environmental conditions strongly control the development, structure, and organization of deep convective clouds and hence the characteristics of associating precipitation (see the review of Houze, 2004 and the references therein). As mentioned above, the future changes of the characteristics of convective precipitation, therefore, should be investigated not only in terms of the precipitation characteristics themselves but also in terms of the environmental stability conditions for deep convective clouds.

Of course, the activity of deep convective clouds is not only regulated by the vertical environmental stability but also by larger-scale weather disturbances such as tropical and extra-tropical cyclones, fronts, and planetary waves. Generally speaking, the control of large-scale weather disturbances in determining the development and organization of deep convective clouds is considered to be much stronger than that without such large-scale effects. Therefore, the precipitation characteristics under global warming have been in most cases investigated in the context of synoptic-scale and/or planetary-scale controls. For example in Japan, the features of monsoon-related rainfall (i.e., Baiu-period rainfall) in future warming climates have been extensively investigated (e.g., Yoshizaki et al. 2005; Kusunoki et al. 2006; Ninomiya 2009; Kusunoki et al. 2011). In other words, the precipitation characteristics significantly depend on the representations of such background large-scale disturbances for which legitimate validation for their representations in climate models is not well founded. Considering these uncertainties, it should not be ruled out to investigate the environmental stability conditions for deep convection without the presence of major large-scale disturbances. It is clear that there are also cases in which deep convective clouds develop under synoptically undisturbed conditions. In these cases, the intensity and organization of deep convective clouds depend on the degree of a convectively unstable state. Del Genio et al. (2007) considered how the intensity of deep convection changes under global warming by examining updraft velocity in response to temperature lapse rate estimated from a simple buoyant energy formulation. Their theoretical approach is based on the idea that the intensity of deep convection depends on the vertical stability that would be determined by synoptic-scale meteorological settings with both disturbed and undisturbed natures. Although external forcings such as synoptic-scale disturbances will play a critical role in determining the intensity of deep convection, the consideration based on a simple theoretical/analytical/experimental framework like the one done in Del Genio et al. (2007) will give theoretical foundations and basic understandings on the changes in deep convection and associating precipitation in a future warmer climate. Furthermore, the changes of vertical stability in the tropical atmosphere were also focused by Santer et al. (2008) in order to understand the modelled temperature trends in GCMs. In this sense, we consider that synoptically undisturbed conditions are a good test bed for discussing convective precipitation under global warming, since we are able to regard the effects of external forcings to be minimal.

In this study, we investigate the environmental stability for precipitating deep convection in synoptically undisturbed conditions under the influence of global warming. Synoptically undisturbed conditions are specifically focused on in order to distinguish the influences of environmental stability on deep convection from large-scale effects.

This chapter is organized as follows. Firstly, the rationale of the present analyses is described in Section 2. We will choose the Tokyo metropolitan area over a flat plain as our analysis region. A wide flat area is favorable for the present study, since the effects of complex topography will not be a major factor. In addition, there are a number of previous studies that investigated the environmental conditions for summertime thunderstorms in that area (Yonetani 1975; Taguchi et al. 2002; Kawano et al. 2004; Nomura and Takemi 2011, hereafter NT11). Next, the changes of the environmental stability in the analysis region are examined from the past observed records. The temporal variability of the environmental conditions in the Tokyo area over the last 35 years are described with the use of surface and upper-air meteorological observations, which will be described in Section 3. In Section 4, we extend our considerations on convective precipitation under future climate conditions. We examine the projected changes of the environmental stability under future global warming by using the outputs of high-resolution global climate simulations at a 20-km resolution. In Section 5, thoughts from these analyses are given as concluding remarks.

2. Environmental stability and deep convection

The intensity of convectively induced precipitation is directly controlled by the structure, organization, and intensity of a single and/or a system of deep cumulonimbus clouds and thus can be related to and diagnosed by the conditions of the convective environments. Vertical wind shear determines the structure and organization of convective systems and hence their intensity, while temperature and moisture conditions characterize static stability that would control the development and maintenance of convective systems.

In our previous works on the sensitivity of mesoscale convective systems (MCSs) to environmental shear, moisture, and temperature profiles, Takemi (2006) examined the effects of tropospheric moisture profile under a single temperature environment. Takemi (2007a), extending the study of Takemi (2006), compared the intensity of MCSs simulated in two contrasting temperature environments characteristic of the Tropics and the midlatitudes under a comparable CAPE condition and found that the midlatitude system is significantly stronger than the tropical one. Takemi (2007a) concluded that the static stability can be regarded as a key parameter that describes the MCS intensity. Takemi (2007b) further investigated numerically the effects of static stability on the MCS intensity by systematically changing temperature lapse rate with CAPE being unchanged. He showed that a colder environment (which is more unstable) is favorable for generating stronger cold pool, which will highly control the scale and strength of convective updrafts and hence the organization and intensity of MCSs. Furthermore, Takemi (2010) concluded that temperature lapse rate in the convectively unstable troposphere is useful in comparing the characteristics of precipitation produced by MCSs that occur in various climate regions of the world. It should be pointed out that the experimental setup employed in those numerical studies was a highly idealized one which assumes horizontally homogeneous stratifications as basic environmental states. Accordingly, the MCS behaviors in such horizontally homogeneous states are regarded as representing deep convection under synoptically undisturbed conditions.

Recent study of NT11 has investigated the environmental stability for afternoon convective rainfalls during summertime under synoptically undisturbed environments over a plain region that includes the Tokyo metropolitan area in Japan. The conventional surface observation data as well as weather charts were used to extract the hot, sunny days under synoptically undisturbed conditions, and the gridded mesoscale analysis data (which have a horizontal resolution of 10 or 5 km) that cover the Tokyo area were used to examine the difference of the characteristics of environmental stability between no-rain, rain, and strong-rain events in the afternoon by calculating stability indices and parameters. The stability indices are useful diagnostic parameters in identifying locations and/or times with high convective potential and therefore are commonly used in the meteorological community. The stability indices and parameters examined in NT11 are convective available potential energy (CAPE), convective inhibition (CIN), lifting condensation level (LCL), level of free convection (LFC), level of neutral buoyancy (LNB), Showalter stability index (SSI), lifted index (LI), K-index (KI), total-totals index (TT), temperature lapse rate from 950 hPa to 500 hPa (TLR), and precipitable water (PW), most of which have been widely used in the literature. Definitions and meanings of the stability indices can be found in Bluestein (1993). In the study of NT11, statistical analysis by t-test statistic was conducted to determine the significance of the distinguishing features of the stability parameters among the no-rain, rain, and strong-rain events. Among the parameters, K-index (George, 1960) indicated the highest significance level. The analyses on the difference of temperature and humidity at each height among the events indicated that the temperatures and moistures at low to middle levels clearly distinguish the stability conditions for the afternoon rain events.

In this way, the environmental thermodynamic stability controls the development, intensity, and organization of deep convective clouds, especially under synoptically undisturbed conditions. Moreover, some studies emphasized the importance of environmental conditions for extreme events in simulated future climates under global warming. For the cases of tropical cyclones, Sugi et al. (2002) noted that the decrease in the occurrence of tropical cyclones in their simulated future climates is due to more stable environments. For the cases of convective precipitation events, on the other hand, Kanada et al. (2010) found that static stability as well as moisture content is more increased in the future climate simulated by a non-hydrostatic regional climate model. In addition, they pointed out that the increased CAPE would result in stronger updrafts and hence intense precipitation. The results of these studies strongly suggest that the environmental stability is closely related to the intensity and behavior of extreme weather.

Based on the above studies, the changes of the environmental stability from the past and in the future will be investigated in the following sections. The Tokyo metropolitan area is chosen as the analysis region, since there are a number of previous studies that investigated the stability conditions for deep convection or thunderstorms over the region (e.g., Yonetani, 1975). The Tokyo metropolitan area is located in the Kanto Plain, the largest plain area in Japan. The reason why a mesoscale region is chosen is because stability conditions widely change even over Japan depending on locations and seasons (Chuda and Niino, 2005). Thus it is convenient to focus on a mesoscale region for the analysis on convective environments.

3. Variation of environmental stability from the past observations

This section provides the results of the analyses on the environmental stability with the use of past records. Conventional meteorological observations during 35 years are examined to demonstrate the variability of the environmental stability under synoptically undisturbed conditions.

3.1 Data and analysis procedure

The environmental stability over the Tokyo metropolitan area or the Kanto Plain is examined here. There is a dense network of surface meteorological observations at horizontal spacings of about 20 km in Japan, called the Automated Meteorological Data Acquisition System (AMeDAS) in addition to the upper-air observations by radiosondes. The data by these conventional observations are used in the present section.

The AMeDAS stations over the Kanto Plain around Tokyo (i.e., within the area of latitude 35.2-36.2 degrees north and longitude 139.00-142.25 degrees east) with their elevations of below 100 m above the mean sea level are selected. On the other hand, the upper-air data used for the calculations of the stability indices and parameters are those obtained at the Tateno station (36.057 degrees north and 140.125 degrees east) located at about 50 km distance northeast of Tokyo. The location is within the Kanto Plain and far from the mountains; therefore, even at one upper-air station, the observations are considered to represent the characteristics over the whole analysis region at least in a climatological sense. The period of these surface and upper-air data used is during the years of 1976-2010, and the July and August data are chosen in order to focus on typical summertime undisturbed conditions.

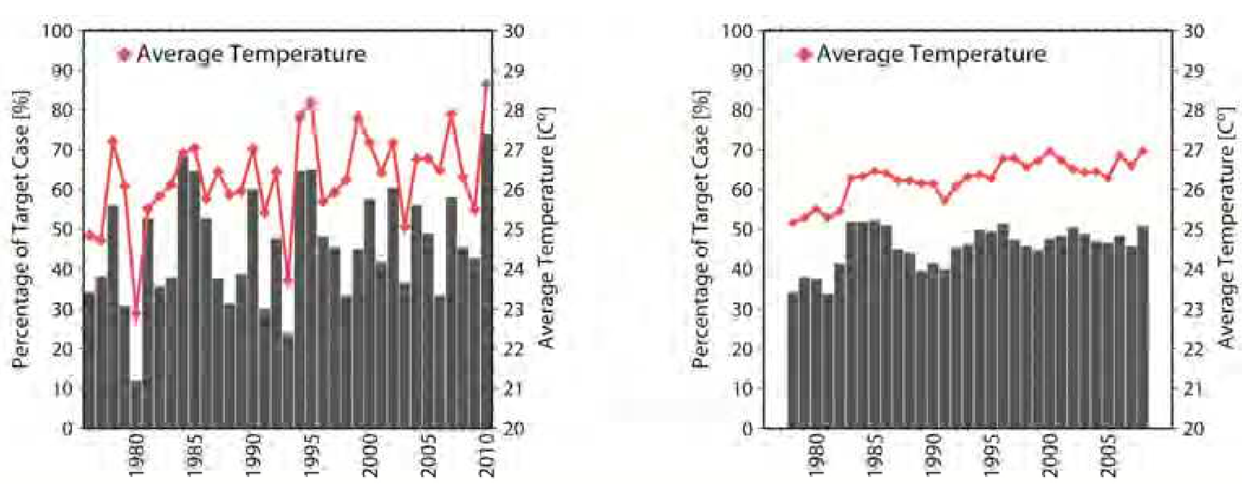

Fig. 1. Time series of (a) the percentage number of the undisturbed days among the total number of days in July and August during 1976-2010 and the annual-mean temperature averaged over the chosen days and (b) the 5-year running means for those shown in (a).

The AMeDAS data as well as surface weather charts issued by Japan Meteorological Agency (JMA) are examined to extract synoptically undisturbed conditions during July and August for the period of 1976-2010. The details of the procedure to extract the undisturbed conditions are given in NT11, but for readers' convenience the procedure is briefly described here. At first, days with the daily maximum temperature exceeding 30 degrees Celsius at least one AMeDAS station in the analysis region are chosen. Secondly, among the chosen days, the days without precipitation during the morning hours at any AMeDAS stations are selected. Thirdly, the days influenced by synoptic-scale disturbances (tropical cyclones, stationary fronts, and extra-tropical cyclones) are excluded by looking at surface weather maps at 0900 Japan Standard Time (hereafter referred to as JST) on those days. After these screenings, we are able to extract hot and sunny days (at least in the morning hours) which are considered to match synoptically undisturbed conditions. Totally 699 days are chosen from the 35-year dataset.

Actually, the number of the selected days widely varies year by year. Figure 1 shows the variation of the number (in percentage) of the undisturbed days among the total number of days in July and August during the period of 1976 and 2010 and their annual-mean temperature for the chosen days. Figure 1a clearly indicates a large variability of these properties throughout the time period. There seems to be a close correlation between the percentage number of the undisturbed days and the average temperature. This suggests that the average temperature increases with the increase in the number of the undisturbed days. Actually, the running means shown in Fig. 1b clearly demonstrate that the average temperature increases with the increase in the number of the undisturbed cases.

Although there is a large variability in the number of the undisturbed days during the analysis period, it was indicated that there is an increasing trend of the surface air temperature irrespective of the variability of the undisturbed occurrence (not shown). These results suggest that the warming trend appears also in the undisturbed situations. Based on this situation, the variability of the environmental stability is examined from the upper-air observations.

For reference, the frequency distributions of maximum hourly precipitation on the chosen days during the period of 2002-2010 (which was investigated in NT11) and the period of 1976-2010 are exhibited in Figure 2. It is clearly seen that intense precipitation events do occur even under synoptically undisturbed conditions.

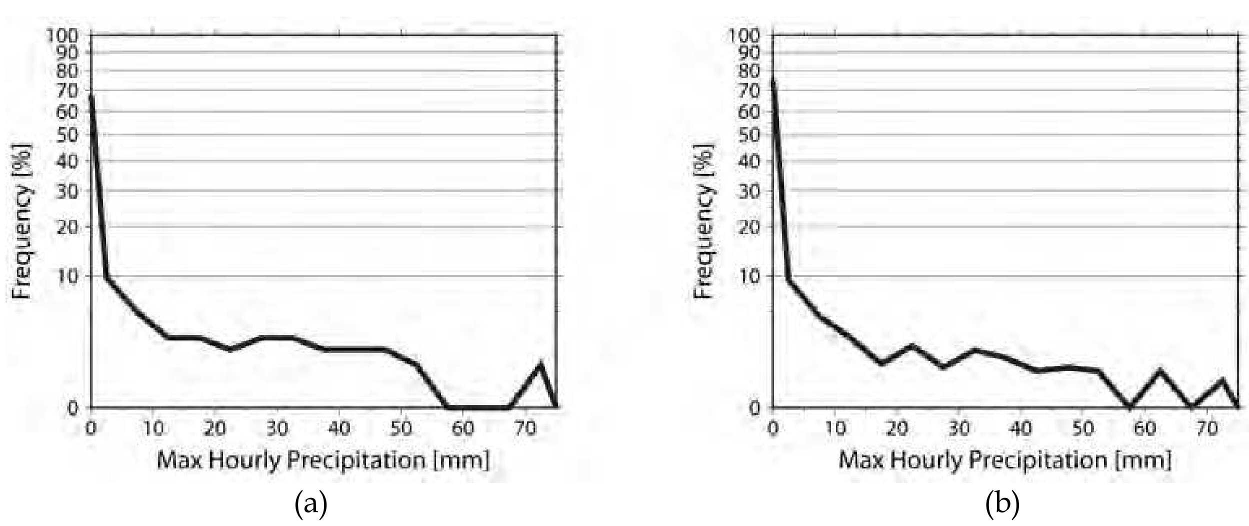

Fig. 2. The frequency distribution of maximum hourly precipitation for (a) the period of 2002 and 2010, which was examined in NT11, and (b) the period of 1976 and 2010.

3.2 Results

The stability indices and parameters mentioned in Section 2, .i.e.: CAPE; CIN; LCL; LFC; LNB; SSI; LI; KI; TT; TLR; and PW, are calculated from the observation data that meet the synoptically undisturbed criteria. Figure 3 shows the time series of the annual means of these stability parameters. In order to demonstrate the long-term trend, 5-year running

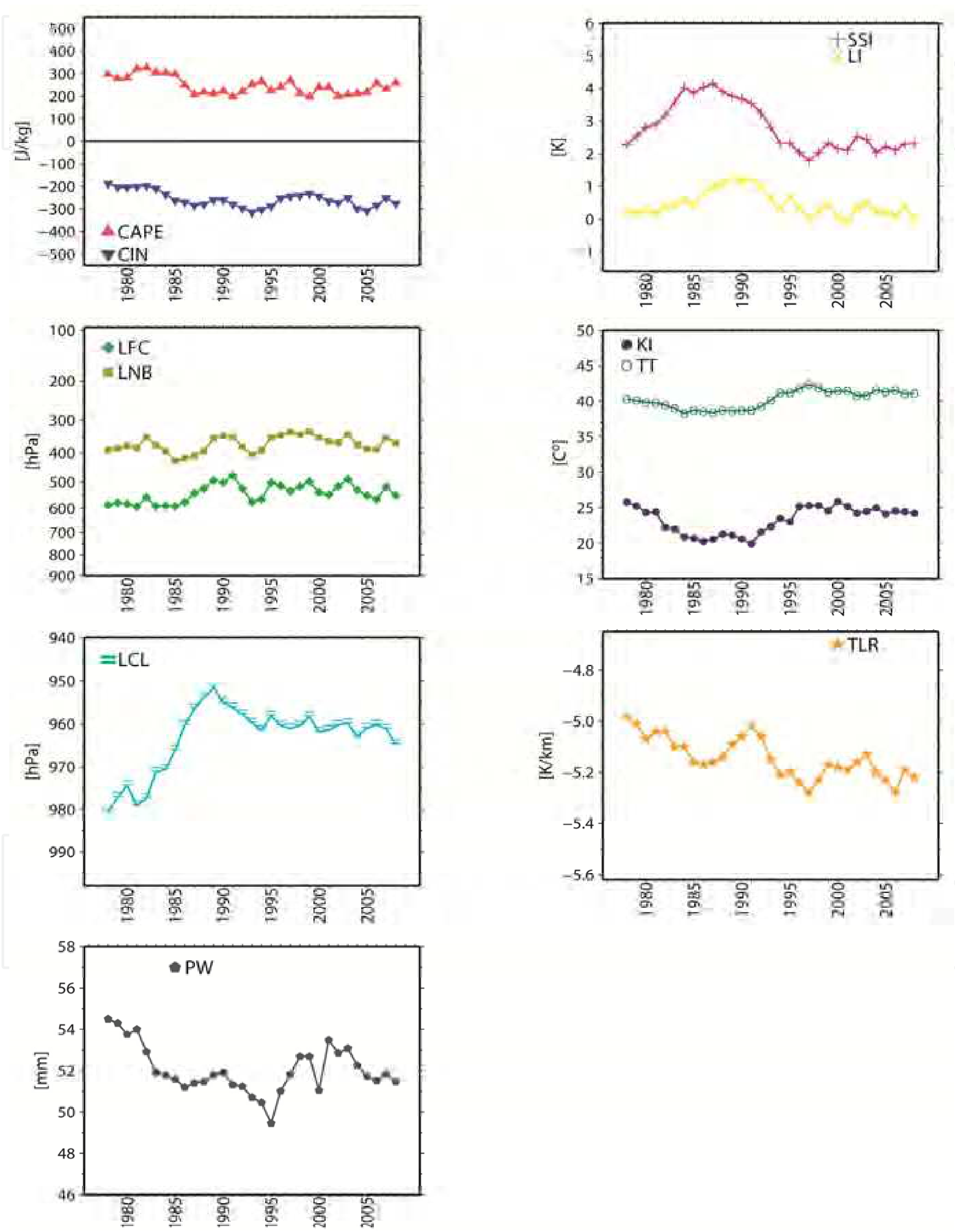

Fig. 3. Time series of the environmental indices and parameters from 1976 to 2010. The data are running means for 5-year period.

means were taken for the annual mean values. Noticeable features are seen for CAPE, CIN, TLR, and PW. CAPE and PW appear to be smaller with time, while the absolute values of CIN and TLR are seen to become larger with time. Smaller CAPE and larger CIN suggest that the atmosphere becomes more stabilized in terms of buoyant energy perspective, while larger TLR indicates that the atmosphere becomes more statically unstable. These points seem to be contradicting, but the reason why this happens is understood by the change in PW. The decrease in PW, indicating that the atmospheric moisture becomes smaller, suggests that it is getting drier. The lower moisture content is considered to be more dominant in reducing the buoyant energy than the contribution from the increase in the temperature lapse rate. It is also found that the LFC and LCL become larger with time, again indicating that the atmosphere is more stabilized.

In order to examine the statistical significance of the changes in these stability parameters, we use the t-test statistic for the differences between the averages during the first 10 years (1976-1985) and during the recent 10 years (2001-2010). The period of the first 10 years is referred to as Past, while the recent 10-year period as Present. The number of the chosen days is 192 for the Past period and is 217 for the Present period.

Test static, T, is defined as:

$$T = \left(x_A - x_B\right)\left(\frac{\sigma_A^2}{n_A} + \frac{\sigma_B^2}{n_B}\right)^{-\frac{1}{2}}, \tag{1}$$

where x_A and x_B are the means for category A and B, respectively, σ_A and σ_B the standard deviations, n_A and n_B denote the number of cases in each category. In this test, if T is larger than 1.96, a significant difference between the categories is statistically indicated. Otherwise, there is no significant difference between each category. A larger value of T means that the difference between each category is more significant.

Figure 4 exhibits the T-values obtained from the t-test statistical analysis as their properties as well as the bar plot. More unstable states in the Present (Past) period than in the Past (Present) are indicated as larger T-values in the Present (Past). It is shown that the

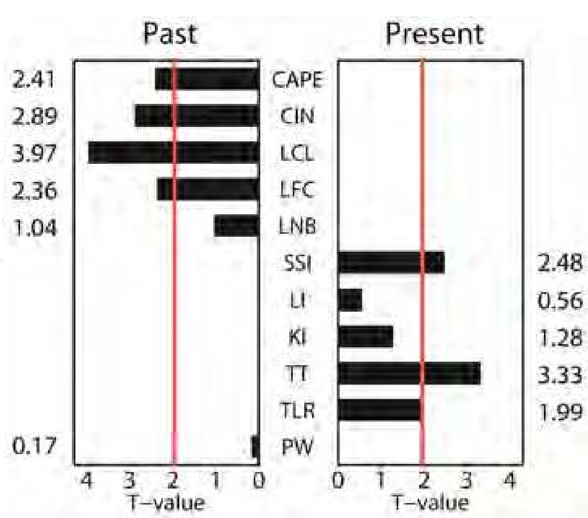

Fig. 4. T values from the t-test statistic for the difference between the averages during 1976-1985 (referred to as Past) and during 2001-2010 (referred to as Present). If the average during the Past indicates a more unstable situation than that during the Present, the bar is plotted in the Past panel. The significance level (1.96) is indicated by a red line.

parameters that exceed the significance level (1.96) for the present data are CAPE, CIN, LCL, LFC, SSI, TT, and TLR. This seems to be consistent with the trend shown in Figure 3. In terms of CAPE, CIN, LCL, and LFC, the atmosphere becomes more stabilized in the Present period than in the Past. In contrast, the temperature lapse rate becomes more unstable in the Present. Actually, the change in the moisture content (i.e., PW) is not statistically significant. The statistically significant trend indicated in Figure 3 is shown to be for CAPE, CIN, LCL, LFC, and TLR.

To see how the vertical profiles affect the significance of the temperature and moisture differences between the Past and the Present periods, we calculate the test statistic *T* for those differences at each height level. Figure 5 indicates the vertical distributions of the T values for the differences in temperature and relative humidity between the Past and the Present periods. The significant differences are seen in the middle layers of 800-600 hPa and at the 500-hPa level for temperature and in the lowest layer of below 900 hPa for relative humidity. In the Present period the 800-600 hPa layer becomes warmer while the 500-hPa level becomes colder. This leads to the increase in temperature lapse rate with time, as indicated in Figures 3 and 4. On the other hands, the reduction of relative humidity is only significant in the lowest levels, indicating that no significant difference is found for the PW change.

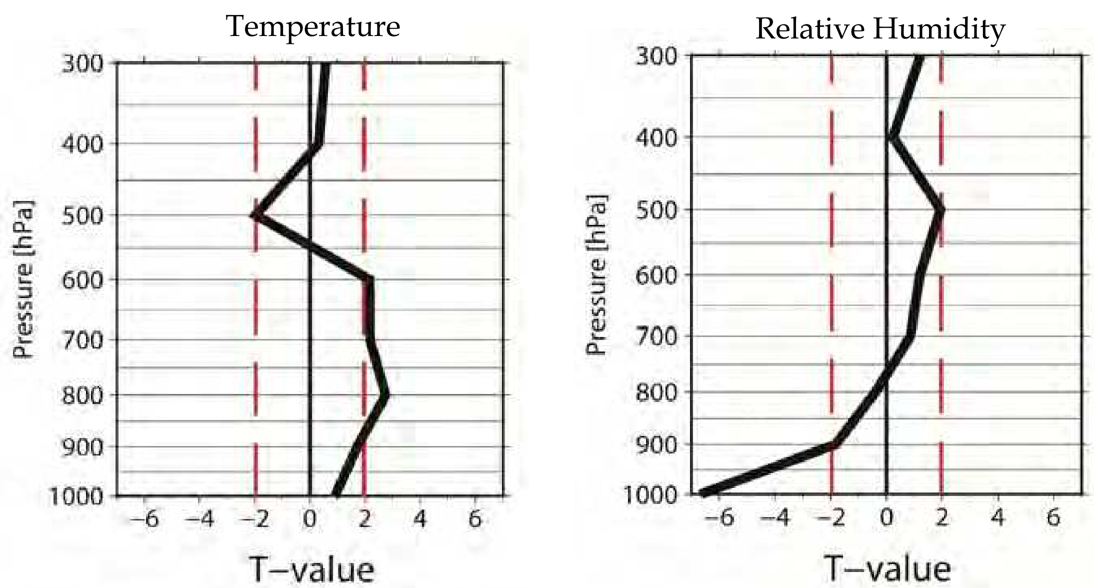

Fig. 5. The vertical profiles of the *T* values for the temperature and relative humidity differences between the Past and the Present periods. The red long-dashed lines indicate the significance level. The positive (negative) *T* value indicates that temperature and relative humidity are larger in the Present (Past) period than in the Past (Present).

4. Projected changes in environmental stability

In this section, we examine the future changes in the environmental stability under the undisturbed conditions by using the simulations outputs from a global circulation model (GCM) for the present and future climates.

4.1 Data and analysis procedure

The data for the present analysis are the gridded outputs at the 20-km horizontal resolution from an atmospheric global circulation model (AGCM) with the resolution of T959L60 (which means triangular truncation of 959 and 60 vertical levels) for present climate and future warming climates. The AGCM was developed by Meteorological Research Institute (MRI) of JMA under one of the projects in the Innovative Program of Climate Change Projection for the 21st Century (the KAKUSHIN program) (Kitoh et al., 2009) and is called as MRI-AGCM3.2S. The original version of this GCM was developed by Mizuta et al. (2006) and has been updated for the KAKUSHIN program (Murakami and Wang, 2010; Kusunoki et al., 2011).

The simulations with MRI-AGCM3.2S were performed for the climate periods of 30 years to represent the present climate (corresponding to the period of 1979-2008), the near-future climate (corresponding to the period of 2015-2044), and the future climate (corresponding to the period of 2074-2104). The near-future and future climate simulations assume a global warming scenario, the A1B IPCC emission scenario (IPCC, 2007). The preliminary experiments (Kitoh et al., 2009) indicated that the simulated present climate was almost the same as that in Mizuta et al. (2006) who validated their GCM simulations with the observed data. Therefore, the present-climate simulation with MRI-AGCM3.2S is considered to be successful in representing the existing climate states. In this study, we use the data periods of 1980-2004 for the present climate, 2020-2044 for the near-future climate, and 2075-2099 for the future climate. The time intervals of the outputs are 1 hour for the surface variables and 6 hours for the upper-air variables.

In order to extract undisturbed conditions from the climate simulation data in which no weather charts and no surface observations are available (although of course there are surface-level outputs from the GCM simulations), we need to employ an objective approach. For this purpose, we examined the meteorological characteristics representative of the synoptically undisturbed conditions from the radiosonde observations and found that the vertical shears of the horizontal winds as well as the wind speeds at upper levels are quite small. This character is clearly distinct from the wind conditions for severe storms and squall lines (Bluestein and Jain, 1985). Therefore, to objectively choose the undisturbed conditions, we apply criteria on wind speed and shear from the GCM outputs. By taking the spatial averages for the wind speeds over the analysis area (i.e., the Tokyo area, part of the Kanto Plain), we examine the following criteria: 1) to use the data only in August to avoid monsoonal stationary fronts; 2) to exclude days with the 500-hPa wind speed of equal to or greater than 10 m s^{-1} and the wind shear of less than 8 m s^{-1} in the layer of 500 and 975 hPa; and 3) to choose days having rainfall of less than 1 mm during the morning period at all the grid points in the analysis area.

To validate this objective approach, we examined the 35-year upper-air observation data and compared the mean vertical profiles of temperature and moisture averaged for the undisturbed conditions independently extracted by the NT11 observation-based approach and by the present objective approach. The number of days chosen by the NT11 approach was 699 (as mentioned in Section 3), while that by the objective approach was 344. Three hundred cases out of the 344 cases extracted by this objective approach satisfy also the NT11 conditions. The mean profiles for the objectively chosen cases were found to be very similar to those for the chosen cases as extracted in Section 3. In this way, the present objective approach is useful in identifying the undisturbed conditions from the GCM outputs.

By applying the objective criteria for the simulation data during the present-climate 25-year period, 182 days were extracted. The vertical profiles of temperature and moisture averaged for the extracted undisturbed cases were compared with the radiosonde observations for the undisturbed days extracted by the same objective approach. From the comparison, it was indicated that the vertical distributions of temperature and moisture obtained from the GCM simulation well capture the existing climate revealed by the upper-air observations. We have also compared the representations of the stability indices and parameters in the GCM simulation with those calculated by the observations and found that the GCM reproduces the general characteristics of the stability conditions. Based on these comparisons, the GCM outputs were demonstrated to be useful in investigating the characteristics of the environmental stability under the undisturbed conditions. In the following, we examine the projected changes in the environmental stability revealed by the GCM climate simulations.

The same criteria were also applied for the simulated near-future and future climates: 160 days were chosen for the near-future climate; and 128 days were chosen for the future climate. In the following, the changes in the stability parameters from the present climate to the future are examined.

4.2 Results

From the analyses on the upper-air observations described in Section 3, it was indicated that the changes in CAPE, CIN, and TLR over the last 35 years demonstrate a statistically significant trend. Thus, the characteristics of the representations of these three parameters in each simulated period are shown here.

Figure 6 compares the frequency distributions of the stability parameters, i.e., CAPE, CIN, and TLR, during the 25-year simulation periods of the present climate, the near-future climate, and the future climate. The higher values of CAPE become more frequent in the future climate, while at the same time the higher values of CIN become more frequent in the future. This result indicates that the potential instability for convection increases but that the energy required to raise low-level air parcels above LFC also increases. In terms of temperature lapse rate, the atmosphere becomes more stable in the future climate than in the present. We have also examined the frequency distributions of PW and found that the atmospheric moisture content increases.

The statistical significance for the differences in the means of the stability parameters between the present and the future climates is examined by t-test static. The T value indicating the significance level for this analysis is 1.96. The parameters that exceed the significance level for the differences between the present and the future climates are TLR (T=3.53), PW (T=7.11), CAPE (T=4.27), CIN (T=2.73), LNB (T=2.23), and LI (T=2.14): CAPE, CIN and PW become larger with the future period; TLR and LI become smaller; and LNB becomes higher.

This statistical analysis as well as the result shown in Figure 6 indicates that the atmosphere becomes more unstable in terms of CAPE, PW, and LNB with the future while becomes more stable in terms of temperature lapse rate and CIN. These results seem to be contradicting with each other, although some interpretations can be made. From the lapse rate change, the activity of deep convection is generally inhibited in the future climate. However, once deep convection develops after penetrating the level of free convection, the intensity of convection will be more enhanced with the consumption of CAPE.

The present analyses on the environmental stability under the synoptically undisturbed conditions from the GCM outputs showed that with the future period the temperature lapse rate in the lower troposphere becomes smaller while precipitable water vapor and CAPE become larger. By examining the statistical significance on the differences of temperature and moisture between the present and the future climates, it was indicated that the increase in precipitable water vapor was due to the increase in water vapor mixing ratio at all the vertical levels while the decrease in temperature lapse rate was due to the larger increase in temperature at higher levels. In addition, it was found that LNB becomes higher with the simulated period. On the other hand, LFC did not vary among the climate periods, although the statistical significance was not identified.

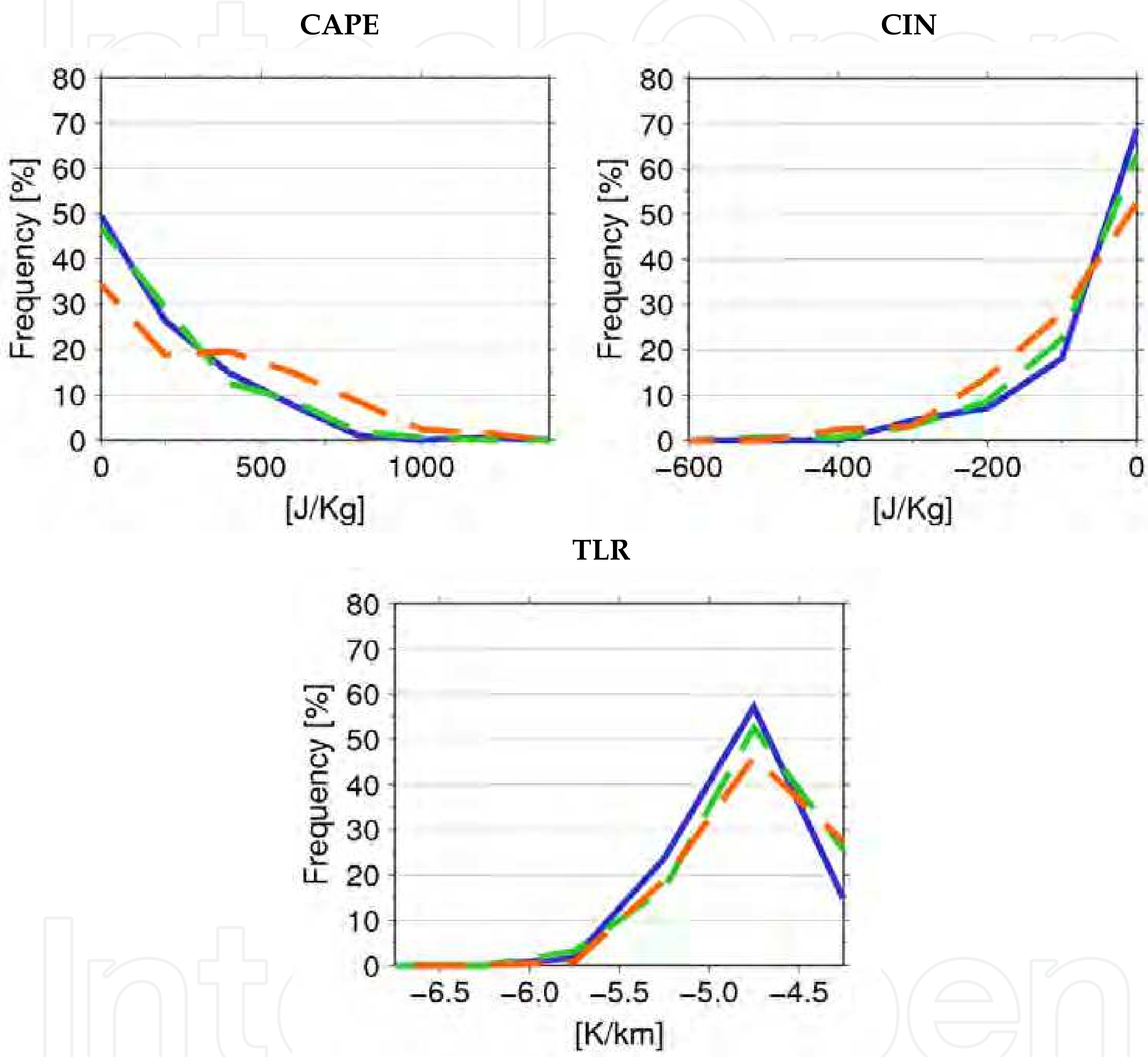

Fig. 6. The frequency distributions of CAPE (upper), CIN (middle), and TLR (lower) averaged over the analysis area during the 25-year periods of the present climate (blue line), the near future climate (green line), and the future climate (red line).

The unchanged height of LFC and the elevated height of LNB suggest that the integrated vertical path in calculating CAPE becomes deeper even with the decreased lapse rate. Considering that CAPE is the integrated buoyancy between LFC and LNB and that buoyancy will not be larger in a lower lapse rate than in a higher lapse rate, the increase in CAPE is considered to be primarily due to the increase in LNB. At the same time, the mean buoyancy between LFC and LNB (like the one defined as normalized CAPE in Blanchard 1998) will not significantly change among the climate periods. The maintained buoyancy with the future period is favorable for developing strong updrafts, since it cancels negative effects of enhanced entrainment in environments with lower lapse rates (Takemi 2007b). In this way, it is considered that the seemingly contrasting features of temperature lapse rate and CAPE in future climates enhance the activity of convection and precipitation.

The precipitation characteristics that will result from the projected changes in the environmental stability are discussed here. Takemi (2007b; 2010) investigated the precipitation characteristics within the MCSs by changing temperature lapse rate and moisture content as well as shear profile in an idealized simulation setup where the base-state atmosphere is horizontally uniform without any external forcing. This idealized setup is regarded as synoptically undisturbed, since only convective forcing is initial thermal and the resultant self-organizing effects. The weak shear condition (i.e., 5 m s^{-1} difference only in the lowest 2.5 km) examined in Takemi (2007b; 2010) corresponds to the synoptically undisturbed conditions examined in this study. Their results indicated that with the same CAPE environment convection intensity (represented as updraft strength) and mean precipitation decrease as temperature lapse rate decreases. In the environments projected in the future periods, temperature lapse rate decreases but CAPE increases. Consequently, convection intensity and mean precipitation does not decrease, according to the results of Takemi (2010). Precipitation amount will be maintained or even intensified in the future climates.

One of the interesting points in Takemi (2010) was that the maximum precipitation intensity increases with the decrease in temperature lapse rate while with CAPE being unchanged. On the other hand, the present analyses of the GCM data indicated that both static stability and CAPE increases. Applying the result of Takemi (2010) to the projected changes in the environmental stability, the precipitation intensity in short time-scales is suggested to increase.

5. Concluding remarks

From the analyses in the GCM climate simulation data, it was indicated that in the future climates temperature lapse rate decreased in the lower troposphere while water vapor mixing ratio increased throughout the deep troposphere. The changes in the temperature and moisture profiles resulted in the increase in both precipitable water vapor and CAPE, which were evaluated as statistically significant. These projected changes will be enhanced with the future period.

However, these projected changes are totally opposite from the analyses on the past 35-year observations. This observational evidence strongly suggests that the GCM simulations need to be investigated with sufficient cautions.

The environmental stability, especially in undisturbed cases, strongly controls the structure, development, and organization of deep convective clouds and associating precipitation. Long-term variability of the general characteristics of precipitation for cases in Japan has been investigated from statistical viewpoints by many studies such as Yonetani (1982), Iwashima and Yamamoto (1993), Fujibe (1998), Sato and Takahashi (2000), Kanae et al. (2004), Fujibe et al. (2005; 2006; 2009), Kamiguchi et al. (2010), and Iwasaki (2010). There have been arguments on the reason for the change in the frequency and intensity of precipitation: some studies attributed to global climate change (i.e., warming); and others implied the effects of urban heat island. However, there have been few studies on the changes in background conditions for such precipitation events in changing climates, that is, environmental characteristics for the development of rain-producing thunderstorms. Studies which investigate the connection between environmental stability and convective precipitation under global warming require sound observational evidence and/or implication.

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The failure of the UN climate change summit in Copenhagen in December 2009 to effectively reach a global agreement on emission reduction targets, led many within the developing world to view this as a reversal of the Kyoto Protocol and an attempt by the developed nations to shirk out of their responsibility for climate change. The issue of global warming has been at the top of the political agenda for a number of years and has become even more pressing with the rapid industrialization taking place in China and India. This book looks at the effects of climate change throughout different regions of the world and discusses to what extent cleantech and environmental initiatives such as the destruction of fluorinated greenhouse gases, biofuels, and the role of plant breeding and biotechnology. The book concludes with an insight into the socio-religious impact that global warming has, citing Christianity and Islam.