Convective Organization, Scale, and Parameterization in General Circulation Models

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Understanding and Representing Convection Across Scales

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Horizontal resolutions in GCMs for climate simulation are moving toward deep convective scales (e.g., Noda et al., 2012, J. Clim., 7 km). At what resolutions is physically sound NOT to parameterize deep convection?
DIAGNOSED VERTICAL TRANSPORT OF MOIST STATIC ENERGY

\[ d = 8 \text{ km} \]
\[ z = 3 \text{ km} \]

To be explicitly simulated

Fractional area covered by updrafts
- a measure of cloud population in the grid cell -

Parameterization must not overdo its job
so that explicitly-simulated transport is not over-stabilized.

\( h \): Deviation of moist static energy from a reference state

\( \langle \ldots \rangle \): Average over all CRM grid points in the sub-domain

\( \langle \ldots \rangle \): Ensemble average over cloud-containing (\( \sigma > 0 \)) sub-domains during the analysis period (12 hr)

\( (\ldots)' = (\ldots) - \langle \ldots \rangle \)

from Akio Arakawa, UCLA
Observational View of Convective Organization (Leary and Houze, 1980)

**FIG. 2.** Schematic vertical cross section of the idealized mesoscale system showing sources and sinks of condensed water. Symbols are defined in Section 2 of the text.
How much convective organization is sub-grid in a climate model? Can we capture it by parameterization? Can some types of convective organization only be simulated explicitly in models of sufficiently high resolution?

Donner et al. (1999, J. Atmos. Sci.)
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condensate > .25 g/kg; rad heating > 14 K/d; rad cooling < -16 /d
Convective Organization and Cumulus Parameterizations on Single Grid Columns
from Benedict et al. (2013, J. Climate)
CRM results provide independent evaluation of entrainment PDF

CRM results from Cris Batstone, CDC; *, *, * from Donner (1993, JAS) entrainment PDF
ENSEMBLE-AVERAGE VERTICAL EDDY TRANSPORT

—— THE EFFECT OF MULTIPLE STRUCTURE OF CLOUDS ——

single
0.5 m/s < w

double
2 m/s < w
0.5 m/s < w < 2 m/s
	réiple
4 m/s < w
2 m/s < w < 4 m/s
0.5 m/s < w < 2 m/s

from Akio Arakawa, UCLA
Radiative Influences

- Breakdown of banded organization
- Effects of clouds on radiative heating and feedbacks to convective organization important

Time series of precipitable water (mm) for fully interactive radiation scheme (left) and interactive radiation without contributions by clouds and precipitation (after Stephens, van den Heever and Pakula, 2008)

from Sue Van Den Heever, CSU
Sizes of Convective Systems in GFDL AGCM

from Donner et al. (2001, J. Climate)
AM3 50km Mesoscale Precipitation Fraction (DJF)
Until recently, cumulus closures have mostly been based on a grid-mean view of interactions between cumulus plumes and their environment, e.g., quasi-equilibrium.
Fig 4a

ARM: 3 h Data

Fig 4b

ARM: 6 h Averages

Fig 4c

ARM: 12 h Averages

Fig 4d

ARM: 24 h Averages

Cloud-resolving models suggest few cumulus plumes “see” grid-mean properties. Sub-grid variability in cloud environments is more relevant.
from Donner et al. (2001, J. Atmos. Sci.)
Control of deep convection by sub-cloud lifting processes: The ALP closure in the LMDZ5B general circulation model
Rio et al., Clim. Dyn., 2012

Sub-cloud lifting processes, boundary-layer thermals (th) and cold pools (wk), provide:

> an available lifting energy: \( \text{ALE} \) (J/kg) and
> an available lifting power: \( \text{ALP} \) (W/m²)

that control deep convection

\[
\text{MAX}(\text{ALEth, ALEwk}) > |\text{CIN}|
\]

Parameterization of boundary-layer thermals (Rio et Hourdin, JAS, 2008)

Parameterization of cold pools (Grandpeix & Lafore, JAS, 2011)

\[
\text{Closure:} \quad M_b = \frac{\text{ALP}}{|\text{CIN}| + 2w_b^2}
\]

\[
\text{ALP = ALPth+ALPwk} \sim w'3
\]

\[
w_b = f(\text{PLFC})
\]
Diurnal cycle of convection over land: From 1D to global simulations

Diurnal cycle of precipitation (mm/day) the 27 of June 1997 in Oklahoma (EUROCS case)

Shift of the local hour of maximum rainfall in 1D and 3D simulations

Observations (TRMM, from Hirose et al., 2008)

LMDZ5A: CAPE Closure  LMDZ5B: ALP Closure

Rio & al., GRL, 2009

Rio & al., 2012
Impact on precipitation mean and variability
IPSL-CM5A/CM5B: 10 years of coupled pre-industrial simulations

Hourdin et al., Clim. Dyn. 2012

Mean precipitation (mm/day)

Intra-seasonal variability of precipitation (SD daily precip, mm/day)

Some impact on precipitation annual mean

Strong impact on intra-seasonal variability

CAPE Closure

ALP Closure
Some types of organized convection have such large space and time scales that they are most easily modeled explicitly in high-resolution models.
Orogenic MCS and the diurnal cycle of precipitation

Vertical shear organizes sequences of cumulonimbus into long-lasting mesoscale convective systems (MCS), which propagate across continents, efficiently transporting heat, moisture and momentum.
Propagating MCS over U.S. continent

NEXRAD analysis
Carbone et al. (2002)

3-km explicit

10-km explicit

10-km Betts-Miller

Moncrieff & Liu (2006)
Effect of resolution on CMT: Negative for 3 km & 10 km grids, positive (incorrect) for 30 km grid

Sign of CMT is negative -- opposite to propagation vector (C) -- due to rearward-tilted airflow from Mitch Moncrieff
Convective momentum transport by MCS in MJOs simulated by a global cloud-system resolving model (NICAM)

\[ \frac{\partial u}{\partial t} + \cdots = -\frac{\partial}{\partial z}\left( u_m w_m \right) = \left( \frac{\partial u}{\partial t} \right)_{\text{convection}} \]

Miyakawa et al. (2011)
Even convective organization with large space and time scales can be simulated to some extent using appropriately cumulus parameterizations.
Orogenic MCS over U.S. continent
Superparameterized Community Atmospheric Model (SPCAM)

CAM: standard convection parameterization — No MCS

SPCAM: convective heating generated on 2-D CRM grid is organized by large-scale shear into propagating MCS on the climate model grid

Pritchard, Moncrieff & Somerville (2011)
AM3-CTL and AM3-A differ in their deep convective closures and triggers.

from Jim Benedict
Summary

- Convective organization occurs in both cloud morphology and cloud environments in observations and cloud-system-resolving models.
- GCMs are beginning to incorporate stratiform portions of convective systems and replace grid-mean closures and triggers with approaches that incorporate sub-grid organization in cloud environments and boundary layers.
- Some aspects of convective organization span space and time scales that are so large that they are best modeled explicitly by high-resolution models. Even these aspects can be at least partly captured by designing traditional cumulus parameterizations appropriately.
Organized Convection: Conceptual (from Brian Mapes)

- local conditions differ from large-scale mean
- preferentially favorable -- by natural selection
  - unfavorable fluctuations & correlations just lead to non-convection
- organization thus a positive effect on convection
  - like boosted parcels, with less dilution (in plume scheme terms)
- organization a positive feedback, but takes time
  - new development updrafts struggle initially for lack of it
- tuned GCMs assume ubiquitous org., not lack of it
  - new convection encounters mean convection's advantages

~20 km (Cloudsat deep echo objects)
Organized Convection: Treatments (from Brian Mapes)

• There are many observed aspects to organization
  – preferential nonwake updraft source, outflow boundary triggering, moist patches aloft, CIN reduction by gravity wave T', correlations of all these, etc.
  – natural selection exploits all (although not with perfect efficiency)

• The concept thus has a footprint in many schemes
  – wake schemes, plume ensembles, "CKE/MKE", parcel boosts, entrained air preconditioning, tails & correlations in PDF scheme(s), nonlinear skews to stochastic CIN/CAPE, etc.

• None is wrong; all are incomplete; any could be tuned to give enough net climatological boost & positive feedback
1. Anvil clouds abut convection in mesoscale storms

- they have significant cross-isentrope flows, hinging on cloud & precipitation processes
  - treatments:
    » append to cumulus scheme (GFDL, Donner)
    » anvil category of LS cloudiness (GEOS-5, Bacmeister &al., Donner anvil also feeds LS cloudiness)

2. Exotic momentum flux effects (like 2D vs. 3D)

- depends on details of geometry, not just clumping
  - hence on shear over various layers
  - uncertain to parameterize; cumulative impacts above noise (?)