Parameterization of Convection in the Global NWP System GME of the German Weather Service

Dmitrii Mironov[†] *and Bodo Ritter*
German Weather Service, Offenbach am Main, Germany
(dmitrii.mironov@dwd.de, bodo.ritter@dwd.de)

In this note, recent results concerning the parameterization of convection in the global numerical weather prediction (NWP) system GME (Majewski et al. 2002) of the German Weather Service (DWD) are briefly described. GME utilises the well-known Tiedtke (1989) mass-flux convection parameterization scheme that contains only minor modifications as compared to its original release. With the ultimate goal to improve the representation of atmospheric convection in numerical models, in GME in particular, the work at DWD over the last one and a half year proceeded along two lines. (i) An analytical study is performed with the aim to better understand what we actually do when applying mass-flux convection schemes, that were initially developed for NWP systems with coarse horizontal resolution (300 to 200 km), in the present-day resolution (50 to 5 km) global and limited-area NWP systems. To this end, the fundamentals of the mass-flux modelling framework are briefly recollected and a number of assumptions that stand behind the current mass-flux convection schemes are critically considered. The analogy between budget equations for the second-order statistical moments of fluctuating fields derived in the mass-flux modelling framework and in the ensemble-mean modelling framework with Reynolds averaging are examined. These exercises help elucidate the essential physics behind the mass-flux approach and the meaning of various disposable parameters of mass-flux schemes. They help address a key question as to which assumptions behind the mass-flux parameterization schemes should be reconsidered and relaxed. (ii) Several modifications in the existing GME mass-flux convection scheme are tested through a series of numerical experiments. The aim of this exercise is to improve the GME performance as much as possible without major changes in the existing convection scheme, i.e. keeping the framework of the traditional mass-flux approach. This purpose is served by tuning/revising convective trigger function, formulation of entrainment and detrainment, and the way convective precipitation is generated and evaporated.

Figure 1 illustrates the GME performance in the Tropics. The diurnal cycle of surface precipitation in the Rondônia area, Brazil, in February is simulated with GME, using the GME binary operational in March 2004 and the 1999 GME analysis stored in the DWD data bank for the model initialisation. The GME output is compared with the output from the two versions of ECMWF IFS (Bechtold et al. 2004) and with observational data from the 1999 Large-Scale Biosphere-Atmosphere Experiment (LBA) wet season campaign (Silva Dias et al. 2002). Observations demonstrate a strong diurnal cycle of surface precipitation that is dominated by convection. As Fig. 1 suggests, the GME performance is not unsatisfactory, although some problems are readily apparent. In particular, a too early onset of strong day-time precipitation and a too early precipitation maximum are predicted. The night-time precipitation maximum seen in observational data is missing in the GME output. The ECMWF IFS shows a similar performance, expect that the night-time precipitation maximum is simulated slightly better with the ECMWF IFS 25R4.

[†]Corresponding author address: Deutscher Wetterdienst, AP2003, Kaiserleistr. 29/35, D-63067 Offenbach am Main, Germany.

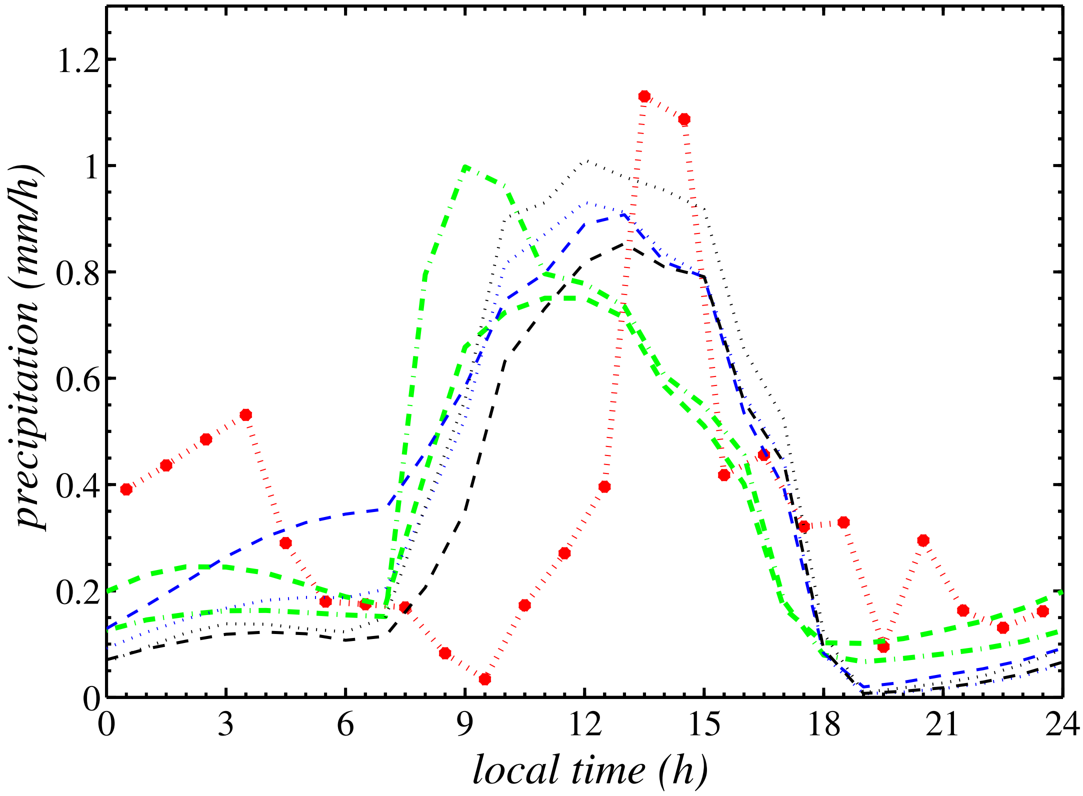

Figure 1. Diurnal cycle of surface precipitation in the Rondônia area. Midnight at Rondônia corresponds to ca. 4:30 UTC. Red heavy dotted curve shows the LBA 1999 observational data. Green heavy dot-dashed curve and green heavy dashed curve show the 24–72 hour (local time) T511 ECMWF forecasts performed with the 25R1 and 25R4 versions, respectively, of the ECMWF IFS. The ECMWF results are obtained by means of averaging over February 2002 and over a lat-long rectangle whose corners' co-ordinates are 7.7 S 74.1 W, 1.8 S 65.0 W, 4.0 S 60.5 W, and 13.8 S 71.7 W. Thin curves show the GME results obtained by means of averaging over the period from 29 January to 28 February 1999 and over the $10° \times 10°$ lat-long square (2 S to 12 S, 63 W to 73 W). Thin dashed curves show the 4–28 h forecast initialised at 00 UTC (blue) and the 16–40 h forecast initialised at 12 UTC (black); thin dotted curves show the 28–52 h forecast initialised at 00 UTC (blue) and the 40–64 h forecast initialised at 12 UTC (black). The 00 UTC GME curves show total precipitation, whereas the 12 UTC GME curves show convective precipitation only.

Further test runs are performed to look at the GME performance in mid-latitudes. Numerical experiments reveal problems with the precipitation timing in mid-latitudes similar to those in the Tropics. In most cases, convection is triggered too early leading to a premature day-time precipitation maximum. Furthermore, convection in mid-latitudes is typically too active.

In an attempt to better understand the reason for the above deficiencies an analytical study of the mass-flux modelling framework is performed. A consideration of basic assumptions that stand behind the current mass-flux parameterizations suggests that many of them are too restrictive. These are, first of all, the assumptions that (a) convection is quasi-stationary (no time-rate-of-change terms in the mass-flux equations), and that (b) in a triple decomposition of the quantity in question (vertical velocity, temperature, humidity) into the contributions from updraughts, from downdraughts, and from the so-called environment, a mean over the environment is equal to a mean over the entire grid box. The assumption (a) deprives a convection scheme of memory. As a result, a scheme responds to external forcing practically instantaneously, leading to a premature initiation of convection and an erroneous diurnal cycle. The assumption (b) actually means that the area covered by convective updraughts and downdraughts is small as compared to the size of the grid box. This assumption is justified, to a good approximation, for the horizontal grid size of order 200-300 km, but is less justified if the grid size is of order 50 km typical of the present-day global NWP systems, not to mention the limited-area NWP systems whose grid size falls below 10 km. Then, there is no wonder that the current mass-flux convection schemes are too active, most notably, in mid-latitudes. A wealth of DWD experience with GME and with the limited-area NWP system LM (Steppeler et al. 2003) strongly suggests that the above is indeed the case. It is notable that the fact that the assumption (b) is invalidated as the resolution of the atmospheric model is increased was pointed out already by Tiedtke (1988, page 21). Unfortunately, little caution has been exercised in numerous subsequent applications, where the Tiedtke (1989) scheme and similar mass-flux convection schemes have been applied without regard for their limits of applicability.

The analogy between the mass-flux and the ensemble-mean (i.e. Reynolds-averaged) budget equations for the second-order statistical moments of fluctuating fields is examined. An analysis of the scalar variance equations has been performed by de Rode et al. (2000) and Lappen and Randall (2001). They found, among other things, that the sum of the lateral entrainment and detrainment rates in the mass-flux equation corresponds to the inverse scalar-variance dissipation time scale in the ensemble-mean equation. We extend the analysis of de Rode et al. (2000) and Lappen and Randall (2001) to examine the budgets of the vertical-velocity variance and of the vertical scalar flux.

We find that the term with the entrainment and detrainment rates in the mass-flux budget of the vertical-velocity variance describes the combined effect of dissipation and of pressure redistribution. A similar term in the mass-flux budget of the scalar flux is the destruction term that describes the pressure effects. This is in apparent contradiction with the interpretation of the entrainment-detrainment term in the mass-flux budget of the scalar variance, where it describes the scalar-variance dissipation. This shows the inherent limitation of the mass-flux models, at least as they are currently used in the NWP systems. Since the scalar-variance dissipation, the velocity-variance dissipation, the pressure redistribution and the pressure gradient-scalar covariance depend on the mean flow variables in very different ways, it seems very difficult, if not impossible, to describe all the above effects in terms of only two quantities, the rates of lateral entrainment and detrainment.

A positive outcome of the above analytical exercise is that it suggests an improved formulation for the rates of turbulent entrainment and detrainment. Using the second-order closure ideas as to the parameterization of the pressure-scalar covariances in convective flows (e.g. Zeman 1981, Mironov 2001), an extended formulation for the rates of turbulent entrainment E_u and detrainment D_u in convective updraughts is derived (details of the derivation will be reported in the subsequent papers). It reads

$$(E_u, D_u) = M_u \left[(\epsilon, \delta) + C_B a_u^2 (1 - a_u)^2 \frac{g}{\overline{\theta}} \frac{\theta_u - \overline{\theta}}{(M_u/\overline{\rho})^2} \right] = M_u \left[(\epsilon, \delta) + C_B \frac{g}{\overline{\theta}} \frac{\theta_u - \overline{\theta}}{(w_u - \overline{w})^2} \right]. \quad (1)$$

Here, g is the acceleration due to gravity, w is the vertical velocity, θ is the potential temperature, M_u is the convective mass flux, a_u is the fractional area coverage of convective updraughts, ρ is the density, and C_B is an dimensionless constant. A subscript "u" refers to convective updraughts. An overbar denotes a grid-box mean. The first term in brackets on the right-hand side of Eq. (1) corresponds to the original Tiedke (1989) formulation, where E_u and D_u are set proportional to the updraught mass flux M_u through the constant fractional entrainment ϵ and detrainment δ rates (their dimensions is m^{-1}). The second term in brackets accounts for an important dependence of E_u and D_u on the potential-temperature (buoyancy) difference between the updraught and the environment.

A series of GME runs are performed to test the extended entrainmet/detrainment formulation (1). By and large, the GME performance in mid-latitude is positively affected in that convective activity is slowed down. The amount of convective precipitation, that is typically overestimated, is reduced and the initiation of convection is somewhat delayed. The GME performance in the Tropics is, however, not improved as the suppression of convective activity is somewhat too strong. The result is not conclusive and further testing is required.

Several other modifications in the existing GME mass-flux convection scheme have been tested two of which are mentioned here. (i) Suppressing convective precipitation in favour of grid-scale precipitation has a neutral or a slightly positive impact on the GME performance in mid-latitudes. However, the performance in the Tropics is slightly deteriorated. (ii) A modified formulation for the trigger-function is developed. Potential temperature and specific humidity of a convective test parcel is determined by means of averaging over the updraught source layer that extends from the first model level above the underlying surface to the cloud base. A zero-order approximation to the cloud base height is found using a test parcel that originates from the first model level above the surface. In this way, the test parcel properties are less dependent on the vertical resolution than the original Tiedtke (1989) formulation currently used in the GME convection scheme. The proposed formulation involves only marginal additional computational cost (it requires only one additional call to a routine that computes the cloud base height). Other trigger-function formulations proposed to date (e.g. Kain 2004) may be somewhat more physically plausible, but they are computationally expensive as they involve an iterative procedure to determine the updraught source layer. The proposed modifications in the trigger-function formulation has a slightly positive impact on the GME performance. Convective activity is slowed down. A day-time precipitation maximum in the Tropics is slightly shifted towards late afternoon, i.e. towards the time it should occur according to the observations.

An overall conclusion is that the performance of the GME mass-flux convection scheme leaves much to be desired, but is not entirely unsatisfactory. The performance will deteriorate as the horizontal resolution is increased. To avoid this requires major changes in the GME convection scheme. In all likelihood, the same is true for most (if not all) other mass-flux convection schemes used in global and limited-area NWP systems. Minor “cosmetic” changes within the existing mass-flux framework will hardly improve the representation of convection. A notable advance requires that a number of basic assumptions behind the mass-flux schemes be reconsidered and relaxed, and advanced formulations for various components of convection schemes be developed. A step forward in this direction is the extended entrainment/detrainment formulation given by Eq. (1). In a long-term prospective, a unified convection-turbulence scheme based on the second-order closure ideas seems to be an attractive alternative. Such scheme should account for non-local features of convective mixing and should treat all sub-grid scale mixing processes in a unified framework. Work along this line is initiated at DWD.

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