Conf-9110325--1

Preprints, 9th Conference on Numerical Weather Prediction, 14-18 Oct 1991, Denver, CO, Amer. Met. Soc., Boston, MA

DOE/ER/61066--2

DE92 007206

A CUMULUS PARAMETERIZATION SCHEME DESIGNED FOR NESTED GRID MESO-β SCALE MODELS

M.J. Weissbluth and W.R. Cotton

Dept. of Atmospheric Science, Colorado State University, Fort Collins, CO 80523

Received OSTI

FEB 03 1992

1 Introduction

Currently, there is no adequate cumulus parameterization that is suitable for use in nested grid simulations having horizontal resolutions between two and fifty kilometers. The few parameterizations which are designed for meso-β scale models are scale specific, *i. e.* they were designed around a specific horizontal grid scale. The result is that they do not function well outside of the intended horizontal resolution since certain assumptions become invalid. Perhaps the most limiting assumption in these cumulus parameterizations is the convection and all associated motions, including compensating subsidence, occur wholly within the grid box. This unrealistically constrains the subsidence and does not allow convection to propagate into contiguous grid volumes. Furthermore, as the grid resolution increases, the resolvable advection and the cumulus parameterization begin to represent the same physical process. This double counting of a physical process by both the resolved scale and the parameterized scale then becomes a concern.

In Weissbluth (1991) and Weissbluth and Cotton (1988), a CCOPE supercell, Florida sea-breeze convection and a tropical squall line were explicitly simulated by the Regional Atmospheric Modeling System (RAMS) developed at Colorado State University. Model output diagnostics were shown to be a powerful tool in interpreting the behavior of the storm since spatial and temporal resolution of the data is uniform and self-consistent, unlike real-world observations of these phenomena. By averaging over suitable areas of the explicit simulations, areal averages of the convective heat, momentum and moisture fluxes were obtained for each of the storms and intercompared. The vertical velocity variance seems to be a rather universal measure of convection regardless of the forcing of convection or its environment. Furthermore, vertical mass and moisture covariances appear strongly linked to $\overline{w'w'}$. For these reasons, we have based the present cumulus parameterization scheme on the prediction of $\overline{w'w'}$.

Weissbluth (1991) and Weissbluth and Cotton (1990) described the modifications made to the traditional Mellor and Yamada (1974) level 2.5 closure. Since the one prognostic variable is $\overline{w'w'}$, the scheme is termed a level 2.5w closure. Within this formulation, realizability conditions are imposed on the mixing coefficients as in Hassid and Galperin (1983) and the clipping approximation of Andre *et al.* (1976) is used. Furthermore, a generalized length scale is used as in Chen and Cotton (1987) to represent stable and unstable conditions where a buoyant heat flux may or may not be present.

The pressure and transport term are closed as in Zeman and Lumley (1976) who modeled these terms for a buoyancy-driven mixed layer. In their original formulation, the shear components were not included since they studied an environment without shear; in our formulation, contributions to $\overline{w'w'}$ from shear is included. The transport term is handled in a relatively sophisticated way in order to include counter-gradient transports in the mixed layer. Our formulation extends the original theory to include the virtual and rainwater effects on the buoyancy terms.

Thus far, only a higher order turbulence scheme has been described. In the following sections, the addition of a deep cumulus compnent will be described that will allow the scheme to be used as a cumulus parameterization scheme. Then, one-dimensional simulations will be presented that describe the limiting states of this cumulus parameterization scheme. It is important to note that in the previous development of this scheme and in the following section, no assumptions about the scale of the cumulus have been made.

2 The convective adjustment model

The level 2.5w model predicts the evolution of horizontally homogeneous convection over land and water. This includes, for example, convection within the PBL and convection forced by the radiative destabilization of statiform cloud layers in the PBL and in the middle and upper troposphere. Alone, however this theory fails to simulate the ensemble-averaged effects of deep convective activity when applied to the free atmosphere. This is because the PBL, for example, is driven by the parameterized heat flux at the ground. The divergence of this heat flux creates an unstable lapse rate which implies strong mixing and an upward transport of heat. The PBL grows slowly by vertically communicating the heat flux upwards until the inversion can no longer be eroded by the PBL eddies. When deep moist convective cells are present in the free atmosphere, however, this theory of contiguous mixing is no longer valid since information about the buoyant parcel is carried from the lifted condensation level (LCL) to the equilibrium temperature level (ETL). Some way is needed to conserve the parcels buoyancy through the depth of the free atmosphere in order to represent the effects of deep moist convection.

Therefore, a convective adjustment scheme first proposed by Manabe *et. al.* (1965) and investigated by Betts (1986), Bougeault (1985) and others is proposed. This model is capable of capturing the strong scalar transports within the core of the convection.

The tendencies to the model variables are specified so that the cumulus forcing becomes

$$\left(\frac{\partial \overline{\mathcal{X}}}{\partial t}\right)_{\text{cumulus}} = \sigma_{u,d}\left[w^{**}\frac{\partial \overline{\mathcal{X}}}{\partial z} + \frac{1}{T}\left(\mathcal{X}_{u,d} - \overline{\mathcal{X}_e}\right)\right]. \quad (1)$$

The second term on the rhs of Eq. 1 is the convective adjustment term where T is the time scale over which convection modifies the environment, $\overline{\mathcal{X}}$ represents any scalar variable, u, d and e represent updraft, downdraft or environmental values of a variable and σ represents cloud core fractional coverage.

The convective time scale is simply specified as

$$\frac{1}{T} = \frac{1}{\rho H}\int_{lcl}^{ct}\sqrt{\overline{w'w'}}\,\rho dz$$

where H is the total cloud height. The first term on the rhs of Eq. 1 is as in Bougeault (1985), except w^{**} is determined from forcing the moist static energy of the convective tendencies to be nil, *i. e.*

$$w^{**} = \frac{1}{T}\frac{\int_{lcl}^{ct}[L(r_{su} - \overline{r_v}) - L(r_{tu} - \overline{r_t}) + C_p(T_u - \overline{T})]\rho dz}{\int_{lcl}^{ct}[L\frac{\partial \overline{r_t}}{\partial z} - L\frac{\partial \overline{r_s}}{\partial z} - C_p\frac{\partial \overline{T}}{\partial z}]\rho dz} \quad (2)$$

There are several interpretations of Eq. 1 which can be made. When cumulus forcing is diagnosed, the first term on the rhs combines with the resolvable advection. Bougeault (1985) then interprets the first term on the rhs as a subsidence term since the resolvable vertical motion in large-scale models is negligible compared to w^{**}. The second term is then interpreted as the detrainment term. In large scale models, then, the subsidence term prompts warming and drying while the detrainment term prompts warming and moistening.

In mesoscale models, the resolved vertical motion may be comparable to w^{**} and a different interpretation of the term is needed. In this case, the advection by the resolved motions and the first term on the rhs (now called the compensation term) combine to give near zero net advection which is desirable since the advection of the scalars is now being accomplished by the convective adjustment term. Double counting is then explicitly eliminated since the convective adjustment term wholly handles the updraft core warming and moistening.

In Eq. 1, either w^{**} or T could be specified and the remaining coefficient determined from a moist static energy balance. Bougeault specified the convective flux as a function of height and diagnosed the detrainment time scale. Here, the convective adjustment time scale is diagnosed from the predicted $\overline{w'w'}$ and the mass flux is diagnosed from an energy balance consideration. This is an artifact of the methodology used to construct Eq. 1; only the convective adjustment term was initially included in the calculations. Due to the difficulty in balancing the moist static energy of the tendencies, the compensation term was later added. The effect of diagnosing w^{**} and determining T from an energy balance on the parameterization scheme is unknown and will be relegated to future research.

3 One-dimensional simulations

The one dimensional simulations of a non-entraining cumulus will be presented here in order to delineate the final or limiting state the cumulus parameterization scheme would reach. This scheme is placed within a model with a large horizontal grid spacing of 1000 km in order to simulate a one dimensional model. There is necessarily little mean vertical motion and thus no feedback between the scheme and the numerical model. Areal coverage of the cumulus is assumed to be unity and the parameterized cumulus is active for 5400 seconds. Since a one-dimensional simulation does not allow for the horizontal convergence of water vapor, this quantity will not be depleted by the cumulus convection. Figures in this section will include the initial and final total water mixing ratio profiles, initial and final potential temperature and final Θ_{il} profiles, and the time evolution of the condensate rate for simulations with and without downdrafts and with and without microphysics. The condensate rate is defined as the total liquid and ice which is produced within the parameterized cloud. The numerical model uses the thermodynamic variable Θ_{il} which is conservative for parcels undergoing adiabadic motions with phase changes. It is non-conservative, however, for all precipitation processes. The expression relating Θ_{il} and Θ is derived in Tripoli and Cotton (1981) and is

$$\Theta = \Theta_{il}\left(1 + \frac{L_{lv}}{C_pT}r_l + \frac{L_{iv}}{C_pT}r_i\right). \quad (3)$$

In order to produce these limiting states, only the convective adjustment term (the second term on the rhs of Eq. 1) is retained since there can be no vertical motion to offset the compensation term.

The limiting state for a non-entraining cumulus cloud with no downdrafts and no microphysics is indicated in Figs. 1a - 1c. The final total water mixing ratio (Fig. 1a) is well mixed through the depth of the cloud as is the final $\overline{\Theta_{il}}$ profile in Fig. 1b. Note that the potential temperature profile in the same figure indicates the atmosphere has warmed at all levels in response to the convection. The condensation rate in Fig. 1c peaks at 310 mm/hr soon after cumulus convection is initiated and assymptotes to near 20 mm/hr. The condensation rates are large since the parameterized cumulus has a fractional coverage of unity. These profiles adequately characterize the expected changes in the environment when a deep, non-entraining, non precipitating cloud with no downdrafts fills a grid volume.

When downdrafts are added to the cumulus parameterization (not shown) the final total water mixing ratio shows a decrease in value where the downdrafts are present. Furthermore, cooling in the lower model levels is apparent. The condensation rate peaks 50 mm/hr higher at 460 mm/hr and assymptotes to a similar value as the no downdraft case.

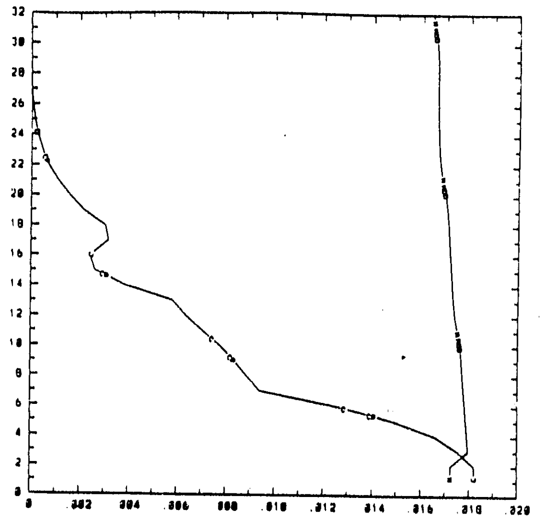

Figure 1a. Vertical profiles of total water mixing ratio, R_T in g/kg (curve MOD) after 5400 s and the initial profile, R_{T_o} (curve CP) in a one dimensional simulation without downdrafts and without microphysics.

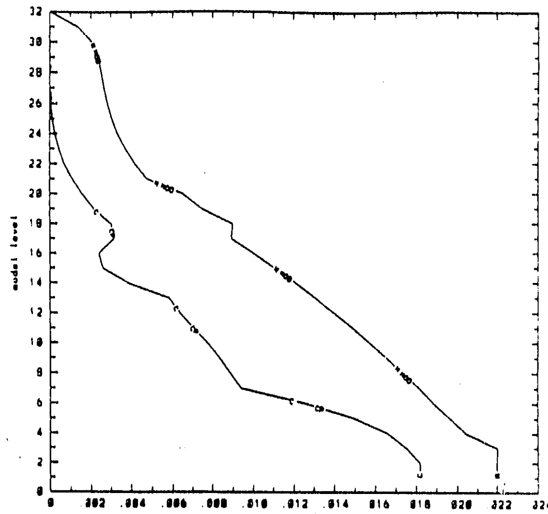

Figure 2a. As in 1a except for a simulation without downdrafts and with microphysics.

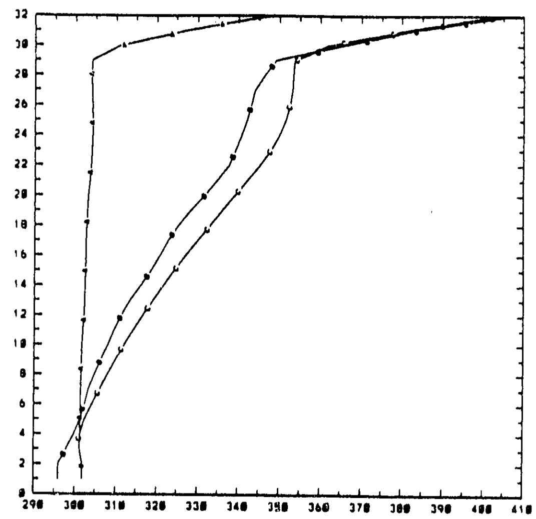

Figure 1b. Vertical profiles of Θ_{il} (curve A), Θ (curve C) after 5400 s and the initial potential temperature profile (curve C) in a one dimensional simulation without downdrafts and without microphysics.

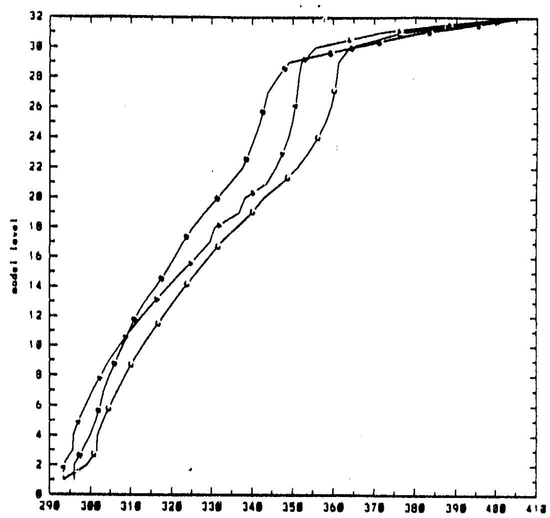

Figure 2b. As in 1b except for a simulation without downdrafts and with microphysics.

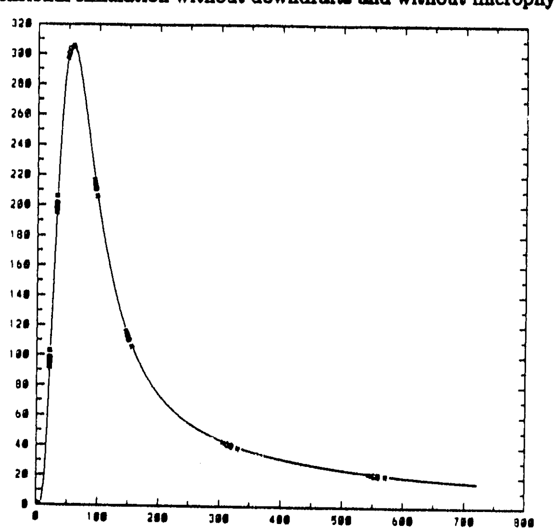

Figure 1c. Time evolution of the condensate rate in mm/hr for 5400 s in a one dimensional simulation without downdrafts and without microphysics.

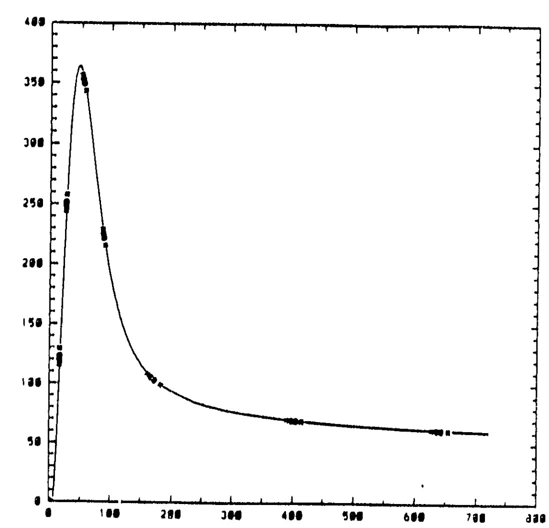

Figure 2c. As in 1c except for a simulation without downdrafts and with microphysics.

The final states when the parameterization is run with microphysics and no downdrafts is indicated in Figs. 2a - 2c. The total water mixing ratios in Fig. 2a are not constant with height since there is now precipitation forming and falling. The final $\overline{\Theta_{il}}$ in Fig. 2b is no longer well mixed due to the precipitation processes, yet the potential temperature profiles are similar to the simulation with no microphysics since the in-cloud potential temperatures are only affected by precipitation through the energy released by the freezing process. The condensation rate peaks at 365 mm/hr and assymptotes near 60 mm/hour.

When both downdrafts and microphysics are added to the cumulus parameterization (not shown), slightly more total water accumulates near the lower layers and slight cooling occurs. The condensation rate is higher than the no downdraft case through the whole simulation with a peak rate of 460 mm/hour and an assymptotic rate of 140 mm/hour.

These limiting solutions indicate that the cumulus parameterization scheme is functioning as desired. The scheme has been incoporated and tested in a fully two dimensional simulation.

4 Conclusions

A generalized cumulus parameterization based upon higher order turbulence closure has been incorporated into one dimensional simulations. The scheme consists of a level 2.5w turbulence closure scheme mated with a convective adjustment scheme. The convective adjustment scheme includes a gradient term which can be interpreted as either a subsidence term when the scheme is used in large scale models or a mesoscale compensation term when the scheme is used in mesoscale models. The scheme aslo includes a convective adjustment term which is interpreted as a detrainment term in large scale models. In mesoscale models, the mesoscale compensation term and the advection by the mean vertical motions combine to yield no net advection which is desirable since the convective moistening and heating is now wholly accomplished by the convective adjustment term; double counting is then explicitly eliminated. One dimensional simulations indicate satisfactory performance of the cumulus parameterization scheme for a non-entraining updraft.

Acknowledgements

We would like to thank Brenda Thompson for her help in processing this manuscript. This research was funded by the National Science Foundation under grant ATM-8814913 and the Department of Energy under grant DE-FG02-90ER61066. Some computations were performed on the National Center for Atmospheric Research (NCAR) Cray X-MP48 computer. NCAR is supported by the National Science Foundation.

References

Andre, J.C., G. DeMoor, P. Lacarrere and R. DuVachat, 1976: Turbulence approximation for inhomogeneous flows. Part I: The clipping approximation. *J. Atmos. Sci.*, **33**, 476-481.

Betts, A.K., 1986: A new convective adjustment scheme. Part I: Observational and theoretical basis. *Quart. J. Roy. Meteor. Soc.*, **112**, 677-691.

Bougeault, P., 1985: A simple parameterization of the large-scale effects of cumulus convection. *J. Atmos. Sci.*, **32**, 1934-1945.

Chen, C. and W. R. Cotton, 1987: The physics of the marine stratocumulus capped mixed layer. *J. Atmos. Sci.*, **44**, 2951-2977.

Hassid, S. and B. Galperin, 1983: A turbulent energy model for geophysical flows. *Boundary-Layer Meteorol.*, **26**, 397-412.

Manabe, S., J. Smagorinsky and R. F. Strickler, 1965: Simulated climatology of a general circulation model with a hydrologic cycle. *Mon. Wea. Rev.*, **93**, 769-798.

Mellor, G.L. and T. Yamada: A hierarchy of turbulence closure models for planetary boundary layers. *J. Atmos. Sci.*, **31**, 1791-1806.

Tripoli, G. J. and W. R. Cotton, 1981: The use of ice-liquid water potential temperature as a thermodynamic variable in deep atmospheric models. *Mon. Wea. Rev.*, **109**, 1094-1102.

Weissbluth, M.J. 1991: Convective parameteristion in mesoscale models. In press. Dep't of Atmos. Sci., Colorado State University, Fort Collins, Co., 80523.

Weissbluth, M.J. and W.R. Cotton, 1988: A diagnostic study of vertical fluxes in cumulus clouds using model output data. Preprints, 10th International Cloud Physics Conf., 15-20 Aug 1988, Bad Homburg, FRG, IAMAP.

Weissbluth, M.J. and W.R. Cotton, 1990: A hybrid cumulus parameterization for meso-β scale models. Preprints, Conf. on Cloud Physics, 23-27 Jul 1990, San Francisco, Ca, AMS.

Zeman, O. and J.L. Lumley, 1976: Modeling buoyancy driven mixed layers. *J. Atmos. Sci.*, **33**, 1974-1988.

END

DATE FILMED

3/25/92