Representing Precipitating Convection in the 10-km-grid Grey Zone: The Organized Convection Issue

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The complete convection problem

- Field campaigns (e.g., GATE, TOGA COARE)
- Improved prediction of weather & climate
- Conceptual models
- Traditional convective parameterization
- Numerical models
- Explicit convection
- Physical basis
- Theoretical-dynamical models

Analysis

Prediction

Complexity

Simplicity
Next-generation global NWP models will have 10-km grid spacing

- Parameterized convection and explicit convection may occur simultaneously.
- Parameterization is ill-conditioned, explicit convection is under-resolved.
- Dynamical structure, scale-selection, transport, scale-interaction are all compromised.
- Positive factors, but pitfalls too, for NWP.
- Next in line are seasonal prediction models and, ultimately, climate models.
A sobering fact:

Physical resolution is 7-10 x grid spacing

… important implications for convection where fastest growth rates are on small scales

… mesoscale organization of convection may be surrogate at 10-km-grid spacing

… however, even under-resolved explicit convection is a vast improvement over convective parameterization
The under-resolved dynamics issue

Traditional convective parameterization based on scale separation

Dynamical scale of convection

Grid resolution

Under-resolved explicit dynamics

Cloud-system resolving models (CRM) at ~100 m grid-resolution
320-km resolution

Provided by T. Enemoto, Earth Simulator
80-km resolution

Provided by T. Enemoto, Earth Simulator
20-km resolution

Provided by T. Enemoto, Earth Simulator
T1279 L96 simulation on Japan’s Earth Simulator:

(15-km horizontal, 500 m vertical)

Ohfuchi et al. (2004)
Precipitating convection

Forcing:
CAPE generation

Response:
Convective regimes

Feedback:
Thermodynamic, radiative & dynamical tendencies

Control:
Wind shear
Macrophysics and convective organization

- **Large-scale environment**
- **Microphysical processes**
  - Phase changes of water;
  - Radiative transfer, energy dissipation
- **CAPE, CIN**
- **Shear control**
- **Scale-interaction**
- **Macrophysical effects**
  - Temperature, moisture, momentum tendencies
- **Precipitating cloud systems**
A ‘field-theory’ for atmospheric convection is the ultimate need
Organized traveling convection of the mesoscale convective system (MCS) kind
Conceptual MCS

(a) Observed

(b) Simplification

- ASCENDING FRONT-TO-REAR FLOW
- DESCENDING REAR INFLOW
- Cloud Top
- Cloud Base
- Radar Echo Boundary
- New Cell
- Storm Motion
- Shelf Cloud
- Gust Front
- Mature Cell
- Region of Stratiform Rain
- Old Cell
- Region of Heavy Convective Showers

- Overturning Updraught
- Jump
- Updraught
- Downdraught
Large-scale convective organization

... correlated with shear zones & steep orography

Laing & Fritsch (1997)
Coma
Convective precipitation: a scaling law?

RADAR derived rain (July)
Spectra averaged between 115W and 75W

MEAN Rain rate variance (mm/hr)^2


Frequency (cycle/day)

CWT

-4/3

-5/3

-1
Convective-stratiform interaction

Lafore & Moncrieff (1989)
Physics of upscale evolution

Stage 1: onset

Stage 2: upscale development

Stage 3: development of mesoscale circulation

An upscale process not parameterized
Steady, finite-amplitude convective overturning
Lagrangian conservation properties

Fundamental Theorem of Calculus applied to the total derivative:

\[
\frac{D}{Dt} \int_{z_0}^{z} F(\psi, z') \, dz' = \frac{Dz}{Dt} F(\psi, z) - \frac{Dz_0}{Dt} F(\psi, z_0)
\]

\[
= wF(\psi, z) - w_0 F(\psi, z_0)
\]

\[
= wF(\psi, z)
\]
Conserved quantities for 2D moist convection

\[
\frac{D\eta}{Dt} = -g \frac{\partial \theta'}{\partial x} = -g \frac{\partial}{\partial \psi} \left( \frac{\partial \psi}{\partial x} \right) = w \frac{\partial F}{\partial \psi} = \frac{D}{Dt} \int_{z_0}^{z} \left( \frac{\partial F}{\partial \psi} \right)_z dz',
\]

\[
\frac{D\phi_p}{Dt} = \dot{Q} = w\Gamma = \frac{D}{Dt} \int_{z_0}^{z} \Gamma_p dz', \quad \text{where} \quad \phi = c_p \ln \theta \quad \text{and}
\]

\( \Gamma_p = \text{moist adiabat} \)

Conserved quantities:

\[ \eta = G_1 (\psi) + \int_{z_0}^{z} \frac{\partial F}{\partial \psi} dz' \quad \text{-- vorticity} \]

\[ \phi_p = G_2 (\psi) + \int_{z_0}^{z} \Gamma dz \quad \text{-- entropy} \]
Generalized nonlinear eigen-value / free-boundary theory of organized convection

Formally represented by Moncrieff & Green’s equation:

\[ \nabla^2 \psi = G(\psi) + \int_{z_0}^{z} \left( \frac{\partial F}{\partial \psi} \right) dz \]

- vorticity along trajectories
- inflow vorticity
- vorticity generated by latent heating

\[ F(\psi, z, c) : \text{parcel buoyancy} \]
A complete analytic solution for unsheared environments

\[ \psi(x, z) = \frac{Uz}{H}(z - H) + \frac{8UH}{\pi^3} \sum_{n=0}^{\infty} \frac{1}{(2n + 1)^3} \sin[(2n + 1)\frac{\pi z}{H} \exp[-(2n + 1)\frac{\pi |x|}{H}]
\]

\[ L\overline{w}(z) = 2Uz\left(1 - \frac{2Uz}{H}\right) \]
What’s what the simplest possible (archetypal) model of steady traveling convection in shear?
Two-branch steady model

Convective overturning in constant shear (A):

\[ \psi = A(z_0 - z_*)^2 \quad \text{inflow (} z_0 < z_* \text{)} \]
\[ \psi = A \beta^2 (z_1 - z_*)^2 \quad \text{outflow (} z_* < z_1 \text{)} \]

\[ z_* = \beta H / (1 + \beta) \]
\[ \beta = \frac{1}{2} (1 + \sqrt{1 + 4Ri}) \]

\[ Ri = \frac{CAPE}{\frac{1}{2} U_0^2} \quad \text{Convective Richardson number} \]

CAPE > 0 so \( 1 < \beta^2 = \frac{\text{outflow shear}}{\text{inflow shear}} \)
free-boundary solution tilts downshear - two-branch model is physically unrealistic
Showers in polar outbreaks over oceans triggered by cellular organization in the boundary layer

Grubisic & Moncrieff (1995)
MCS-like convective organization: two key dimensionless quantities

Convective Richardson number:

\[ R = \frac{\text{CAPE}}{\frac{1}{2} c^2} \]

\[ \Delta p \quad \frac{1}{2} c^2 \]

Bernoulli number:

\[ E = \frac{\Delta p}{\frac{1}{2} \rho c^2} \]

Density-current-like (hydraulic) behavior
Formal definition of convective organization

• Integrating the horizontal momentum equation along trajectories gives a dimensionless quantity $D$, the ratio of the eddy Reynolds number to dynamical quantities.

• Organized convection characterized by $D \ll 1$

$$\frac{u_c}{u_{\psi}}(x, t) = 1 + \int \left[ \left( \frac{K_E}{u_{\psi} L} \right) \left( \frac{L}{u_c} \right) \nabla^2 u_c - \left( \frac{u_{\psi}}{u_c} \right) \frac{\partial}{\partial x} \frac{p}{\rho u_{\psi}^2} \right] dx$$

$$D = \frac{K_E}{U L} \frac{\Delta p}{\rho u_{\psi}^2 (H/L)^2}$$

$u_c$ and $u_{\psi}$ --- in-cloud & inflow horizontal velocities, respectively
The simplest possible three-branch set of solutions: The archetypal regimes

\[
E = \frac{\Delta p}{\frac{1}{2} \rho c^2}
\]
The simplest possible three-branch set of solutions: The archetypal regimes

Free-boundary solution for $E = 0$

Moncrieff (1992)
Vertical transport of horizontal momentum
Conceptualization of momentum transport

Eddy tilt
backward relative to propagation vector

\[ \rho u w \]

\[ \left( \frac{\partial u}{\partial z} \right)_{\text{convection}} \]
Validation against numerical simulation

Wu and Moncrieff (1996)
Mesoscale convective systems generate shear -- redistribute horizontal momentum in the vertical: a positive dynamical feedback recalling that MCS live on shear flow.

Grabowski & Moncrieff (2001)
Traveling organized convection over the continental US
A problem of elevated heating, shear flow, traveling organized convection and the diurnal cycle

To first order, elevated solar heating determines start position & start time of traveling convection

Afternoon

Next morning

Cumulonimbus

Mesoscale downdraft

MCS - a family of cumulonimbus

$c = 15 \text{ ms}^{-1}$

$\sim1000 \text{ km}$
Amplitude of diurnal cycle:

Variance explained by 1st harmonic of rainfall frequency
Jun-Aug 2003

percentage of total variance

Knievel et al. (2004)
Phase of diurnal cycle: getting it right means getting traveling convective systems right ...
MM5 incorporating NCEP MRF boundary layer & surface exchange schemes, Noah LSM, GSFC microphysics, Betts-Miller convective parameterization, 40-km ETA model analysis for lateral boundary conditions and large-scale forcing. Simulate 3-10 July 2003 at 3-km, 10-km, 30-km, 60-km grid-resolution

Moncrieff and Liu (2005)
Precipitation: 3-km grid resolution

Mountains

Plains
Meridionally averaged rain-rate

NEXRAD analysis Carbone et al. (2002)
3-km explicit
10-km explicit
10-km Betts-Miller
Parameterized vs. explicit precipitation

Total

Parameterized

Explicit
3-km grid resolution

Mesoscale downdraft

Not represented in parameterizations, not adequately simulated at ~10-km grid-resolution
Under-resolution distorts airflow

\[ \Delta = 10 \text{ km} \]

\[ \Delta = 30 \text{ km} \]
Momentum transport:

\[ 
\ddot{A} = 3 \text{ km} 
\]

\[ 
\ddot{A} = 10 \text{ km} 
\]

\[ 
\ddot{A} = 30 \text{ km} 
\]
Resolution dependence of convective heating

Systematic warming: mesoscale downdrafts too weak – can we parameterize them?
Parameterizing convective organization
Organized convection: a parameterization challenge

Ordinary

- Entraining plume (small-scale mixing)
- Environmental shear omitted
- Local response
- Closed system (confined subsidence)
- Weak scale-interaction
- Gravity waves not involved

Organized

- Organized flow (mesoscale dynamics)
- Environmental shear important
- Local and remote response
- Open system (wave response)
- Strong scale-interaction
- Convectively-generated gravity waves
Upscale evolution

Stage 1: onset

Mesoscale latent heating

Mesoscale downdraft evaporative cooling

Stage 2: upscale development

Stage 3: development of mesoscale circulation

An upscale process not parameterized
Simple parameterization of stratiform heating / mesoscale evaporation

\[ \dot{Q}_m (p, t) = \alpha_1 \dot{Q}_c (t) \sin \partial \frac{p - p_s}{p_s - p_*} \quad p_* \leq p \leq p_s \]

\[ \dot{Q}_m (p, t) = \alpha_2 \dot{Q}_c (t) \sin \partial \frac{p_s - p}{p_* - p_t} \quad p_t \leq p \leq p_* \]

\[ Q_c = \text{parameterized convective heating} \]

\[
\tilde{A} = 60 \text{ km}
\]
Decomposition of convective tendency

\[
\frac{\delta \bar{\phi}}{\delta t} = \frac{\partial}{\partial z} \left[ (M_c - \varepsilon_c \bar{M}) (\bar{\phi} - \bar{\phi}_c) \right] + \frac{\partial}{\partial z} \left[ (M_m - \varepsilon_m \bar{M}) (\bar{\phi} - \bar{\phi}_m) \right]
\]

\( M_c, M_m \) and \( \bar{M} \) are convective–scale, mesoscale and resolved–scale mass fluxes; \( \varepsilon_c \) and \( \varepsilon_m \) are the fractional areas of convective–scale and mesoscale updrafts, respectively.

For organized convection \( \varepsilon_c \ll \varepsilon_m \) and \( \varepsilon_m = 1 \), approximately.

So the grid–scale term in the mesoscale parameterization is equivalent to \( (\bar{\phi} - \bar{\phi}_m)^m \frac{\partial \bar{M}}{\partial z} \)

Cheng & Yanai (1989)
Effect of mesoscale parameterization on convective heating

Mesoscale downdraft cooling
Remarkably similar results for tropical super-clusters suggest a degree of universality ...
Superclusters resemble huge mesoscale convective systems (in a GCM)

Moncrieff and Klinker (1997)
Total, parameterized (under-resolved) grid-scale tendencies of predicted superclusters
MCS-like dynamical structure is remarkably ubiquitous: widely seen in large-domain explicit convection simulations and ‘super-parameterized’ simulations.

To some degree this evinces physical aliasing (‘surrogacy’).
Rain-rate spectra: Observed and simulated

Moncrieff, Liu and Hsu (2005)
Summary

- Universal convective organization ubiquitous in many regions of the world

- Dynamical models of MCS-like organization have stood the test of time, new application -- represent organized convection structures in modern explicit models

- At ~10-km grid-resolution, the representation of convection is markedly different from conventional parameterization

- Mesoscale downdrafts represented by a simple parameterization, promotes propagation, work continues

- Under-resolved explicit circulations have practical advantages, care is needed but points to ways forward

- Results for the U.S. continent apply to other regions of the world where steep orography, organized convection and shear-flow exist

- Convective parameterization is being redefined, should help break the vexing bottleneck in convective parameterization – dynamics are to the fore