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# A Finite Difference Approximation for Convective Transports Which Maintains Positive Tracer Concentrations

S. BRINKOP AND R. SAUSEN

DLR, Institut für Physik der Atmosphäre, Oberpfaffenhofen, 82234 Weßling, Germany

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**Abstract**

We have modified the mass-flux convection scheme of Tiedtke (1989) in order to ensure positive tracer concentrations during the course of a GCM integration. The model with the new numerics has been tested against the standard scheme in several 3-D climate model simulations which differ with respect to the location of the tracer source. Typical difference patterns associated with the prescribed tracer source can be noticed from the results. In the case of a strong surface source, the upward transport away from the surface tends to be reduced with the new scheme compared to the standard scheme. However, in the case of atmospheric tracer sources at an upper tropospheric level the upward transport above the source and downward below it are both enhanced. A student-t test confirms that these difference patterns are highly significant (99 %).

## 1 Introduction

Cumulus convection is a major process in determining the temperature and moisture vertical profiles of the atmosphere through condensation and the corresponding diabatic heating. Accordingly, convective processes must be adequately represented in large-scale models of the atmosphere. In the framework of environmental tracer studies it is important to include convective tracer transports in the respective parameterizations. This has been done in the case of the general circulation model (GCM) ECHAM, which has been developed as a sophisticated tool of climate research (Roeckner et al., 1992). Convection is parameterized by a state-of-the-art mass-flux scheme (Tiedtke, 1989). This parameterization can also be found in the weather prediction models of the German Weather Service (Cress et al., 1995) and in the forecast model of the European Centre of Medium Range Weather Forcasts (ECMWF). A convection scheme should guarantee non-negative concentrations. This is of particular importance for humidity and for tracer studies. Unfortunately, this constraint is not fulfilled for all possible conditions by the Tiedtke scheme. The main problem shows up in cases of convective activity connected with strong vertical tracer gradients, when more mass can be moved away from a grid box than is available. This results in a numerically modified tracer distribution that is clearly unwarranted. Apart from this basically numerical feature, subsequent physical effects like the interaction of tracers with radiation or chemistry may be expected to enhance this error dramatically. We have modified the mass-flux scheme of Tiedtke (1989), such that tracer concentrations remain non-negative throughout a model integration.

## 2 Development of an Alternative Numerical Scheme

A detailed analysis of the numerics of the mass-flux scheme revealed several sources of potential negative tracer concentrations. The main source is due to the discretization of the tracer variables. In the operational versions of ECHAM a tracer concentration $\overline{X}_k$ is defined as a prognostic variable on full levels (middle of a layer, index $k$). However, in the numerical scheme for the calculation of convective transports $\overline{X_k}$ is interpolated from full levels to half levels (index $(k+\frac{1}{2})$) according to

$$X_{k+\frac{1}{2}} = \frac{1}{2}\left(\overline{X_k} + \overline{X_{k+1}}\right) \qquad (2.1)$$

The prognostic variables temperature $T$ and humidity $q$ are extrapolated to the half levels according to Eq. (25) of Tiedtke (1989). This deviates from the treatment of variables outside the convection routine. The modifications in the convection routine refer to tracers only. Thus, tracers are left on full levels in the new scheme. In the original model the transport equations are discretized as centered-finite differences in updraught, downdraught and the environment. Now they take the form of upwind schemes. The calculation of tracer mass fluxes below cloud base also has been changed. The technical details are described in Brinkop and Sausen (1996).

## 3 Testing the New Numerical Scheme

In order to test the new numerical scheme of the mass-flux parameterization we performed a variety of numerical simulations with the ECHAM3 model (Roeckner et al., 1992) applying the three-dimensional (3-D) and, additionally the 1-D version. Here we concentrate on some of the 3-D results, while a number of 1-D simulation results are presented by Brinkop and Sausen (1996).

### 3.1 Mass Conservation

First it was checked whether the mass conservation constraint is fulfilled during a model integration period. It can be expected that tracer mass increases during a model integration because negative tracer concentrations calculated by the convection scheme are set to zero by the semi-Lagrangian advection scheme. We run the 3-D model over 15 time steps from a critical initial tracer distribution without sources and sinks. The initial tracer distribution is prescribed globally at 1000 hPa in one layer only. By analyzing the differences between initial and final total tracer mass we found that with the new formulation the tracer mass remains constant during a model integration whereas with the standard formulation the mass increases by 12 %. As indicated by a larger number of similar simulations, the magnitude of the mass increase depends on the altitude where the initial tracer is located. Strong tracer gradients in the boundary layer seem to be most critical in generating large negative tracer concentrations and hence creating additional tracer mass.

### 3.2 Permanent July Simulations

In this section the results of two simulations with the ECHAM model with different sources of tracer mass are presented. The model was integrated from a balanced climate state over 26 month in perpetual July mode. Only the last 20 months were choosen for comparison between the standard and the modified model version. In experiment SL the tracer sources are prescribed at all surface points while in experiment AL they are prescribed in the free atmosphere at 326 hPa. The sources are uniformly distributed over the respective model level. The half-lifetime of tracers of 3.83 days is assumed globally, recalling the life time of a standard tracer like radon. In both the SL and the AL case a comparison of zonal mean tracer distributions simulated by the revised scheme and the original scheme reaches differences up to 10 %. Both cases produce a quite characteristic difference pattern. In the SL case (Figure 1) the new scheme transports less tracer mass into the free atmosphere than the standard scheme. Instead, more tracer mass remains in the lowest model layers. The typical difference pattern for AL (Figure 2) shows a completely different structure. Here, the new scheme transports more tracer mass downwards than the standard scheme, which is an effect of the new discretisation of tracer variables on model full levels. Additionally, more tracer mass can also be found above the source, leading to a distinct dipole structure. Applying a student t-test it can be proved that all these differences have not a random character but are statistically significant. The 99 % significance level (shaded area in Figures 1 and 2) is reached for almost the whole region affected by the difference patterns just described.

## 4 Conclusion

We have modified the mass-flux convection scheme of Tiedtke (1989) in order to ensure positive tracer concentrations during the course of a model integration. Tracer concentrations now remain on full levels in the convection scheme as it is already discretized in the rest of the model. We do not conclude that the result of former tracer simulations with the frequently used standard scheme have been

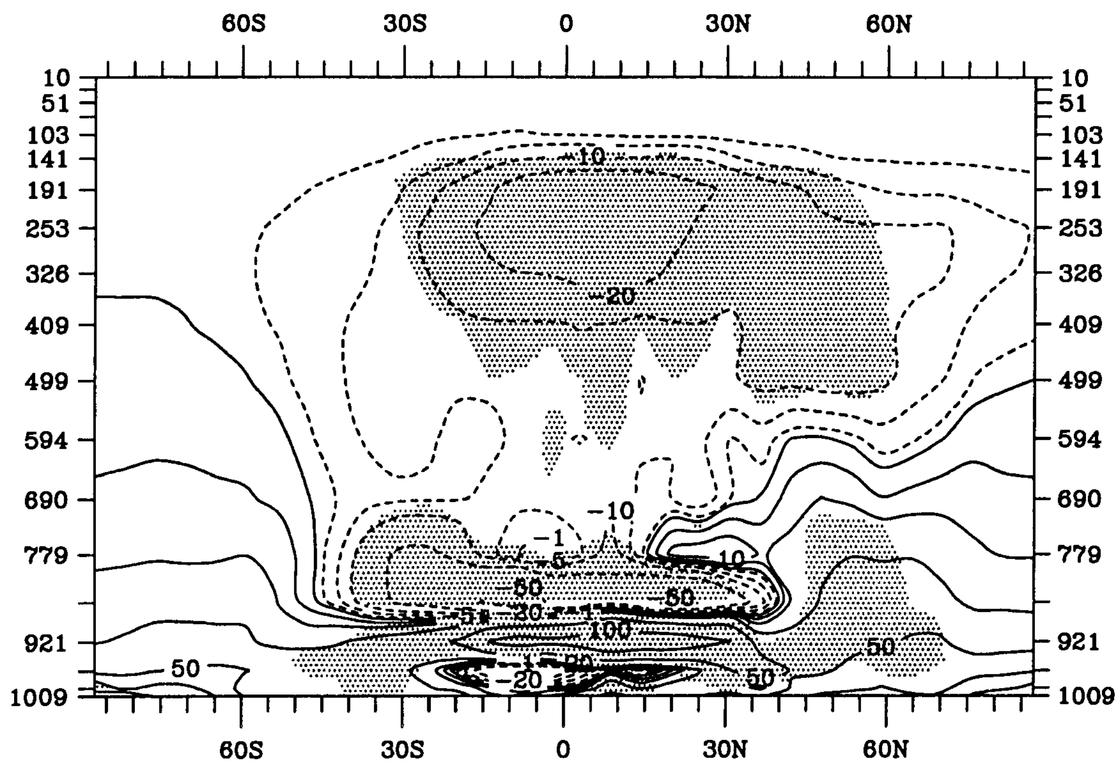


**Figure 1:** Model run SL (surface source): New - Cntl in $10^{-16}$ kg/kg, significance level of 99 % reached in shaded area.

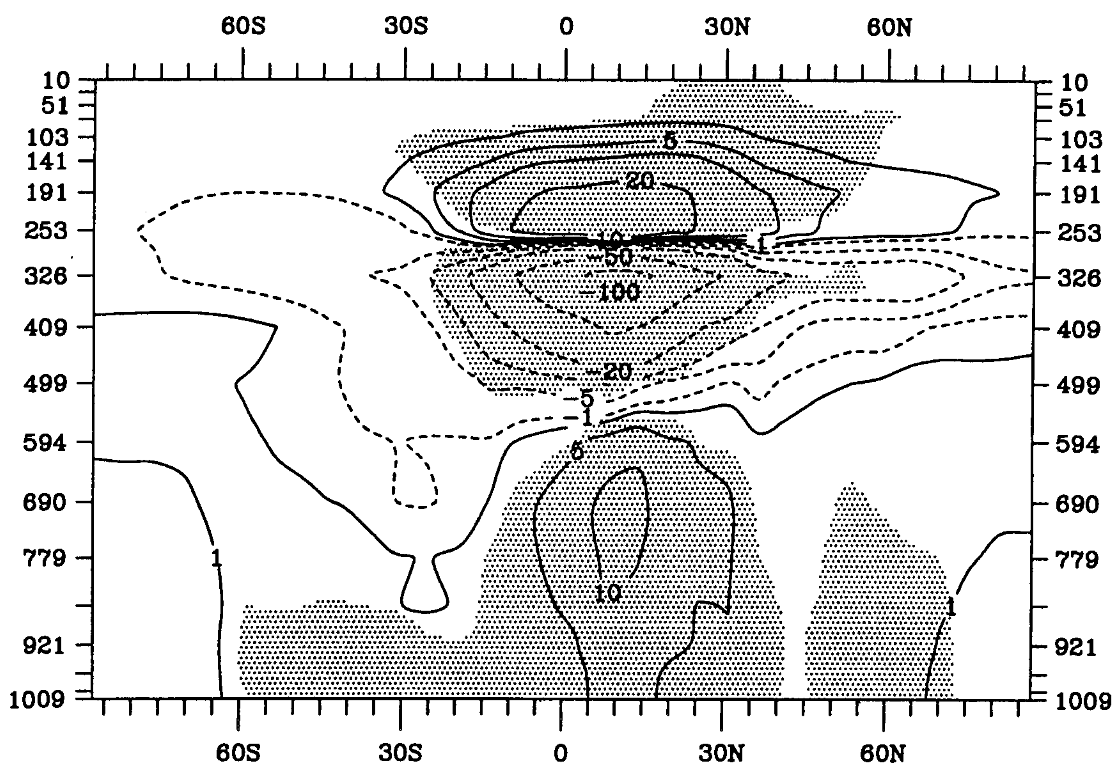


**Figure 2:** Model run AL (atmosphere source): New - Cntl in $10^{-12}$ kg/kg, significance level of 99 % reached in shaded area.

proven worthless by the results of this paper. The resulting distributions remain rather similar after all. Nevertheless, due to the significance and robustness of the difference pattern in connection with a prescribed source it can be expected that the results of former tracer studies will significantly change. This might become very important in simulations, where the tracer interacts with other physics as for instance radiation or chemistry. Most importantly, regarding chemical species as tracers, the mass is conserved without additional correction terms.

So far only the numerics of the tracer transport have been corrected. It is intended also to correct the heat and moisture transport and corresponding variables to get a consistent modification of the numerics in the convection routine.

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