A CPT for Improving Turbulence and Cloud Processes in the NCEP Global Models

Steven Krueger & Prabhat Kumar (U. of Utah)

Shrinivas Moorthi, Alex Belochitski, & Fanglin Yang (EMC/NCEP)

David Randall, Don Dazlich, Minoru Chikira (CSU)

Robert Pincus (U. of Colorado)

Peter Bogenschutz (NCAR)

Applying an economical scale-aware PDF-based turbulence closure model in NOAA NCEP GCMs

Alex Belochitski, Steven Krueger,
Shrinivas Moorthi, Peter Bogenschutz, Robert Pincus

Assumed PDF Method

- **One approach for better representing SGS clouds and turbulence is the assumed PDF Method, which parameterizes SGS clouds and turbulence in a unified way.**

- **We assume that there exists a joint PDF of vertical velocity, *w*, total water (vapor + cloud condensate) mixing ratio, q_t, and a temperature variable, θ_l:**

$$P = P(w, q_t, \theta_l)$$

Steps in Assumed PDF Method

The assumed PDF method contains three main steps that must be carried out for each grid box and time step.

- **Prognose means and diagnose various higher order moments**
- **Use these to select a particular PDF member from the assumed functional form**
- **Use the selected PDF to compute buoyancy flux, cloud fraction, and condensate mixing ratio.**

Details of SHOC: Our Assumed PDF Method

- **Typically requires the addition of several prognostic equations into model code (Golaz et al. 2002, Cheng and Xu 2006, 2008) to estimate the turbulence moments required to specify the PDF.**

- **Our approach is called *Simplified Higher-Order Closure (SHOC)*:**

Outputs of SHOC

- By integrating over the the portion of the PDF where water vapor is above saturation, one can determine:

  1. Non-precipitating condensate mixing ratio

  2. Cloud fraction

Implementing SHOC in GFS

- SHOC is now incorporated in the current version of GFS, as well as the upcoming version of model based on NOAA Environmental Modeling System (NEMS).
- Turbulent diffusion coefficients computed by SHOC are now used in place of those produced by the boundary layer turbulence and shallow convection parameterizations (Han and Pan, 2011).
- Large-scale microphysics scheme (Zhao and Carr, 1997) is no longer used to calculate cloud fraction or the large-scale condensation/ deposition. Instead, SHOC provides these variables.
- Radiative transfer parameterization uses cloudiness computed by SHOC.
- A new prognostic scalar, SGS TKE, was added to GFS. SGS TKE equation is integrated forward in time in a semi-implicit manner.

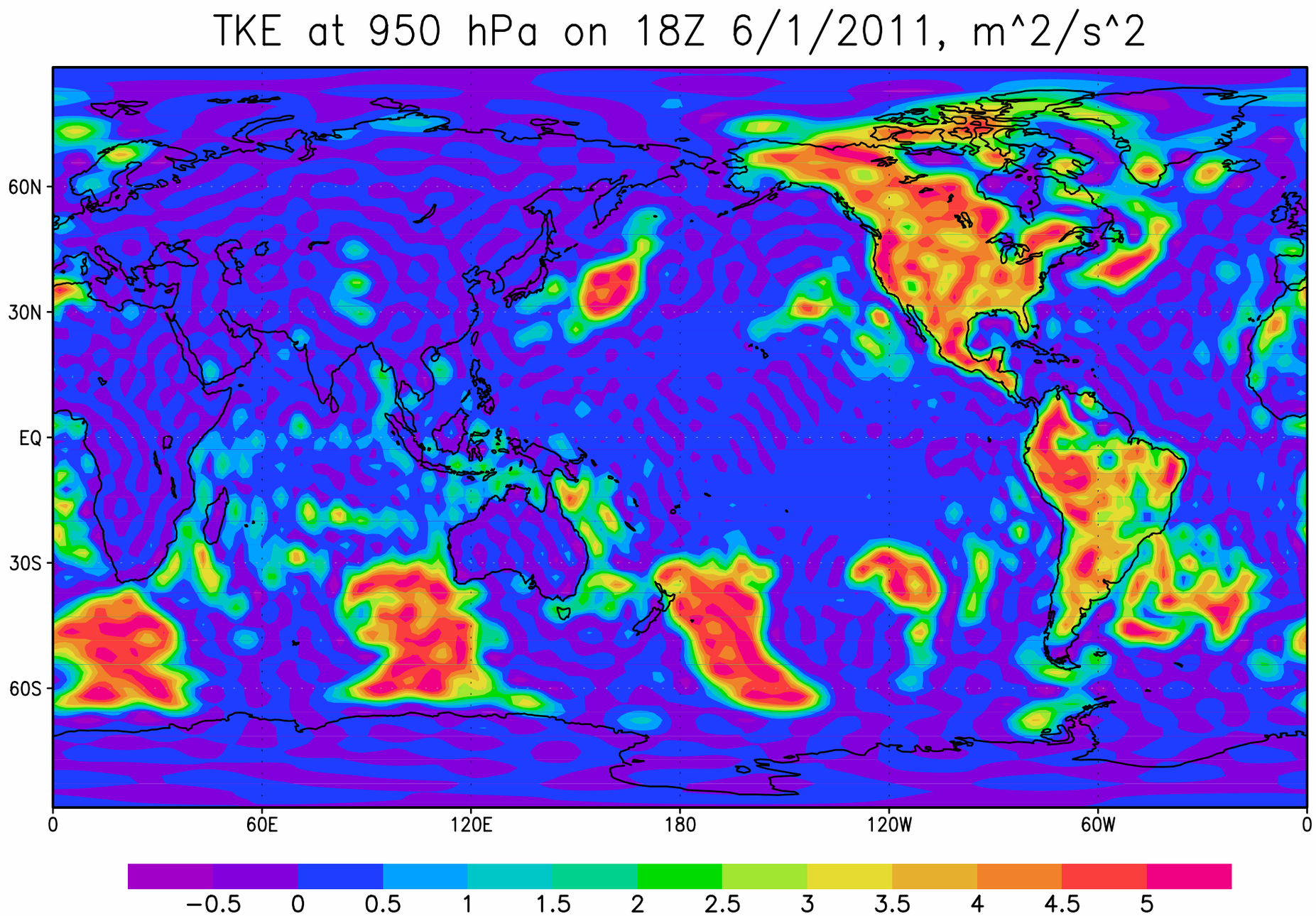
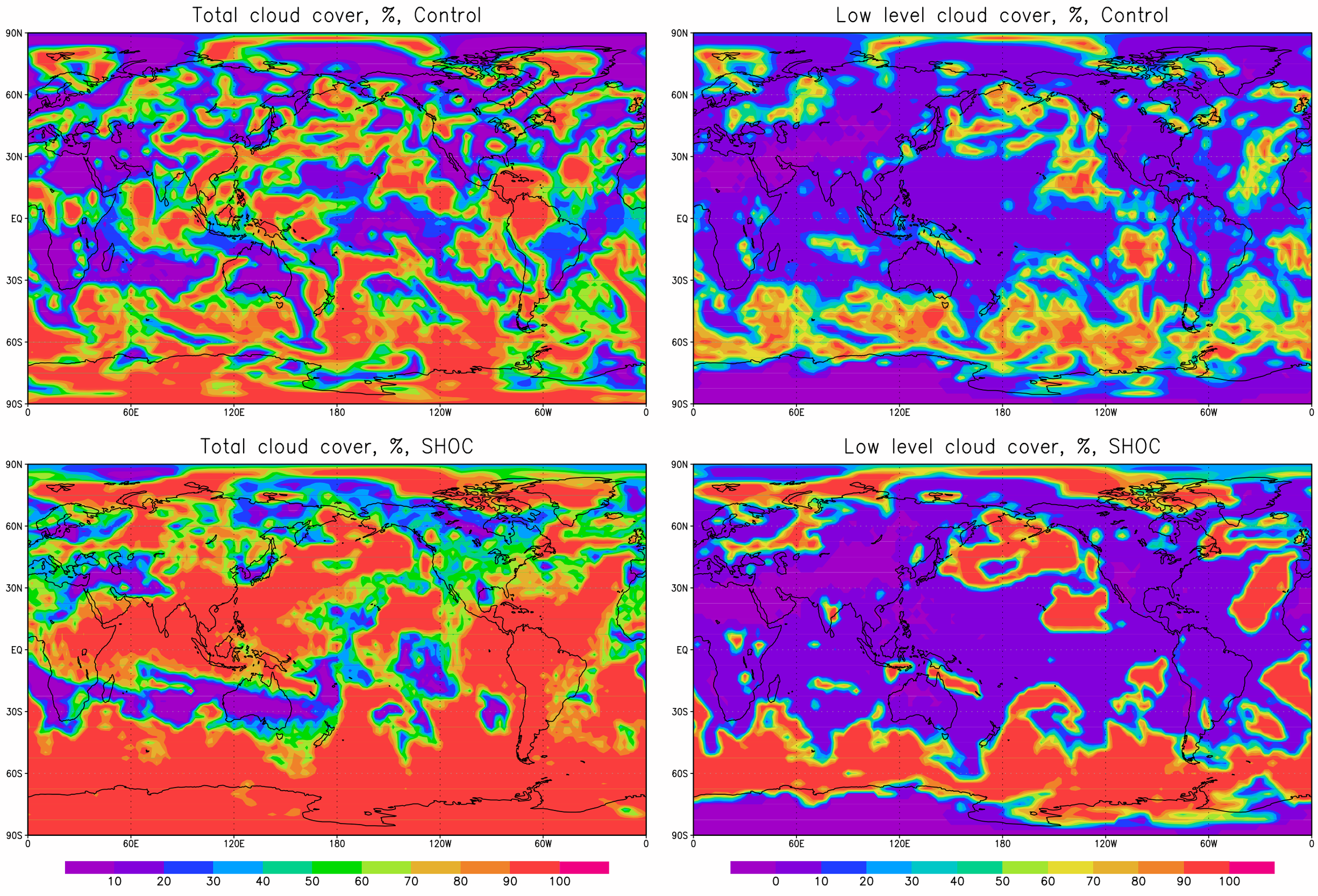
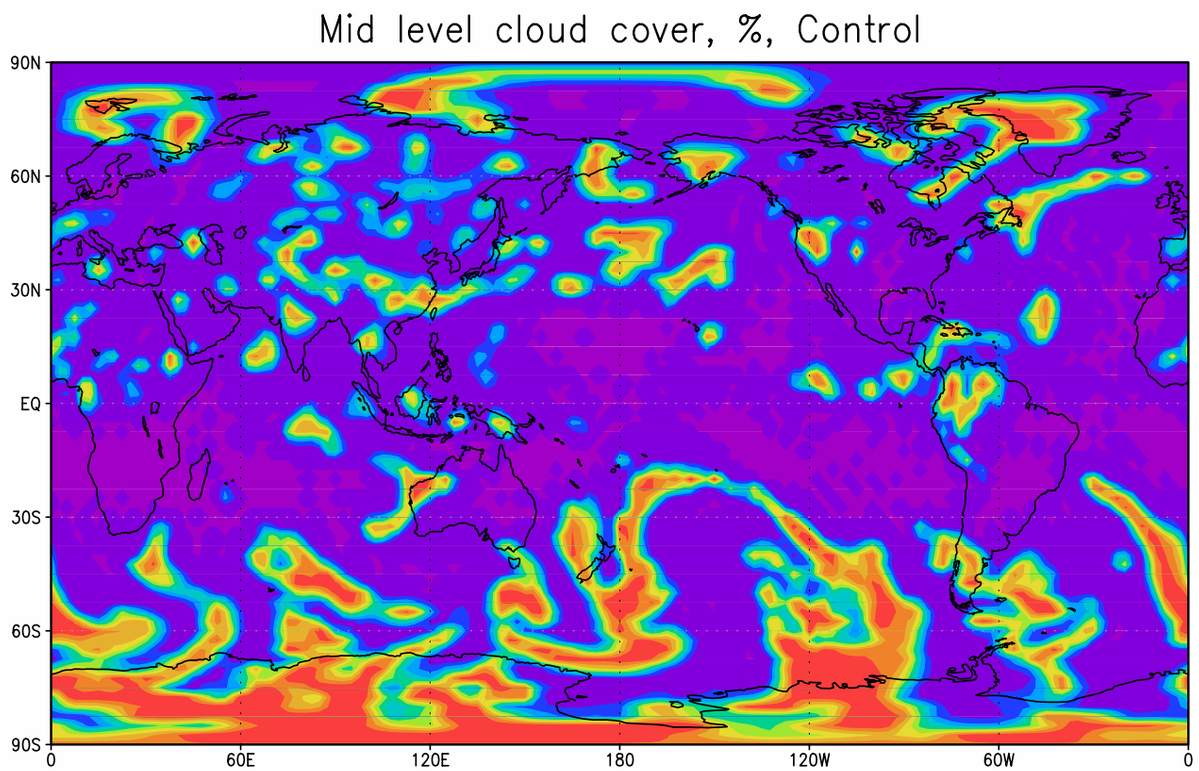


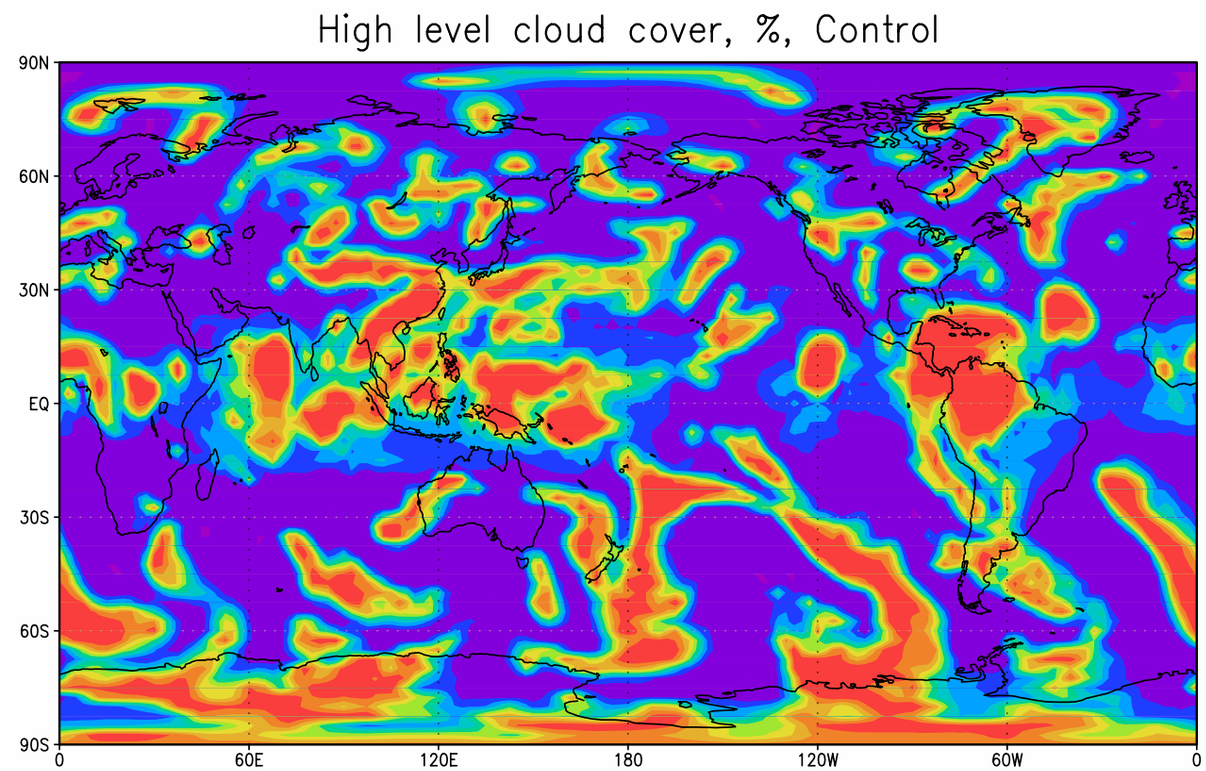
Figure 1: Turbulent kinetic energy (TKE, m^2/s^2) at 950 hPa on 18Z 6/1/2011 (daytime over North and South Ameruca) in NCEP GFS initialized on 0Z 6/1/2011 and run at T62 resolution.

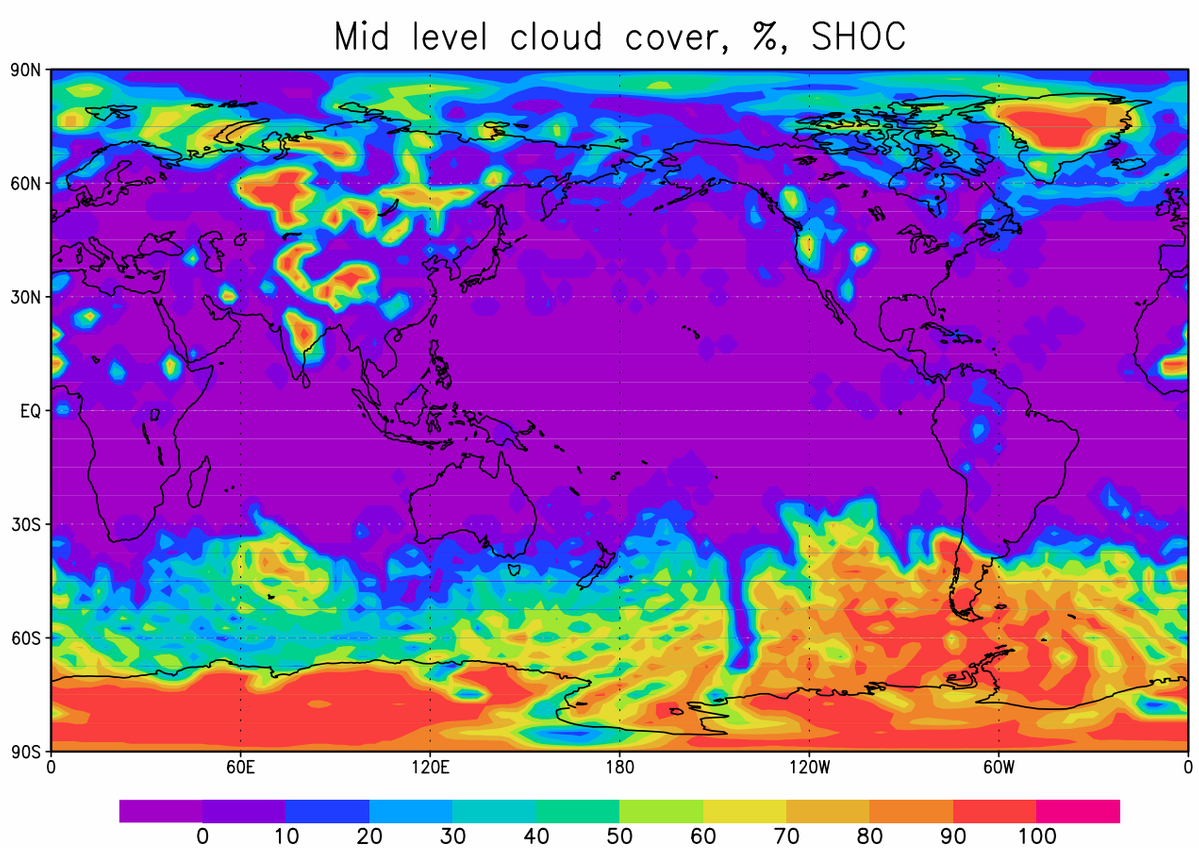
Day 5 of the forecast: GFS vs. GFS/SHOC (continued)

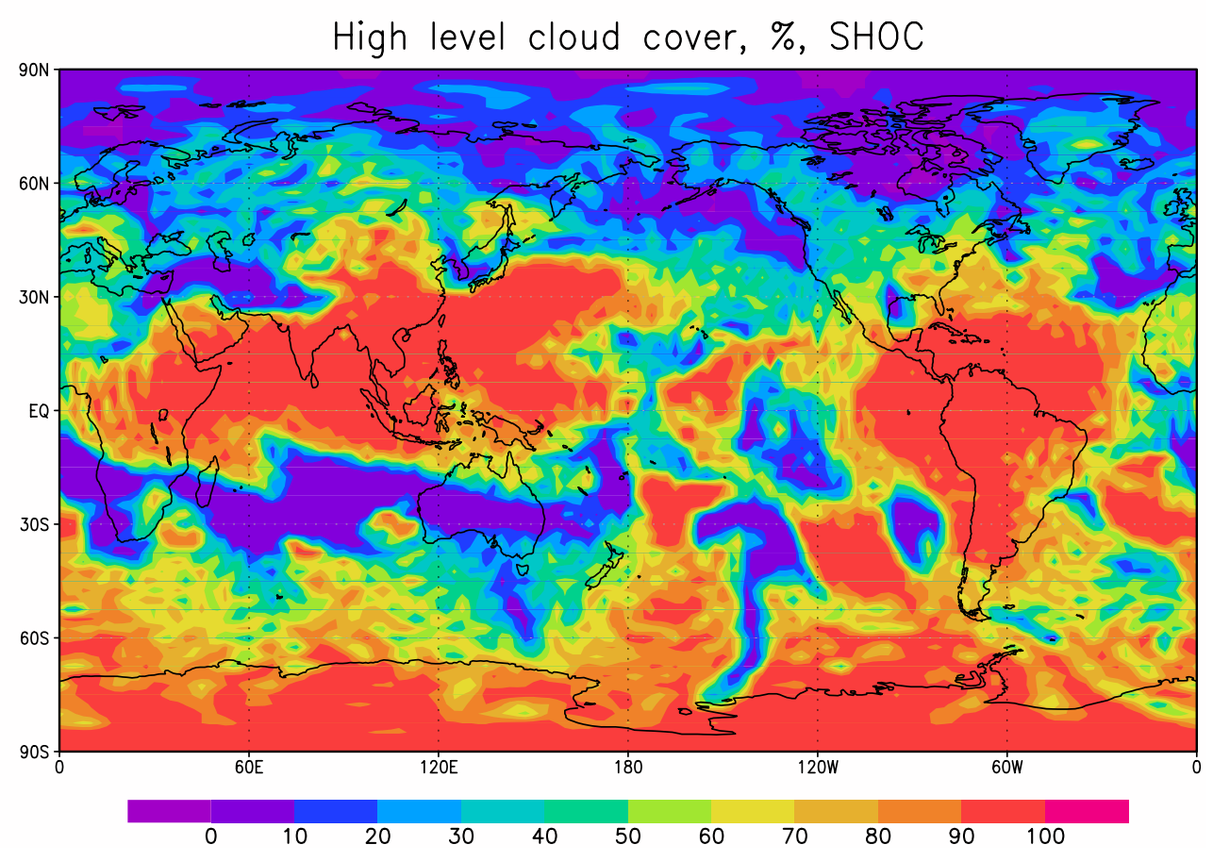


Day 5 of the forecast: GFS vs. GFS/SHOC (continued)







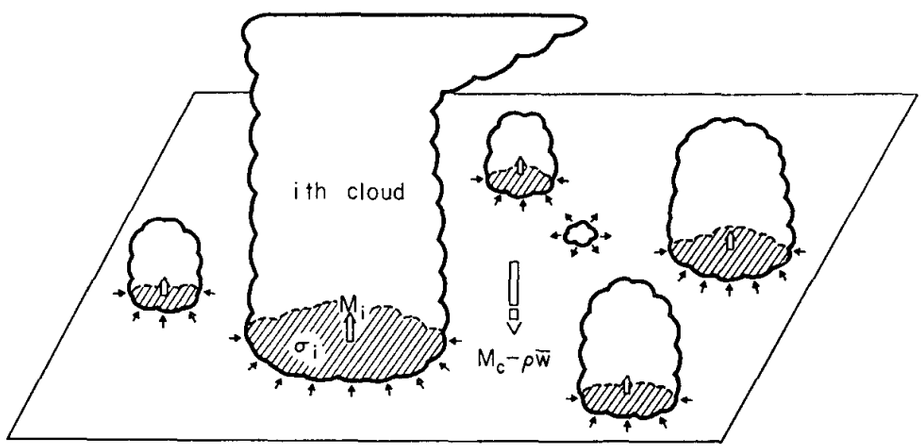


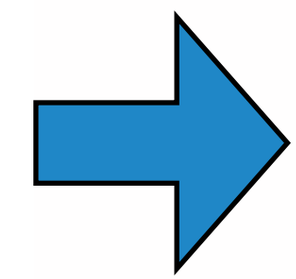
Implementing the Arakawa-Wu Unified Parameterization in the GFS

David Randall, Don Dazlich, and Minoru Chikira

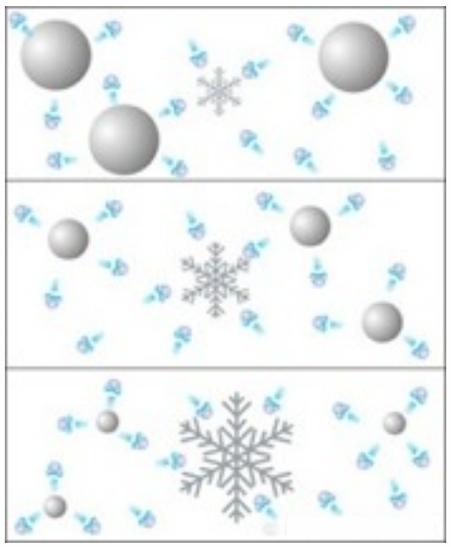
- Grow individual clouds when/where the resolution is high.
- Parameterize convection when/where resolution is low.
- Continuous scaling.
- One set of equations, one code.
- Physically based.

Resolution-Dependent Parameterizations





Increasing resolution



GCM

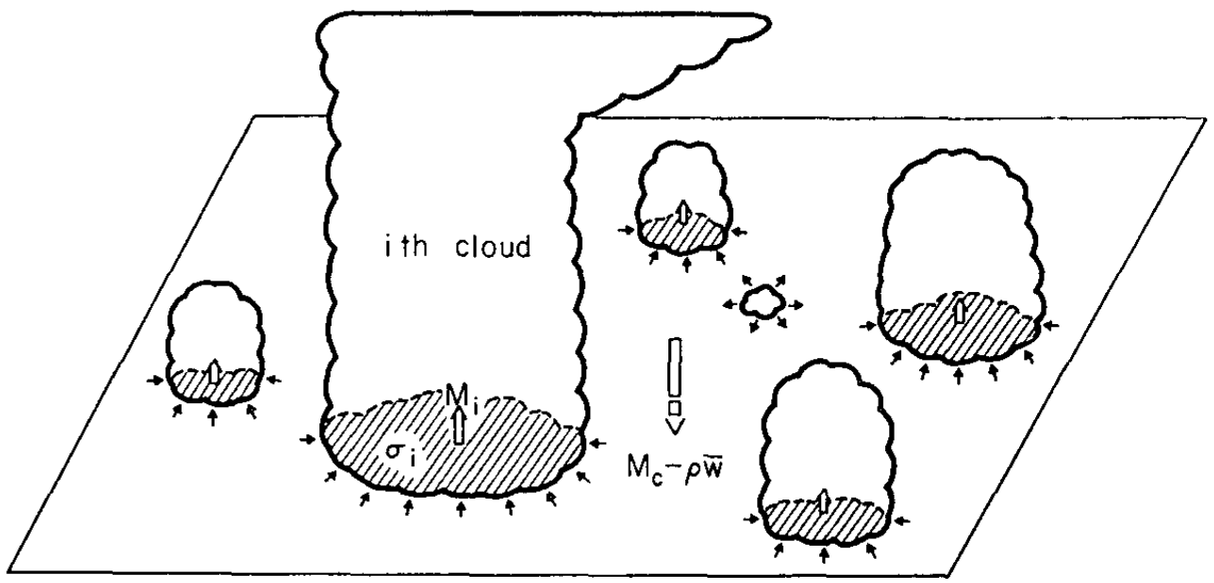
Parameterizations for low-resolution models are designed to describe the collective effects of many clouds, including strong convective transports.

CRM

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

Resolution-independent cumulus parameterizations

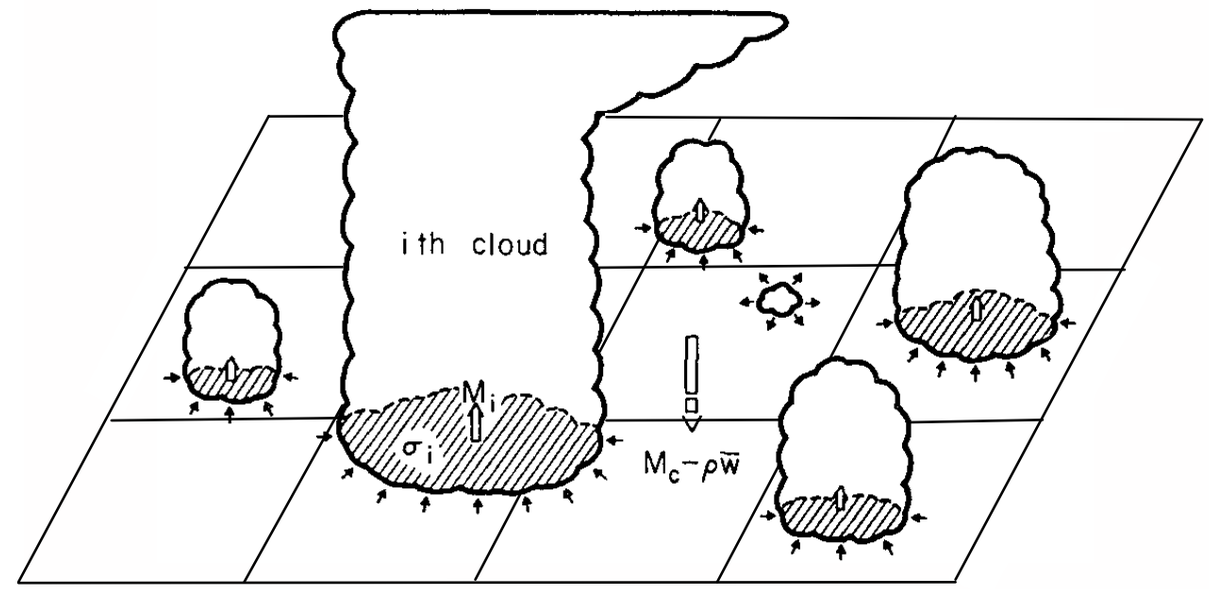
Low resolution



Updrafts are assumed to occupy
a small fraction of each grid cell.

Convective transport on *subgrid* scale

High resolution



Some grid cells are
almost filled by updrafts.

Convective transport on *grid* scale

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

Starting point

For the case of a top-hat PDF, we can derive

$$\overline{w'\psi'} \equiv \overline{w\psi} - \overline{w}\,\overline{\psi} = \sigma\left(1-\sigma\right)\Delta w \Delta\psi \ , \tag{1}$$

where

$$\left(\overline{\ }\right) \equiv \sigma\left(\ \right)_c + \left(1-\sigma\right)\left(\tilde{\ }\right) \text{ and } \Delta\left(\ \right) \equiv \left(\ \right)_c - \left(\tilde{\ }\right), \tag{2}$$

σ is the fractional area covered by the updraft, an overbar denotes a domain mean, the subscript c denotes a cloud value, and a tilde denotes an environmental value. We expect Δw and $\Delta\psi$ to be independent of σ. In that case, (1) implies that $\overline{w'\psi'}$ is a parabolic function of σ.

Closure assumption

Define $\left(\overline{w'\psi'}\right)_E$ as the flux required to maintain quasi-equilibrium. The closure assumption used to determine σ is

$$\boxed{\sigma = \frac{\left(\overline{w'\psi'}\right)_E}{\Delta w \Delta \psi + \left(\overline{w'\psi'}\right)_E}} . \tag{3}$$

The quantities on the right-hand side of (3) are expected to be independent of σ. Eq. (3) is guaranteed to give

$$0 \le \sigma \le 1 . \tag{4}$$

By combining (3) and (1), we obtain

$$\boxed{\overline{w'\psi'} = (1-\sigma)^2 \left(\overline{w'\psi'}\right)_E} . \tag{5}$$

This shows that the actual flux is typically less than the value required to maintain quasi-equilibrium. In fact, the actual flux goes to zero as $\sigma \to 1$.

Chikira's generalized closure

Chikira uses

$$\sigma_1 = \frac{\left(\overline{w'h'}\right)_{E,1}}{\Delta w_1 \delta h_1 + \left(\overline{w'h'}\right)_{E,1}} ,$$

$$\sigma_i = \left(1 - \sum_{j=1}^{i-1} \sigma_j\right)\left[\frac{\left(\overline{w'h'}\right)_{E,i}}{\Delta w_i \delta h_i + \left(\overline{w'h'}\right)_{E,i}}\right] \text{ for } i = 2 \ldots N ,$$

which leads to

$$\left(\overline{w'h'}\right)_1 = \left(1 - \sigma_1\right)\left(\overline{w'h'}\right)_{E,1} ,$$

$$\left(\overline{w'h'}\right)_i = \left(1 - \sum_{j=1}^{i} \sigma_j\right)\left(\overline{w'h'}\right)_{E,i} .$$

Chikira-Sugiyama Scheme in GFS - past 12 months

- The Chikira-Sugiyama scheme was installed in the GFS and debugged.
- Initial testing was done with 5-day forecasts.
- Moorthi modified a cloud base spectral parameter and got successful Hurricane Sandy forecasts at T1574.
- 3-year climatology runs were done at T62 and T126.
- The updraft fraction diagnostic (by cloud type) has been added to the code in preparation for AW implementation.

Some global means with 3-year T126 runs

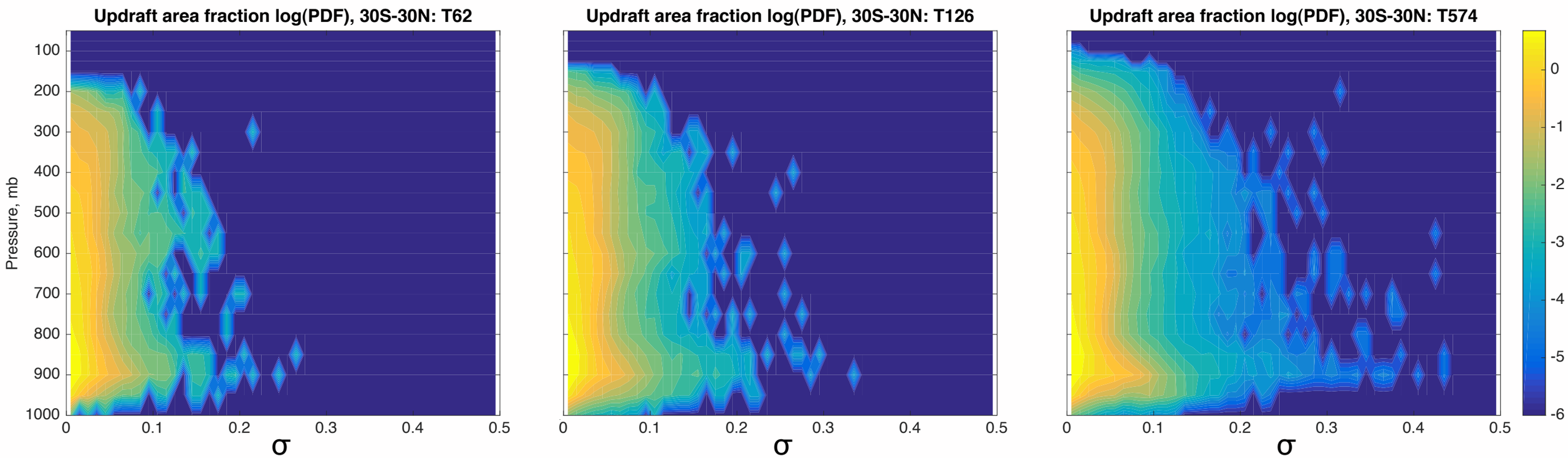
C-S produces energy budgets significantly closer to balance at the surface and top of atmosphere. This is due to increased cloud cover reducing the net SW.

Surface - W/m^2	Control	C-S
Net DownwardEnergy Flux	11.9	5.1
Net Downward LW Flux	65.3	62.0
Net Downward SW Flux	182.4	171.5
Upward LW Flux	398.2	398.6
Upward SW Flux	31.4	30.4
Sensible Heat Flux	15.7	13.4
Latent Heat Flux	89.5	90.9

TOA - W/m^2	Control	C-S
Net Downward Radiation Flux	15.4	6.5
Net Downward SW Flux	257.9	247.6
Outgoing LW Radiation	242.5	241.1

AW assume σ<<1 for low resolution. As resolution enters the 'gray zone' σ attains larger values. Does this in fact happen?

Run GFS with CS scheme. Add diagnostic for σ as the AW implementation will compute it. Run one day sampled every 6 hours.



Yes! σ<<1 for low resolution and increases with resolution. We can continue with the implementation of AW in the cumulus parameterization.

Summary of progress

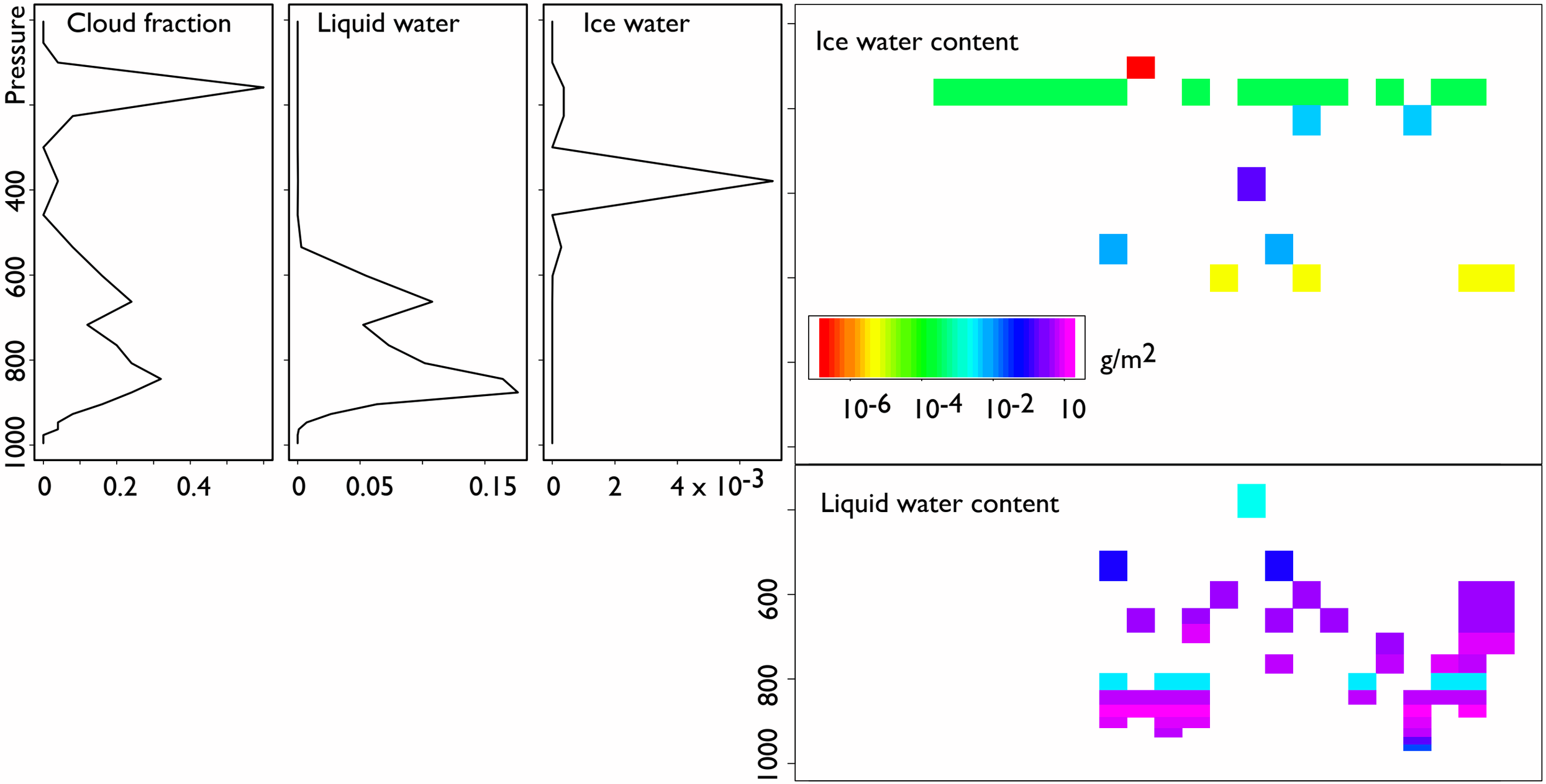
- ✓ Install Chikira-Sugiyama parameterization in GFS
- ✓ Test for a range of resolutions
- ✓ Generalize Arakawa-Wu extension to permit multiple updraft types, and also downdrafts
- ✓ Compute sigma in GFS for a range of resolutions
- Modify GFS to use the computed values of sigma
  - Convective transports
  - Microphysics

We are here

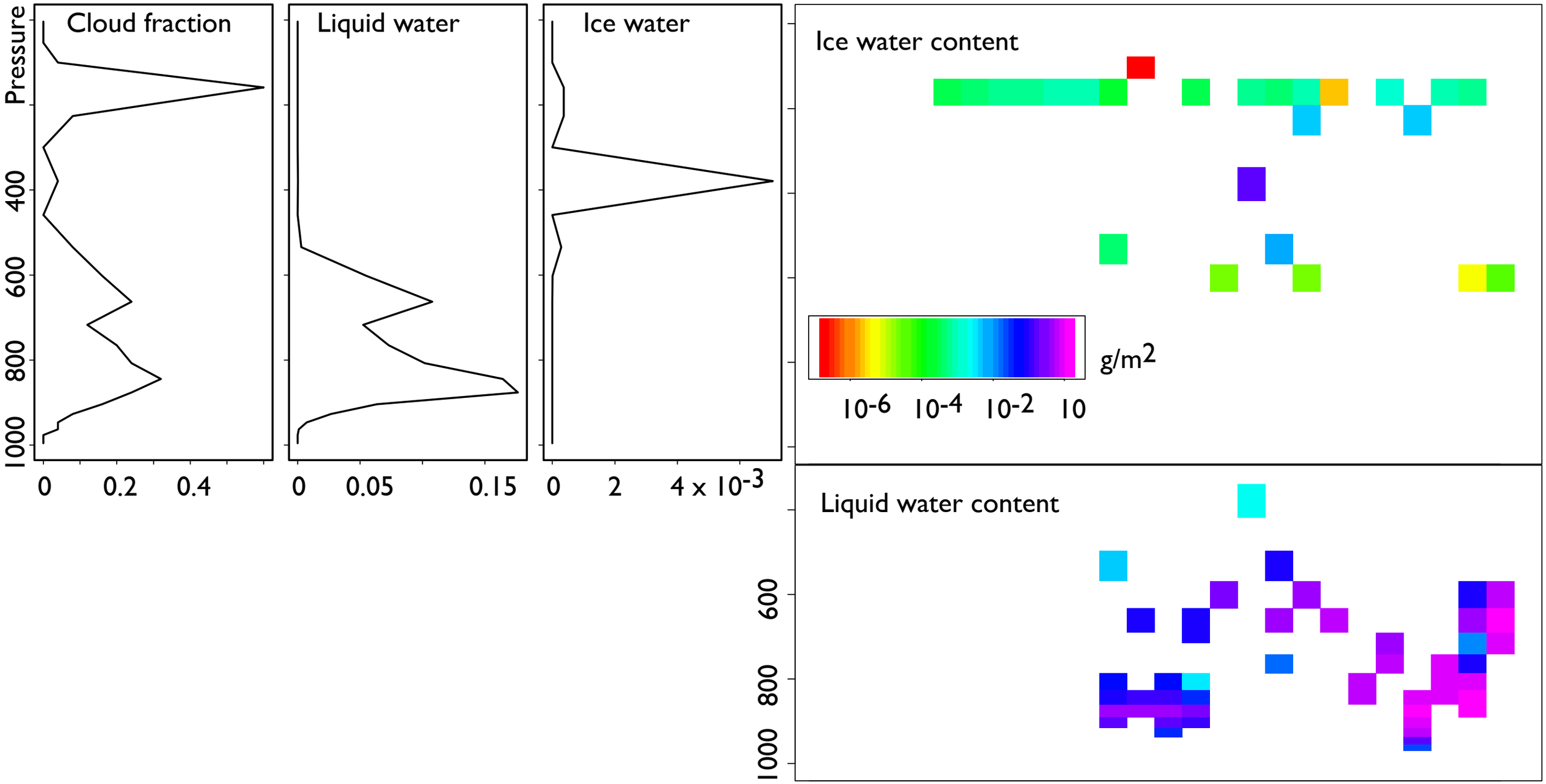
- Test for a range of resolutions, including the highest practical resolution
- Compare with results from unmodified Chikira-Sugiyama parameterization

Interactions of Clouds, Radiation, and Microphysics

- We hope to improve the representation of the interactions of clouds, radiation, and microphysics in the GFS/CFS by using the additional information provided by the PDF-based SGS cloud scheme.



uses only the mean value of liquid or ice concentration at each level



uses a distribution of liquid or ice concentration at each level obtained from SHOC

Treating cloud variability in radiation

Radiation in the GFS uses "RRTMG" which in turn treats fractional cloudiness with McICA (Monte Carlo Independent Column Approximation).

McICA approximates broadband radiation calculations over a distribution of cloud properties with a single broadband calculation over a discrete set of random samples.

The variability in cloud properties predicted by SHOC can be included equally accurately at near-zero expense.

Status

- Actively spinning up —
- We've figured out how to do the sampling of the double-Gaussian PDF (via a sensible linearization of the T-q PDFs into a monovariate PDF of saturation deficit).
- We have access to the EMC subversion server and the right branches.
- We've plotted out the implementation.
- But we don't have access to the NOAA supercomputers yet so we can't try anything, even to see if things compile.