Super-parametrization in climate and what do we learn from high-resolution

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Scales of Atmospheric Motion

10,000 km 1000 km 100 km 10 km 1 km 100 m 10 m

Planetary waves Extratropical Cyclones Mesoscale Convective Systems Cumulonimbus clouds Cumulus clouds Turbulence =>

Global Climate Model (GCM) Cloud System Resolving Model (CSRM) Large Eddy Simulation (LES) Model

scales-separation parameterized convection
Cloud Processes

Radiation

Cloud-scale motions

Turbulence

Microphysics

These processes interact strongly on the cloud scale.
• Initial conditions problem
• Confronted with truth everyday

• Boundary conditions problem
• No truth is known
• The only hope is physical realism (resolve everything!)
• Response to SST is not sensitive to microphysics;
• CRM+High-Order-Closure (HOC) SGS parameterization reproduces “Present”, but not “Present-minus-Future”;
• RCE with HOC has about twice as large equilibrium climate sensitivity (ECS) parameter;
• “Coarse” RCE with 4 km grid spacing appears to be the threshold when the ECS becomes invariant of the resolution
• SGS parameterizations can significantly alter climate sensitivity
Great, but too expensive.

Global CRM? Resolve everything!
The large-scale forcing data would come from observations (GATE, TOGA, ARM, KWAIJEX, etc.)

All super-parameterization does is compute $Q_1$ and $Q_2$
Super-parametrization (SP)
Multiscale-Modeling Framework (MMF=GCM+SP)

\[
\frac{\partial \bar{S}}{\partial t} = -\nabla \bar{s} \bar{V} - \frac{\partial \bar{s} \bar{\omega}}{\partial p} + Q_1
\]

GCM Resolved

Column-Physics (SP)

CRM Forcing:

\[
-\nabla \bar{s} \bar{V} - \frac{\partial \bar{s} \bar{\omega}}{\partial p} = \frac{\bar{s}^* - \bar{s}^n}{\Delta t}
\]

CRM Tendency:

\[
Q_1 = \frac{\bar{s}^{n+1} - \bar{s}^*}{\Delta t}
\]

Dynamics Step:

\[
\begin{align*}
\bar{s}^n & \rightarrow \bar{s}^* \\
\Delta t & \rightarrow \Delta t_{CRM}
\end{align*}
\]
MMF is very expensive, but highly scalable on supercomputers.

Efforts are under way to develop stochastic conventional parameterizations, but the super-parameterization generates stochastic heating and drying rates in a particularly natural way.

Finally, the SP-CAM is almost embarrassingly parallel, so that it can make efficient use of a very large number of processors. The reason is that the many copies of the CRM (one per CAM grid column) run independently, with no communication among themselves. As a result, for a given GCM grid spacing the SP-CAM can use many more processors than a conventionally parameterized model. Although the SP-CAM does much more arithmetic per simulated day than a conventionally parameterized GCM with the same resolution, the ability of the MMF to utilize more processors than a conventional GCM means that the wall-clock time required to complete a given simulation with the super-parameterization is only moderately longer than that required with a conventional parameterization. An example is shown in Fig. 11. The MMF is orders of magnitude less expensive than a global cloud-resolving model (GCRM; e.g., Tomita et al., 2005).

Over the past two decades, cloud-parameterization testing has become organized on an international scale, beginning with NASA's FIRE program in the 1980s (Cox et al., 1987), and continuing in the 1990s and beyond with DOE's ARM Program (Stokes and Schwartz, 1994).

Fig. 11: Plots of simulated years per wall-clock day versus the number of processors used, for the conventional CAM (black dots) and the SP-CAM (blue dots). The GCM grid spacing is 2.5º of longitude by 2º of latitude for both models. Note that the axes are logarithmically scaled. The figure shows that, with this resolution, the SP-CAM can efficiently use thousands of processors, while the CAM is limited to hundreds. The timing tests were performed on Hopper, a Cray XE6 at the National Energy Research Scientific Computer Center (NERSC), by Mark Branson of Colorado State University.

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6 NASA is the National Aeronautics and Space Administration.
7 FIRE was the First ISCCP Regional Experiment; ISCCP is the International Satellite Cloud Climatology Project.
8 DOE is the U.S. Department of Energy.
9 Atmospheric Radiation Measurement Program.

from M. Branson (2013)
Super-Parameterization - Summary

- Runs like conventional parameterization: profile in, profile out; hence, the name, super-parameterization (term coined by David Randall);

- The CRMs do not communicate directly with each other (‘embarrassingly’ parallel problem);

- Radiation is usually computed on CRM grid; no cloud-overlap assumptions are needed;

- Momentum tendencies are not generally returned to GCM due to wrong momentum transport by 2D CRM; however use of 3D CRM is possible;

- Surface fluxes are still computed on GCM grid;

- Tendencies due to terrain are also due to GCM (no topography in CRM);

- PBL parameterization is generally off for scalars, but not wind;

- The width of the CRM domain is not tied to the GCM grid size (same way as a convective parameterization using no Δx information);

- GCM grid-cell should be large enough to contain large-scale convective systems.
The super-parameterization improves variability on a wide range of time scales.

- Diurnal cycle
- Extreme Precipitation
- MJO
- African Easterly Waves
- Monsoon/BSISO
- ENSO
- ...

http://www.cmmmap.org/research/pubs-mmf.html
Diurnal cycle of precipitation
JJA Local Time of Precipitation Frequency Maximum

Observations (Dai, 2001)

Common bias (early maximum around noon) of many climate models
We still don’t understand why 4-km 2D CRM can do such a good job...
Eastward propagation is robust in SP-CAM even at T42!

Only large-scale processes are responsible for propagation of MCSs.

Kooperman et al 2013
SP-CAM is better than CAM to simulate the extreme precipitation.

Li, Rosa, Collins & Wehner, 2012
PDF of Rainfall
SP-CAM vs CAM T85

SP-CAM does better job than CAM in simulating heavy rain rates

Zhou and Khairoutdinov 2015
Change of today’s extreme (99th) precipitation event frequency in RCP8.5 climate

SP-CAM predicts much bigger increase in extreme precipitation frequency than CAM

Zhou and Khairoutdinov 2015
Madden-Julian Oscillation (MJO)
Осцилляция Маддена-Джулиана
From the inception, SP-CAM/SP-CCSM has been arguably the best framework for MJO simulation.
Intraseasonal Variability in Tropics
Intraseasonal Variability in Tropics

SP-CAM

NOAA OLR

CAM

Seasonal Cycle of MJO

NOAA

SP-CAM

Khairoutdinov, DeMott, Randall 2008

El Nino

La Nina

Normal
Coupled SP-CCSM

Coupling to the ocean improves subseasonal variability

DeMott et al (2011)
Zonal cross-section of MJO

Benedict and Randall 2008
Large increase of MJO in warmer climate

Arnold et al, PNAS 2014
Self-aggregation of convection on sphere
SST=const, Solar=const, f=0

Aggregation does not occur without interactive longwave!

Surface fluxes help, but are not essential.
Restoring full rotation: Model produces an “MJO”
In Obs and SP-CAM, heavy rainfall corresponds to regions with high humidity, especially in low-to-mid troposphere.

Is high sensitivity of precipitation to humidity the key for simulating MJO?

Thayer-Calder and Randall (2009)
African Easterly Waves

AEWs are well simulated in SP-CCSM, but virtually missing in CCSM.

Fig. 2. Average JJAS signal-to-noise space–time spectra averaged between 15°S and 15°N at all longitudes for disturbances that are (a)–(c) symmetric and (d)–(f) antisymmetric about the equator from (left) observations, (middle) SP-CCSM, and (right) CCSM.
African Easterly Waves

OLR anomalies and 850 mb streamfunction and winds

SP-CCSM couples convection and waves right to simulate AEWs even at T42! Again, as in MJO, mid-tropospheric moisture anomaly appears to be the key to simulating AEWs.

McCary, Randall, Stan 2014
El Nino amplitude and periodicity is better simulated by SP-CCSM.
Super-parameterized GCMs

- 2001: SP-CAM
- 2007: SP-fvGCM: NASA GSFC (Wei-Kuo Tao)
- 2010: SP-WRF: (Stefan Tulich)
- 2011: SP-CFS: Indian Institute of Tropical Meteorology
- 2014: SP-IFS: ECMWF
SP-CFS (IITM)

Goswami et al, JC (2015)
SP-IFS – Super-parameterized IFS

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- First implemented in OpenIFS, which is a free running IFS (cycle 38R1), but without data assimilation system;
- Summer 2014: T159 (~1.125° x 1.125°) 3-year runs with SP-OIFS;
- Fall 2014: SP is implemented in IFS CY40R3.
- Fall 2014: SP is in IFS Single-Column Model CY40R1;
- Currently, implemented in CY41R3 and can be run using prepIFS system.
Preliminary results using T159 SP-OpenIFS

- SP: 32 x 74; $\Delta x=4$ km; $\Delta t=20s$;
- All IFS cloud and convective parameterizations are off;
- PBL/mixing parameterizations are allowed;
- Radiation coupling through SP’s mean profiles (not on CRM grid as done in SP-CAM);
- Free continuous climate run for 3 years starting Aug 2000.
Mean climatology of SP-IFS doesn’t look bad for a model which hasn't been properly tuned.
Frequency Spectrum (Subseasonal):
Precipitation in Tropics (15ºS-15ºN)

Symmetric

Anti-Symmetric
Frequency Spectrum (S/N): Precipitation in Tropics (15°S-15°N)

Symmetric

Anti-Symmetric
Variance: 20-100 day filtered precipitation

**Summer (May-Oct)**

(b) 20-100 day variance, PRCP, TRMM, Summer

**Winter (Nov-Apr)**

(b) 20-100 day variance, PRCP, TRMM, Winter

(b) 20-100 day variance, PRCP, CTRL, Summer (May-Oct)

(b) 20-100 day variance, PRCP, CTRL, Winter (Nov-Apr)

(b) 20-100 day variance, PRCP, SP32, Summer (May-Oct)

(b) 20-100 day variance, PRCP, SP32, Winter (Nov-Apr)
Variance: 20-100 day filtered U850

Summer (May-Oct)

Winter (Nov-Apr)

ERA40

IFS

SP-IFS
MJO eastward propagation

Lag correlation (U850, Winter)

Reference domain:
1.25S-16.25N, 68E-96E
* US CLIVAR MJO Diagnostic metrics
Summer ISO northward propagation

Lag correlation (U850, Summer)

ERA40

Reference domain: 3.75N-21.25N, 68E-96E
Tuning for cloud fraction using SCM IFS (TWP ICE case)

IFS

SP-IFS (control)

SP-IFS (tuned)
Bias in OLR in SP-IFS CY40R1 forecast

SP-IFS (before tuning)
Bias in OLR in SP-IFS CY40R1 forecast

SP-IFS (after tuning)

IFS
What have we learnt from SP?

- Even small-domain 2D CRM works better than current convective parameterizations to represent variability of climate system on various timescales.
- We know much more about MJO now thanks to the SP.
- As the SP interacts with a GCM as an ordinary parameterization (1D profile in, 1D profile out), it is in principle possible to develop a parameterization that works as well as the SP.

Lots of MMF publications:

http://www.cmmap.org/research/pubs-mmf.html