Tests of a New Trigger Function in a Cumulus Parameterization scheme

Tae Kwon Wee and Dong-Kyou Lee
School of Earth and Environmental Sciences, Seoul National University, Seoul, Korea

1. Introduction

The convective triggering function is a set of algorithm for determining the location and timing of sub-grid scale convective initiation. Rogers and Fritsch (1996) comprehensively discussed many details on this subject and proposed a general framework of the convective trigger function. As noted by them, when and where convection occurs in a given simulation influences many nonlinear feedbacks that can substantially alter the results of the simulation (Rogers and Fritsch 1996). Kain and Fritsch (1992), Stensrud and Fritsch (1994), and Hong and Pan (1998) showed that some simulations are quite sensitive to the convective trigger function used.

The purposes of this study are to investigate underlying mechanisms and assumptions to the process of convective initiation, to analyze its impact on simulation results, and to develop a new trigger function. This new trigger function is formulated and implemented in a mesoscale model (PSU-NCAR mesoscale model MM5) and its validity is evaluated comparing with other simulations.

2. Parameterization for convective triggering

The general basis of the convective trigger function developed in this study follows the two-step methodology proposed by Rogers and Fritsch (1996): estimation of the magnitude of largest sub-grid scale vertical velocity perturbation originating from within each potential source layer, and calculation of whether or not this perturbation is strong enough to overcome the total grid-resolvable negative inhibition between the source layer and the level of free convection (LFC).

Previous studies emphasized the role of thermals in the free convective boundary layer in initiating convection. Rogers and Fritsch (1996) used the free convective scaling velocity as a representative of the sub-grid scale triggering energy in free convective regime. Hong and Pan (1998) used a temperature perturbation based on the surface similarity relationship to check the buoyancy of updraft parcel at the cloud base level with respect to its environment in the free convective boundary layer. Though all of these studies noticed the importance of sub-grid scale perturbation in case of mechanically driven, marginally neutral, and stably stratified boundary layers, any acceptable formulation that keeps consistency with the expression of perturbation in free convective regime and is applicable to these environments is not yet developed. Also the transition processes among different PBL regimes must be accounted.

We used the model predicted turbulent kinetic energy (TKE) to compute a sub-grid scale triggering energy. TKE has many benefits as follows. First of all, TKE is a sub-grid scale quantity in nature and it can represent more detailed vertical structure of PBL than surface heat flux. While sub-grid scale fluxes are instantaneous variables, TKE retains its own history for some length of time because it is a prognostic and advective quantity. Also, the square root of TKE is one of the basic velocity scale, what is called as the turbulent velocity scale, which can be used regardless of atmospheric stratification (Stull 1988). In this point TKE is a more general velocity scale than the free convective velocity scale that is usable only for the free convective regime. The use of the turbulent scaling velocity in the stable or neutral boundary layer can be justified as a velocity perturbation generated due to surface inhomogeneities. Accordingly, TKE can provide us with a way of effectively handling the transition among different PBL regimes for this reason. Furthermore, a TKE-based trigger enables us to get a reasonable linking of sub-grid scale perturbation with resolvable-scale upward motion.

Considering the aforementioned benefits of TKE, we designed several triggering formulations. First, it is assumed that TKE is the magnitude of the triggering energy not accounting enhancement due to grid-scale motion. Next, we assumed that grid-scale upward (downward) motion strengthens (weakens) eddy activities in PBL.

Maybe there is a wide spectrum of perturbations ranging from a grid-scale to small eddies in a given grid box, but only upward motions involved with these perturbations would serve to trigger convection. Therefore, we tried to infer a grid-volume averaged updraft velocity using the grid-scale vertical motion and TKE. It is assumed that the distribution of vertical velocity of perturbations in a given grid column follows a Gaussian distribution with that its mean value is grid-scale vertical motion ($\overline{w}$) and standard deviation (σ) is the square root of TKE. Then we can get a fraction of updraft (P_{w+}) in a grid element as follows:

$$P_{w+} = \frac{1}{\sqrt{2\pi}\sigma}\int_0^\infty e^{-\frac{1}{2}\left(\frac{w-\overline{w}}{\sigma}\right)^2} dw \qquad (1)$$

and a triggering energy (ΔE_1) is defined as

$$\Delta E_1 = q \cdot P_{w+}\,, \qquad (2)$$

where q ($m^2\ s^{-2}$) is TKE at the source layer. Similarly, an expectation value ($\overline{w_+}$) of the upward velocity can be computed by

$$\overline{w_+} = \frac{1}{\sqrt{2\pi}\sigma}\int_0^\infty e^{-\frac{1}{2}\left(\frac{w-\overline{w}}{\sigma}\right)^2} w\ dw\,. \qquad (3)$$

To get another triggering energy (ΔE_2), the following relationship is assumed:

$$\Delta E_2 = c_2 \cdot \overline{w_+}^2\,, \qquad (4)$$

where c_2 is a proportionality coefficient set to 25. The last triggering energy (ΔE_3) has an elliptical form as

$$\Delta E_3 = \frac{\overline{w}^2}{a^2} + \frac{q}{b^2}\,, \qquad (5)$$

where a and b are proportionality factors defined as $a^2 = 0.1(L/\Delta x)^2$ and $b^2 = 1 - a^2$, respectively, where Δx (m) is horizontal grid size of a numerical model, and L (=25000m) is a reference grid spacing.

We expect above formulations to work in fashion as not to generate too much large values of triggering energy and to express a close link between the sub-grid scale perturbation and the grid-scale vertical motion.

3. A short-term verification

An examination of model sensitivity to convective triggering formulations described in the preceding section was conducted. To fully identify the characteristics of trigger functions, we performed a short-term verification over the 2-month period June-July 1993 inclusive. The summer of 1993 was an extremely wet period and a number of mesoscale convective systems contributed to the rainfall that led to the flooding of the Mississippi and Missouri Valley region. Rainfall during the period, especially June and July, was unusually heavy with numerous locations receiving new monthly records (Kunkel et al. 1994, Junker el al. 1999). The model was initialized at every 0000 UTC and 1200 UTC, and was run out to 36 hours. The model domain is configured with a two-way interactive nested grid with a coarse-mesh resolution of 75km and a fine-mesh resolution of 25km. The important model physics include a TKE-based PBL parameterization known as the Gayno-Seaman scheme (Ballard et al. 1991) and an grid-resolvable precipitation scheme for rainwater and cloud water with a simple ice physics scheme (Dudhia 1989).

Numerical simulations conducted in the present study are briefly summarized in Table 1. The first simulation (F-C) uses the Kain-Fritsch cumulus parameterization with the Fritsch-Chappell trigger that defines the magnitude of a temperature perturbation at the LCL based on resolvable-scale vertical velocity. In the second experiment (NEW) we also use the KF scheme but replace its FC trigger with a newly developed one (i.e. ΔE_1 in section 2). The last experiment, NCU, uses only a grid-resolvable precipitation process.

Table 1 Summary of experiments.

Experiment	Description
F-C	Fritsch-Chappell trigger
NEW	New trigger (ΔE_1)
NCU	No cumulus parameterization

Fig. 1 shows space-time averaged skill scores as a function of rain threshold. It is noteworthy that the newly developed trigger stands out as being the most skillful over the whole ranges of precipitation threshold values in terms of Heidke Skill Score (HSS) and True Skill Statistics (TSS). NCU showed better skill than F-C for HSS and F-C outperformed NCU for TSS. F-C showed Bias Scores (BS) greater than one regardless of threshold values used, which reflects overestimation of precipitation area. NCU made over (under) estimation of rainfall area for small (large) threshold value. New also showed overestimation of rainfall area but its Bias Score is relatively small compared to that of F-C.

Fig. 2 shows the time series of rainfall rates averaged for model domain and all events of simulations. NCU showed time-delayed evolution of precipitation about 6-9 hours, while F-C showed most rapid increase of rainfall rates at the early several hours. New lies between them. These two, the time-delayed development of precipitation of NCU and premature evolution of rain of F-C, are well known problems (Molinari and Dudek 1992). So, we can expect that NEW is in a reasonable range. The tendencies of the F-C trigger to initiate convection prematurely are attribute to two factors. First, the value of convective inhibition assumed in F-C trigger is too small. Second, this trigger is apt to permit too large magnitudes of the convective triggering energy. On the other hand, the new trigger allowed the sub-grid scale convection to be delayed until CIN is diminished or the triggering energy is accumulated enough to overcome CIN.

It is revealed that this delayed activation of implicit clouds provide NEW with an opportunity that a upscale growth of the sub-grid scale cloud to the grid-resolvable disturbance occurs in more realistic and timely manner. Also, it seems that the new trigger developed in the present study may perform better than the F-C trigger because TKE is a good representative of the sub-grid scale velocity variance in variety of environment. Furthermore, it is revealed that the process of convective initiation significantly influences the following scale interactions between the sub-grid scale and the grid-resolvable scale and that the scale interaction is an important ingredient for successful simulations. It is also found that an upper limit of achievable magnitude of convective triggering energy is an important factor that determines the characteristics of such scale interactions. Successful results obtained from new trigger imply that the magnitude of TKE can be a reasonable upper bound of the achievable convective triggering energy.

Acknowledgements

This research was partly supported by the Ministry of Environment and CRAY Research/Development.

References

Ballard S. P., B. W. Golding and R. N. B. Smith, 1991: Mesoscale model experimental forecasts of the Haar of northeast Scotland, *Mon. Wea. Rev.*, 119, 2107-2123.

Dudhia, J., 1989: Numerical study of convection observed during the winter monsoon experiment using a mesoscale, two-dimensional model. *J. Atmos. Sci.*, 46, 3077-3107.

Hong, S.-Y., and H.-L. Pan, 1998: Convective trigger function for a mass-flux cumulus parameterization scheme, *Mon. Wea. Rev.*, 126, 2599-2620.

Kain, J. S., and J. M. Fritsch, 1992: The role of the convective trigger function in numerical forecasts of mesoscale convective systems. *Meteoro. Atmos. Phys.*, 49, 93-106.

Kunkel, K. E., S. A. Changnon, and J. R. Angel, 1994: Climatic aspects of the 1993 upper Mississippi River basin flood. *Bull. Amer. Meteor. Sco.*, 75, 811-822.

Junker, N. W., R. S. Schneider, and S. L. Fauver, 1999: A study of heavy rainfall events during the Great Midwest flood of 1993. *Weather and Forecasting*, 14, 701-712.

Molinari, J. and Dudek, M., 1992: Prameterization of convective precipitation in mesoscale numerical models: A critical review. *Mon. Wea. Rev.*, 120, 326-344.

Rogers, R., and J. M. Fritsch, 1996: A general framework for convective trigger functions. *Mon. Wea. Rev.*, 112, 2084-2104.

Stensrud, D. J., and J. M. Fritsch, 1994: Mesoscale convective systems in weakly forced large-scale environments. Part III: Numerical simulations and implications for operational forecasting. *Mon. Wea. Rev.*, 122, 2084-2104.

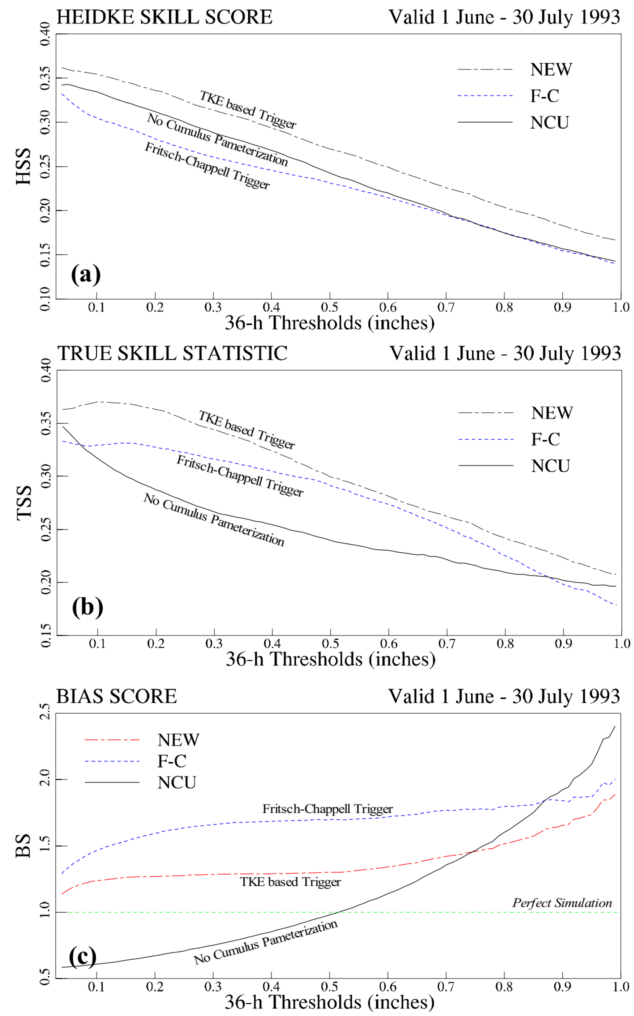

Figure 1: Comparison of space-time averaged skill scores as a function of rain threshold. (a) Heidke Skill Score (HSS), (b) True Skill Statistics (TSS), and (c) Bias Score (BS).

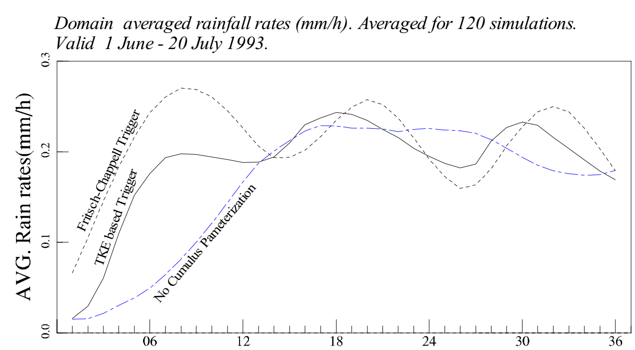

Figure 2: Comparison of the time series of rainfall rates averaged for model domain and all events of simulations.