13.7 IMPACT OF THE BOUNDARY-LAYER PROCESSES ON SIMULATED TROPICAL RAINFALL

Young-Hwa Byun and Song-You Hong*
Yonsei University, Seoul, Korea

1. INTRODUCTION

On simulating the tropical rainfall, simulation results due to different models with different physics packages vary considerably, as is revealed in numerous studies such as on General Circulation Model (GCM) Intercomparisons. According to these studies, the internal variability of models with different physics is extreme in the models with identical dynamic cores (Shukla 2000), and as well, the differences of models in performance are related to the physical parameterizations and particularly to the convection schemes in the models (Kang et al. 2002).

Recent studies, however, suggest that the BL scheme may be a sensitive factor that is particularly related to precipitation physics in global short- and medium-range forecast models, as well as in mesoscale models (e.g., Hong and Pan 1996). In recent years, the nonlocal scheme based on Troen and Mahrt (1986) has been applied to GCMs as well as numerical prediction models (Hong and Pan 1996). In particular, Hong and Pan (1996) successfully used this concept with the NCEP MRF model (hereafter, the MRF BL scheme). The MRF BL scheme is preferable because, compared with the local-K approach through the inclusion of countergradient flux terms, it enables realistic development of a well-mixed layer. However, there appear to be some deficiencies in the MRF BL scheme: recent studies report excessive mixing (Hong and Pan 1996; Davis and Bosart 2002).

Recently, a new nonlocal diffusion concept to improve deficiencies in Troen and Mahrt (1986) was proposed by Noh et al. (2003) and implemented within a numerical model by Hong et al. (2003), after further generalization and reformulation. The key to the new BL scheme is that the entrainment processes above minimum flux level are expressed explicitly in the turbulence diffusion equations for the prognostic variables.

In the present study, we investigated changes in tropical precipitation due to using, in a GCM, the new BL scheme by Hong et al. (2003) and Noh et al. (2003) through a comparison with the current MRF BL scheme (Hong and Pan 1996). In particular, we focused on the effect on the simulation of tropical rainfall of the BL scheme's dependence on two different cumulus parameterization schemes.

* Corresponding author address: Song-You Hong, Yonsei University, Dept. of Atmospheric Sciences, e-mail: shong@yonsei.ac.kr

2. THE MODEL AND EXPERIMENT DESIGNS

2.1 The National Centers for Environmental Prediction (NCEP) Medium-Range Forecast (MRF) model

The model used in this study is a version of the NCEP MRF model with the physics package that was operational as of January 2000. In this model, BL physics employs a nonlocal diffusion scheme (Hong and Pan 1996). The cumulus parameterization for deep convection uses the simplified Arakawa-Schubert (SAS) scheme. This follows Pan and Wu (1995), which is further based on Arakawa and Schubert (1974), as simplified by Grell (1993) with a saturated downdraft. We also selected another convection scheme for this study. This is the relaxed Arakawa-Schubert (RAS) scheme based on Moorthi and Suarez (1992), which was implemented in the recent NCEP seasonal forecast model (Kanamitsu et al. 2002a).

2.2 The BL parameterization scheme

The MRF BL scheme (Hong and Pan 1996) is a control scheme in this study. In the MRF BL scheme, turbulent diffusivity coefficients are calculated from a prescribed profile shape as a function of BL heights and scale parameters derived from similarity requirements. Above the mixed layer, the local diffusion approach is applied to account for free atmospheric diffusion.

On the other hand, Noh et al. (2003) proposed some modifications, based on the large-eddy simulation data, of the previous K-profile model of the BL reported by Troen and Mahrt (1986). The modifications include three parts: First, the heat flux from the entrainment at the inversion layer is incorporated into the heat and momentum profiles. Second, vertically varying parameters are proposed, in contrast to constant values in the previous model. Finally, nonlocal mixing of momentum is included. A brief description of the new BL parameterization scheme of Hong et al. (2003) appears below. The turbulence diffusion equation can be expressed for the mixed layer by equation (1).

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial t}\left[K_C\left(\frac{\partial C}{\partial t} - \gamma_C\right) - \overline{(w'C')_h}\left(\frac{z}{h}\right)^3\right] \quad \cdots \quad (1)$$

Here, K_c and γ_c are the eddy diffusivity coefficient and a correlation to the local gradient, respectively. $\overline{(w'C')_h}$ is the flux at the inversion. Compared with the MRF BL scheme, the formula includes an asymptotic flux term at the inversion layer, i.e., the last term inside the square bracket of eq. (1) explains entrainment processes at the BL top. A detailed description of the new BL scheme, including equation sets, is presented in Hong et al. (2003) and Noh et al. (2003).

2.3 Experiment designs

To investigate the effect of the BL scheme's dependence on different parameterization schemes for deep convection, we performed four experiments, as seen in Table 1.

Table 1. Summary of numerical experiments.

Experiments	BL scheme	Convection scheme
CNT_S	MRF BL	SAS
NEW_S	New BL	SAS
CNT_R	MRF BL	RAS
NEW_R	New BL	RAS

The MRF model used in this study employs a resolution of T62L28. To avoid introducing uncertainties with the initial data, 10-member ensemble runs for each experiment were performed with an approximate four-week lead-time for the boreal summers (June-July-August) of 1996, 1997 and 1999. The initial data for each ensemble was taken from the NCEP/Department of Energy (DOE) reanalysis II data (Kanamitsu et al. 2002b), starting from 0000 UTC of the 1st day of May to the 10th day with a 24-hour interval.

In this study, we chose three years in which to examine the effect of the BL scheme on different Sea Surface Temperature (SST) anomalies. SST in 1996 showed a normal condition over the equatorial Pacific; and in 1997 and 1999, SST distribution revealed warm and cold anomalies over the eastern Pacific, respectively. Observed SST data were used with a resolution of one degree (Reynolds and Smith 1994) during the simulation period. Observed precipitation was taken from the Climate Prediction Center (CPC) Merged Analysis Monthly Precipitation data (CMAP) (Xie and Arkin, 1997).

3. RESULTS AND DISCUSSIONS

3.1 Tropical precipitation

In Fig. 1, both the CNT_S and the NEW_S experiments overall produce a tropical rainfall pattern comparable to the observation showing the main rain belt along the Intertropical Convergence Zone (ITCZ). However, it is apparent that the CNT_S experiment has some discernible defects, including excessive precipitation over the trade-wind region north of the equator and underestimated precipitation over the western equatorial Pacific. This aspect commonly appears in 1997 and 1999 (not shown). On the other hand, the new BL scheme improve the overall tropical precipitation pattern due to a considerable decrease in excessive rainfall over the eastern Pacific and an increase in insufficient rainfall over the western Pacific north of the equator (Fig. 1c). In terms of its amount, global mean rainfall from the NEW_S experiment decreases approximately 10 percent as compared with the CNT_S case, which is closer to what was observed (Table 2).

Table 2. Global mean precipitation (mm day^{-1}) of summer obtained by each experiment.

Year / Expr.	1996	1997	1998
CMAP	2.71	2.73	2.55
CNT_S	3.64	3.68	3.64
NEW_S	3.37	3.42	3.38
CNT_R	3.23	3.22	3.25
NEW_R	2.96	2.97	2.97

In the RAS convection scheme, it is also clear from Table 2 that the new scheme reduce the global mean precipitation by nearly 10 percent (c.f., CNT_R vs. NEW_R); in turn, mean precipitation of the NEW_R case comes close to the CMAP observation. According to the right panels of Fig. 1, the CNT_R experiment shows a relatively well-organized rainfall pattern simulation when compared with the observation, except for an overestimate in rainfall near the Indian Ocean. In particular, over the eastern equatorial Pacific, the CNT_R experiment shows a better pattern than the CNT_S case in a quantitative respect by an overall decrease in equatorial precipitation along the ITCZ.

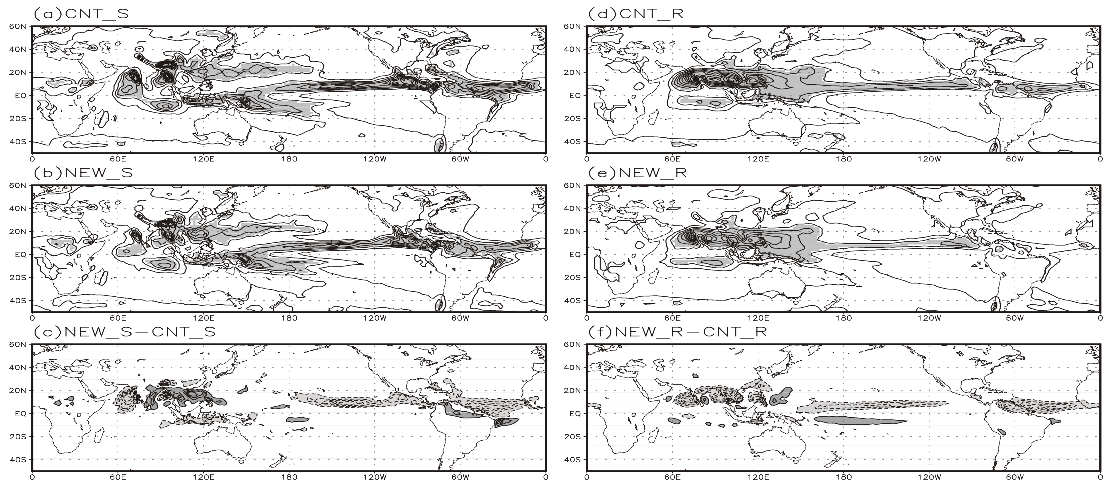

Fig. 1. Comparison of summer mean precipitation (㎜ mon^{-1}) obtained from the simulated summer of 1996. The left panels show the experiment with the SAS convection scheme, and the right panels with the RAS scheme. Contour intervals are 100 ㎜ starting from 100 ㎜, and shaded areas designate the precipitation amount greater than 200 ㎜ where values are statistically significant at the 95% level for the simulated results (a,b,d,e). (c) and (f) are differences between the simulations with the new and the control schemes. In (c) and (f), contour intervals are 50 ㎜, and dark (light) shades denote the precipitation amount greater (less) than +50 ㎜ (-50 ㎜), respectively. Zero lines are omitted.

3.2 Large-scale circulation

Figure 2 represents the distinctions in zonal mean temperature and specific humidity between the CNT_S and NEW_S experiments. Variations for the RAS convection scheme follow the analyses of SAS runs (not shown). In Fig. 2, it is apparent that temperature and moisture in the lowest layer below 950 hPa become colder and wetter due to the new BL scheme. Above it generally appears warmer and drier air between 950 and 850 hPa. Such a feature results from less mixing due to the new scheme. Consequently, the model with the new BL scheme results in smaller Convective Available Potential Energy (CAPE) than the control scheme due to less mixing of heat and moisture, and in turn, reduces rainfall over the eastern Pacific.

However, the effect of the new scheme over the western Pacific varies, depending on the convection scheme selected. Over the western Pacific, an increase in tropical precipitation is shown in the SAS case, whereas a decrease occurs in the RAS case (see Fig. 1). To clarify the change in large-scale patterns connected with the change in tropical rainfall, the streamlines in the zonal and vertical directions were plotted in Fig. 3. In the SAS case, it is apparent that the NEW_S experiment intensifies rising motion in the western Pacific and weakens sinking motion in the eastern Pacific, when compared with the control scheme (cf., Fig. 3a).

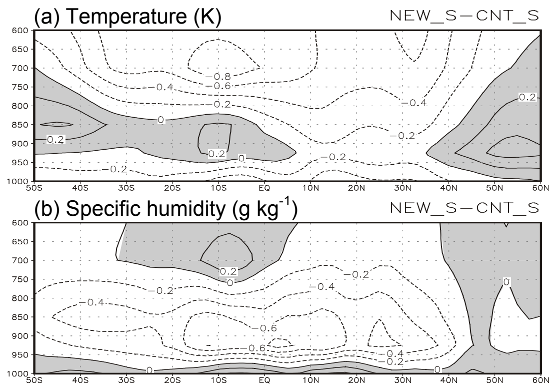

Fig. 2. Differences of zonal mean (a) temperature (K) and (b) specific humidity (g kg^{-1}) between the new and the control schemes for the SAS convection case in summer 1996. Shaded areas indicate the values greater than zero.

This means that the new BL scheme plays a role in strengthening the Walker Circulation (hereafter WC), resulting in a large amount of low-level moisture advection toward the western Pacific due to the intensified trade wind. Consequently, the enhanced WC in the NEW_S experiment leads to an increase in tropical precipitation over the western Pacific with active precipitation processes due to the large CAPE. However, the effect of the new BL scheme in the simulation with the RAS convection scheme is less distinct than in the SAS case (c.f., Fig.

3b). In the figure, an intensification of the WC is not clear, though strengthened rising motion appears near the central Pacific near 170°E~150°W. Rather the WC in the NEW_R case is weakened, leading to an overall weakness of the low-level easterly wind.

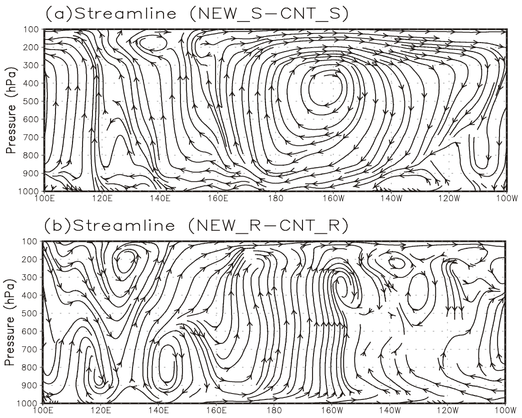

Fig. 3. Streamline for longitude-height section of wind differences. All the variables are averaged from 20°S to 30°N for summer 1996. (a) indicates the differences between the new and the control schemes for the SAS convection scheme, and (b) is the difference for the RAS convection scheme.

4. CONCLUSION

Overall, the new scheme improves the precipitation over the tropics by reducing rainfall in the central and eastern equatorial Pacific Ocean. This reduction is a direct effect of the new BL scheme's resulting in less mixing of heat and moisture, which in turn produces smaller CAPE. This effect is common, irrespective of the convection scheme.

Meanwhile, in case of the effect of BL processes over the western Pacific, the model with the SAS convection scheme improves precipitation over the western Pacific by increasing rainfall when the new scheme is used, whereas the RAS scheme suppresses rainfall activity in that region. The response over the western Pacific is rather indirect and closely related to the change of large-scale circulation induced by BL processes.

The results of this study demonstrate that the simulation of tropical precipitation in GCM can be significantly improved by a change of BL processes. This implies that, in seasonal predictions as well as short-range forecasts, BL processes in GCM are as important as precipitation processes. Moreover, these results suggest that balance between BL processes and convection processes should be considered essential to improving precipitation simulation.

5. ACKNOWLEDGMENTS

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6. REFERENCES

Arakawa, A., and W. H. Schubert, 1974: Interaction of a cumulus ensemble with the large-scale environment. Part I. *J. Atmos. Sci.*, **31**, 674-704.

David, C., and L. F. Bosart, 2002: Numerical simulations of the genesis of hurricane Diana (1984). Part II: Sensitivity of track and intensity prediction. *Mon. Wea. Rev.,* **130**, 1100–1124.

Grell, G. A., 1993: Prognostic evaluation of assumptions used by cumulus parameterization. *Mon. Wea. Rev.,* **121**, 764-787.

Hong, S.-Y., and H.-L. Pan, 1996: Nonlocal boundary layer vertical diffusion in a Medium-Range Forecast model. *Mon. Wea. Rev.,* **124**, 2322-2339.

________, J. Dudhia, and Y. Noh, 2003: A new vertical diffusion package with explicit treatment of the entrainment processes. International workshop on NWP models for heavy precipitation in Asia and Pacific areas. 4-6 February. Japan Meteorological Agency, Tokyo, Japan.

Kanamitsu, M., and Coauthors, 2002a: NCEP Dynamical seasonal forecast system 2000. *Bull. Amer. Meteor. Soc.,* **83**, 1019-1037.

_______, W. Ebisuzaki, J. Woollen, S.-K. Yang, J.J. Hnilo, M. Fiorino, and G. L. Potter, 2002b: NCEP-DOE AMIP-II Reanalysis (R-2). *Bull. Amer. Meteor. Soc.,* **83**, 1631-1643.

Kang, I. -S., and Coauthors, 2002: Intercomparison of the climatological variations of Asian summer monsoon precipitation simulated by 10 GCMs. *Clim. Dyn.,* **19**, 383-395.

Moorthi, S. and M. Suarez, 1992: Relaxed Arakawa-Schubert: A parameterization of moist convection for general circulation models. *Mon. Wea. Rev.,* **120**, 978-1002.

Noh, Y., W. G. Chun, S. Y. Hong and S. Raasch, 2003: Improvement of the K-profile model for the planetary boundary layer based on large eddy simulation data. *Bound.-Layer Meteor.*, **107**, 401-427.

Pan, H.-L., and W.-S. Wu, 1995: Implementing a mass flux convective parameterization package for the NMC medium-range forecast model. NMC office note 409, 40 pp. [Available from NCEP/EMC, 5200 Auth Road, Camp Springs MD 20746].

Reynolds, R. W., and T. M. Smith, 1994: Improved global sea surface temperature analyses using optimum interpolation. *J. Clim.*, **7**, 929-948.

Shukla, J., and Coauthors, 2000 : Dynamic seasonal prediction, *Bull. Amer. Meteor. Soc.,* **81**, 2593-2606.

Troen, I. W., and L. Mahrt, 1986: A simple model of the atmospheric boundary layer; sensitivity to surface evaporation. *Bound.-Layer Meteor.*, **37**, 129-148.

Xie, P., and P. A. Arkin, 1997: Global precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model prediction. *Bull. Amer. Meteor. Soc.,* **78**, 2539-2558.