Problems on the usage of Kain-Fritsch parameterization in a 5km model: Statistical comparison with cloud-top heights of cumulonimbi simulated by a cloud resolving model

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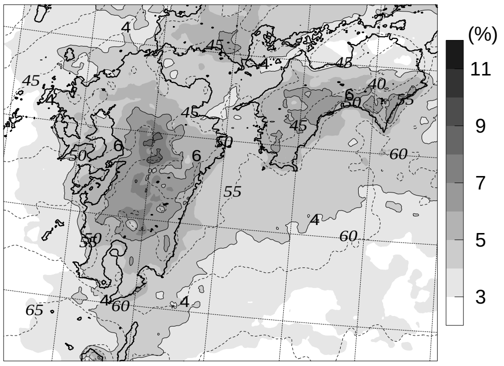
The major index to estimate cloud-top heights of moist convection (CTOPs) is the level of neutral buoyancy (LNB). Kato et al. (2007) showed that during the Baiu season the vertical profile of the appearance rates of LNB have two peaks at the middle level (~ 700 hPa) and the upper level (~ 200 hPa). These results are statistically obtained from objective analysis data with the horizontal resolution (dx) of 20 km, produced by the Japan Meteorological Agency (JMA). The major purpose of this study is to statistically examine the relationship between the LNB and the CTOPs simulated by a cloud-resolving model with dx = 1 km (1km-CRM). Moreover, in order to clarify the contribution of moist convection to total rainfall amount, the rainfall amount is also statistically estimated according to CTOPs of moist convection. Further, the results of 5-km nonhydrostatic model (5km-NHM) are compared with those of 1km-CRM to study problems on precipitation processes, especially cumulus parameterization.

Numerical models used in this study are the JMA-nonhydrostatic model (JMA-NHM, Saito et al., 2006). The same dynamical and physical processes but for the precipitation and atmospheric boundary layer are used in both models: In the 1km-CRM, a bulk-type microphysics scheme predicting the specific humidity of cloud water q_c, cloud ice q_{ci}, rainwater q_r, snow q_s, and graupel q_g are used, while a moist convection parameterization scheme (Kain and Fritsch, 1990) is additionally used in the 5km-NHM. As for the atmospheric boundary layer processes, the 1km-CRM predicts the turbulent energy, while the 5km-NHM prognostically estimates the turbulence energy and incorporates a mixing length formulation that supports a realistic boundary layer growth. The initial and boundary conditions of the 5km-NHM are produced from JMA objective analysis data with dx = 10 km that are available 3-hourly. The initial times of the 5km-NHM are 00 UTC, 06 UTC, 12 UTC and 18 UTC between 1 May and 31 July 2007, while those of the 1km-CRM are simply interpolated from the 3-h forecasts of the 5km-NHM. The hourly data between 4-h (7-h) and 9-h (12-h) forecasts of the 1km-CRM (5km-NHM) are used in this study.

CTOPs and cloud-bottom heights (CBTMs) are determined by the threshold values of $q_c + q_{ci} + q_s = 0.01$ g kg^{-1} and that of $q_c + q_{ci} = 0.1$ g kg^{-1}, respectively. Cumulonimbi are defined as the moist convection with rainfall in this study. The following conditions for their judgment are used; 1) the distance from the ground to CTOP > 2 km, 2) the distance from the ground to CBTM < 2.5 km, 3) the distance between CTOP and CBTM > 1 km, and 4) vertically-integrated $q_r + q_s + q_g$ below a 5-km height ≥ 0.1 mm in the case of CTOP < 8 km. Noted that the location of CTOP may be different from that of CBTM, due to the tilting of cumulonimbi. The difference of vertical scales of cumulonimbi is accepted in this study. The rainfall amount is estimated as follows. The vertically-integrated amount of q_r below a 2-km height is calculated, and the averaged q_r is estimated from it. Then, the terminal velocity of rainwater is estimated from the averaged q_r to obtain the hourly rainfall intensity.

Figure 1 shows the appearance rate distributions of LNB and CTOP of simulated cumulonimbi. The LNB appears at almost a half rate (50 %), while the highest appearance rate of CTOPs is at most 10 % even on the land. These statistical results agree with those of Kato et al. (2007) and Kato (2005). Moreover, the appearance rates of CTOPs are relatively higher on the land than over the sea, while those of LNB have opposite features. Terrain-induced updrafts often lift a low-level air to the LFC, and consequently higher appearance rates of CTOPs can be produced on the land. Further, CTOPs are overestimated on the land and underestimated over the sea by the 5km-NHM.


(a) 1km-CRM: 20070501 - 20070731

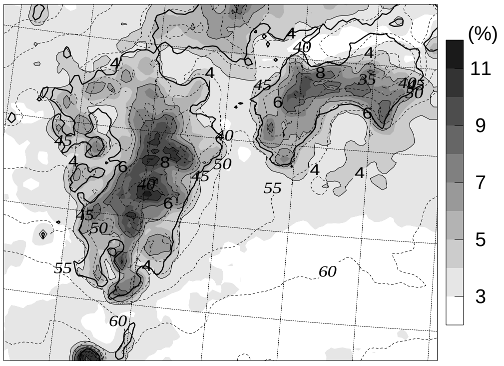

(b) 5km-NHM: 20070501 - 20070731

Fig. 1 Appearance rates of CTOP (shade) and LNB (dashed contours), averaged between 1 May and 31 July 2007, estimated by the (a) 1km-CRM and (b) 5km-NHM.

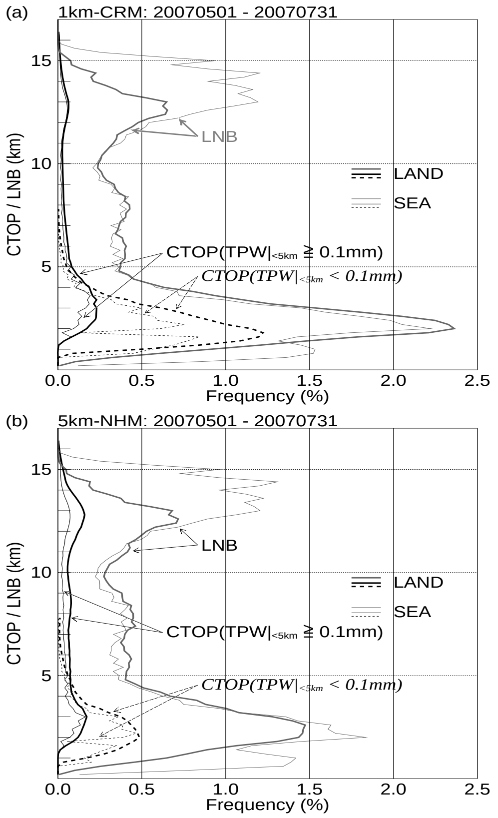


Fig. 2 Vertical profiles of appearance frequencies of LNB (grey lines) and CTOP (solid lines), averaged between 1 May and 31 July 2007, estimated by the (a) 1km-CRM and (b) 5km-NHM. Dashed lines denote the results for CTOPs with vertically-integrated total amount of rainwater, snow and graupel (TPW) below a height of about 5 km < 0.1 mm. Thick and thin lines present the results on the land and over the sea, respectively. Each frequency is calculated by dividing heights into 80 levels with an interval of 200 m.

Two vertical peaks appear in the appearance rates of the LNB estimated from the simulation results (grey lines in Fig. 2), as well as Kato et al. (2007). Any remarkable differences are not found between the LNB profiles of 1km-CRM and 5km-NHM. Meanwhile, two peaks also appear in the vertical profile of the appearance rates of simulated CTOPs (solid lines). The rates at the top peak around 13 km are less than 10 % of those of the LNB. The appearance rates for CTOPs not to satisfy the condition 4) for judging cumulonimbi (dashed lines) have a peak around a 2-km height, and the rates corresponding to the peak are about a half of those of the LNB. Such CTOPs could form associated with the cumulus and cumulus congestus. Moreover, the 5km-NHM overdevelops cumulonimbi, especially on the land, while the moist convection formed corresponding to the lower LNB appears at about a half rate in comparison with that simulated by the 1km-CRM.

The contribution rate of cumulonimbi, defined in this study, to total rainfall amount is about 70 % both over the sea and on the land (not shown). The vertical profile of the contribution rates on the land, estimated from the results of 1km-CRM, show that in June and July the maximum contribution rate is brought from cumulonimbi with a CTOP of 3 ~ 4 km (Fig. 3a). In May, the contribution rate associated with such cumulonimbi is as large as that found at the upper level of about 12 km. These results mean that slight numbers of developed cumulonimbi with a CTOP exceeding 10 km (see Fig. 2) produce considerably large rainfall amount, while about a half of total rainfall amount is produced by cumulonimbi with a CTOP lower than 5 km. In comparison with the results of 1km-CRM (Fig. 3a), the 5km-NHM (Fig. 3b) overestimates the contribution of developed cumulonimbi, and it underestimates that of the moist convection formed corresponding to the lower LNB independent of the seasonal change. Moreover, in May and June another peak is found around a height of 7-9 km. This could be brought from the over-development of cumulonimbi with a CTOP lower than 5 km by using the Kain-Fritsch convective parameterization scheme.

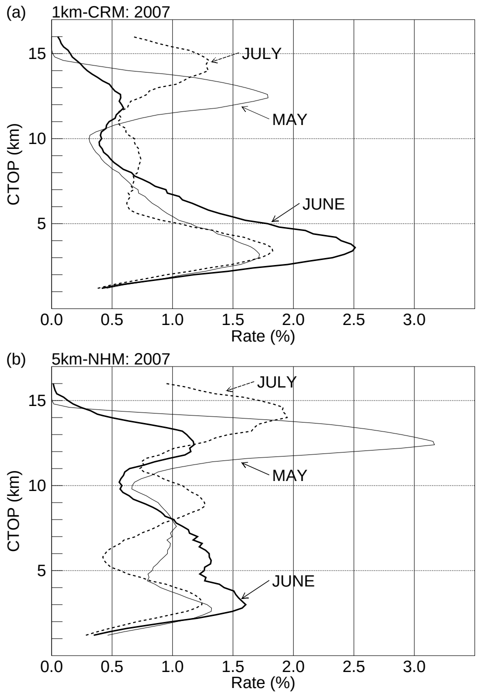


Fig. 3 Same as Fig. 2, but for the seasonal change of contribution rates to total rainfall amount according to CTOPs on the land.

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