FV3GFS Deep and Shallow Cumulus Convection Schemes

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Introduction

Contributions from the cumulus convection (sub-grid scale) to the large scale heat, moisture and momentum are (Peter Bechtold, 2017):

- Heat (dry static energy):

  $$(\partial s/\partial t)_{cu} = L(c-e) - \partial w' s'/\partial z$$

- Moisture (specific humidity):

  $$(\partial q/\partial t)_{cu} = -(c-e) - \partial w' q'/\partial z$$

- Momentum:

  $$(\partial V/\partial t)_{cu} = -\partial w' V'/\partial z$$

Task of Convection Parameterization (1)

- Large Scale convective tendency for dry static energy:

$$(\partial s/\partial t)\downarrow cu = L(c-e) - \partial w\uparrow' s' /\partial z$$

Cond/Evap term Eddy Transport term

- To calculate the collective effects of an ensemble of convective clouds in a model column as a function of grid-scale variables.
- Parameterization needs to describe Condensation/Evaporation and Eddy Transport

Task of Convection Parameterization (2)

- In practice, convection parameterization includes three major steps:
  1. Determine the occurrence and localization of convection -- Trigger of convection
  2. Determine the vertical distribution of heating, moistening and momentum changes -- this task is generally done with the aid of a Cloud model
  3. Determine the convection intensity (energy conversion) -- Closure

Types of Convection Schemes

- Moisture convergence schemes:

  Kuo 1965, 1974
- Convective adjustment schemes:

  Betts and Miller 1986, Betts-Miller-Janjic (1994)
- Mass-flux schemes:

  Arakawa and Schubert 1974;
  Bougeault 1985;
  Tiedtke 1989;
  Gregory and Rowntree 1990;
  Kain and Fritsch, 1990, 1993, Kain 2004;
  Moorthi and Suarez 1992, 1998;
  Pan and Wu 1995, Han and Pan 2011, Han et al. 2017;
  Emanuel 2001;
  Bechtold et al. 2001, 2004, 2013, 2014;
  Chikira and Sugiyama 2010;
  Grell and Freitas 2014

The Mass-Flux Approach (1):

Parameterization:

Look for a simple expression for the

Eddy Transport Term:

$$w' \phi' = M_u(\phi_u - \phi)$$

Where $\phi = s, q, V$

ϕ_u is the average over the cumulus regions

ϕ is the average over environment regions

M_u is the convective mass-flux (*m/s*)

The Mass-Flux Approach (2):

To predict the influence of convection on the large scale, we need to describe

1) The convective mass-flux (M_u).

2) The values (s, q, V) inside the

convective elements (ϕ_u)

3) The condensation/evaporation term

This requires a cloud model and a closure to determine the absolute value of the mass flux.

Cloud Model:

- Cloud model determines the vertical structure of convective heating and moistening

- Assuming steady state, and define η as normalized mass flux, then the mass conservation equation is written as:

$$1/\eta \, \partial\eta/\partial z = \varepsilon - \delta$$

where ε and δ are the entrainment and

detrainment rates (scaled, with unit m^{-1})

- Other conservative variables such as dry (or moisture) static energy, total water (or water vapor and liquid water) can be written similarly for the cloud model

- Precipitation: Rain/snow conversion rate: $r = c_0 \, q_l$

Entrainment and Detrainment:

- Entrainment is the single most important parameter in a mass flux convection parameterization
- So far there is no universally valid formulation of entrainment rates applicable to all convection situations and in all schemes
- The entrainment and detrainment rates

$$1/\eta\,\partial\eta/\partial z=\varepsilon-\delta \Leftrightarrow \partial M{\downarrow}u\,/\partial z=E-D$$

ε,δ [m $^{-1}$] denote fractional entrainment/detrainment
E,D [s $^{-1}$] are entrainment/detrainment rates

- Detrainment rate = entrainment rate at cloud base
- Entrainment/detrainment rates are larger in shallow convection compared to those in deep convection

Convective Closure:

- Convective closure determines the mass flux at cloud base, which gives overall magnitude of the heating (and surface precipitation in deep convection)
- Quasi-equilibrium assumption (Arakawa and Schubert, 1974):

  Assume an equilibrium established over a typical time scale of 60 minutes between the production of CAPE (or cloud work function) by the large scale, and its consumption by the convective activity.

$$(dA/dt)_{ls} + (dA/dt)_{cu} \approx 0$$

Where A is cloud work function. Using above equation, one can derive the mass flux at cloud base M_b.

Momentum Transport:

- Cumulus momentum transport is included in both deep and shallow convection parameterizations.
- Contribution to large-scale momentum tendency from cumulus convection:

$$(\partial V/\partial t)_{cu} = (1-c) M_u \, \partial V/\partial z + D(V_u - V)$$

Where $c = 0.55$, represents the effect of convection-induced pressure gradient force,

M_u is the convective mass flux (m/s), and

D is the detrainment rate (s^{-1}).

Overshoot of Cloud Top:

- Cloud parcel is assumed overshoot beyond the level of neutral buoyancy due to its inertia
- Cloud top stops at the height where a parcel lifted from the neutral buoyancy level with energy equal to 10% of the CWF (Cloud Work Function)
- Convective overshoot is applied to both deep and shallow convection schemes

Downdraft:

- Downdraft is assumed to be saturated
  - Precipitation evaporates to keep downdraft saturated
  - Precipitation evaporates not only inside the cloud, but also below the cloud base
- Downdraft initiating level z_0 :

$$h_d(z_0)=\min(h(z))$$

where $h(z)$ is the moist static energy.

- Initial downdraft mass flux is assumed to be proportional to updraft mass flux at cloud base:

$$M_0=\alpha M_b \quad \text{and} \quad \alpha\leq 0.3$$

where α is a function of condensation/evaporation and averaged vertical wind shear

Trigger Function:

- Trigger function determines the presence of cumulus convection
- Trigger functions are uniquely formulated for each cumulus parameterization scheme.
- FV3GFS trigger function:
  - First test for deep convection

    Find the level of maximum moist static energy between the surface and 700mb level, this level is defined as the Convection Starting Level (CSL). A parcel lifted from the CSL without entrainment must reach the level of free convection (LFC) within the range of 120–180 mb. If the cloud is thicker than 200 mb, deep convection is activated. Otherwise, the convection is treated as being shallow.

  - Shallow convection:

    Convection starting level is defined as the level of maximum moist static energy within the PBL.

    The cloud top in shallow convection is limited to P/Ps=0.7

  - No convection triggered if CIN (convective inhibition) is less than

    -120 m^2/s^2

Shallow Cumulus Convection:

- Shallow cumulus convection plays important role in both tropical and subtropical climate dynamics
- The trigger functions for shallow convection is slightly different compared to that of deep convection (page 15)
- The cloud model is the same as that of deep convection, but no downdraft. The entrainment and detrainment rates are parameterized differently compared to those of deep convection.

- Closure: The cloud-base mass flux (M_b) is given as:

$$M_b = 0.03\, w_*$$

where w_* is the convective boundary layer velocity scale

Scale-aware Parameterization (1):

- A scale-aware parameterization may be necessary for the grid sizes of 500m ~ 10 km where the strong updrafts are partially resolved.
- Based on Arakawa & Wu (2013):

  New cloud base mass flux:

  $$m_b' = (1-\sigma_u)^2 m_b$$

  Where

  σ_u : the updraft area fraction (0~1.0)

  m_b : original cloud base mass flux ($\sigma_u \approx 0$).

  m_b' : updated cloud base mass flux with a finite σ_u

Scale-aware Parameterization (2):

For grid size < 8km, cloud base mass flux is modified for deep convection scheme:

- cloud-base mass flux is given by a function of mean updraft velocity rather than by AS's quasi-equilibrium,

$$M_b = 0.03 \langle w_u \rangle$$

where $\langle w_u \rangle$ is the cumulus updraft velocity averaged over the whole cloud.

- When the convective turnover time > advective time, the convective mixing is not fully conducted before the cumulus cloud is advected out of the grid cell, and the cloud base mass flux is further reduced

Aerosol-aware Parameterization:

- Rain conversion rate in the updrafts is a function of CCN number concentration:

$$c_0 = a\exp(b(T - T_0)) \quad \text{for } T \le T_0$$

$$c_0 = a \quad \text{for } T > T_0$$

and $a = \min\left([-0.7\ln(N_{ccn}) + 24] \times 10^{-4},\quad 0.002\right)$

Where N_{ccn} is the CCN number concentration in cm^{-3}

Since N_{ccn} is not a prognostic variable in the current FV3GFS model, the following numbers are used,

N_{ccn} =100 over ocean

FV3GFS parameter setup

Parameters calling shallow and deep convection schemes:

shal_cnv: for calling shallow convection
Imfshalcnv: for mass-flux shallow conv scheme
- =1: current operational version as of 2016
- =2: scale & aerosol-aware mass-flux shallow convection scheme (2017)
- =0: modified Tiedtke's eddy-diffusion shallow conv scheme
- =-1: no shallow convection used

Imfdeepcnv: for mass-flux deep conv scheme
- =1: current operational version as of 2016
- =2 scale & aerosol-aware mass-flux deep convection scheme (2017)
- =0: old SAS convection scheme before July 2010

Default value:

```
shal_cnv       = ${shal_cnv:-".true."}
imfshalcnv     = ${imfshalcnv:-"2"}
imfdeepcnv     = ${imfdeepcnv:-"2"}
```

Thank you