Organized Convection Parameterization for Global Climate Models

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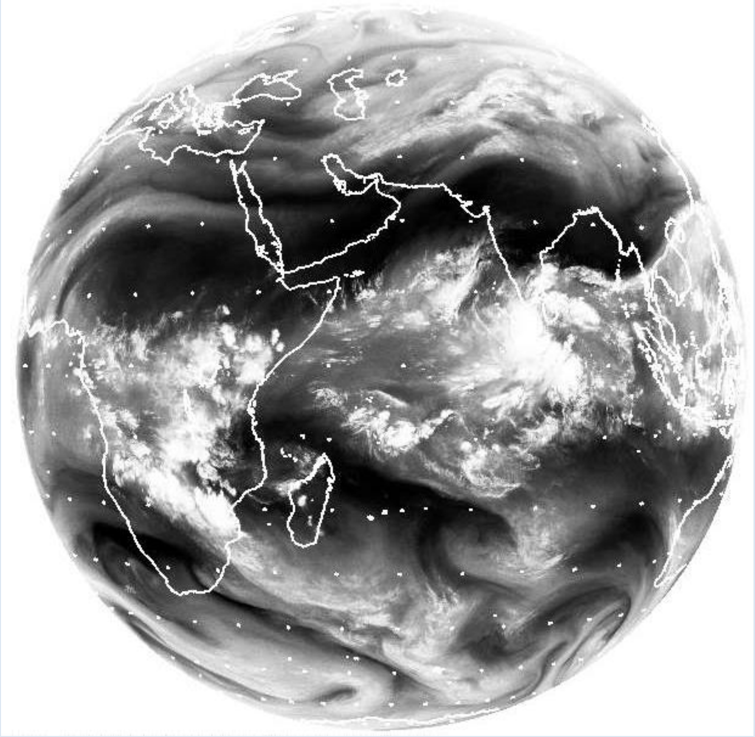
<u>New Paradigm</u>
Dynamical-system Approach to Organized Convection Parameterization for Next-generation GCMs



Special Symposium on Mesoscale Meteorological Extremes: Understanding, Prediction, and Projection
American Meteorological Society 99th Annual Meeting, Phoenix, AZ, January 5-10, 2018

Summary

- Excellent progress over half-a-century in our knowledge of **organized convection processes** (notably MCSs) utilizing field-campaign & satellite measurements, cloud-resolving simulations, and theoretical-dynamical principles.

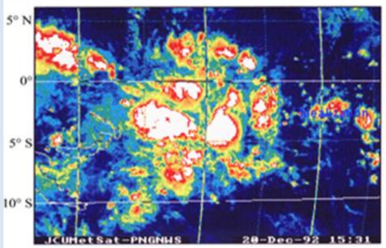
- But **organized convection parameterization** has languished, arguably due to its perceived complexity, and is missing from contemporary GCMs.

- **Multiscale coherent structure parameterization (MCSP**) based on nonlinear principles minimizes the physical and dynamical complexity issue

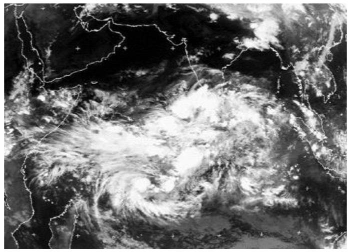
- **Prototype MCSP** approximating MCS heat and momentum transports in the NCAR Community Atmosphere Model (CAM) is **proof-of-concept**.

⏲ (10 km, hour)
Cumulonimbus

⏲ (100 km, day)
Mesoscale Convective System
(MCS)

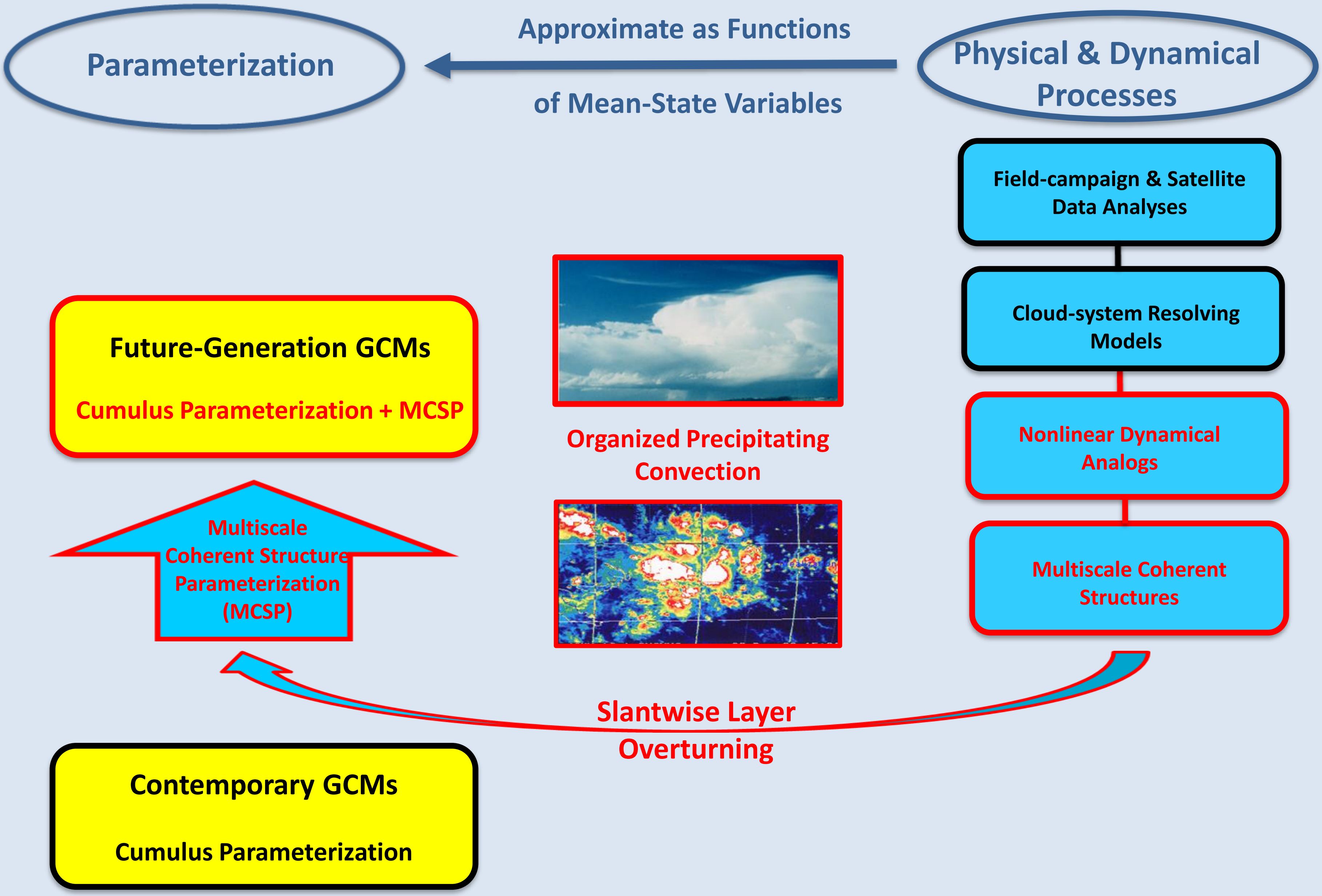


⏲ (1,000 km, week)
Tropical Supercluster

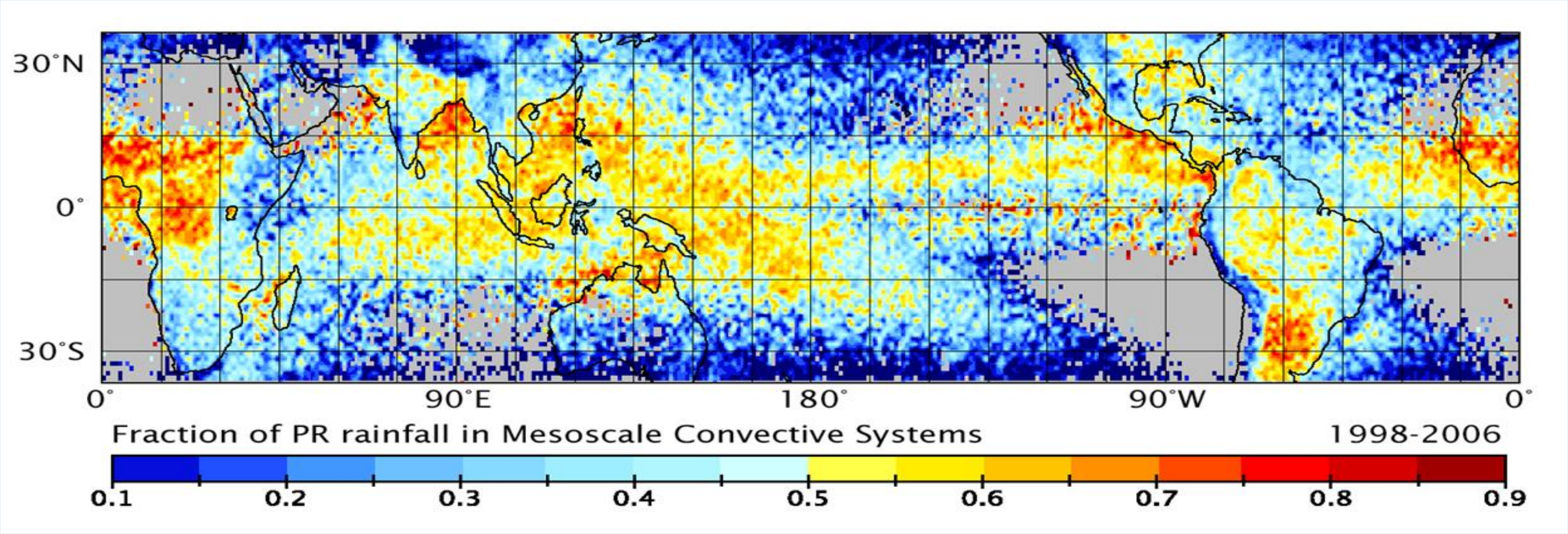


⏲ (10,000 km, months)
Madden-Julian Oscillation
(MJO)

MCSP Strategy



MCS in Global Context



Tao & Moncrieff (2009)

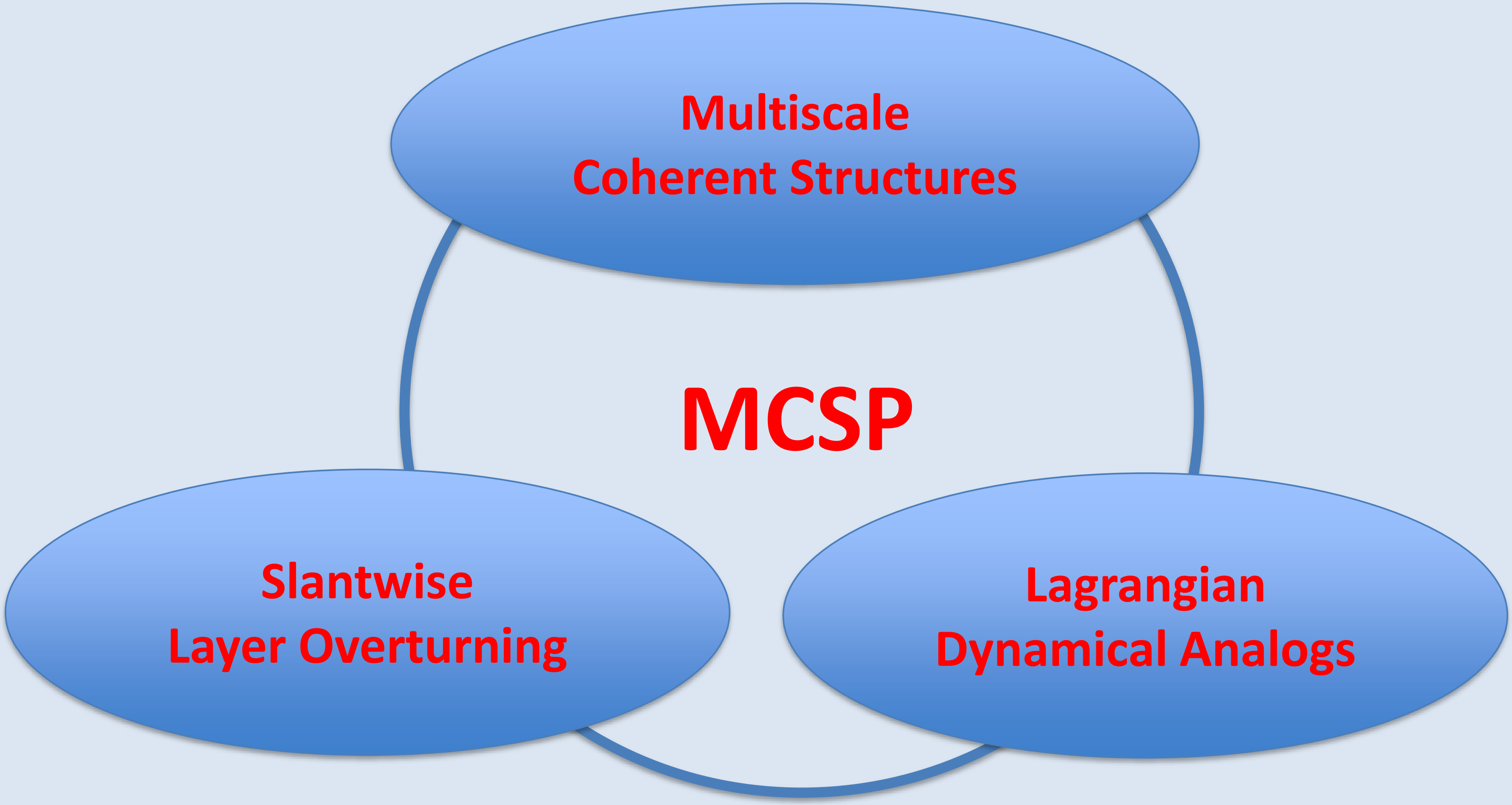
TRMM Precipitation Radar analyses show MCSs:

- **Provide >50% of tropical precipitation, >70% in certain regions**
- **Interact with meteorological phenomena that challenge contemporary GCMs**

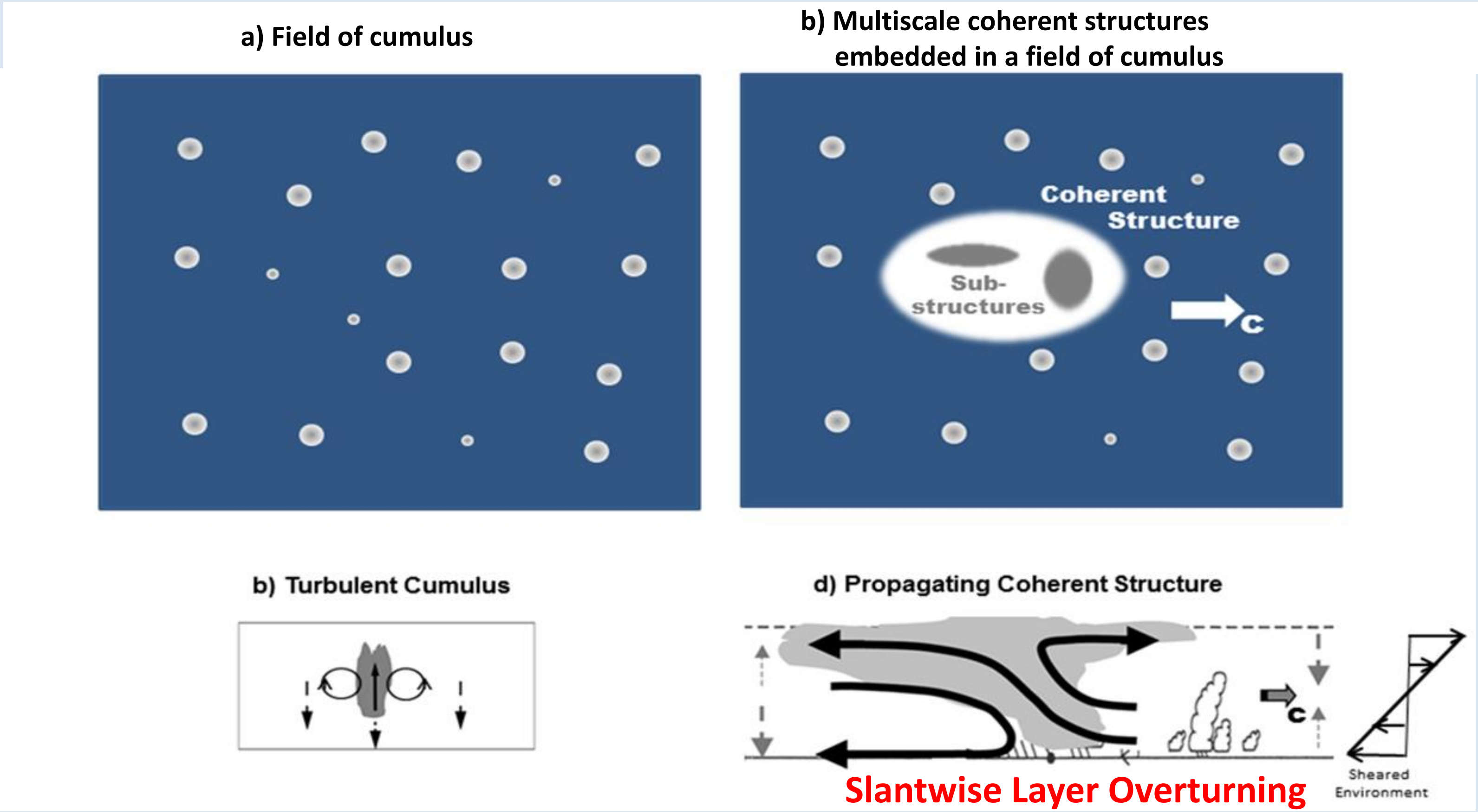
MCSs are missing from GCMs – not parameterized, not resolved

MCS presence is imperative for reliable projection of precipitation extremes by GCMs

Fundamental Principles

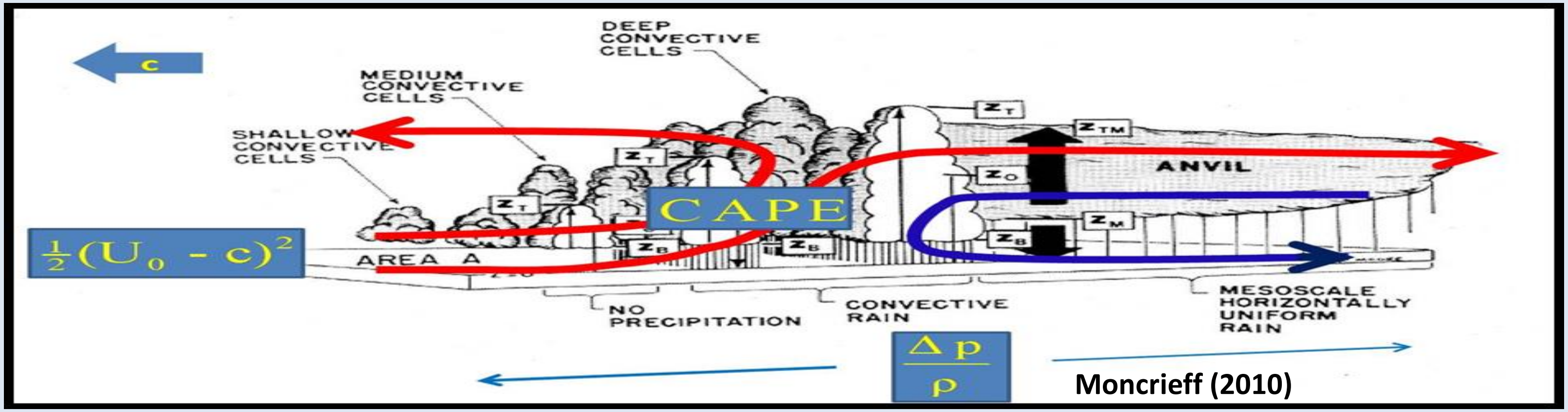


Multiscale Coherent Structures



Moncrieff & Waliser (2015)

Slantwise Layer Overturning



- **Slantwise layer overturning <u>exchanges entire layers</u>, distinct from local mixing.**

- **Driven by horizontal pressure gradient (Δp), controlled by vertical shear, overturning involves**

  - **<u>3 energy categories</u>: convective available potential energy (CAPE); available kinetic energy due to shear AKE = $\frac{1}{2}(U_0 - c)^2$; pressure work APG = $\Delta p/\rho$**

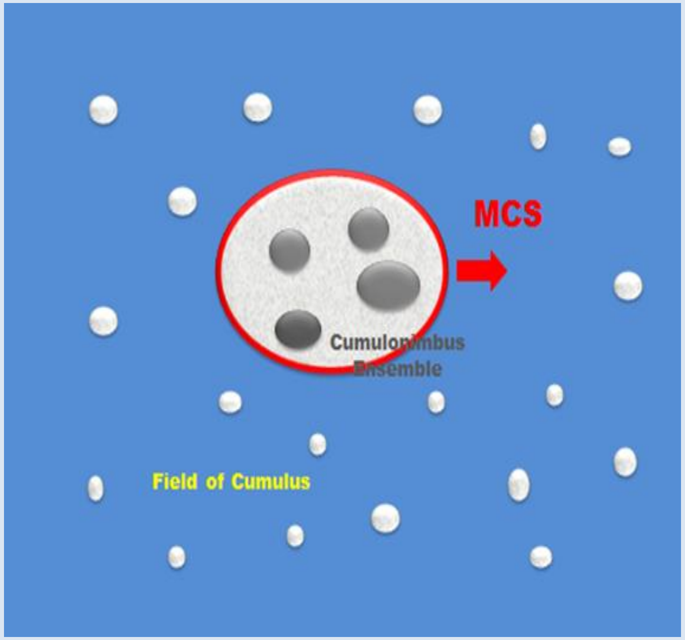
  - **<u>2 key quantities</u>: convective Richardson number, R = $\frac{\text{CAPE}}{\text{AKE}}$; Bernoulli number, E = $\frac{\text{APG}}{\text{AKE}}$**

  - **<u>Novel heat & momentum transports</u>**

Moncrieff (1992)

Lagrangian Dynamical Analogs

- Persistent multiscale coherent structures (MCS) in fully nonlinear Lagrangian form, $\frac{D}{Dt} = \frac{\partial}{\partial t} + \frac{\partial}{\partial x} + \frac{\partial}{\partial y} + \frac{\partial}{\partial z}$, are steady in the system-relative coordinate frame, so $\frac{\partial}{\partial t} = 0$.
- The field of cumulus, assumed part of the turbulent environment, is represented by contemporary cumulus parameterization.



- Transform the set of nonlinear equations into exactly integrable form, $DF_i/Dt = 0$.
- Integrate along trajectories (ψ) to provide a set of conserved quantities, $F_i = C_i(\psi)$.
- These quantities provide analytic Lagrangian models of slantwise layer overturning
- Models have been verified using cloud-system resolving models and observations.

Moncrieff (1992)

Prototype MCSP

- **Canonical formulation**

  - **1st and/or 2nd baroclinic (top-heavy) mesoscale heating**
  - **1st baroclinic acceleration by momentum transport**

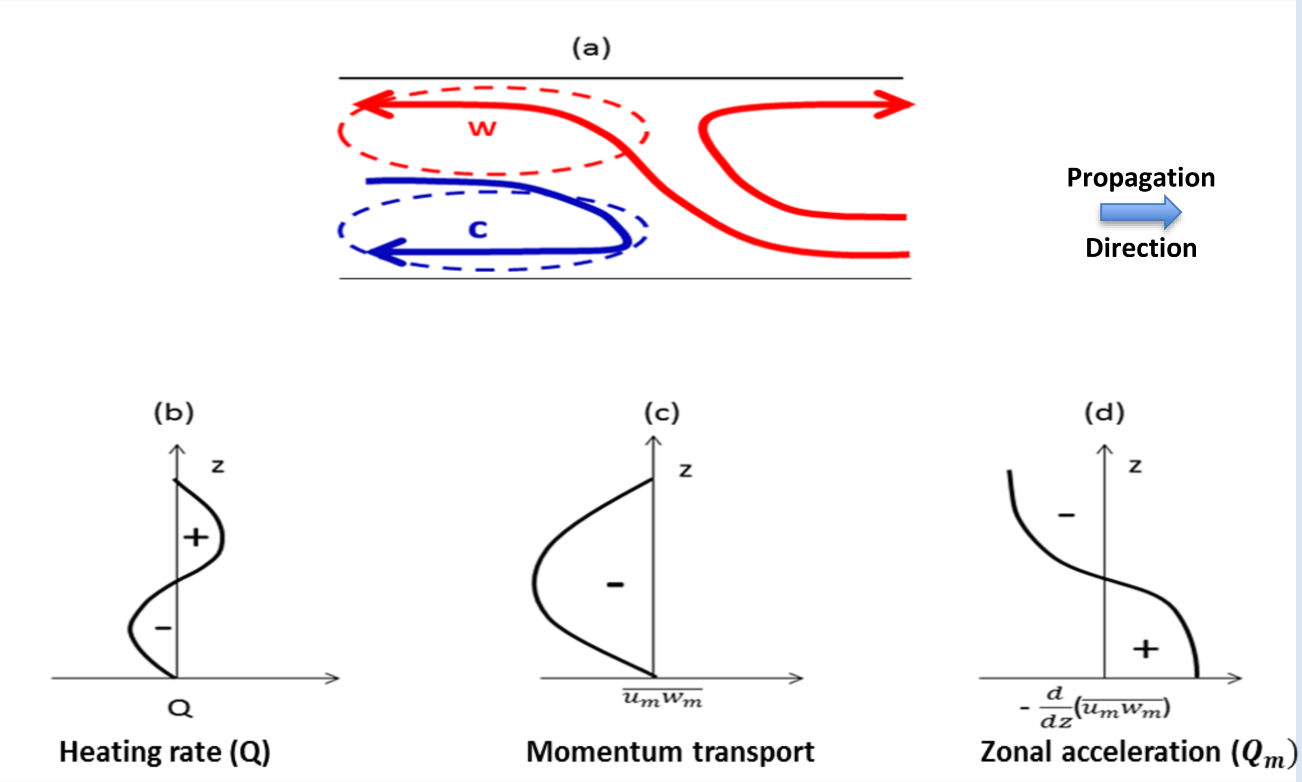
- **Add the "missing process" of mesoscale slantwise layer overturning to the existing cumulus parameterization, i.e.,**

$$\left[\frac{\delta}{\delta t}\right]_{total} = \left[\frac{\delta}{\delta t}\right]_{cumulus} + \left[\frac{\delta}{\delta t}\right]_{mesoscale}$$

- **Large-scale effects of organized convection unambiguously measured as differences between GCM runs with & without MCSP**

- **Minimal computational overhead**

Heat & Momentum Transport



$$Q(p,t) = Q_c(\mathrm{t})[\alpha_1 \sin \pi \frac{p_s - p}{p_s - p_t} - \alpha_2 \sin 2\pi \frac{p_s - p}{p_s - p_t}]$$

1st baroclinic 2nd baroclinic

$$Q_m(\mathrm{p,t}) = \alpha_3 \cos(\frac{p_s - p}{p_s - p_t})$$

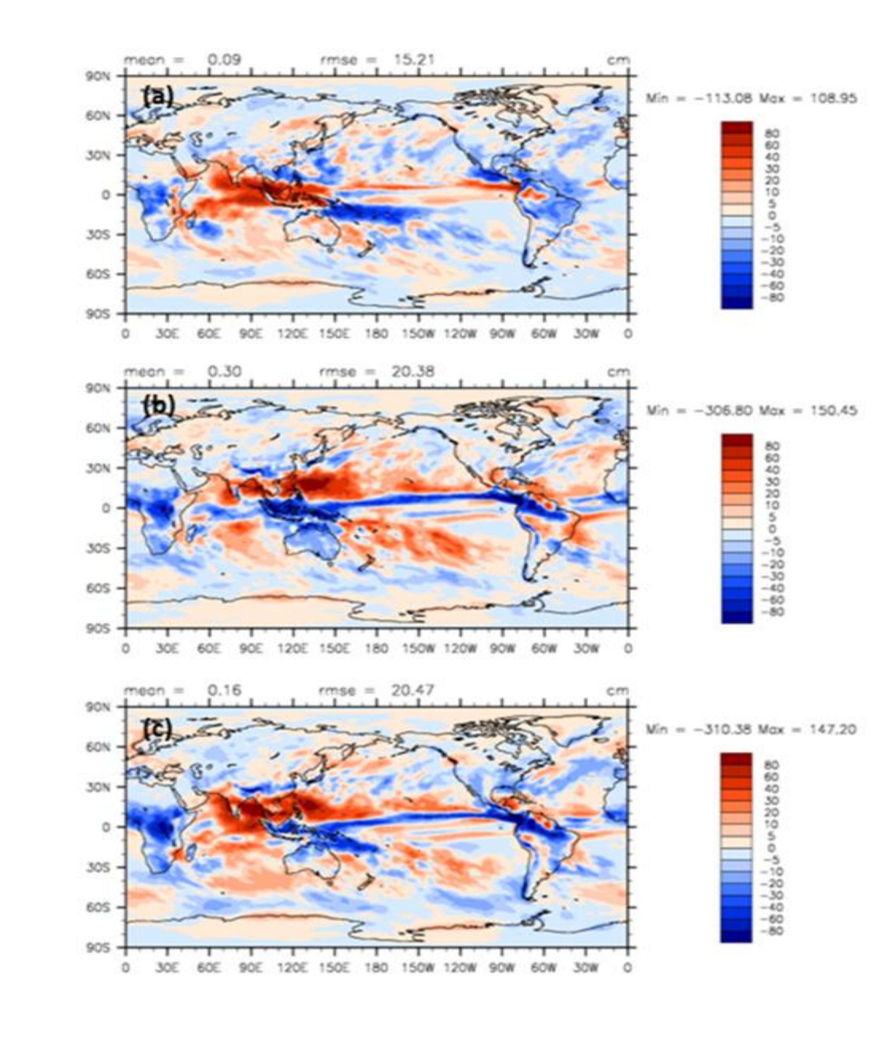
1st baroclinic

MCSP Effects: Annual Precipitation

1st Baroclinic momentum transport

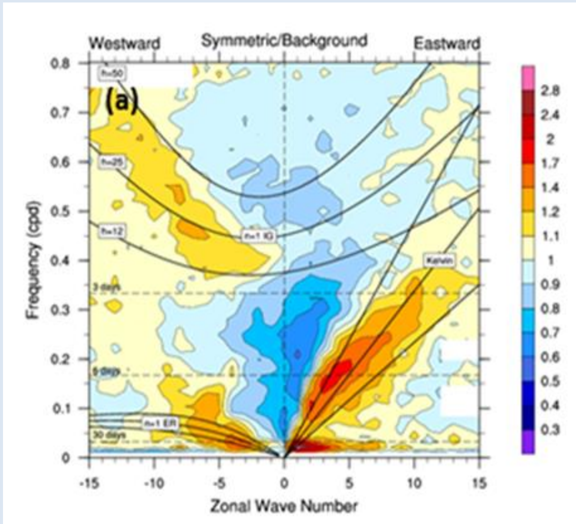
2nd Baroclinic heating

Momentum transport & heating

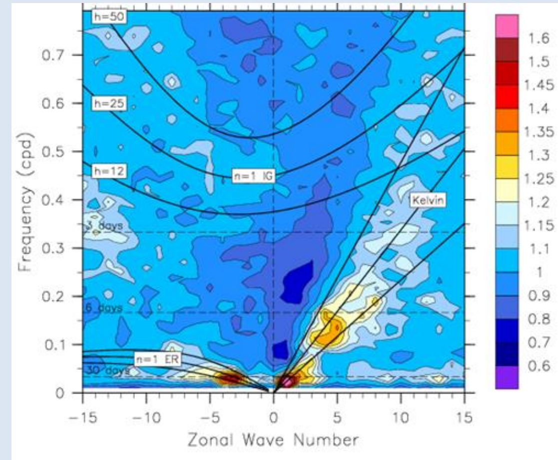


Moncrieff, Liu, and Bogenschutz (2017)

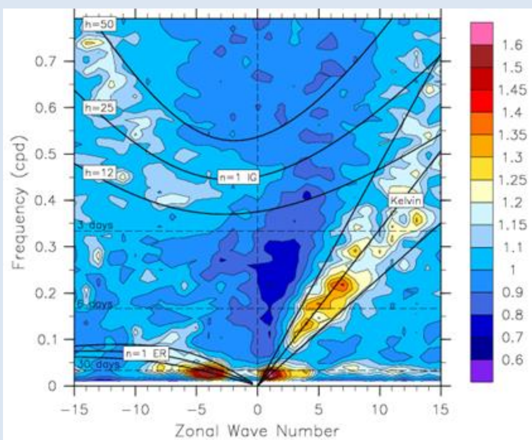
MCSP Effects: Tropical Wave Modes



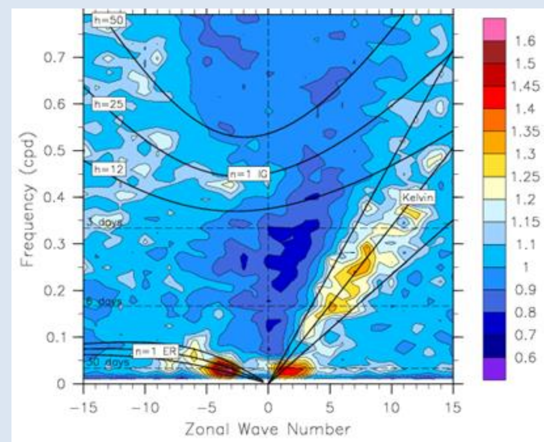
NCEP Reanalysis



CAM 5.5 Control



MCSP: 2[nd] Baroclinic Heating
($\alpha_1 = 0, \alpha_2 = 1$)



MCSP: 2[nd] Baroclinic Heating &
Momentum Transport (α_3 = 1)

Moncrieff, Liu, and Bogenschutz (2017)

Conclusions

- Prototype MCSP in CAM shows organized convection is <u>parameterizable</u> using 3 basic principles:

Multiscale Coherent Structures, Slantwise Layer Overturning, Lagrangian Dynamical Analogs

- Prototype MCSP effects on CAM demonstrates in a minimalist way:
  - 1st unambiguous measure of the global effects of organized convection
  - Upscale precipitation distribution, convection-wave interaction, and MJO
  - Organized convective heating & momentum transport effects are distinct
  - Organized precipitation distribution consistent with TRMM analyses
  - Cumulus & organized convection parameterization unified
  - Computationally efficient, hence MCSP usable in full suite of GCMs

- Next steps
  - Add shear-selection & other regimes of convective organization to MCSP
  - MCS parameterization in an idealized GCM (Yang, Majda, and Moncrieff, 2019)
  - Implement MCSP in the DOE Energy Exoscale Earth System Model (E3SM)
  - Quantify the scale-invariance properties of MCSP

- Strategic aspects
  - Theoretical-dynamical aspects of the convective parameterization ‘gray-zone’
  - Virtual global field campaigns & the weather-climate intersection (*cf.* YOTC)
  - Utilize regional-refined GCMs for research into MCSP development

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