Monthly maximum number of consecutive dry days in Japan and its reproducibility by a 5-km-mesh cloud-system resolving regional climate model

Masuo Nakano¹, Sachie Kanada¹, Teruyuki Kato² and Kazuo Kurihara³
¹Japan Agency for Marine-Earth Science and Technology, Tsukuba, Ibaraki, Japan
²Japan Meteorological Agency, Chiyoda, Tokyo, Japan
³Meteorological Research Institute, Tsukuba, Ibaraki, Japan

Abstract:

The geographical distribution of the Monthly maximum number of Consecutive Dry Days (MCDD) over Japan during June–October in 2002–2006 is investigated from observed raingauge data. In June and July, areas with low MCDD (< 6 days) are analyzed associated with the climatological location of the Baiu front. In August, low MCDD [high MCDD (> 10 days)] is found in inland areas [coastal areas of the Seto Inland Sea, southern Kanto, and parts of Hokkaido]. In September and October, low MCDD [high MCDD] is found on the Japan Sea side of Honshu [in Kyushu and coastal areas of the Seto Inland Sea]. The reproducibility of the MCDD by a 5-km-mesh cloud-system resolving regional climate model (NHM-5km) is statistically examined in numerical experiments with regional objective analysis data of the Japan Meteorological Agency. NHM-5km performs well in reproducing the features of the local geographical distribution and seasonal march of MCDD, although MCDD is slightly overestimated. The MCDD values averaged for 11 sub-regions of Japan are compared with observations, revealing a good agreement (correlation coefficient, 0.755; root mean square error, 1.49; mean error, 1.10). Moreover, annual variations in MCDD averaged over Japan are well reproduced by the model.

KEYWORDS regional climate model; maximum number of consecutive dry days

INTRODUCTION

IPCC (2007) reported that the frequency and intensity of extreme weather are increasing in many parts of the world due to anthropogenic global warming. For accurate projections of the frequency and intensity of extreme weather in the future climate, it is necessary to assess its reproducibility in the present-day climate.

Recent studies have shown that 5-km-mesh cloud-system resolving regional climate models perform well in simulating the precipitation characteristics in terms of total amount and frequency distribution of daily/hourly precipitation (Wakazuki et al., 2007; Kanada et al., 2008). On the other hand, Mizuta et al. (2005) examined the reproducibility of duration of dry days in terms of the maximum number of consecutive dry days (CDD; Frich et al., 2002) simulated in the present-day climate experiment by a 20-km-mesh atmospheric global climate model (AGCM-20km; Mizuta et al., 2005, 2006), and they found that AGCM-20km underestimated the value of CDD over the Japanese Islands. Mizuta et al. (2005) also explained this underestimation in terms of model biases related to precipitation, stating that heavy precipitation is rarely simulated, whereas weak precipitation is simulated more frequently than that observed. Since the frequency distribution of daily precipitation has a strong relationship with CDD, aforementioned findings by Wakazuki et al. (2007) and Kanada et al. (2008) imply that cloud-system resolving climate experiments with a horizontal resolution of several kilometers are able to quantitatively reproduce observed CDD in the present-day climate, however this has yet to be researched.

CDD is conventionally defined as an annual value (e.g., Frich et al., 2002), and its geographical distribution over the Japanese Islands, as calculated from Radar-Raingauge analyzed precipitation data of the Japan Meteorological Agency (JMA), has been studied to verify the results of model simulations (Mizuta et al., 2005). According to Inoue and Matsumoto (2003), central and western Japan has four natural seasons (Baiu–summer–Akisame–autumn) from June to October and each season has duration of 1–1.5 months. The Baiu [Akisame] is the rainy season between spring and summer [summer and autumn]. Therefore, monthly values of CDD (MCDD) in the warm season (June–October) over the Japanese Islands, yet to be examined in detail, are useful to examine model performance in representing the seasonality of dry day duration.

The goal of this study is to clarify the characteristic features of MCDD over the Japanese Islands during the warm season (June–October), and to statistically examine the reproducibility of simulated MCDD by a cloud-system resolving nonhydrostatic regional climate model with a horizontal resolution of 5 km (NHM-5km).

METHOD AND NUMERICAL EXPERIMENTS

To clarify the characteristic features of observed MCDD over the Japanese Islands during the warm season (June–October), MCDD is defined as the monthly value of CDD between the first and last days of each month from Automated Meteorological Data Acquisition System (AMeDAS) raingauge data of the JMA. AMeDAS has a horizontal resolution of nearly 17 km. Here, a dry day is defined as a day with a precipitation amount less than 1
Numerical experiments are conducted using NHM-5km (Kanada et al., 2008; Nakano et al., 2010) which is improved from the JMA nonhydrostatic model (JMA-NHM) (Saito et al., 2007) to simulate regional climatology. Kanada et al. (2008) showed that the NHM-5km well reproduced regional total precipitation amount and frequency distribution of daily precipitation in Japan using the same simulation results. To reduce the inconsistency in synoptic-scale atmospheric states between NHM-5km and regional objective analysis (RANAL) data of the JMA, which arises after several days integration, the spectral boundary coupling (SBC) scheme (Kida et al., 1991) is applied for layers above a 7 km height. In the SBC scheme, large-scale wave components (wavelength > 1000 km) of horizontal momentum and potential temperature are adjusted to those in RANAL. The Mellor–Yamada–Nakanishi–Niino Level 3 scheme (Nakanishi and Niino, 2004) is used for the planetary boundary layer. A bulk-type microphysics scheme with an ice phase (Murakami, 1990) and the Kain–Fritsch convective parameterization scheme (Kain and Fritsch, 1990) are used in combination for precipitation processes. For other model information, see Saito et al. (2007) and Nakano et al. (2010). The NHM-5km model domain occupies an area of 3345 × 2635 km² (Figure 1). The model has 50 vertical levels at variable intervals from 40 m (near the surface) to 886 m (top of the domain); the model top is located at a height of 21.8 km.

NHM-5km is continuously integrated from 0000 UTC 17 May to 0000 UTC 01 November for each year from 2002 to 2006. Output during the first 15 days is discarded as the spin-up period, and the data are analyzed from 0000 UTC 01 June.

RESULTS

Geographical distribution of MCDD

Figures 2a–e show the geographical distribution of the 5-year (2002–2006) mean of observed MCDD for each month. In June (Figure 2a), the Baiu rainy season begins from the southern part of the Japanese Islands (see Sato and Takahashi, 2001). Low MCDD (< 6 days) is found along the Pacific coast of the Japanese Islands and also in mountainous areas of central Honshu. This low MCDD is caused mainly by convective activity around the Baiu front. Relatively high MCDD (> 8 days) is found in northern Kyushu, western Honshu, and Hokkaido. In July (Figure 2b), low MCDD is mainly found between latitudes of 35°N and 40°N. The Baiu front is usually analyzed between latitudes of 30 [35]°N and 35 [40]°N in June [July] (Sato and Takahashi, 2001). Thus, the northward shift of low MCDD area from June to July is consistent with that of the Baiu front. On the other hand, MCDD exceeding 10 days is found in coastal areas of the Seto Inland Sea, southern Kanto, and northern Hokkaido.

The Baiu season usually terminates in late July and the Pacific high-pressure zone usually covers the Japanese Islands in August. Because mountainous regions experience frequent afternoon thunderstorms, low MCDD (< 6 days) is found in inland areas. High MCDD (> 10 days) is found in coastal areas of the Seto Inland Sea, southern Kanto, and central Hokkaido (Figure 2c).

From September to October, the Pacific high-pressure zone usually retreats southward and low-pressure systems periodically pass over the north or northern part of the Japanese Islands. Associated with these mid-latitude disturbances, westerly winds prevail in northern Japan. These westerly winds cause weak precipitation in the upwind (Japan Sea) side of the mountain range. Consequently, low MCDD is found on the Japan Sea side of Honshu (Figures 2d and 2e). On the other hand, MCDD exceeding 12 days is found in Kyushu and coastal areas of the Seto Inland Sea. In October (Figure 2e), most areas in southern Kyushu have MCDD exceeding 12 days.

The simulation results are shown in Figures 2f–j. The simulated geographical distributions of MCDD are in good agreement with those observed, although MCDD values are slightly overestimated in some areas. Their seasonal variations are also quantitatively reproduced. In the following two subsections, performance of NHM-5km is statistically examined.

Average MCDD for sub-regions

For quantitative examinations, 5-year mean MCDD values at the model grid points nearest to individual AMeDAS stations are computed, and then the values are averaged over each of the 11 sub-regions shown in Figure 1. These MCDD values for sub-regions are compared with those of AMeDAS raingauge data in Figure 3.

Although positive biases are commonly found in the simulations, the biases are generally less than 2 days. In September, NHM-5km overestimates 5-year mean MCDD by more than 2 days for HO, TJ, TP, and HK, where observed MCDD is relatively low (< 6 days). In October, NHM-5km overestimates MCDD by more than 2 days for the WJ, ST,
and OA regions, where observed MCDD is relatively high (~10 days). In June and July, positive biases exceeding 2 days are found in TJ and TP, respectively. The largest positive bias is +3.8 days, obtained for the OA region in October. Five negative bias plots are also found, four of which are found in the OA region (maximum bias of −1.9 days). The correlation coefficient (R), root mean square error (RMSE), and mean error (ME) are 0.755, 1.49, and 1.10, respectively. The linear regression line between simulated (y) and observed (x) MCDD values, obtained using the least-squares method, is \( y = 0.862x + 2.171 \).

The 5-year mean MCDD for the OA region (red symbols in Figure 3) is plotted away from the values for other regions. When the OA data are omitted, the R and RMSE values improve to 0.858 and 1.41, respectively. The poor correlation in the OA region may reflect the small number of data available for comparison (e.g., only 18 AMeDAS stations).

The 55 simulated MCDD values for each sub-region and each year are compared with AMeDAS observations for each of the 5 months, revealing that the simulations generally have positive biases (data not shown). The RMSE is larger in September and October than in June–August, and R is the smallest for June and the largest for October (Table I). Interannual variations in MCDD

The reproducibility of not only mean values but also the interannual variations in MCDD is important when examining climate change. Figure 4 shows interannual
variations in MCDD averaged over the Japanese Islands. Positive biases are found for all months except July 2002; however, the biases are not large (< 2 days for most months). Positive biases exceeding 2 days are found for only 3 months (September 2004 and October of 2002 and 2006).

RMSE values for interannual variations in MCDD averaged over the Japanese Islands are less than 2 days. RMSE for August is the smallest among the 5 months (0.93 days), and the RMSE for October is the largest (1.88 days). These results show that NHM-5km performs well in reproducing the interannual variation in MCDD.

SUMMARY AND CONCLUDING REMARKS

The geographical distribution of MCDD over the Japanese Islands was examined from raingauge data observed during June–October in 2002–2006. In June and July, areas with low MCDD (< 6 days) were analyzed associated with the northward shift of the Baiu front. In August, low MCDD was found in inland areas, whereas MCDD values exceeding 10 days were found in coastal areas of the Seto Inland Sea, southern Kanto, and parts of Hokkaido during July–August. In September and October, low MCDD [high MCDD (> 12 days)] was found on the Japan Sea side of Honshu [in Kyushu and coastal areas of the Seto Inland Sea].

To validate the reproducibility of MCDD by NHM-5km, numerical experiments were performed for each period of June–October over 5 years (2002–2006), using initial and boundary conditions derived from RANAL data. The features of the geographical distribution of MCDD simulated by NHM-5km are in good agreement with those observed, although MCDD values are slightly overestimated. Their seasonal variations are also quantitatively reproduced.

For quantitative analyses, the Japanese Islands were divided into 11 sub-regions. The 5-year mean MCDD for each sub-region were compared between simulations and observations. Linear regression analysis revealed the following relationship between simulated MCDD ($y$) and observed MCDD ($x$): $y = 0.862x + 2.171$, with a correlation coefficient, root mean square error (RMSE), and mean error of 0.755, 1.49, and 1.10, respectively. For annual variations in MCDD averaged over the Japanese Islands, the simulations are in good agreement with observations.

The results indicate that NHM-5km performs well in quantitatively reproducing not only total precipitation amount and frequency distribution of daily precipitation as reported by Kanada et al. (2008) but also the characteristics of MCDD in numerical experiments with RANAL data. This is in contrast to the finding of Mizuta et al. (2005) that their 20-km-mesh AGCM (AGCM-20km) was unable to quantitatively represent CDD in present-day climate experiments (the simulation data were underestimated). It is important to examine the performance of NHM-5km nested within present-day climate experiments with AGCM-20km, since the output of AGCM-20km may contain biases relative to RANAL data. Under the framework of the KAKUSHIN program (Kitoh et al., 2009), we are currently examining climate change (e.g., in terms of CDD) from the output of NHM-5km nested within AGCM-20km. The results of an analysis of NHM-5km performance regarding MCDD will be reported as soon as possible.

ACKNOWLEDGEMENT

This study was conducted under the framework of the KAKUSHIN program, supported by the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT). Numerical simulations were performed using the Earth Simulator. The authors thank the editor and two anonymous reviewers for useful comments. The GFD-DENNOU Library was used to compile figures.

REFERENCES

Frich P, Alexander LV, Della-Marta P, Gleason B, Haylock M, Klein Tank AMG, Peterson T. 2002. Observed coherent changes in climatic extremes during the second half of the twentieth century. *Climate Research* 19: 193–212. doi:10.3354/cr019193.

Inoue T, Matsumoto J. 2003. Seasonal and secular variations of sunshine duration and natural seasons in Japan. *International Journal of Climatology* 23: 1219–1234. doi:10.1002/joc.933.

IPCC. 2007. *Climate Change 2007: The Physical Science Basis*. Japan.
MONTHLY CDD IN JAPAN SIMULATED BY NHM-5km

Contribution of Working Group I to the Forth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

JMA. 2008. Global warming projection Vol. 7: Climate change projection around Japan for the A1B and B1 SRES scenarios, 59 pp. (in Japanese) [English version is available online at http://ds.data.jma.go.jp/tcc/tcc/products/gwp/gwp7/index-e.html]

Kain JS, Fritsch JM. 1990. A one-dimensional entraining / detraining plume model and its application in convective parameterization. Journal of the Atmospheric Sciences 47: 2784–2802. doi:10.1175/1520-0469(1990)047<2784:AODEPM>2.0.CO;2.

Kanada S, Nakano M, Hayashi S, Kato T, Nakamura M, Kurihara K, Kitoh A. 2008. Reproducibility of maximum daily precipitation amount over Japan by a high-resolution non-hydrostatic model. Scientific Online Letters on the Atmosphere 4: 105–108. doi:10.2151/sola.2008-027.

Kida H, Koide T, Sasaki H, Chiba M. 1991. A new approach for coupling a limited area model to a GCM for regional climate simulations. Journal of the Meteorological Society of Japan 69: 723–728.

Kitoh A, Ose T, Kurihara K, Kusunoki S, Sugi M, KAKUSHIN Team-3 Modeling Group. 2009. Projection of changes in future weather extremes using super-high-resolution global and regional atmospheric models in the KAKUSHIN Program: Results of preliminary experiments. Hydrological Research Letters 3: 49–53. doi:10.3178/hrl.3.49.

Mizuta R, Uchiyama T, Kamiguchi K, Kitoh A, Noda A. 2005. Changes in extremes indices over Japan due to global warming projected by a global 20-km-mesh atmospheric model. Scientific Online Letters on the Atmosphere 1: 153–156. doi:10.2151/sola.2005-040.

Mizuta R, Oouchi K, Yoshimura H, Noda A, Katayama K, Yukimoto S, Hosaka M, Kusunoki S, Kawai H, Nakagawa M. 2006. 20-km-mesh global climate simulations using JMA-GSM model – Mean climate states –. Journal of the Meteorological Society of Japan 84: 165–185. doi:10.2151/jmsj.84.165.

Murakami M. 1990. Numerical modeling of dynamical and microphysical evolution of an isolated convective cloud—The 19 July 1981 COCOPE cloud. Journal of the Meteorological Society of Japan 68: 107–128.

Nakanishi M, Niino H. 2004. An improved Mellor–Yamada Level-3 model with condensation physics: Its design and verification. Boundary-Layer Meteorology 112: 1–31. doi:10.1023/B:BOUN.0000020164.04146.98.

Nakano M, Kanada S, Kato T. 2010. Statistical analysis of simulated direct and indirect precipitation associated with typhoons around Japan using a cloud-system resolving model. Hydrological Research Letters 4: 6–10. doi:10.3178/HRL.4.6.

Saito K, Ishida J, Aranami K, Hara T, Segawa T, Narita M, Honda Y. 2007. Nonhydrostatic atmospheric models and operational development at JMA. Journal of the Meteorological Society of Japan 85B: 271–304. doi:10.2151/jmsj.85B.271.

Sato N, Takahashi M. 2001. Long-term variations of the Baiu Frontal Zone and midsummer weather in Japan. Journal of the Meteorological Society of Japan 79: 759–770. doi:10.2151/jmsj.79.759.

Wakazuki Y, Kanada S, Muroi C, Hashimoto A, Kato T, Nakamura M, Noda A, Yoshizaki M, Yashinaga K. 2007. Regional climate projection experiments on the Baiu frontal activity around the Japan islands using a non-hydrostatic cloud-system-resolving model. Journal of the Earth Simulator 8: 13–25.