Dynamical System Approach to Organized Convection Parameterization for GCMs

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Year of Tropical Convection (YOTC)
Organized Convection & Parameterization

Weather
Mesoscale Processes
Climate

CESM AMWG Meeting, NCAR, 27 February – 1 March, 2017
Fraction of Tropical Rainfall from MCSs (TRMM Precipitation Radar, PR)

MCSs are missing from GCMs: Neither resolved nor parameterized

Tao & Moncrieff (2009)
Properties of Organized Moist Convection

- Propagating systems affect the type, intensity, and distribution of precipitation; therefore land-ocean-atmosphere interaction; distinctive diabatic heating & momentum transport properties

- Organized convection controlled by vertical shear; momentum transport has novel scale-interaction properties

- Advanced understanding of the observational, numerical, and theoretical aspects of organized convection processes but their parameterization has languished

- New paradigm: Dynamical systems approach treating organized convection as coherent structures in a turbulent environment

- Minimalist form described here, basically a proof-of-concept
Multiscale Coherent Structure Parameterization (MCSP)

a) Cumulus Field

b) Turbulent Cumulus

c) Coherent Structure in Cumulus Field

d) Slantwise Overturning Model

Transport module
Slantwise overturning is a collective effect of cumulonimbus ensembles in shear flow.

Lagrangian Slantwise Overturning Models are steady solutions of the full nonlinear 2D vorticity equation. The sole assumption -- latent heating a separable function of vertical velocity -- holds for squall lines, MCS, superclusters, and convectively coupled waves. This demonstrates key scale-invariant properties.

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

- **F**: Buoyancy along trajectories
- **G**: Environmental shear

Models verified by field-campaign & CRM data.

3D models are based on other Lagrangian conservation properties.
Context

- **MCSP adds** missing convective organization to cumulus parameterization

- **Focus on tropical phenomena and regions** (e.g., MJO, ITCZ, SPCZ, Warm-Pool, Maritime Continent) that particularly challenge GCMs

- **Specifically, summarize parameterization aspects of**:


  **More context**:


Westward-moving Meso-synoptic Superclusters are embedded in Eastward-moving MJO & Kelvin waves

Nakazawa (1988)
WRF Nested Computational Domains
(d01 - 4 km grid; d02 - 1.3 km grid)
YOTC global analysis for lateral boundary conditions
April 2010 MJO

Note: Separable relationship

\[ Q \propto w \]
Upscale Evolution of Cumulus Ensemble to MCS

Onset

Environmental Shear

Evolution of Ensemble

New cumulus continually triggered by density currents

Slantwise Overturning Circulation

1

2

3 … n

Δp

Stratiform Heating

Evaporative Cooling

2nd Baroclinic Mesoscale Heating

Parameterized Deep Convection
2nd Baroclinic Heat & Momentum Tendencies

(a)

Heating
Momentum Transport
Momentum Tendency

(b) Heating
(c) Momentum Transport
(d) Momentum Tendency
CAM 5.5 MCSP Experiments

• Seek simplest possible (minimalist) formulation/explanation

• Does heat and momentum transport by slantwise overturning generate large-scale precipitation patterns seen in TRMM?

• 2\textsuperscript{nd} baroclinic tendencies:
  i) Top-heavy convective heating
  ii) Counter-gradient momentum transport

• Analyze years 2-8 of 10-year CAM 5.5 simulations
Convective Heating Formulation

Vertical average of deep convection heating rate

$$Q_m (p, t) = \alpha_0 Q_c (t) [\alpha_1 \sin \pi \alpha \left( \frac{p_s - p}{p_s - p_t} \right) - \alpha_2 \sin 2\pi \left( \frac{p_s - p}{p_s - p_t} \right)]$$

Deep Heating (1st Baroclinic)

‘Top heavy’ Heating (2nd Baroclinic)

Minimalist formulation: 2nd Baroclinic Tendency ($\alpha_0 = 1; \alpha_1 = 0$)

$$\dot{Q}_{total} = \dot{Q}_c + \dot{Q}_m$$
\[ Q_m(p,t) = \alpha_3 \cos \pi \left( \frac{p_s - p}{p_s - p_t} \right) \]
CAM 5.5 Global Precipitation

MCSP – CAM 5.5 Control
Momentum ($\alpha_3 = 1 \text{ m s}^{-1} \text{ day}^{-1}$)

MCSP – CAM 5.5 Control
Heating ($\alpha_2 = 0.5$)

MCSP – CAM 5.5 Control
Heating & Momentum
($\alpha_2 = 0.5; \alpha_3 = 1 \text{ m s}^{-1} \text{ day}^{-1}$)
NCEP Reanalysis (OLR)

Precipitation Rate CAM 5.5 Control

MCSP Momentum Transport \( (\alpha_3 = 1 \text{ ms}^{-1} \text{day}^{-1}) \)

Precipitation Rate MSCP Heating \( (\alpha_1 = 0.5) \)
Dynamical-System Approaches: MCSP & MCP

- \(O(10 \text{ km})\) Grid
  - Global NWP
  - Next-generation GCMs
  - Organized Convection Parameterization

- \(O(100 \text{ km})\) Grid
  - Traditional GCM
  - Cumulus Parameterization

- Multiscale Coherent Structure Parameterization (MCSP)

- Multicloud Parameterization (MCP)

- Tropical Convection

- Monsoons

- Intraseasonal Variability

- InterTropical Convergence Zone

- Water Cycle

- Organized Moist Convection in Shear

- Physical & Dynamical Processes

- \(O(1 \text{ km})\) Grid
  - Cloud-System Resolving Model (CRM)

- Dynamical Analogs
Conclusions

- **MCSP (in minimalist form)**
  - Upscale effects on ITCZ, SPCZ, warm-pool, equatorial Africa, Maritime Continent qualitatively agree with TRMM measurements
  - Quantifies large-scale effects of convective organization
  - Distinguishes between heating and momentum transport effects
  - Salient to role of moist mesoscale processes in regard to, for example:
    i) Next-generation GCMs; ii) Subseasonal-to-Seasonal prediction (S2S); iii) Year of the Maritime Continent (YMC)

- **Examples of next steps in MCSP development**
  - Observation-based $\alpha$-parameters
  - Add shear-selection mechanisms
  - Add propagation direction to momentum parameterization
  - Apply in aquaplanet simulations
  - Compare with Khouider & Majda MCP that replaces cumulus parameterization
  - Compare with superparameterization

- **Small computational overhead makes MCSP feasible for long integrations**
References


Total Water: SSMI & AMSRE

Morphed composite: 2009-01-25 00:00:00 UTC

Courtesy: Tony Wimmer & Chris Velden, CIMSS, University of Wisconsin at Madison
Complex Convection-Wave Interaction for the April 2010 MJO during YOTC