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学位論文題目	A numerical study on the improvement of a cumulus parameterization using a cloud-resolving model and with its application to typhoon simulation (雲解像モデルを用いた積雲対流パラメタリゼーションの改善と台風シミュレーションへの応用に関する数値的研究)
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論 文 内 容 要 旨

Abstract

Tropical cyclone forecasting is one of the most important subjects in the numerical weather prediction. Intensification, maintenance, and decay of tropical cyclones depend greatly on latent heat released by cumulus convection. Many studies pointed out that the location and amount of released latent heat significantly influence the track and intensity of tropical cyclones (e.g., Schubert and Hack 1982). The effect of latent heat released by cumulus convection is parameterized in the numerical model whose horizontal grid spacing is too coarse to explicitly represent cumulus convection. Although the introduction of cumulus parameterization to numerical models has contributed to prediction performance, prolonged efforts have been made to reduce errors induced by cumulus parameterization. In this study, a new method for a cumulus parameterization is developed to reduce the errors and to improve the performance of numerical prediction for tropical cyclones.

Many kinds of methods for cumulus parameterization have been developed. Among them, the scheme developed by Arakawa and Schubert (1974) has been widely used. Kuma et al. (1993) pointed out that the tracks of simulated typhoons improve when Arakawa-Schubert (AS) cumulus parameterization is implemented into the numerical model they used. The AS scheme is based on cloud mass flux, an important variable for cumulus convection and widely used in cumulus parameterizations. Upward mass flux in a cumulus is considered to increase with height because the surrounding air enters the uprising air. Entrainment rate is defined as the rate of the entrained air to the uprising air. In the AS scheme, the following assumptions are employed: entrainment rate is constant with height and detrainment occurs only at the cloud-top level. However, it has been pointed out, from observations and numerical experiments, that entrainment rate depends on height and that detrainment occurs not only at cloud top but also at other levels (e.g., Raymond and Wilkening 1985; Lin 1999).

In this study, using a cloud-resolving model (CRM), the vertical profile of cumulus mass flux is investigated. It is found from the investigation that the vertical profile have characteristic structures. On the basis of the findings, we develop a new approach to calculating cloud mass flux and applied the new method to the AS scheme. It is found that prediction performance improved in the numerical simulation for a typhoon when we use the numerical model in which the modified AS scheme is implemented.

The numerical model we used was the Meteorological Research Institute / Numerical Prediction Division Nonhydrostatic Model (MRI/NPD-NHM; Saito et al. 2001). The model was used as a CRM for numerical simulations of cumuli contained in a rainband of typhoon Saomai (2000). In the numerical simulations, cloud microphysics is explicitly treated and no cumulus parameterization is used. A grid-nesting strategy is adopted for the initial and the lateral boundary conditions. Triply nested MRI/NPD-NHM is employed: 5-km, 1-km, and 200-m horizontal grid spacing. The initial and boundary data for the outermost model are produced by Regional Spectral Model (RSM; NPD/JMA 1997).

The vertical profile of entrainment rate in a cumulus is determined using output from MRI/NPD-NHM with 200-m horizontal grid spacing. Before the calculation, a cumulus area is extracted from the output. Entrainment rate, derived from the calculation based on the vertical gradient of cloud mass flux, is clearly shown to be larger near cloud base and top. Between the heights of cloud base and top, the entrainment rate is smaller and even negative in many cases, suggesting laterally detrained air from a cumulus into the environment. From the analyses where the entrainment rate is divided into three terms, it is found that the contributions of updraft and cloud amount are dominant and that the contribution of density is negligible. The term of updraft contribution is relatively large near cloud base and top compared to the levels in between. The term is proportional to the sum of vertical forcing and is inversely proportional to the square of vertical velocity. Since convective updrafts tend to have a minimum at cloud base and top, the updraft term is larger there. Similarly, the contribution of cloud amount tends to be larger near cloud base and top because cloudy areas rapidly expand at those levels accompanying cloud growth.

On the basis of the results of the CRM simulations, the method for calculating cloud mass flux in the AS scheme is modified. The modified part is in the calculation for the vertical profile of entrainment rate. We adopt the vertically variable entrainment rate that represents larger near cloud base and top, and smaller in between, instead of constant with height. Lateral detrainment is employed at the heights between cloud base and top in addition to the cloud-top detrainment considered in the original scheme.

The modified AS scheme is evaluated using the case of typhoon Saomai. We use MRI/NPD-NHM with the 20-km horizontal grid spacing. The model includes the AS scheme and the large-scale condensation scheme instead of cloud microphysics. The results show that the unrealistic precipitation area located to the southeast of the typhoon is suppressed in the simulation using the modified scheme. Detailed analysis demonstrates that the operational AS scheme makes moist static energy less over the troposphere than that in the CRM simulation. The results are attributed to an underestimate of specific humidity. In the simulation using the modified scheme, in contrast, values in specific humidity in the middle and upper troposphere approach those reproduced by the CRM. The marked difference in the amount of moisture between the two experiments is also observed over an outer area (i.e., between the 250 and 500 km radius) of Saomai. The results suggest that the improvement in moisture occurs not only in the rainband but also over the outer area of the typhoon.

The difference in specific humidity between the two experiments is explained by the difference in cloud mass flux. In the simulation with the modified AS scheme, cloud mass flux is weaker, in the middle and upper troposphere, than that in the other simulation because the modified scheme includes the lateral detrainment. The effect of cloud mass flux term on moisture tendency is the greatest among other terms that could influence the moisture tendency due to the cumulus parameterization. The weaker cloud mass flux in the modified scheme is therefore responsible for inhibiting the decrease in specific humidity.

In the present study, the cloud mass flux in the cumulus parameterization is corrected on the basis of the findings obtained from the CRM output data, thereby improving prediction performance of tropical cyclone simulations. It is possible that the present method is generally applied to other cumulus parameterizations based on cloud mass flux. It is also demonstrated that the results of CRM simulations are extremely useful for the validation of scheme modification.

論文審査の結果の要旨

台風の主なエネルギー源は積雲対流よる潜熱加熱である。通常，気象予測のための数値シミュレーションモデルは解像度が低いため，個々の積雲を陽に表現することはできない。積雲対流の効果はパラメータ化して表現する必要があり，さまざまな手法が提案されている。ただし，積雲対流のパラメータ化手法は観測に基づく妥当性の検証がきわめて難しく，その不完全性が台風予報精度向上の大きな障害となっている。

本研究では，200mメッシュの雲解像モデルを用いて積雲対流シミュレーションを実施し，その結果を整理して予報モデルの積雲対流パラメータ化を改良し，台風予報へのインパクトを調べた。気象庁の予報モデルでは荒川とシュバートによって提案されたパラメータ化手法を採用している。この手法では雲が周囲の空気を取り込むエントレインメント率について鉛直に一定であることを仮定している。村田昭彦は雲解像シミュレーションによりエントレインメント率は鉛直依存性が極めて大きいことを見出した。特に，大気の中層ではデトレインメントが卓越している。これは積雲対流の構造について新しい理解をもたらすとともに，従来のパラメータ化手法の問題点を明らかにするものである。荒川—シュバートのパラメータ化手法にエントレインメントの鉛直依存性を取り入れ，台風予報を行ったところ，水蒸気の鉛直分布が雲解像シミュレーションに近づくとともに，進路予報が改善されることを確認した。

本研究で行った積雲対流のパラメータ化の改良は台風予報の向上に寄与するものであり，村田昭彦が自立して研究活動を行うに必要な高度の研究能力と学識を有することを示している。したがって，村田昭彦提出の博士論文は，博士（理学）の学位論文として合格と認める。