Testing a Resolution-Independent Parameterization of Deep Convection

David Randall, Minoru Chikira, Donald Dazlich, and Shrinivas Moorthi

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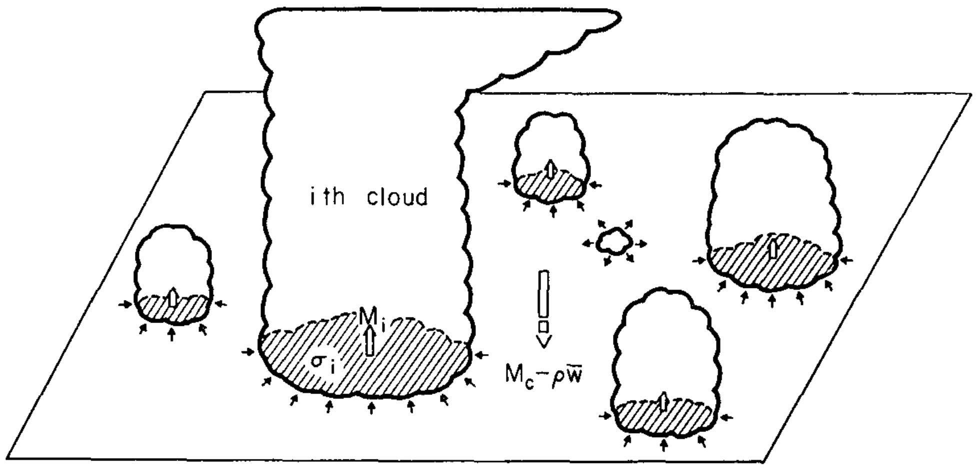
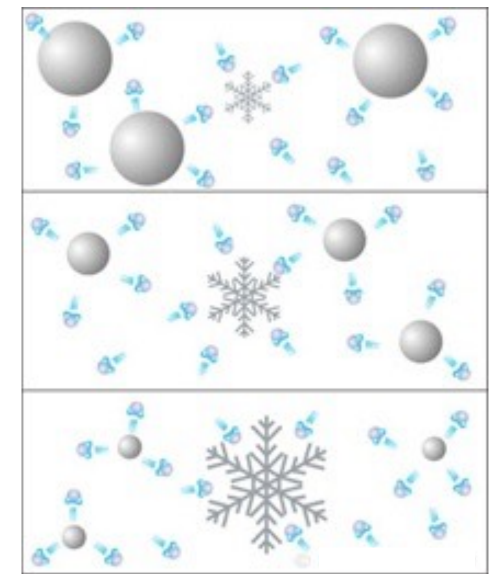
Work carried out for a Climate Process Team led by Steve Krueger.

The nature of a model's subgrid-scale physical processes depends on the horizontal grid spacing.





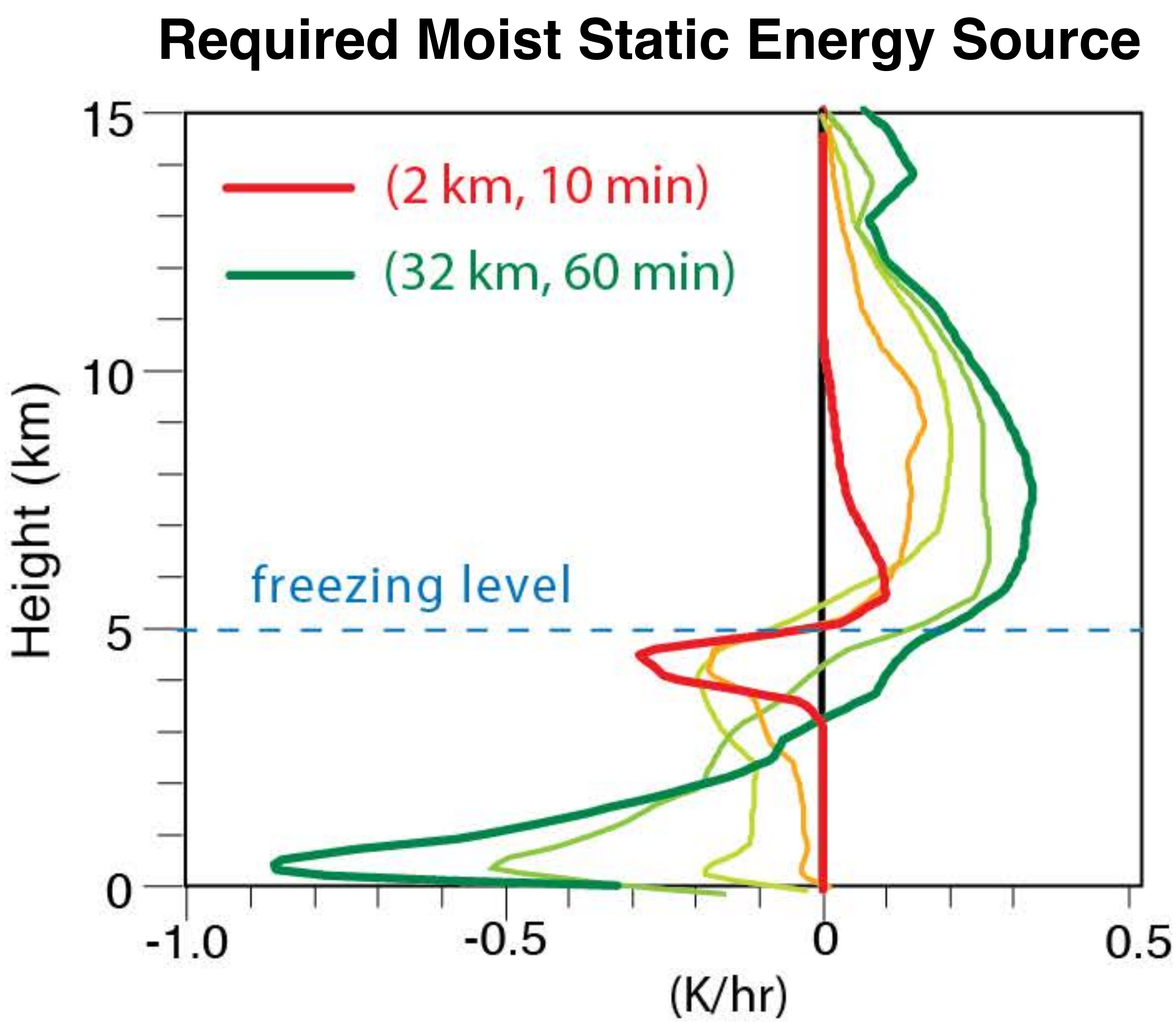
Low resolution

Parameterizations for low-resolution models describe the collective effects of many clouds, including strong convective transports.

High resolution

Parameterizations for high-resolution models describe what happens inside individual clouds.

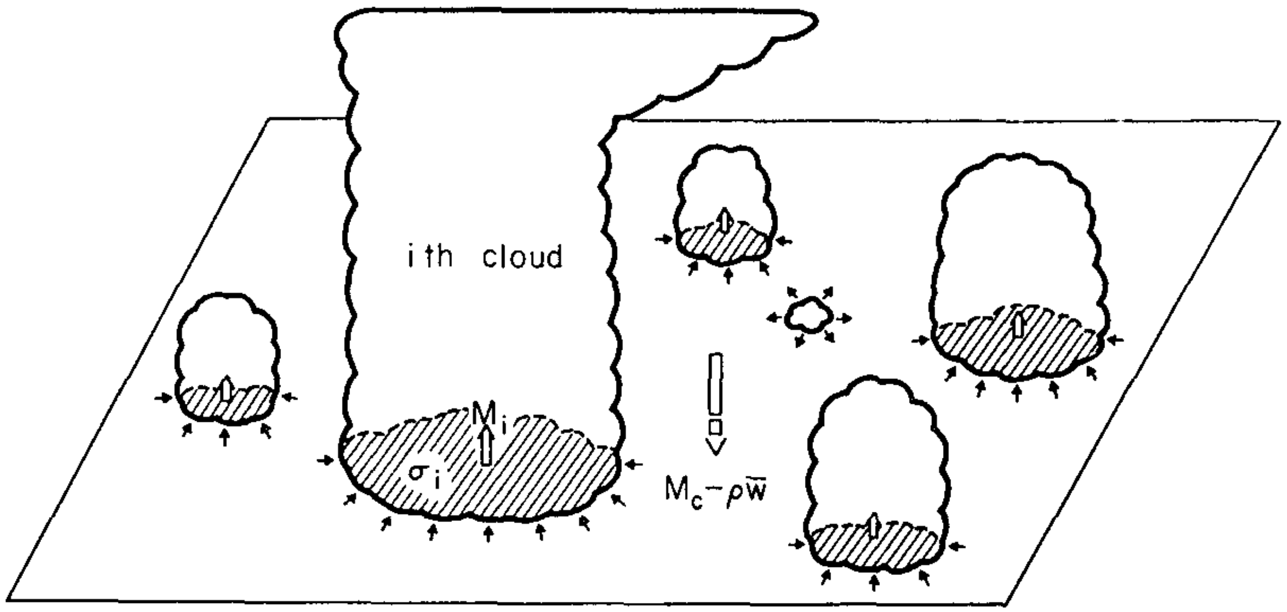
An example of resolution-dependence



Jung, J.-H. and A. Arakawa, 2004.: The resolution dependency of model physics: Illustrations from nonhydrostatic model experiments. *J. Atmos. Sci.*, **61**, 88-102.

Resolution-independent cumulus parameterizations

Low resolution



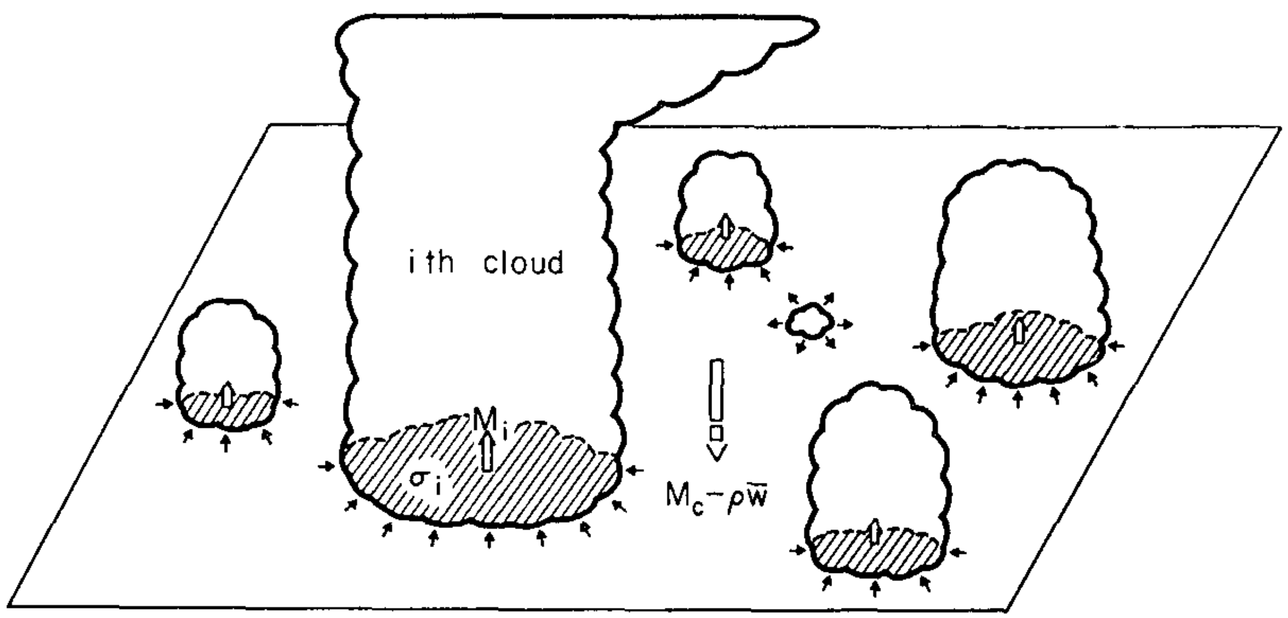
Updrafts occupy
a small fraction of each grid cell.

Quasi-equilibrium

Convective transport on *subgrid* scale

Resolution-independent cumulus parameterizations

Low resolution



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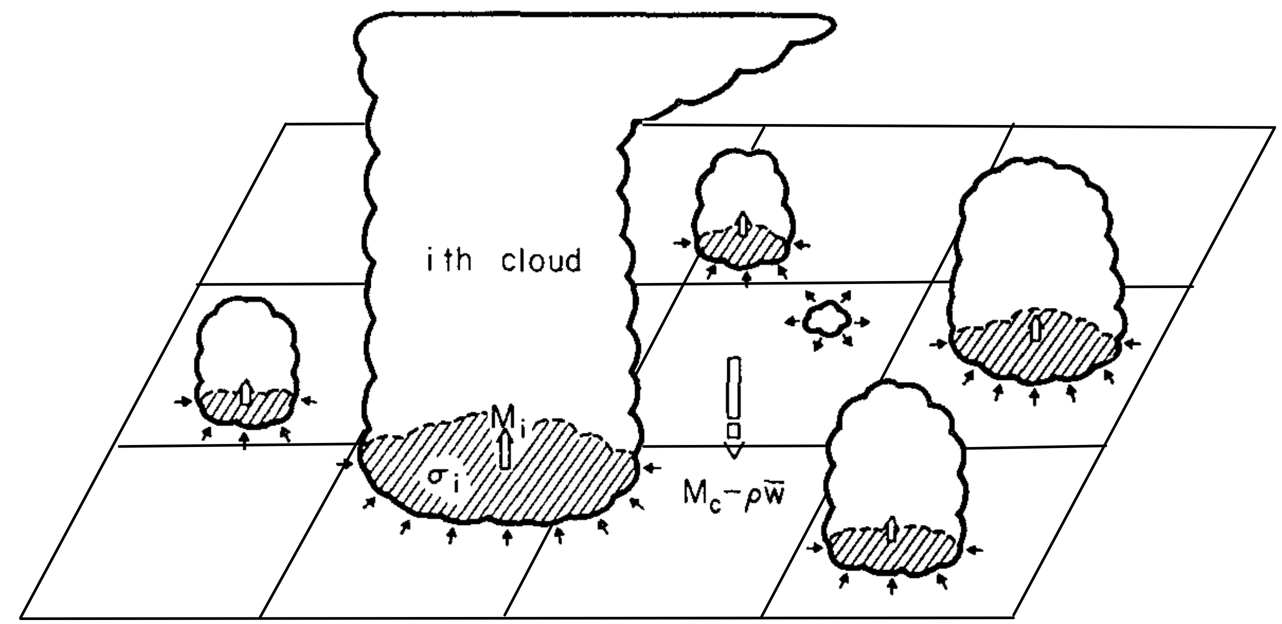

Some grid cells are
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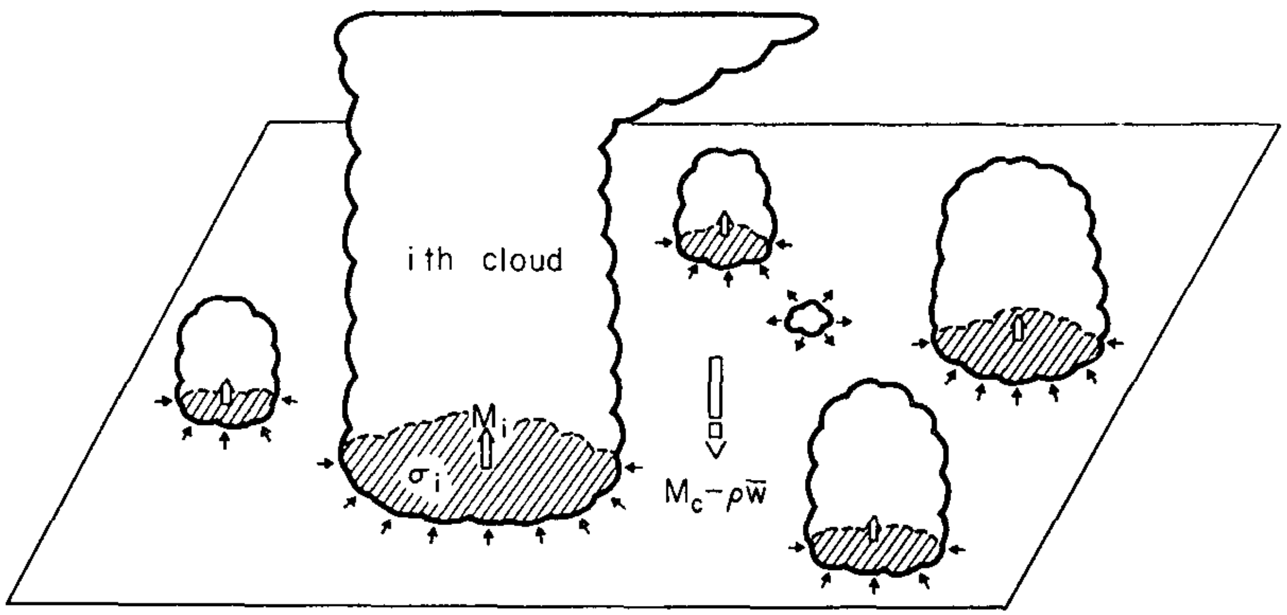
Non-equilibrium

Convective transport on *grid* scale

Resolution-independent cumulus parameterizations

Low resolution



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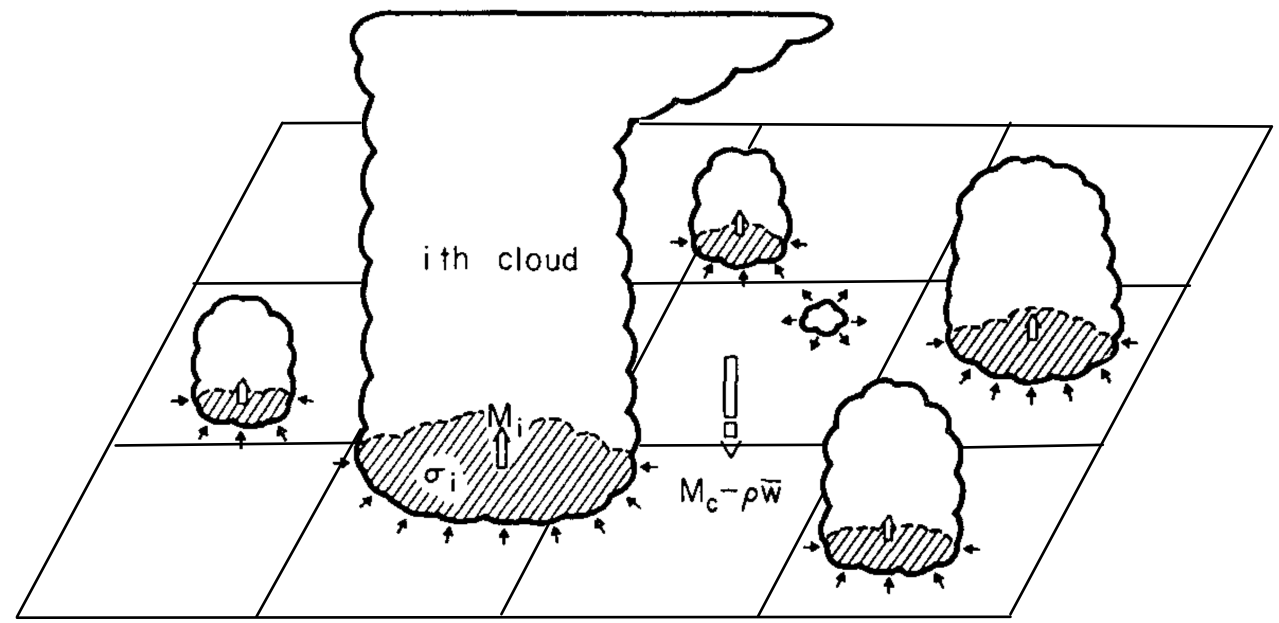

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almost filled by updrafts.

Non-equilibrium

Convective transport on *grid* scale

A resolution-independent cumulus parameterization must determine σ,
the fraction of each grid cell that is occupied by convective updrafts.

The Unified Parameterization of Arakawa and Wu

Goals:

- Individual clouds when/where the resolution is high.
- Parameterized convection when/where resolution is low.
- Continuous scaling.
- One set of equations, one code.
- Physically based.

Atmos. Chem. Phys., 14, 5233–5250, 2014
www.atmos-chem-phys.net/14/5233/2014/
doi:10.5194/acp-14-5233-2014

Atmospheric Chemistry and Physics
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A scale and aerosol aware stochastic convective parameterization for weather and air quality modeling

G. A. Grell[1] **and S. R. Freitas**[2]

[1]Earth Systems Research Laboratory of the National Oceanic and Atmospheric Administration (NOAA), Boulder, Colorado 80305-3337, USA
[2]Center for Weather Forecasting and Climate Studies, INPE, Cachoeira Paulista, Sao Paulo, Brazil

The Unified Parameterization is a “framework.”

The Unified Parameterization is built on top of a user-supplied conventional parameterization.

The conventional parameterization has to determine the updraft vertical velocity.

At low resolution, the conventional parameterization dominates.

Two ways to close a parameterization

Closures typically determine the convective mass flux:

$$M_c \equiv \rho\sigma\left(w_c - \overline{w}\right).$$

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$$\sigma \leq 1 .$$

Alternatively, we can formulate a closure for sigma itself, and design the closure so that sigma cannot be larger than one.

In that case, if the updraft vertical velocity is known, then the convective mass flux can be computed by multiplication.

What does sigma closure mean?

We can interpret sigma as the fractional area covered by one updraft, multiplied by the number of updrafts.

Closing for sigma is like closing for the number of updrafts.

The conventional parameterization

The mass flux given by the conventional parameterization is *defined* by

$$\left(M_c\right)_E = \rho\sigma\left(w_c - \overline{w}\right) .$$

The conventional parameterization uses a conventional closure, such as quasi-equilibrium, and is based on the usual assumption of small sigma.

How do we close for sigma?

For the conventional parameterization

$$\sigma = \frac{\left(M_c\right)_E}{\rho\left(w_c - \overline{w}\right)} \quad \text{assuming small sigma .}$$

How do we close for sigma?

For the conventional parameterization

$$\sigma = \frac{\left(M_c\right)_E}{\rho\left(w_c - \overline{w}\right)}$$ assuming small sigma .

Close the Unified Parameterization by modifying the above formula to

$$\sigma = \frac{\left(M_c\right)_E}{\rho\left(w_c - \overline{w}\right) + \left(M_c\right)_E} .$$

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$$\sigma = \frac{\left(M_c\right)_E}{\rho\left(w_c - \overline{w}\right) + \left(M_c\right)_E} \quad .$$

This gives small sigma and is consistent with the conventional parameterization when $\left(M_c\right)_E \ll \rho\left(w_c - \overline{w}\right)$.

It gives $\sigma \to 1$ when $\left(M_c\right)_E \gg \rho\left(w_c - \overline{w}\right)$.

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It is similar but not identical to the closure proposed by Arakawa & Wu.

What makes sigma go to one?

When the grid-scale motion is strongly upward, which can happen with high resolution, a conventional parameterization has to fight hard to stabilize the column.

This causes the mass flux determined by the conventional closure to become very large:

$$\left(M_c\right)_E \gg \rho\left(w_c - \overline{w}\right) \quad .$$

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$$\left(M_c\right)_E \gg \rho\left(w_c - \overline{w}\right) \ .$$

This will never happen with low resolution unless the model is blowing up!

For $\sigma \to 1$, the parameterized fluxes become small.

For the unified parameterization,

$$M_c = \rho\sigma\left(w_c - \overline{w}\right) \; .$$

Combining this with our closure,

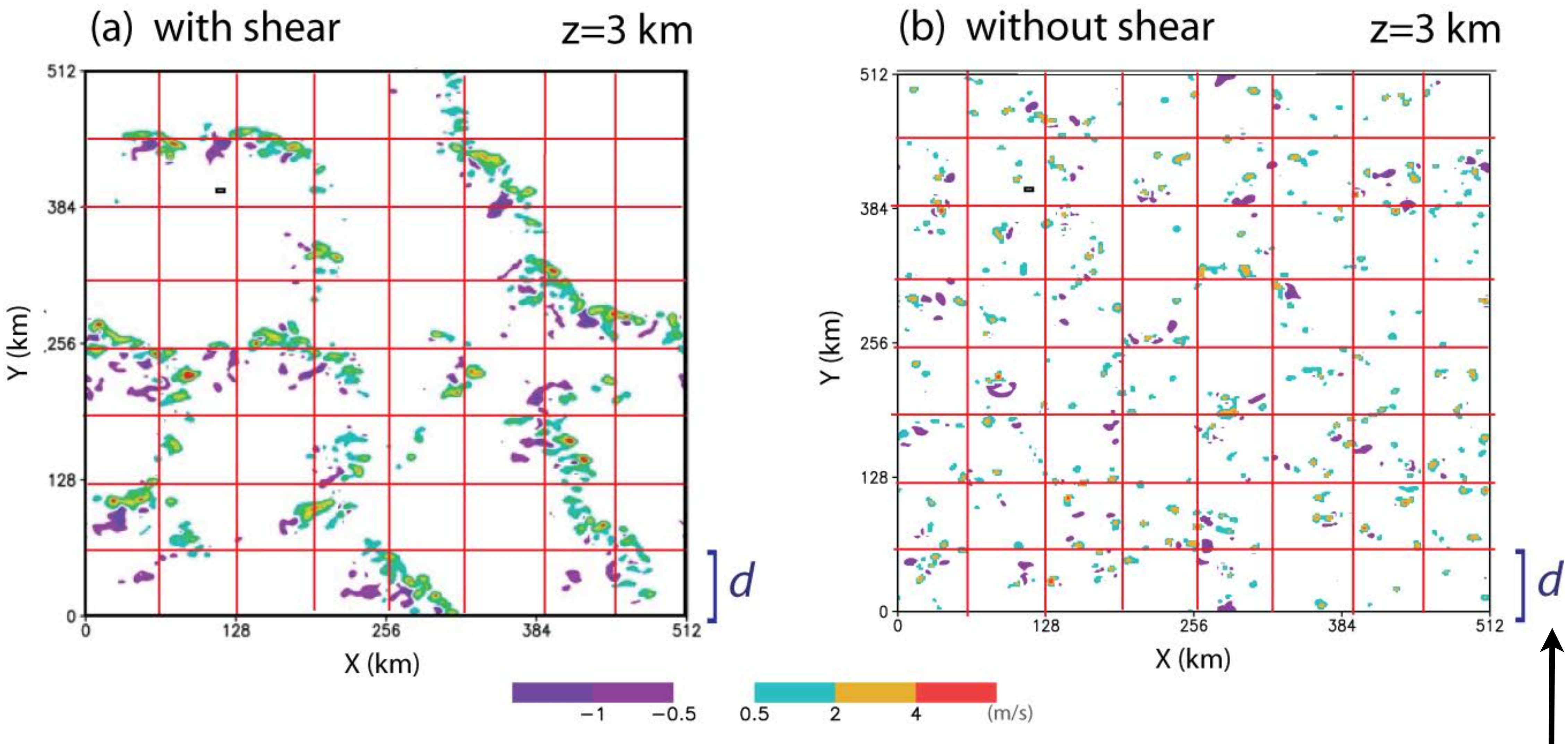
$$\sigma = \frac{\left(M_c\right)_E}{\rho\left(w_c - \overline{w}\right) + \left(M_c\right)_E} \; ,$$

we find that

$$M_c = \left(1 - \sigma\right)\left(M_c\right)_E \; .$$

The parameterized mass flux goes to zero as sigma goes to one.

Use a CRM to test ideas.

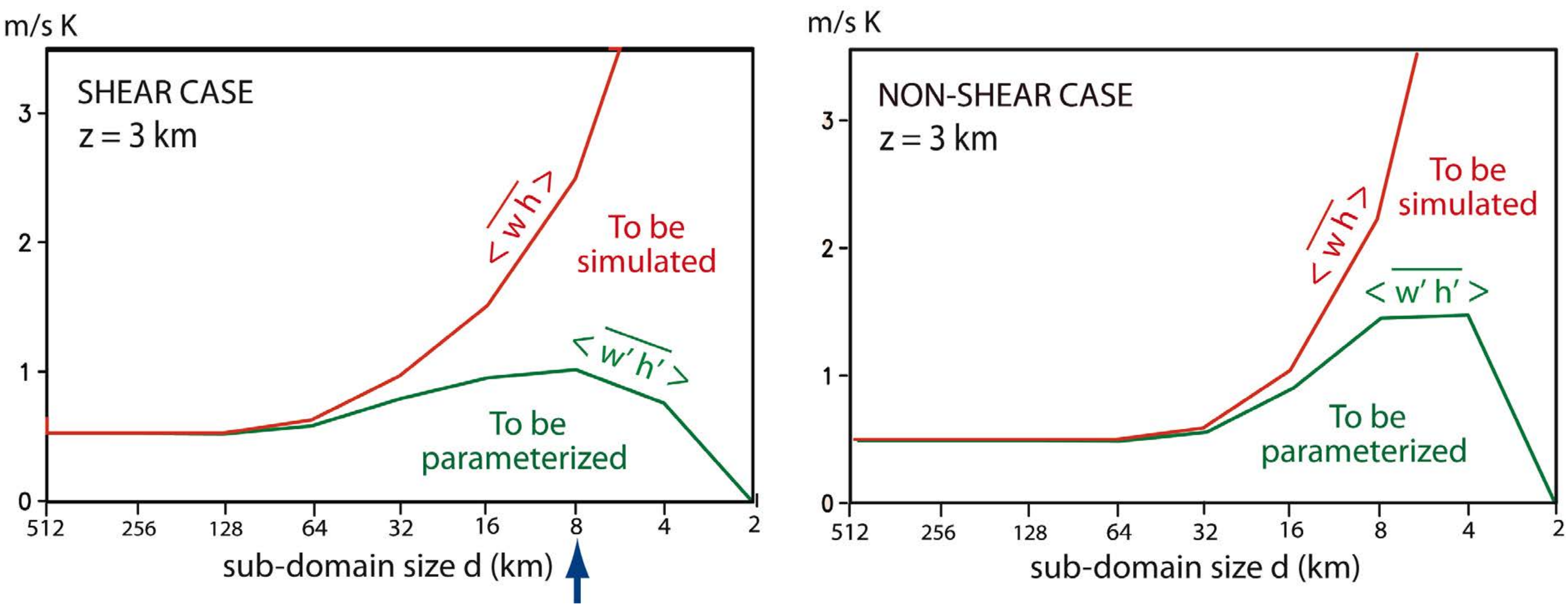


Vertical velocity 3 km above the surface

Subdomain size, used to analyze dependence on grid spacing

Figure from Akio Arakawa

SGS flux as a function of grid size



Red curve is total flux.

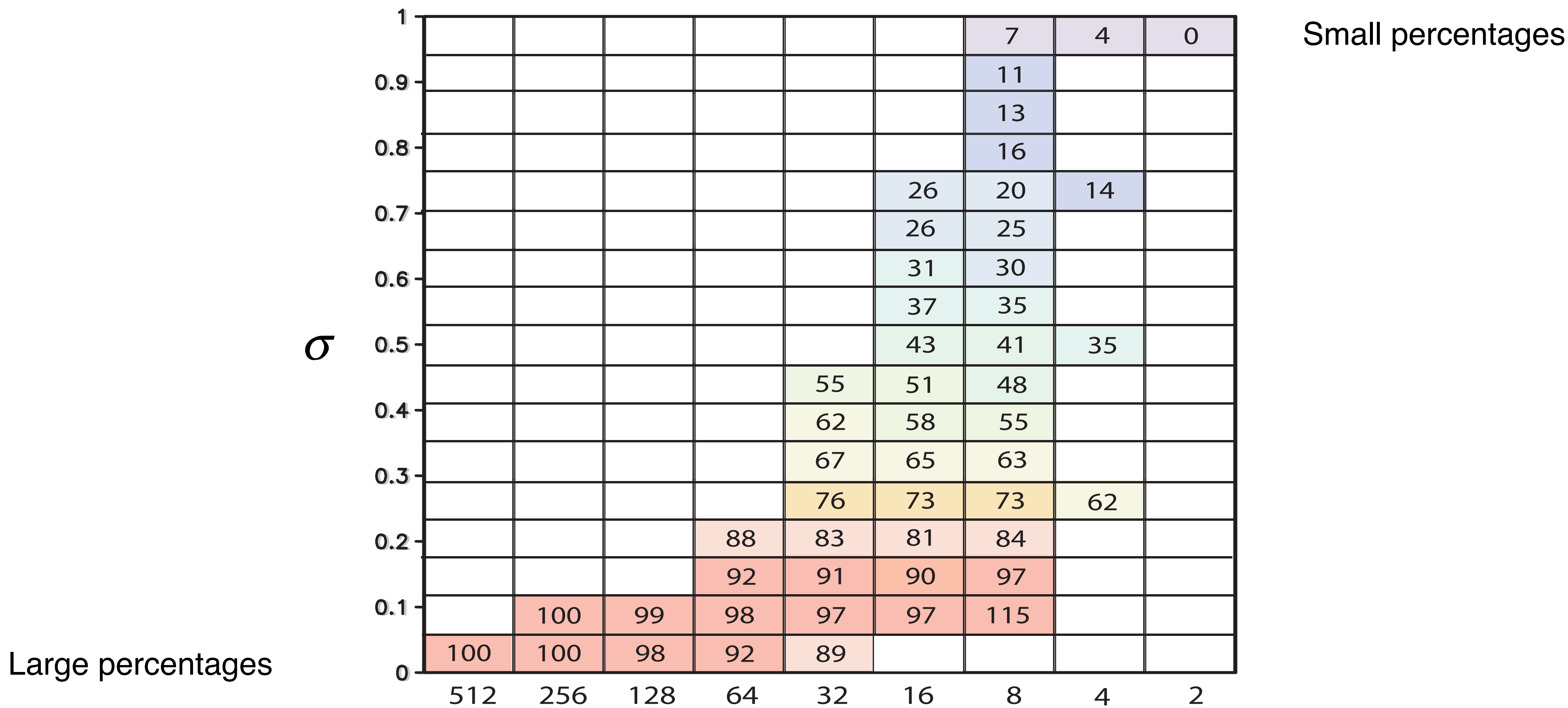
Green curve is subgrid flux to be parameterized.

The subgrid part is dominant at low resolution, but negligible at high resolution.

Figure from Akio Arakawa

Flux partitioning

Numbers and colors show percentage of the total flux due to unresolved processes.



horizontal grid spacing, km

The dependence on σ, for a given grid spacing, is strong.
The dependence on grid spacing, for a given, σ is weak.

Figure from Akio Arakawa

A generalization is needed.

Arakawa and Wu considered a single updraft "type" in a uniform environment.

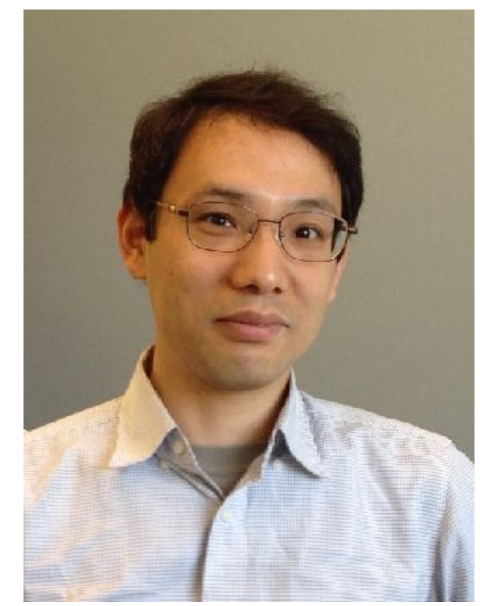
We need a generalization that allows multiple updraft types, and also downdrafts, sharing an environment.

Generalization

Minoru Chikira has generalized the Unified Parameterization so that it can be used with arbitrarily many updraft and downdraft types.

$$\sigma_1 = \frac{\left(M_1\right)_E}{\rho \delta w_1 + \left(M_1\right)_E} \quad ,$$

$$\sigma_i = \left(1 - \sum_{j=1}^{i-1} \sigma_j\right)\left[\frac{\left(M_i\right)_E}{\rho \delta w_i + \left(M_i\right)_E}\right] \text{for } i = 2 \ldots N \quad .$$



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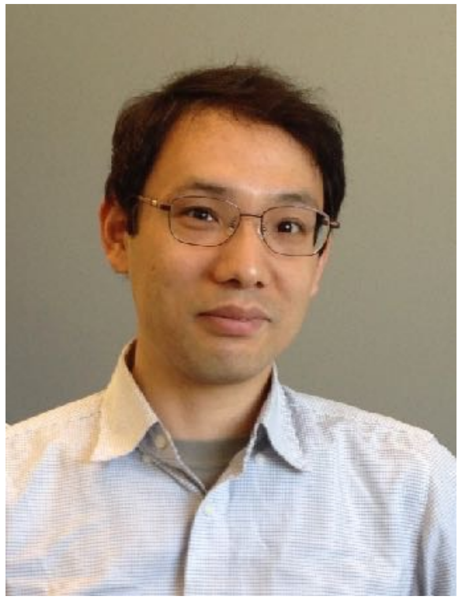

Area not already occupied

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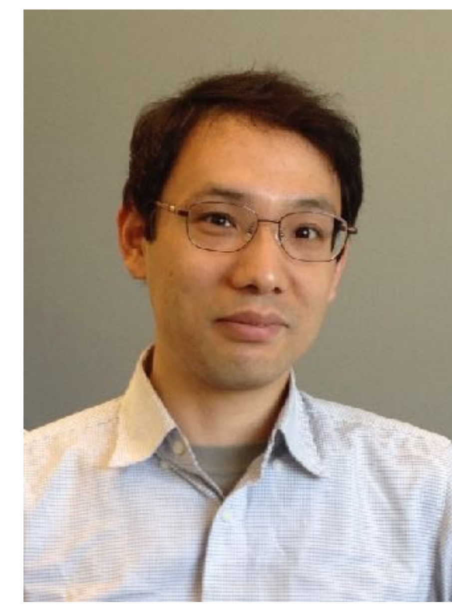


We can prove that sigma decreases monotonically as its subscript increases, and that the sum of all sigmas is less than or equal to one.

Implementation

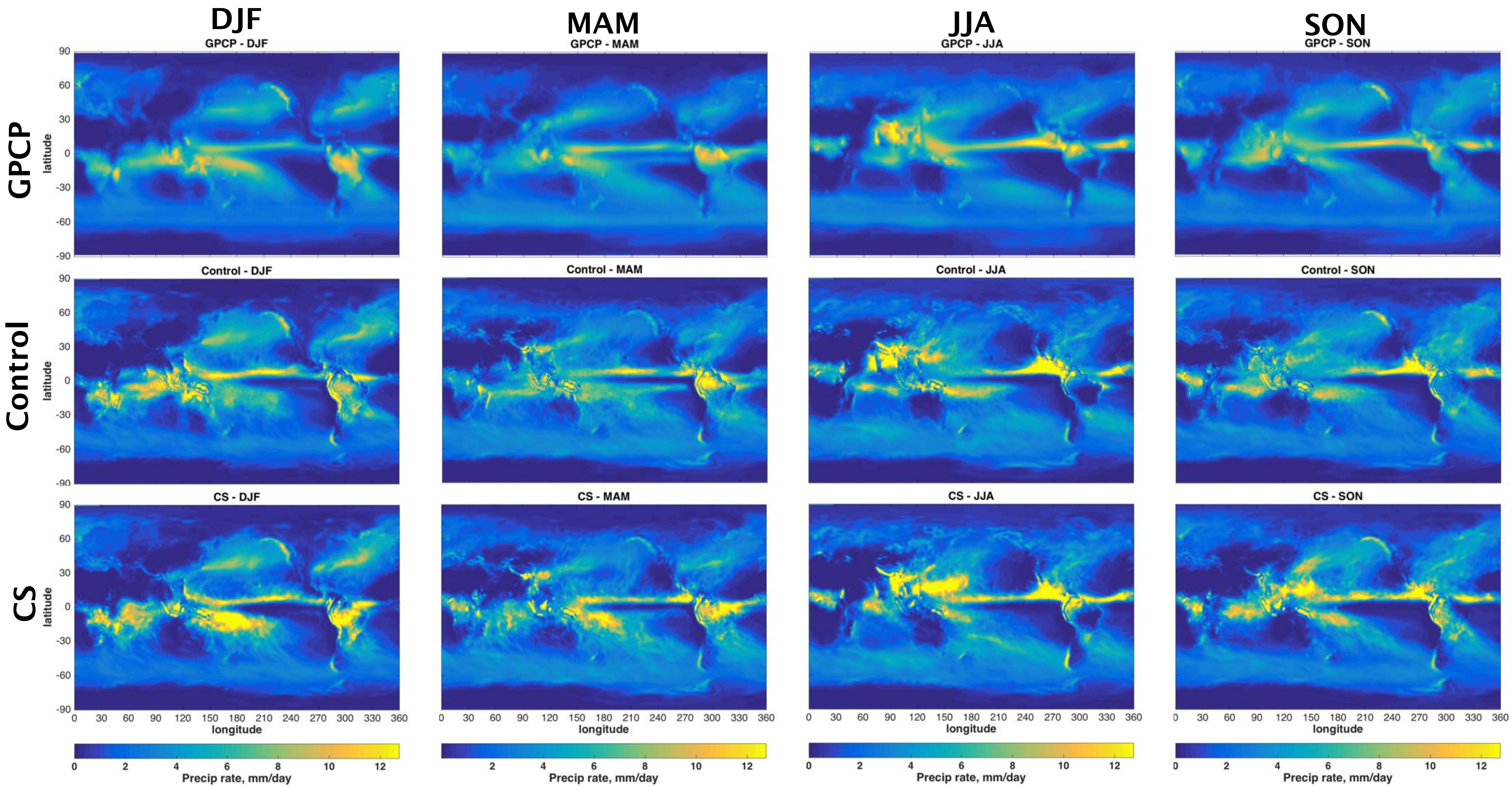
We have implemented the Unified Parameterization in both the CAM and the GFS.

We use the Chikira-Sugiyama parameterization as the “conventional parameterization.

The Chikira-Sugiyama Parameterization

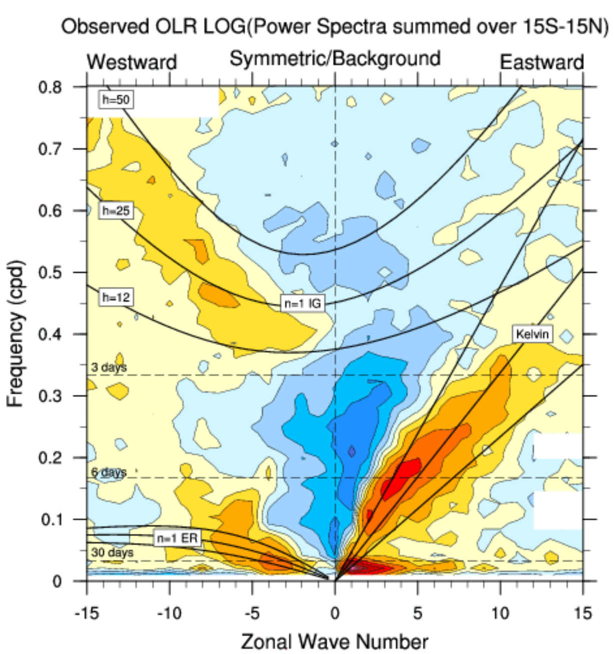
- A spectrum of updrafts is allowed.
- The spectral parameter is cloud-base vertical velocity.
- The height-dependent entrainment rate is determined using the method of Gregory.
- The height-dependent updraft vertical velocity is diagnosed using the equation of vertical motion.
- The cloud-base mass flux is determined using the prognostic closure of Randall and Pan.
- Downdrafts are included.
- The parameterization was tested first in MIROC5, then in CAM, and then in the GFS.
- In the tests with GFS, we supplement the Chikira-Sugiyama parameterization of deep convection with the SAS shallow convection scheme.

Tests of CS in GFS

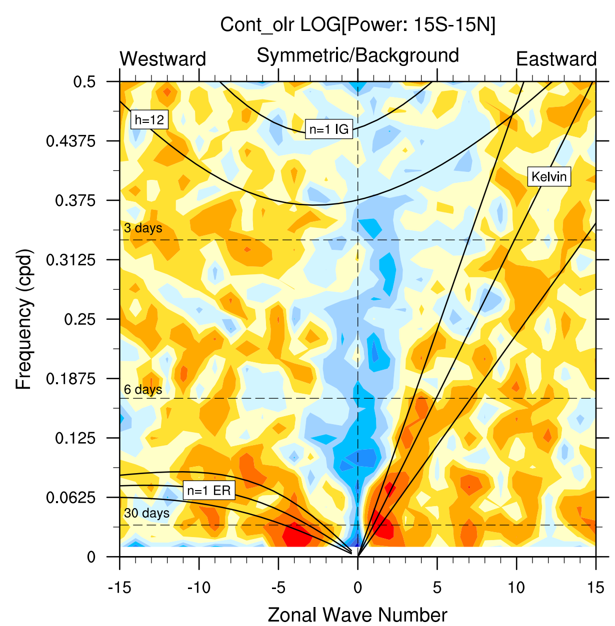


Zonal propagation

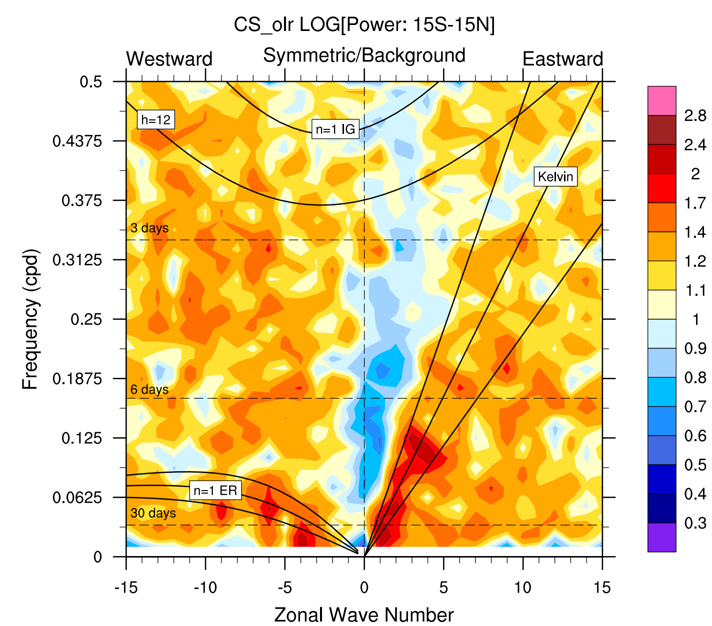
Observed



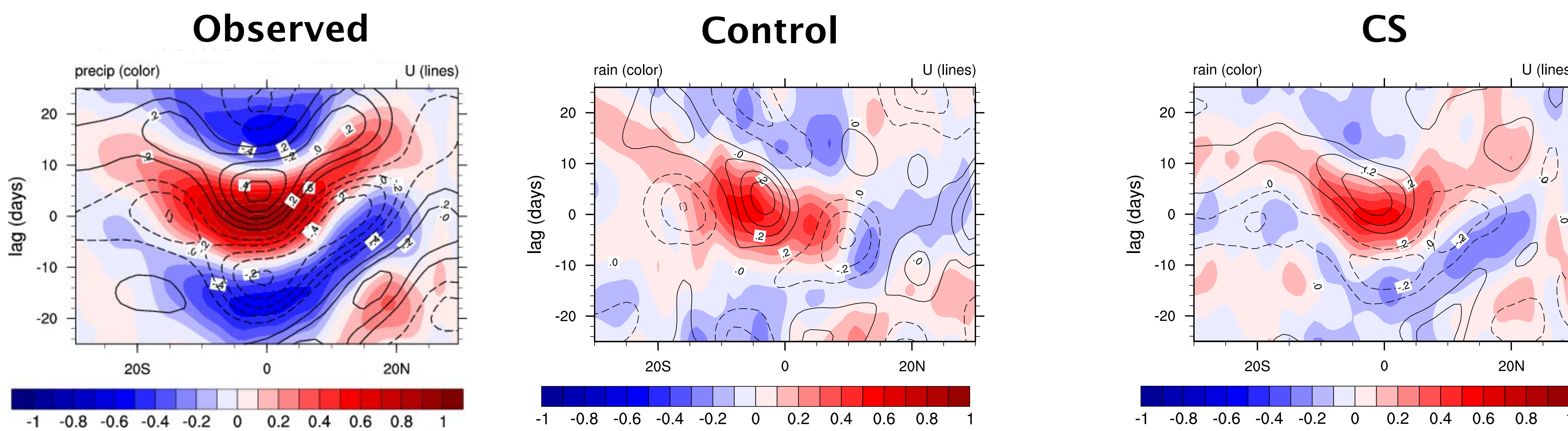
Control



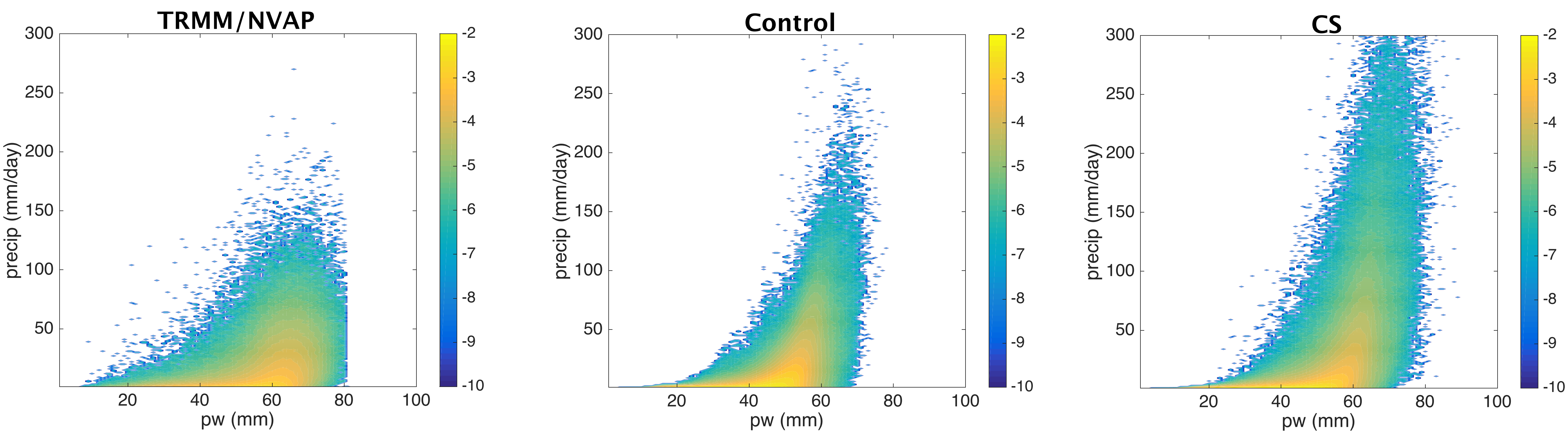
CS



Meridional propagation



Joint PDFs



TRMM/NVAP
Control
CS
precip (mm/day)
pw (mm)
300
250
200
150
100
50
20
40
60
80
100
-2
-3
-4
-5
-6
-7
-8
-9
-10

Implementing the UP on top of CS

Step 1: Conversion to flux form

- The original version of the CS parameterization was coded using the commonly used "compensating subsidence & detrainment" form of the equations.

- That form is only valid for small sigma.

- We therefore had to convert the code to the "flux divergence and source/sink" form, which is valid even for large sigma.

General

$$\rho \frac{\partial \overline{s}}{\partial t} = -\rho \overline{\mathbf{V}} \cdot \nabla \overline{s} - \rho \overline{w} \frac{\partial \overline{s}}{\partial z} + \overline{Q_R} + \rho L \overline{C} - \frac{\partial F_s}{\partial z}$$

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$$F_s = M_c \left(s_c - \bar{s} \right)$$

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$$\frac{\partial M_c(z)}{\partial z} = E(z) - D(z)$$

General

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$$F_s=M_c\left(s_c-\overline{s}\right)$$

$$\sigma\ll 1$$

$$\overline{s}\cong\tilde{s}$$

$$\frac{\partial M_c(z)}{\partial z}=E(z)-D(z)$$

$$\frac{\partial}{\partial z}\left(M_c s_c\right)=E\overline{s}-Ds_c+\rho\sigma_c LC_c$$

General

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Restricted

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$$F_s = M_c \left(s_c - \bar{s} \right)$$

$$\sigma \ll 1$$

$$\bar{s} \cong \tilde{s}$$

So we went back

$$\frac{\partial M_c(z)}{\partial z} = E(z) - D(z)$$

$$\frac{\partial}{\partial z}\left(M_c s_c \right) = E\bar{s} - D s_c + \rho \sigma_c L C_c$$

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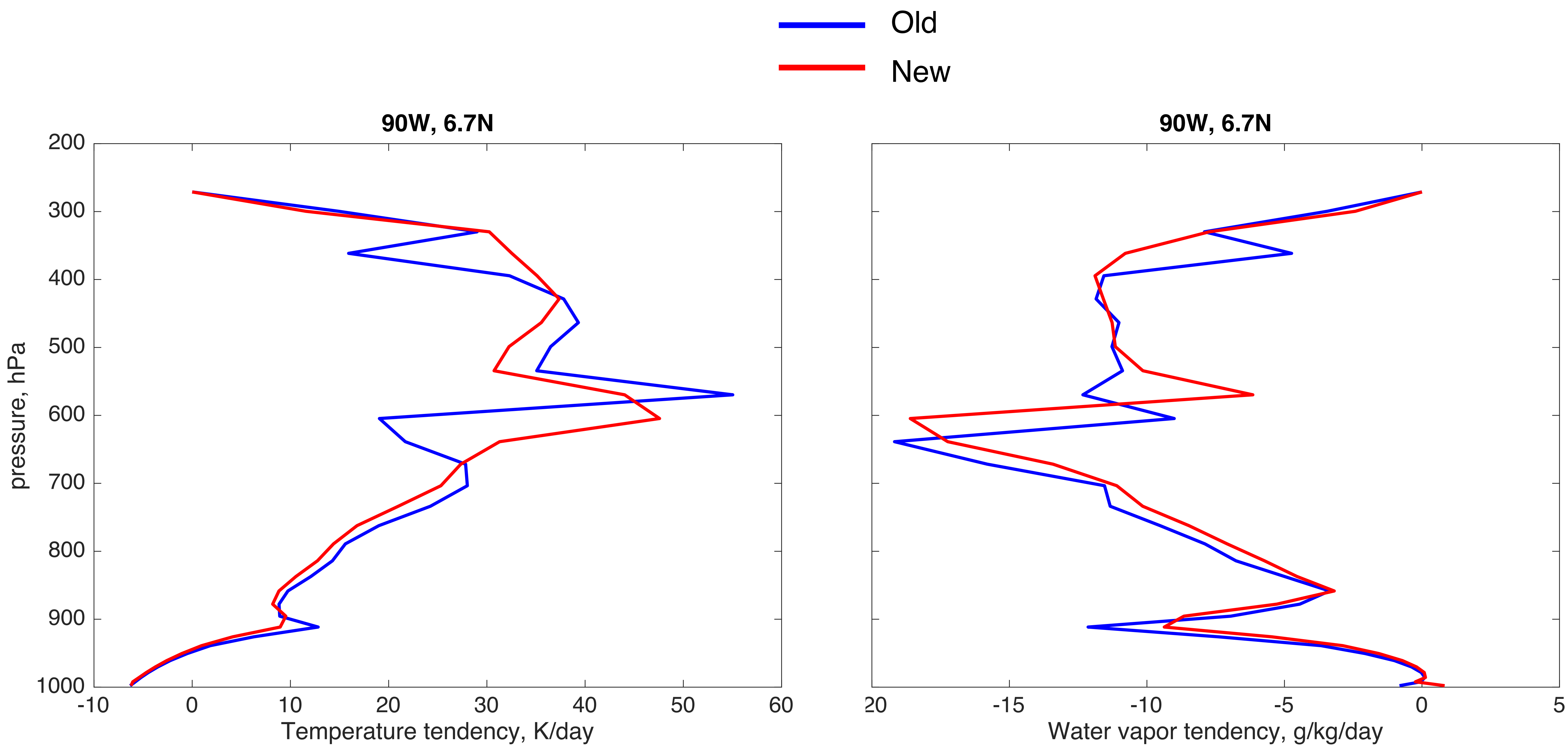
Do they give the same answers?



An example: One grid point on one time step.

Step 2: Use the closure to calculate sigma

$$\sigma_1 = \frac{(M_1)_E}{\rho \delta w_1 + (M_1)_E} \quad ,$$

$$\sigma_i = \left(1 - \sum_{j=1}^{i-1} \sigma_j\right)\left[\frac{(M_i)_E}{\rho \delta w_i + (M_i)_E}\right] \text{for } i = 2 \ldots N$$

We already talked about this.

Step 3: Radiation and microphysics

$$\rho \frac{\partial \bar{s}}{\partial t} = -\rho \bar{\mathbf{V}} \cdot \nabla \bar{s} - \rho \bar{w} \frac{\partial \bar{s}}{\partial z} + \overline{Q_R} + \rho L \bar{C} - \frac{\partial F_s}{\partial z}$$

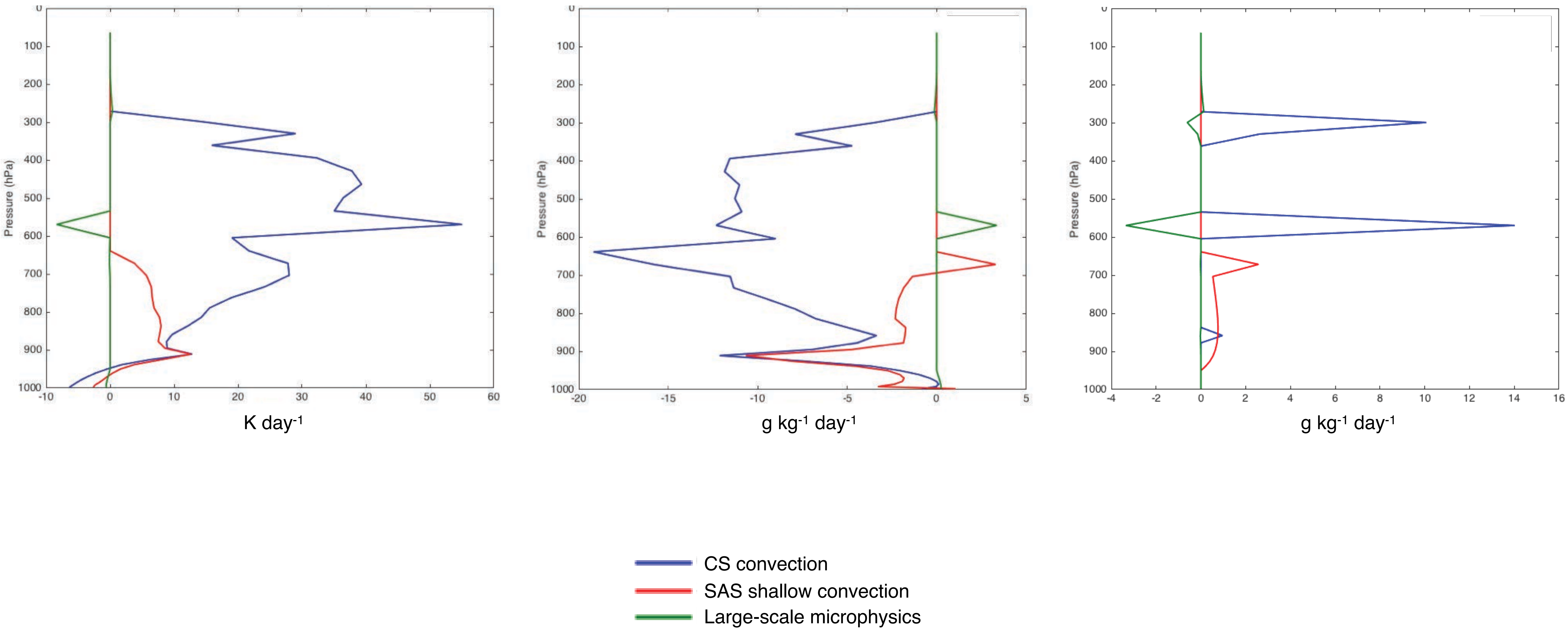
Following Wu & Arakawa (2014), we area-weight the tendencies due to radiation and microphysics, including area-weighted contributions from updrafts, downdrafts, and the environment.

What the pieces look like

Temperature tendency

Water vapor tendency

Condensed water tendency



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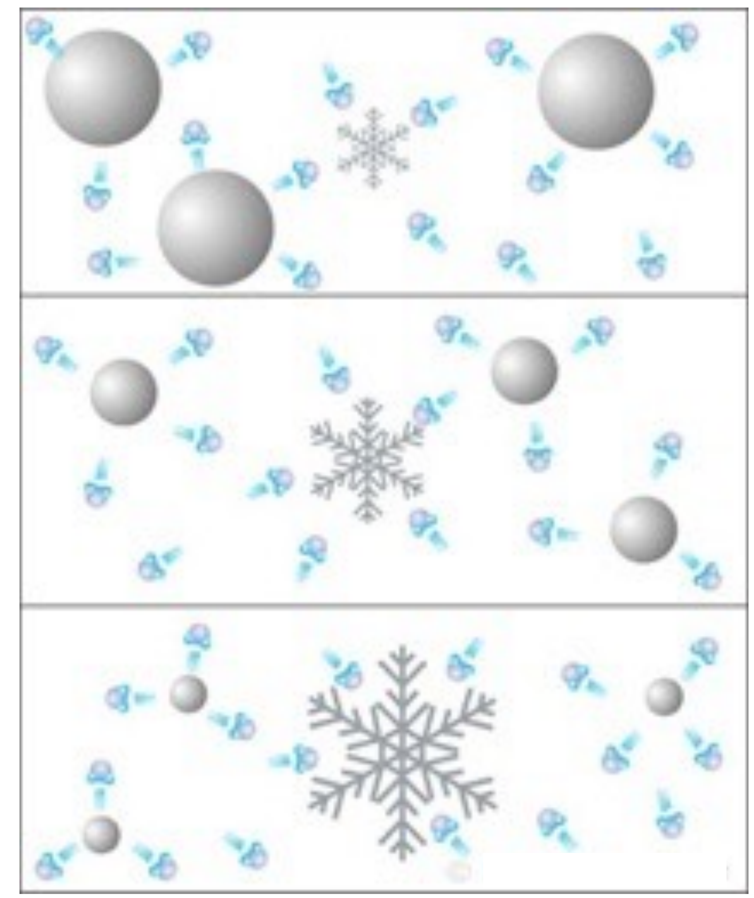
An issue with the microphysics

In principle, all of the convective updraft and downdraft "types" and the environment should use the same microphysics parameterization.



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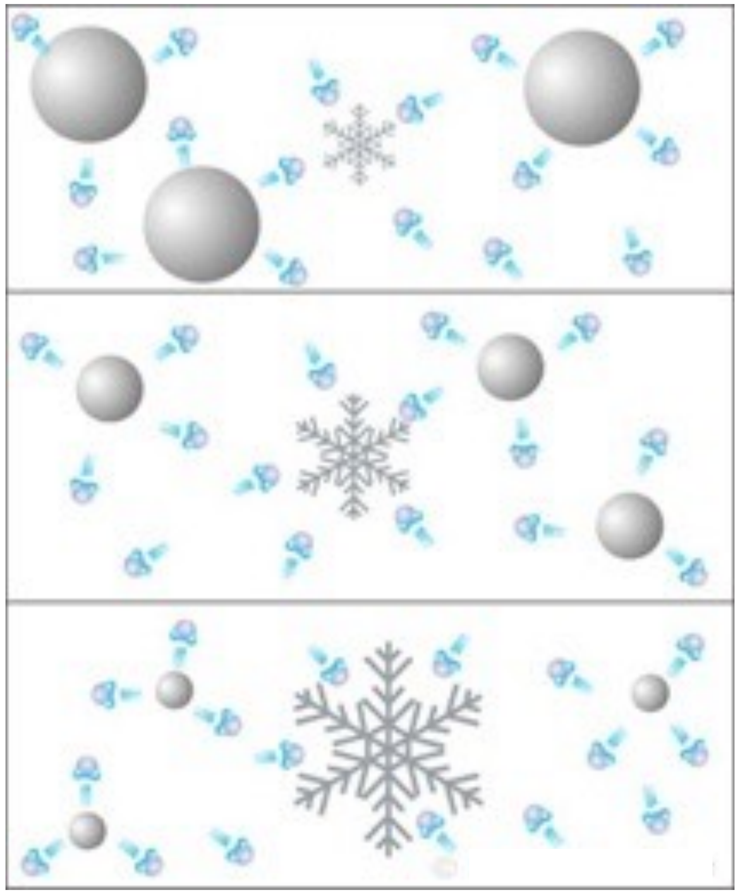
With a state-of-the-art microphysics parameterization, the cost would be prohibitive.



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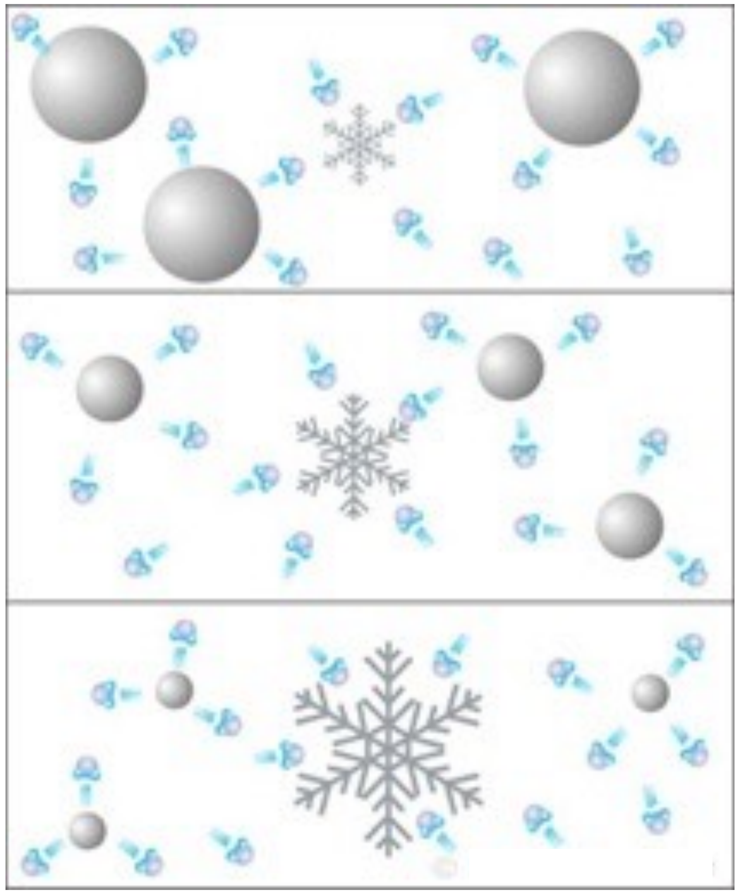
We have used the standard GFS microphysics parameterization for the environment, and a highly simplified scheme for the convective updrafts and downdrafts.



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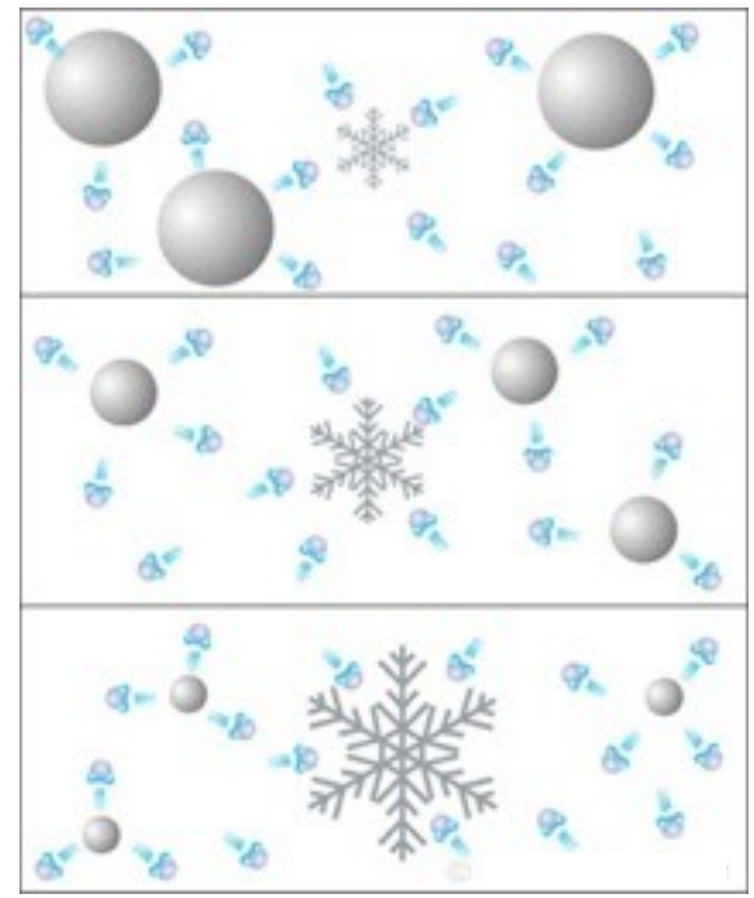
In principle, all of the convective updraft and downdraft “types” and the environment should use the same microphysics parameterization.

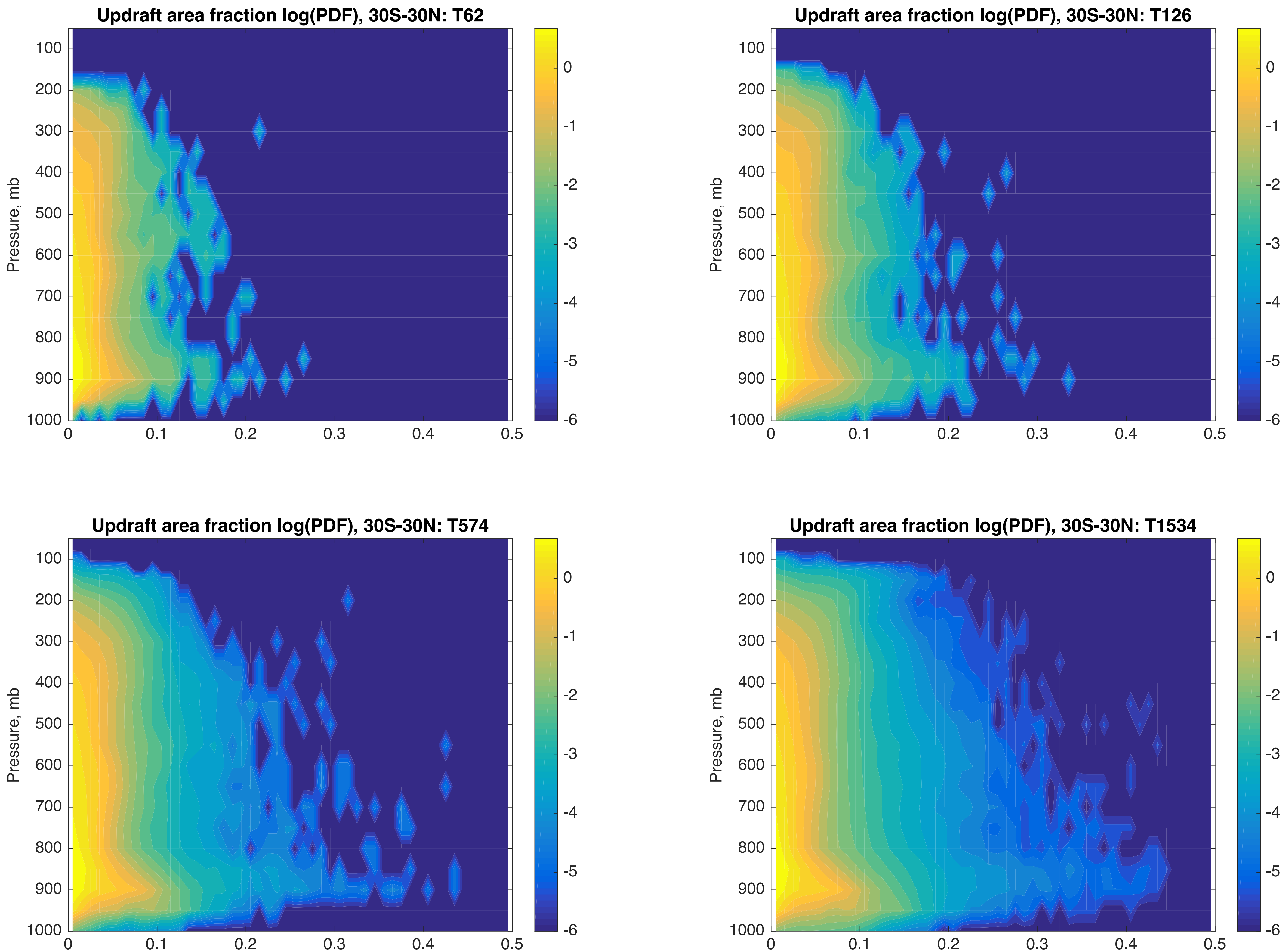
With a state-of-the-art microphysics parameterization, the cost would be prohibitive.

We have used the standard GFS microphysics parameterization for the environment, and a highly simplified scheme for the convective updrafts and downdrafts.

A better solution is needed.



Sigma increases at higher resolution



These plots are for the sum of sigma over all cloud types. The zeros for grid cells without convection are included in the pdfs. Twelve separate time-slices over 24 hours have been used to cover the diurnal cycle.

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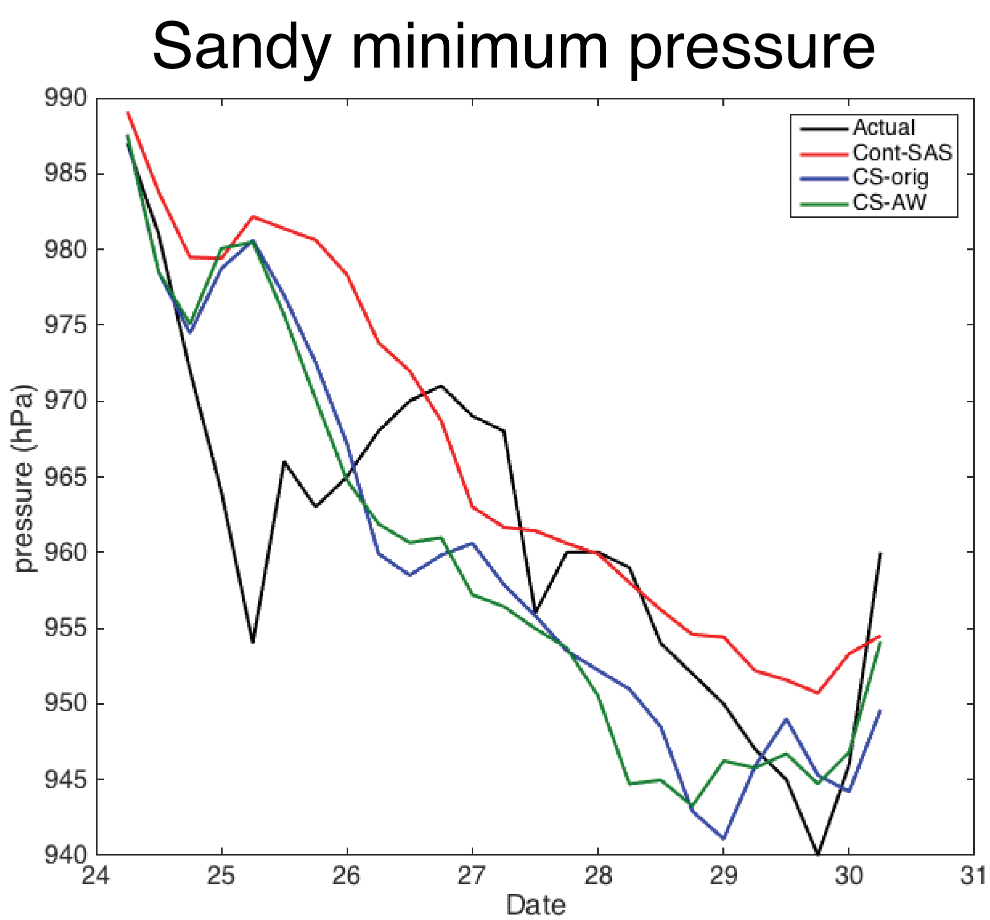

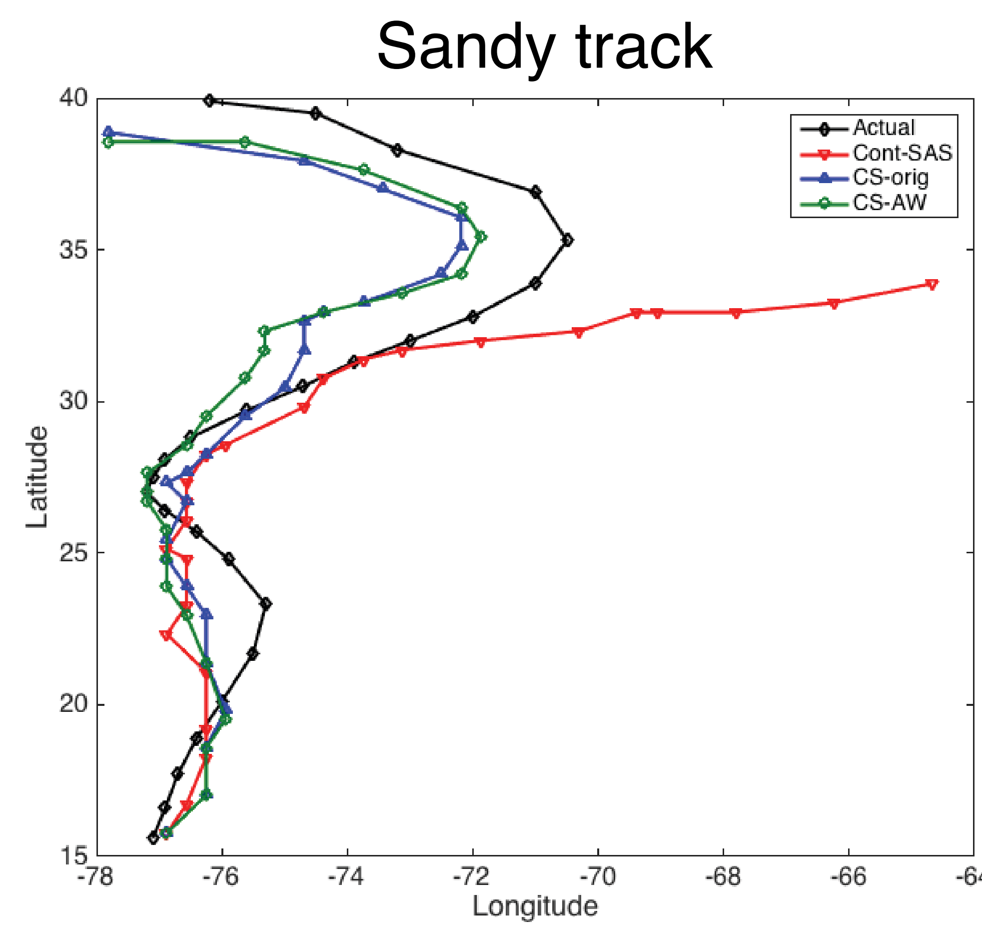

Future work

- Move to NGGPS
- Test at higher resolution
- Find a better compromise for the microphysics

Conclusions

- The Unified Parameterization has a closure for sigma rather than a closure for the mass flux.
- We have generalized the closure to work with a spectrum of updrafts and downdrafts.
- We have tested the parameterization in the GFS, using the Chikira-Sugiyama parameterization as a base.
- Future work should include improving the consistency of the cloud microphysics across updrafts, downdrafts, and environment.