A Next-Generation Fractional Cloudiness Parameterization

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Introduction

What is a stratiform cloud? The distinction between "convective" and "stratiform" clouds is somewhat arbitrary. Virtually all stratiform clouds contain buoyancy-driven turbulence (e.g., Lilly 1968). On the other hand, many convective clouds extend upward from and/or grow upward into stratiform cloud layers. For purposes of this paper, we define stratiform clouds to be clouds that are, in an area-averaged sense, neutrally buoyant with respect to their environments, level by level throughout their vertical extents. In contrast, then, "convective" clouds are those which are either positively or negatively buoyant at some levels, in an area-averaged sense. For example, cumulus or cumulonimbus clouds are positively buoyant through a large fraction of their vertical extents, and they may also contain regions of negatively buoyant convective downdrafts.

We have designed a new fractional cloudiness parameterization for use in large-scale models. The new parameterization is a "Next-Generation" version of Eauliq, the stratiform cloud parameterization developed by Fowler et al. (1996) and Fowler and Randall (1996a, b). The key features of the new parameterization are:

- a prognostic fractional cloudiness, representing the fractional area covered by stratiform clouds, following the approach developed by M. Tiedtke for use in the European Centre for Medium Range Weather Forecasting (ECMWF) model

- separate prognostic temperatures and water vapor mixing ratios for the clear and cloudy portions of each grid cell

- separate vertical velocities for the clear and cloudy portions of each grid cell, allowing the model to represent some aspects of mesoscale circulations

- cumulus clouds entrain from both the clear and cloudy portions of a grid cell; they detrain only into the cloudy portion of a grid cell

- cumulus-induced subsidence in the cloudy portion of a grid cell affects the cloud water and ice there

- the stratiform clouds are turbulent due to radiative and phase-change effects, and their evolution is affected by this turbulence.

Basic Equations

The basic equations of our model are as follows:

Continuity equation for "clear air":

$$\frac{\partial}{\partial t}\left(m^i A^i{}_{clr}\right) = -\sum_{i'} \hat{m}^{i+i'} \nu^{i+i'}{}_n l^{i+i'} A^{i+i'}{}_{clr} - A^i{}_{cld} A^i{}_{clr} m^i \left\{ C_{clr,cld}\left[\frac{\dot{q}^i_{c\,cond} + \dot{q}^i_{i\,cond}}{\left(q^i_*\right)_{clr} - \left(q^i_\nu\right)_{clr}}\right] + C_{cld,clr}\left(\frac{\dot{q}^i_{c\,evap} + \dot{q}^i_{i\,evap}}{q^i_c - q^i_i}\right)\right\} - \frac{\partial}{\partial z}\left\{\left[m^i \overline{w}^i - m^i A^i{}_{cld}\left(w^i{}_{cld} - w^i{}_{clr}\right)\right] A^i{}_{clr}\right\} + \left(M_c \frac{i\partial A^i{}_{clr}}{\partial z} - D^i A^i{}_{clr}\right), \quad (1)$$

Continuity equation for "cloudy air":

$$\frac{\partial}{\partial t}\left(m^i A^i{}_{cld}\right) = -\sum_{i'} \hat{m}^{i+i'} \nu^{i+i'}{}_n l^{i+i'} \hat{A}^{i+i'}{}_{cld} + A^i{}_{cld} A^i{}_{clr} m^i \left\{ C_{clr,cld}\left[\frac{\dot{q}^i_{c\,cond} + \dot{q}^i_{i\,cond}}{\left(q^i_*\right)_{clr} - \left(q^i_\nu\right)_{clr}}\right] + C_{cld,clr}\left(\frac{\dot{q}^i_{c\,evap} + \dot{q}^i_{i\,evap}}{q^i_c + q^i_i}\right)\right\} - \frac{\partial}{\partial z}\left\{\left[m^i\overline{w}^i + m^i A^i{}_{clr}\left(w^i{}_{cld} - w^i{}_{clr}\right)\right]A^i{}_{cld}\right\} + \left[M_c \frac{i\partial A^i{}_{cld}}{\partial z} + \left(1 - A^i{}_{cld}\right)D^i\right], \tag{2}$$

Continuity equation for the entire grid box:

$$\frac{\partial m^i}{\partial t} = \sum_{i'} \hat{m}^{i+i'} \nu^{i+i'}{}_n l^{i+i'} - \frac{\partial}{\partial z}\left(m^i \overline{w}^i\right) \tag{3}$$

Conservation of an intensive variable, h, for "clear air":

$$\frac{\partial}{\partial t}\left(m^i h^i{}_{clr} A^i{}_{clr}\right) = -\sum_{i'} \hat{m}^{i+i'} \nu^{i+i'}{}_n l^{i+i'} \hat{A}^{i+i'}{}_{clr}\ \hat{h}^{i+i'}{}_{clr} - A^i{}_{cld} A^i{}_{clr} m^i \left\{ C_{cld,clr}\left(\frac{\dot{q}^i_{c\,evap} + \dot{q}^i_{i\,evap}}{q^i_c - q^i_i}\right) h^i{}_{cld} + C_{clr,cld}\left[\frac{\dot{q}^i_{c\,cond} + \dot{q}^i_{i\,cond}}{\left(q^i_*\right)_{clr} - \left(q^i_\nu\right)_{clr}}\right] h^i{}_{clr}\right\} - \frac{\partial}{\partial z}\left\{\left[m^i\overline{w}^i + m^i A^i{}_{cld}\left(w^i{}_{cld} - w^i{}_{clr}\right)\right] h^i{}_{clr} A^i{}_{clr}\right\} + \left(S_h\right)^i{}_{clr}\, A^i{}_{clr} + \left[M^i_c \frac{\partial}{\partial z}\left(h^i{}_{clr}\, A^i{}_{clr}\right) - D^i h^i{}_{clr} A^i{}_{clr}\right], \tag{4}$$

Conservation of an intensive variable, h, for "cloudy air":

$$\frac{\partial}{\partial t}\left(m^i h^i{}_{cld} A^i{}_{cld}\right) = -\sum_{i'} \hat{m}^{i+i'} \nu^{i+i'}{}_n l^{i+i'} \hat{A}^{i+i'}{}_{cld}\ \hat{h}^{i+i'}{}_{cld} + A^i{}_{cld} A^i{}_{clr} m^i \left\{ C_{clr,cld}\left[\frac{\dot{q}^i_{c\,cond} + \dot{q}^i_{i\,cond}}{\left(q^i{}_*\right)_{clr} - \left(q^i{}_\nu\right)_{clr}}\right] h^i{}_{clr} + C_{cld,clr}\left(\frac{\dot{q}^i_{c\,evap} + \dot{q}^i_{i\,evap}}{q^i{}_c - q^i{}_i}\right) h^i{}_{cld}\right\} - \frac{\partial}{\partial z}\left\{\left[m^i\overline{w}^i + m^i A^i{}_{clr}\left(w^i{}_{cld} - w^i{}_{clr}\right)\right] h^i{}_{cld} A^i{}_{cld}\right\} + \left(S_h\right)^i{}_{cld}\, A^i{}_{cld} + \left[M^i_c \frac{\partial}{\partial z}\left(h^i{}_{cld}\, A^i{}_{cld}\right) + D^i\left(h^i{}_{cu} - h^i{}_{cld} A^i{}_{cld}\right)\right], \tag{5}$$

Conservation of an intensive variable, h, for whole grid cell:

$$\frac{\partial}{\partial t}\left(m^i \overline{h}^i\right) = -\sum_{i'} \hat{m}^{i+i'} \nu^{i+i'}{}_n l^{i+i'}\ \hat{h}^{i+i'} + \sum_{i'} G^{i+i'}(h) - \frac{\partial}{\partial z}\left[m^i \overline{w}^i \overline{h}^i + m^i A^i{}_{clr} A^i{}_{cld}\left(w^i{}_{cld} - w^i{}_{clr}\right)\left(h^i{}_{cld} - h^i{}_{clr}\right)\right] + \left[A^i{}_{cld}\left(S^i{}_h\right)_{cld} + A^i{}_{clr}\left(S^i{}_h\right)_{clr}\right] + M^i{}_c \frac{\partial \overline{h}^i}{\partial z} + D^i\left(h^i{}_{cu} - \overline{h}^i\right) + E^i\left[A^i{}_{clr}\left(\overline{h}^i - h^i{}_{clr}\right) + A^i{}_{cld}\left(\overline{h}^i - h^i{}_{cld}\right)\right]. \tag{6}$$

Each of these equations includes terms representing horizontal advection by the mean flow. We assume that such advection is between subdomains of like type. For example, cloudy air in one grid cell is advected into the cloudy portion of a neighboring grid cell.

Similarly, each equation contains terms representing the lateral exchanges of air between the cloudy and clear portions of a grid cell. These exchanges are associated with condensation or evaporation.

Each equation includes cumulus terms, which appear in the form of entrainment, detrainment, and "compensating subsidence." The vertical velocities in the clear and cloudy regions satisfy the following relationships:

$$m^i w^i{}_{clr} = \left(m^i \overline{w}^i - M^i{}_c\right) - m^i A^i{}_{cld}\left(w^i{}_{cld} - w^i{}_{clr}\right) \quad (7)$$

$$m^i w^i{}_{cld} = \left(m^i \overline{w}^i - M^i{}_c\right) + m^i A^i{}_{clr}\left(w^i{}_{cld} - w^i{}_{clr}\right) \quad (8)$$

These equations have actually been used in Eqs. 1-6, which is why Eqs. 1-6 do not refer to $m^i w^i{}_{clr}$ or $m^i w^i{}_{cld}$. They do refer to a mesoscale mass flux, $m^i A^i{}_{clr}\left(w^i{}_{cld} - w^i{}_{clr}\right)$. To determine this mesoscale mass flux, we assume that it acts to keep the stratiform cloud neutrally buoyant, by removing virtual temperature differences between the cloud and its environment.

Conclusions

We are currently in the early stages of testing this new parameterization in a single-column model, using Atmospheric Radiation Measurement (ARM) Program data from the Southern Great Plains (SGP) site. We hope to perform further tests of the parameterization in a full three-dimensional climate model by the end of this calendar year.

References

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