Organized Convection Parameterization for GCMs

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Cloud-System Resolving Models

Next-generation GCMs
Cumulus Parameterization + Organized Convection Parameterization

Contemporary GCMs
Cumulus Parameterization

Organized Convection

Field-Campaigns
Cloud-System Resolving Models
Dynamical-System Analogs

Lagrangian Coherent Structure Paradigm:
Slantwise Layer Overturning

Express as functions of mean-state variables

Improve Treatment of Convection in GCMs
Understand the Global Water & Energy System
Convection: #1 Atmospheric Transport Process

**Extratropics**
- Quasi-dry baroclinic slope convection with embedded moist convection
- Downscales Control

**Tropics:**
- Multiscale cloud systems & convection-wave interaction are integral to the large-scale circulation
- Upscale Cascade
Organized Convection

- **Definition:** The quasi-laminar exchange of tropospheric layers (slantwise layer overturning) driven by the baroclinic generation of vorticity in cumulonimbus ensembles whose transport properties differ importantly from unorganized cumulus convection, e.g.,
  - Up-gradient momentum transport (negative viscosity)
  - Top-heavy’ diabatic heating
  - Key role of vertical shear

- **Missing from GCMs -- not parameterized, not resolved**
  - Formidable parameterization challenge
  - New approach needed

**Cross-scale Self-similarity**

Mesoscale (MCS)  
\[ O (10-100 \text{ km}) \]

Large-scale (MJO)  
\[ O (1000 - 10000 \text{ km}) \]
Approaches

EXPLICIT

• Global CRM: NICAM, 800m, 3.5km, 7km, 14km grids; MPAS, 3 km …
• ECMWF IFS: Virtual Global Field Campaigns, 9 km grid
• Superparameterized models
• Variable-Resolution GCMs

DYNAMICAL SYSTEM

• Multiscale Coherent Structure Parameterization (MCSP): Organized convection added to cumulus parameterization (Moncrieff & colleagues)
• Multi-Cloud Parametrization (MCP): Three cloud types (congestus, deep convection, stratiform) replace cumulus parameterization (Majda & colleagues)
MCSs Provide > 60% of Tropical Rain

Tao & Moncrieff (2009)
Long-lasting Lagrangian coherent structures are assumed steady \( \frac{\partial}{\partial t} = 0 \) in a system-relative frame-of-reference, embedded in a turbulent environment.

Transform the full nonlinear equations into total-derivative (Lagrangian) form by expressing convective heating as a separable function of vertical velocity:

\[
Q = w \Gamma = \frac{D}{Dt} \int_0^z \Gamma \, dz
\]

Integrate the transformed equations along trajectories \( \psi \) to give conserved quantities \( F_i = C_i(\psi) \), where \( C_i \) is the base-state value of the \( i \)-th quantity.

Calculate heat & momentum transport and tendencies.

Scale-invariant Formulation: Physical basis for observed self-similarity of MCS, superclusters, convectively-coupled waves…
### Largangian-Conserved Quantities

| $F_1 = \rho \vec{v} \cdot d\vec{S}$ | $= C_1(\psi)$ | Mass |
| $F_2 = \delta \phi_p - \int_{z_0}^{z} \left( \Gamma - B \right) dz$ | $= C_2(\psi)$ | Thermodynamics |
| $F_3 = \frac{1}{2} v^2 + \frac{\delta p}{\rho} - \int_{z_0}^{z} \delta \phi_p \, dz$ | $= C_3(\psi)$ | Energy |
| $F_4 = \frac{\eta}{\rho} - \int_{z_0}^{z} g \left( \frac{\partial \phi_p}{\partial \psi} \right)_z \, dz$ | $= C_4(\psi)$ | Vorticity |
| $F_5 = u - \int_{z_0}^{z} \left( \frac{\partial}{\partial \psi} \right) \frac{\delta p}{\rho} \, dz$ | $= C_5(\psi)$ | Momentum |
| $F_6 = \frac{1}{\ell} \vec{\omega} \cdot \nabla C_2$ | $= C_6(\psi)$ | Potential Vorticity |

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*z(z_0) → z_0(\psi)*
Example of Slantwise Layer Overturning

Cloud-water path averaged across 120 km y-domain

Lane & Moncrieff (2015)
Slantwise Layer Overturning Models

Three Forms of Energy: Potential, Kinetic, Pressure Work

\[ E = \frac{\Delta p}{\rho \frac{1}{2} (U_0 - c)^2} \]

\[ R = \frac{CAPE}{\frac{1}{2} (U_0 - c)^2} \]

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

- \( F \): Buoyancy (CAPE)
- \( G \): Environmental shear
A) Orogenic mesoscale systems

B) Multiscale tropical systems
A) Orogenic Mesoscale Convective Systems (MCS)
Precipitation: Low Confidence over Continents
(2090-2099 c.f. 1990-1999)
Mesoscale Convective Complexes, MCCs (Extreme MCSs) in Shear-Flow Downstream of Mountains

Laing & Fritsch (1997)
Diurnal variability of summer precipitation

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

Time of peak in 1st harmonic of rainfall frequency
Jun-Aug 2003

Knievel et al. (2004)
MCS & Diurnal Cycle

Afternoon

Elevated heating:
Starting Block

Vertically shear:
Controls mesoscale system dynamics and propagation

Next morning

MCS: Cumulonimbus Ensemble

~1000 km

C ~ 10 m/s

Mesoscale descent
CRM Simulation of Warm-season Convection over U.S.

(Dotted region: budget calculations)

Moncrieff & Liu (2006)
Rain Rate
(Meridional average)

NEXRAD analysis
Carbone et al. (2002)

3-km explicit

10-km explicit

10-km Betts-Miller
Total

Parameterized

Explicit
Resolution-dependent Convective Heating

Warming Bias: Mesoscale downdrafts weak or non-existent
Resolution-Dependence of Dynamical Structure

System-relative Flow & Condensate

\[ \Delta = 3 \text{ km} \quad \Delta = 10 \text{ km} \quad \Delta = 30 \text{ km} \]

3-km & 10-km grids – realistic & similar
30-km grid – unrealistic
Resolution-dependence of Momentum Transport

Δ = 3 km

Δ = 10 km

Δ = 30 km
‘Predictor-Corrector’ Parameterization

- Step 1: Cumulus scheme gives convective heating -- “predictor”
- Step 2: Heating profile adjusted by 2nd-baroclinic heating -- “corrector”

Convection Parameterization (Betts-Miller)

Convection Parameterization + Predictor-Corrector Parameterization

Rainfall (WRF: U.S. Domain WRF, 60 km grid)

Moncrieff & Liu (2006)
Orogenic MCS in SP-CAM3.5

- Standard CAM - no MCS
- SP-CAM - Propagating MCS
- 2nd-baroclinic heating communicated from CRM grid to climate grid & controlled by vertical shear

Pritchard, Moncrieff & Somerville (2011)
B) Multiscale Convective Organization in the Tropics

Acknowledgments:

• NASA ROSES/MAP Grant: Diagnostic Analysis & Cloud System Modeling of Organized Tropical Convection in the YOTC - ECMWF Global Database to Develop Climate Model Parameterization

Precipitable Water during YOTC

Courtesy: Tony Wimmers & Chris Velden
(CIMSS, U. Wisconsin/Madison)
Multiscale Organization in the MJO

- MJO: Eastward-Moving Cloud Envelope
- Kelvin Waves (A, B, C, D)
- Westward-Moving Meso-Synoptic Systems (C)

Nakazawa (1988)
Supercluster: TOGA COARE Field Campaign

T213 (~100 km grid) ECMWF IFS

Moncrieff & Klinker (1997)
MCSP \equiv \begin{align*} &\text{Mesoscale Convective System Parameterization} \\ &\text{Multiscale Coherent Structure Parameterization} \end{align*}

Scale-separation not assumed; Grid-averaged quantities non-zero; Lagrangian transport provides tendency equations
WRF Simulation Domain

- Time-dependent lateral boundary conditions, ERA-I
- Domain d01, 4 km grid
- Domain d02, 1.3 km grid

Moncrieff, Liu, Bogenschutz (2017)
April 2009 MJO during YOTC

Moncrieff, Liu & Bogenschutz (2017)
MCSs Embedded in a Westward-moving Inertio-Gravity Wave
Cross-section of Westward-Moving MCS
Mesoscale Organization

Lafore et al. (2017)

2nd Baroclinic Mesoscale Heating
Organized convection represented by slantwise layer overturning affects the large-scale distribution of precipitation and tropical-waves, ITCZ, SPCZ, Maritime Continent, warm-pool ...

Prototype MCSP: Minimalist formulation of:
   i) Top-heavy convective heating tendencies
   ii) 2nd-baroclinic momentum tendencies
Prototype MCSP in CAM 5.5

- Add slantwise layer overturning to existing convection parameterization, i.e., CLUBB + ZM
- Shear-selection principle preferable: Next stage of MCSP development

\[
\begin{bmatrix}
\frac{\delta}{\delta t}
\end{bmatrix}_{\text{TOTAL}} = \begin{bmatrix}
\frac{\delta}{\delta t}
\end{bmatrix}_{\text{CONVECTION}} + \begin{bmatrix}
\frac{\delta}{\delta t}
\end{bmatrix}_{\text{MESOSCALE ORGANIZATION}}
\]
2\textsuperscript{nd} Baroclinic Heating & Momentum Tendencies

![Diagram of baroclinic heating and momentum transport](image)

- Heating
- Momentum Transport
- Acceleration
2\textsuperscript{nd} Baroclinic Momentum Transport

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

\[ Q_m(p,t) = \alpha_3 \cos \pi \left( \frac{p_s - p}{p_s - p_t} \right) \]
$Q_m (p, t) = - Q_c \alpha_2 \sin 2\pi \left( \frac{p_s - p}{p_s - p_t} \right)$
Annual Precipitation Rate (15S-15N average)

MCSP Momentum Transport

MCSP 2nd Baroclinic Heating

Momentum + Heating
Annual Precipitation (8-year average)

MCSP Momentum Transport

MCSP 2nd Baroclinic Heating

Momentum + Heating
CAM 5.5 Precipitation Rate (15S -15N average)

NCEP Reanalysis

CAM 5.5 Control

MCSP: Momentum Transport ($\alpha_2 = 1$ m/s/day)

MCSP: $2^{nd}$ Baroclinic Heating ($\alpha_1 = 1$)
Comparison with other methods
Khoudier-Majda Multicloud Model Parameterization

- Similarity between Slantwise Layer Overturning & Multi-Cloud Model Approaches

Multi-Cloud Model
Khoudier & Majda (2007)

Slantwise Layer Overturning mapped onto Multi-Cloud Model
Multicloud Model Applied in EMC CFSv2

Goswami et al. (2017)
Predictor-Corrector Parameterization applied in CAM3.3

Cao & Zhang (2017)
Superparameterization

Khairoutdinov et al. (2005)
Conclusions

• **Multiscale Coherent Structure Parameterization (MCSP) with slantwise overturning as the transport module adds organized convection to contemporary convective parameterization**
  - Prototype MCSP, the minimalist form, produces upscale effects
  - Computationally efficient, MCSP applicable to long climate simulations
  - Effects of organized convection is quantified as difference with & without MCSP
  - Effects on tropical variability resembles more complex approaches
  - Effects of heating & momentum transport (e.g., Indian Ocean, Maritime Continent, Tropical Western Pacific, ITCZ) are distinct
    - Self-similarity between squall lines, MCSs, superclusters, Kelvin waves stems from the convective heating being a separable function of the vertical velocity

• **Future development of MCSP:**
  - Add a shear-selection mechanism
  - Add higher-order baroclinic modes
  - Calculate heating & momentum from slantwise overturning model
  - Investigate new scale-selection mechanisms for convective organization
  - Examine effects of westward-moving disturbances on MJO structure and propagation
On the Cool Bias

• Organized convection, represented by slantwise layer overturning, will warm the troposphere

• This warming is missing from contemporary convection parameterizations

• Therefore, without convective organization, GCMs should have a cool bias

• Recently, a few GCMs participating in the coupled model inter-comparison project (CMIP) have a cool bias

• Are these “few GCMs” better?
References


Weather

Climate

Subseasonal-to-Seasonal (2 weeks - 2 months)

Mesoscale Processes
Tracking Method

Huang et al. (2018)
Regional-Refined Community Model (RRCM)
Convective Organization in RRCM (6-km grid)
Heating  c.f. Vertical Velocity

Oh et al. (2015)
Toward Mesoscale-Permitting GCMs

Physical resolution of a numerical model is 5-8 times coarser than the computational grid:

- O (100 km) grid: Traditional cumulus parameterization
- O (10 km) grid: Mesoscale circulation permitted, cumulus parameterized
- O (1 km) grid: Mesoscale circulation resolved, cumulus permitted
- O (100 m) grid: Cumulus resolved, convective parameterization redundant
MCS: A Tightly Coupled Cumulonimbus Ensemble

Houze et al. (1980)