407 – mesoscale model parameterizations

Parameterizations of short- and long-wave radiation

Reading: Savijarvi, H., 1991: Fast radiative transfer schemes for mesoscale models.

Radiative transfer affects the mesoscale energetics in two main ways:

(1) effect on the surface energy balance; and
(2) direct radiative heating/cooling of the air.

Direct radiative heating of the air usually is small for mesoscale time scales. The short-wave heating rate typically is about 1 K/day (during the daylight hours only). The long-wave flux divergence usually works out to a net cooling of about 1-2 K/day.

Some notable exceptions are:

- shallow layer close to the heated or cooled ground surface. For example, direct radiative cooling of the near-surface air is thought to be important for the generation of drainage flows along slopes.
- cooling at or near cloud top. Most low- and mid-level clouds radiate nearly as black bodies, leading to large cooling rates at the cloud edges (top). Radiative cooling is important e.g. for stratocumulus.

Representation of clouds and precip

<u>explicit</u> - cloud-scale properties at a grid location are identical to resolvable (grid) scale properties.

<u>implicit</u> - cloud-scale properties and processes may differ from grid scale.

Molinari & Dudek proposed:

<u>hybrid</u> schemes: implicit and explicit schemes <u>interact</u> through detrainment of hydrometeors from the implicit (cloud-scale) to the grid scale: the conservation eqs thus have an extra term

$$\frac{\partial \bar{q}_x}{\partial t} = [\ldots] + S_{x,\,conv}$$

where $S_{x,\,conv}$ is the source term from the convective parameterization. Note that simply including both explicit and explicit schemes does <u>not</u> make a hybrid scheme: they must be linked together.

Explicit schemes (microphysics) e.g. Kessler, Lin et al, WSM-6, Ferrier

Simplest is saturation adjustment: when RH > 100% excess moisture falls as rain.

- May or may not require column saturation
- Can set threshold RH < 100%
- a problem is scale mismatch between precip + grid average. Tends to perform better as horizontal grid spacing decreases.

More sophisticated:
add conservation equations for various "species" of liquid and/or solid water. Most basic scheme adds an eq. for cloud water. More eqs. can be added for rain water, ice (many species).

A very common implementation is the Kessler-type "warm rain" parameterization. An example:

$$\frac{dq_c}{dt} = -\left(\frac{dq_{v,sat}}{dt}\right) - A_r - C_r$$

where $\frac{dq_{v,sat}}{dt}$ = change in q_{sat}

A_r = auto conversion

C_r = collection (collision/coalescence)

$$\frac{dq_r}{dt} = \frac{1}{\bar{\rho}} \frac{\partial}{\partial z}\left(\bar{\rho} V_{T,r} q_r\right) - E_r + A_r + C_r$$

$V_{T,r}$ = rain terminal velocity
E_r = rain evaporation rate

Then for the vapor,

$$\frac{dq_v}{dt} = \frac{d q_{v,sat}}{dt} + E_r$$

Notice E_r, A_r, and C_r act to transfer water substance from one species to another. Typical representations are:

$$A_r = k_1 \left(q_c - \hat{q}_c\right)$$

$$C_r = k_2 \, q_c \, q_r^{0.875}$$

$$E_r = \frac{1}{\bar{\rho}} \left[\frac{\left(1 - \frac{q_v}{q_{v,sat}}\right) C_{vent} \left(\bar{\rho} q_r\right)^{0.525}}{k_3 + \left(\frac{k_4}{\bar{\rho} \, q_{v,sat}}\right)} \right]$$

$$V_{T,r} = k_5 \left(\bar{\rho} q_r\right)^{0.1346} \left(\frac{\bar{\rho}}{\rho_0}\right)^{-1/2}$$

implicit

Convective adjustment

This is the simplest way of treating the release of convective instability. In this situation, if the atmosphere is conditionally unstable, i.e.

$$\gamma \geq \gamma_m$$

and saturation is reached anywhere in the unstable layer,

$$q \geq q_s$$

then the temperature and humidity fields are re-adjusted so that the lapse rate is neutral to a moist adiabat:

$$\gamma = \gamma_m$$

and the atmosphere is saturated,

$$q = q_s.$$

The reduction of q to q_s will leave some water left over, Δq, which is assumed to precipitate. The total heating of the column is then:

$$-\int_{p_{top}}^{p_{sfc}} L_c \, \Delta q \, dp = \int_{p_{top}}^{p_{sfc}} c_p \, \Delta T \, dp$$

Of course, when T is increased q_s increases, so an iterative solution is required to simultaneously enforce the energy balance and other requirements.

Notice also that the conversion of latent to sensible heat views the column as a whole (i.e., the <u>integral</u> over the column) and not level-by-level. That is, we do not necessarily have $-L_c \Delta q = c_p \Delta T$ at each level.

Convective adjustment has a long history in GCMs. A problem with the simplest form of convective adjustment is that the latent heat is released <u>instantaneously</u>. This causes large "shocks" to the model dynamics. Can be alleviated by spreading the adjustment over a long time; i.e.,

$$\frac{\partial T}{\partial t} = \ldots + \frac{\Delta T}{\tau}$$

$$\frac{\partial q}{\partial t} = \ldots + \frac{\Delta q}{\tau}$$

Convective adjustment also neglects various details, e.g., overshooting, downdraft cooling ...

Kuo scheme / Kuo-Anthes scheme

Basic assumption is that deep convection is related to the instantaneous value of the grid-scale moisture convergence. In other words, moisture is "consumed" at the same rate that it is supplied. As we saw previously, the Kuo scheme defines the moisture accession M_t as:

$$M_t = -\frac{1}{g}\left[\int_0^{p_{sfc}} \nabla\cdot(\vec{V}q)\,dp + F_{q,sfc}\right]$$

Then the Kuo scheme defines the precipitation rate as:

$$-\int_0^{p_{sfc}} (C-E)\,dp = -(1-b)\,g\,M_t$$

The remainder of M_t goes into moistening of the atmospheric column:

$$\int_0^{p_{sfc}} \left(\frac{\partial q}{\partial t}\right) dp = g\,b\,M_t$$

Recall that the Kuo scheme relates convection to the consumption (or supply) of <u>water mass</u>. In fact convection is <u>not</u> caused by the supply of water mass, but by the release of available potential energy. Therefore the Kuo scheme is <u>fundamentally ill-posed</u>.

Many of the practical shortcomings of the Kuo scheme arise from the fallacious nature of this assumption. For example, the Kuo scheme cannot achieve radiative-convective equilibrium, since by $\int \left(\frac{\partial q}{\partial t}\right) dp = g\, b\, M_t$ the atmosphere must <u>moisten</u> for convection to occur unless $b = 0$. This can only happen if (1) we adopt Anthes' formulation for b <u>and the atmosphere is saturated</u>, or (2) we "tune" $b \equiv 0$ to satisfy this particular application. Situation (1) is unrealistic; (2) implies non-generality.

Betts-Miller scheme

This is the scheme used in the NCEP Eta model. It is a "lagged convective adjustment" scheme that adjusts the profile so that below the freezing level it approaches the wet virtual adiabat (i.e., including the effects of liquid water) rather than θ_e.

The adjustment occurs over some time period τ which decreases as the horizontal grid spacing becomes smaller; typically $\tau \lesssim 1$ hr for mesoscale applications. B & M "recommend that τ should be set so that the model atmosphere nearly saturates on the grid scale in major convective disturbances."

The heating and moistening rates are then given by:

$$\frac{\partial T}{\partial t} = \frac{T_R - \overline{T}}{\tau}$$

$$\frac{\partial q}{\partial t} = \frac{q_R - \overline{q}}{\tau}$$

where (T_R, q_R) apply to the final (reference) profile and $(\overline{T}, \overline{q})$ is the initial grid-scale value.

The precip rate is then

$$PR = \int_{p_1}^{p_2} \left(\frac{q_R - \bar{q}}{\tau} \right) \frac{dp}{g}$$

i.e., PR is the net change of water content due to the adjustment process. The scheme is replaced by a shallow-convection version if $PR < 0$.

The B-M scheme is structured so that the atmosphere moistens up to a certain point and then the precipitation all falls out. This is unlike the Kuo scheme, in which the moisture <u>convergence</u> is directly related to the precip.

Fritsch-Chappell scheme / Kain-Fritsch scheme

Basic assumption is that deep convection acts to remove the instantaneous ABE. This differs from other schemes in which the deep convection is determined by the moisture flux convergence, or the rate of destabilization by the large scale.

The ABE is assumed to be removed over some time period τ which presumably reflects the lifetime of convective elements (typically, $\tau \approx 30$ min). Thus the convection feeds back to the large scale according to:

$$\frac{d\bar{a}}{dt} = [\,...\,] + \left(\frac{\partial \bar{a}}{\partial t}\right)_{conv} \qquad [a = \theta,\ q_v]$$

where $$\left(\frac{\partial \bar{a}}{\partial t}\right)_{conv} = \frac{\hat{a} - a_0}{\tau}$$

Here $\hat{a}$ = final value of a after ABE is removed by convection and a_0 is the value of a right when the convection starts.

Advantages / disadvantages of explicit schemes

Performs well when the system is

1. Well resolved by the model grid
2. Convectively stable (related to (1))

To some extent, can be "tuned" to the grid size by specifying saturation threshold

~ 80-90% for coarse GCMS

~ 95-100% for mesoscale

Poor performance for deep convection at mesoscale resolutions:

- system usu. too shallow (can't resolve updrafts)
- often produces delay with subsequent explosive growth and overprediction of precip.

More realistic (detailed) physics usu improve performance

- addition of eqs for q_c, q_r
- water loading, rain evap, partial cloud cover

Strengths/weaknesses of implicit param.

- Generally performs well for deep, precipitating convection

- Cannot represent large-scale, convectively stable processes

- Assumes scale separation between cloud and environment

- Convection is tied to a single grid column and does not move (can develop convection in adjacent grid)

- Sensitive to "trigger function" that determines whether the scheme is activated.

- Assumptions in the scheme can preclude some physically realistic situations (e.g., shallow but intense winter-time convection)

F-C contains a rather detailed <u>1-D cloud model</u> used to determine the adjustment. Mass fluxes are computed for the updraft and downdraft, then the compensating subsidence is found by requiring that the mass fluxes balance:

$$\bar{\rho}\,\bar{w}\,(\Delta x\,\Delta y) = \rho_u w_u A_u + \rho_d w_d A_d + \rho_s w_s\left[(\Delta x\,\Delta y) - A_u - A_d\right]$$

An iterative solution is then required to determine the updraft area (mass flux) leading to the desired moist-adiabatic profile.