A new unified stochastic parameterization for boundary layer, shallow and deep convection

Kay Sušelj and Joao Teixeira

Jet Propulsion Laboratory/California Institute of Technology
Pasadena, California, USA

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Why a new turbulence parameterization?

POOR REPRESENTATION OF SUBTROPICAL CLOUD TRANSITIONS

- GEOS-5 model
- Observations (surface radiation budget)

Model-Observations

Example from Song & Zhang (2009)

Annual precipitation

- Observations
- CMAP
- NCAR CCSM3
Parameterization development and validation ‘test-bed’

CONVECTION IN MARINE AND CONTINENTAL ENVIRONMENTS

- Development and testing of parameterization in a single-column model framework (“a vertical column of a GCM”)
- Validation of benchmark cases against Large Eddy Simulations (LESs)/Cloud Resolving Models (CRMs)

Marine boundary layer

- BOMEX (Siebesma et al., 2003)
- nCOC (van Zanten et al., 2011)
- Steady-state transition (Chung et al., 2012)
- DYCOMS (Stevens et al., 2005)

Continental convection

- explicit models (CRMs)

- ARM – non-precipitating (Brown et al., 2002)
- EUROCS – precipitating (Guichard et al., 2004)
Parameterization model

EDDY-DIFFUSIVITY/MASS-FLUX (EDMF) MODEL

EDMF framework - decomposition of a model grid-box into:

1. Multiple convective updrafts and/or downdrafts
2. Environment

First-order moments:
\[ \bar{\varphi} = a_E \varphi_E + \sum_i a_i \varphi_i \]

Second-order moments:
\[ \varphi' \psi'' = a_E \bar{\varphi} \tilde{\psi}' |_E + a_E (\varphi_E - \bar{\varphi})(\psi_E - \bar{\psi}) + \sum_i a_i \bar{\varphi}' \tilde{\psi}'_i + \sum_i a_i (\varphi_i - \bar{\varphi})(\psi_i - \bar{\psi}) \]

- Index representing thermals
- Index representing environment
- Fraction area of environment/ thermals
- Mean values
- Deviation from mean

Top-hat approximation for updrafts/downdrafts
**Eddy-diffusivity/mass-flux (EDMF) model**

**KEY IDEAS**

**Mass-flux parameterization:**

a) **Updrafts**
- Multiple steady-state surface-driven updrafts with constant fraction area
- At the surface – a tail of the (assumed joint normal) distribution $N(w, \theta_v, q_v)$
- Entrainment rate modeled as stochastic and discrete process
- Simple microphysics

b) **Downdrafts**
- Each precipitating updraft has a complementary downdraft
- Downdraft forced by evaporation of rain (negative buoyancy)
- Downdrafts modify surface distributions of thermodynamic variables and entrainment rate

**Eddy-diffusivity parameterization:**

- Eddy-diffusivity coefficient a function of ‘environmental’ $tke$
- Diagnostic length-scales in agreement with Quasi-Normal Scale Elimination (QNSE) theory
EDMF model – eddy-diffusivity

EDDY-DIFFUSIVITY/Viscosity Parameterization

\[
\bar{\varphi'} w' = a_E \bar{\varphi'} w'|_E + a_E (\varphi_E - \bar{\varphi})(w_E - \bar{w}) + \sum_i a_i (\varphi_i - \bar{\varphi})(w_i - \bar{w})
\]

\[
\bar{\varphi'} w'|_E = -K_{m;h} \frac{\partial \varphi}{\partial z} \quad \text{Down-gradient approximation for environmental turbulent flux}
\]

\[
K_{m;h} = l_{m;h} \sqrt{e_E} \quad \text{Eddy-diffusivity coefficient a function of environmental tke (prognostic equation for mean tke)}
\]

\[
l_{m,h} = l_0(kz, \tau \sqrt{e_E}, \sqrt{e_E}/N) \cdot \alpha_{m;h}(Ri) \quad \text{Diffusive/viscousive length scale (diagnostic equation)}
\]

Stability function – QNSE theory
EDMF model – mass-flux

**UPDRAFT EQUATIONS**

\[
\overline{\varphi' w'} = a_E \overline{\varphi' w'}|_E + a_E (\varphi_E - \overline{\varphi})(w_E - \overline{w}) + \sum_i a_i (\varphi_i - \overline{\varphi})(w_i - \overline{w})
\]

Multiple steady-state updrafts coupled with microphysics:

\[
\frac{\partial \varphi_i}{\partial z} = \epsilon_i (\overline{\varphi} - \varphi_i) + \frac{S_i^\varphi}{w_i} \quad \varphi = \{u, v, \theta_L, q_t\}
\]

\[
\frac{1}{2} \frac{\partial w_i^2}{\partial z} = aB_i - b\epsilon_i w_i^2
\]

\[
RRi(z) = \int_z^\infty \rho S_i^{qt}(1 - f) \, dz
\]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>( \epsilon_i )</td>
<td>Entrainment coefficient</td>
</tr>
<tr>
<td>( B_i )</td>
<td>Updraft buoyancy</td>
</tr>
<tr>
<td>( S_i^{\varphi} )</td>
<td>Rate of microphysical processes</td>
</tr>
<tr>
<td>( w_i )</td>
<td>Updraft vertical velocity</td>
</tr>
<tr>
<td>( RR )</td>
<td>Rain rate</td>
</tr>
<tr>
<td>( f )</td>
<td>Fraction of rain falling out of updr</td>
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WHY DO THE UPDRAFTS DIFFER?

1. Surface conditions differ for each updraft
   • Updrafts represent surface driven plumes
   • Discretized tail of assumed joint normal distribution of surface $w$, $\theta_v$ and $q_t$ (Cheniet 2003)
   • Number of updrafts and the total updraft area – model choice (see sensitivity study)

2. Entrainment rate parameterization
   • Stochastic discrete process
   • Probability of entrainment the same for all plumes, actual entrainment is one realization
EDMF results – marine shallow convection

BOMEX CASE (SIEBESMA ET AL., 2003): MASS-FLUX REPRESENTATION OF CUMULUS CONVECTION

Comparison of EDMF moist updrafts/cloud properties against LES results

Low sensitivity of the EDMF results to selection of surface updraft area & number of updrafts
EDMF results – marine precipitating convection

RICO CASE (VAN ZANTEN ET AL., 2014)

Comparison of EDMF moist updrafts against LES results – profiles after 24 hours of simulation

Cumulative surface precipitation: difference between EDMF realizations & sensitivity to the number of updrafts
EDMF results – diurnal cycle of precipitating convection over land

EUROCS CASE (GUICHARD ET AL., 2004)

Profiles of thermodynamic variable at the onset of shallow convection (12:00 LT)

Profiles of thermodynamic variable in the afternoon (18:00 LT)
Final thoughts

MULTI-PLUME STOCHASTIC MODEL

- Realistically simulate different surface driven convection regimes:
  a. Dry convection
  b. Moist non-precipitating
  c. Shallow precipitating
  d. Deep convection
- No CAPE/CIN-type closure needed
- Low sensitivity to most of the model choices (e.g. number of updrafts, surface updraft fraction area)
- Coupling of microphysics and turbulence dynamics is done in a physically consistent way
- Easily implemented in a fully 3D weather prediction/climate model:
  a. Proven to be successful in weather prediction model (operational NAVGEM model; Sušelj et al., 2014)
  b. Implementation in WRF model – see Poster “Cloud response to Eddy Diffusivity Mass Flux (EDMF) based Boundary Layer Parameterization” by R. Bhattacharya et al.
Thank you for your attention