Pushing Cumulus Parameterization to Higher Resolution

What are the Limits?

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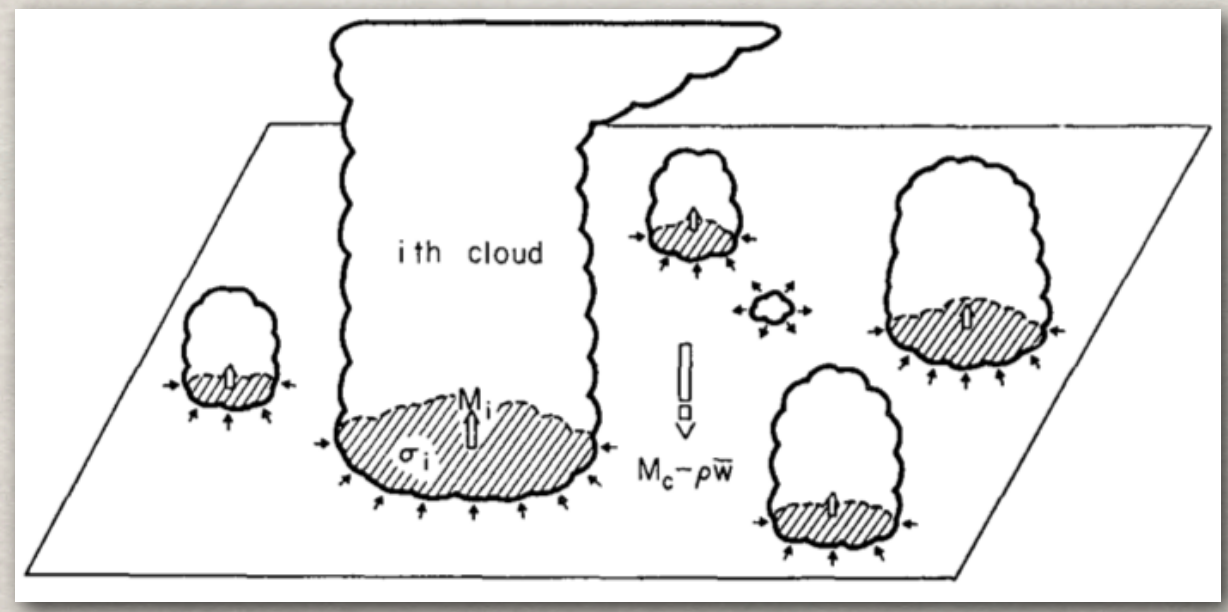
Cumulus Parameterization

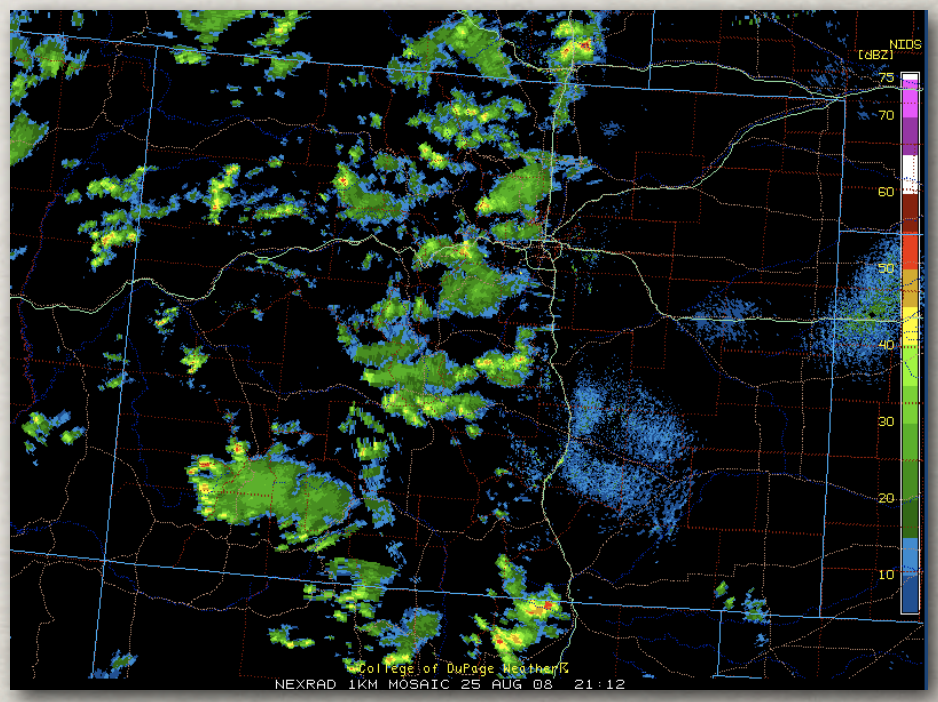
- Describes interaction of a cumulus cloud ensemble with the large-scale
  - Often looking for the "expected values" of influence from an ensemble of clouds in quasi-equilibrium with the large-scale conditions.
  - Requires spatial and temporal scale separation.



AS 74

How many thunderstorms fit?

- With a grid spacing of 20 km or less, we definitely do not have a statistically meaningful sample of large clouds in each grid column.
- Even with a grid spacing of 200 km, the number of large clouds in a column is worryingly small.



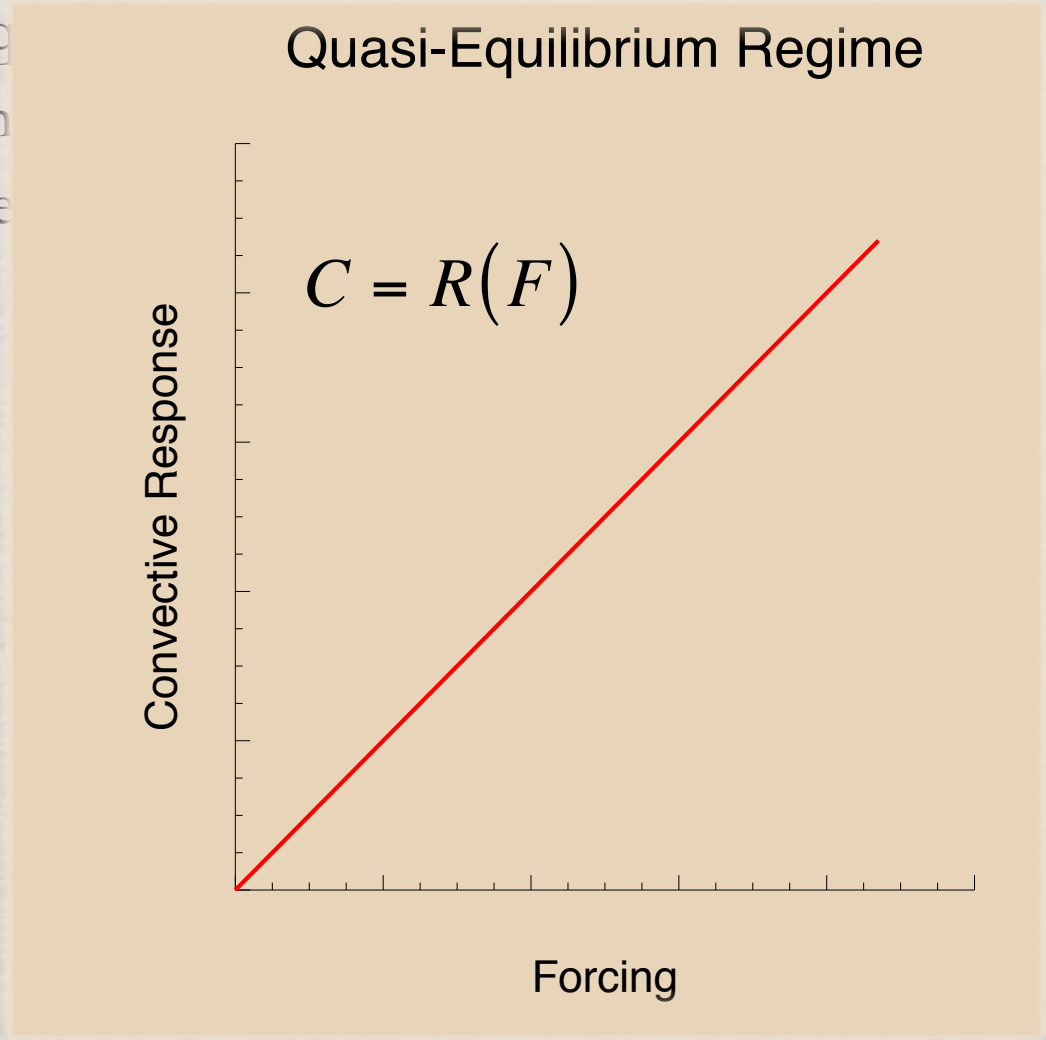
~700 km

How QE Breaks Down

- **Quasi-equilibrium** regime
  - Forcing determines response
  - No memory
- **Non-equilibrium** regime, still deterministic
  - Out of phase, forcings change too rapidly
  - Past history of the convective statistics matters
- **Non-deterministic** regime
  - As computational areas decrease in size, the stochastic component of convection becomes significant.
  - Creates uncertainty due to small sample size -- noise from below

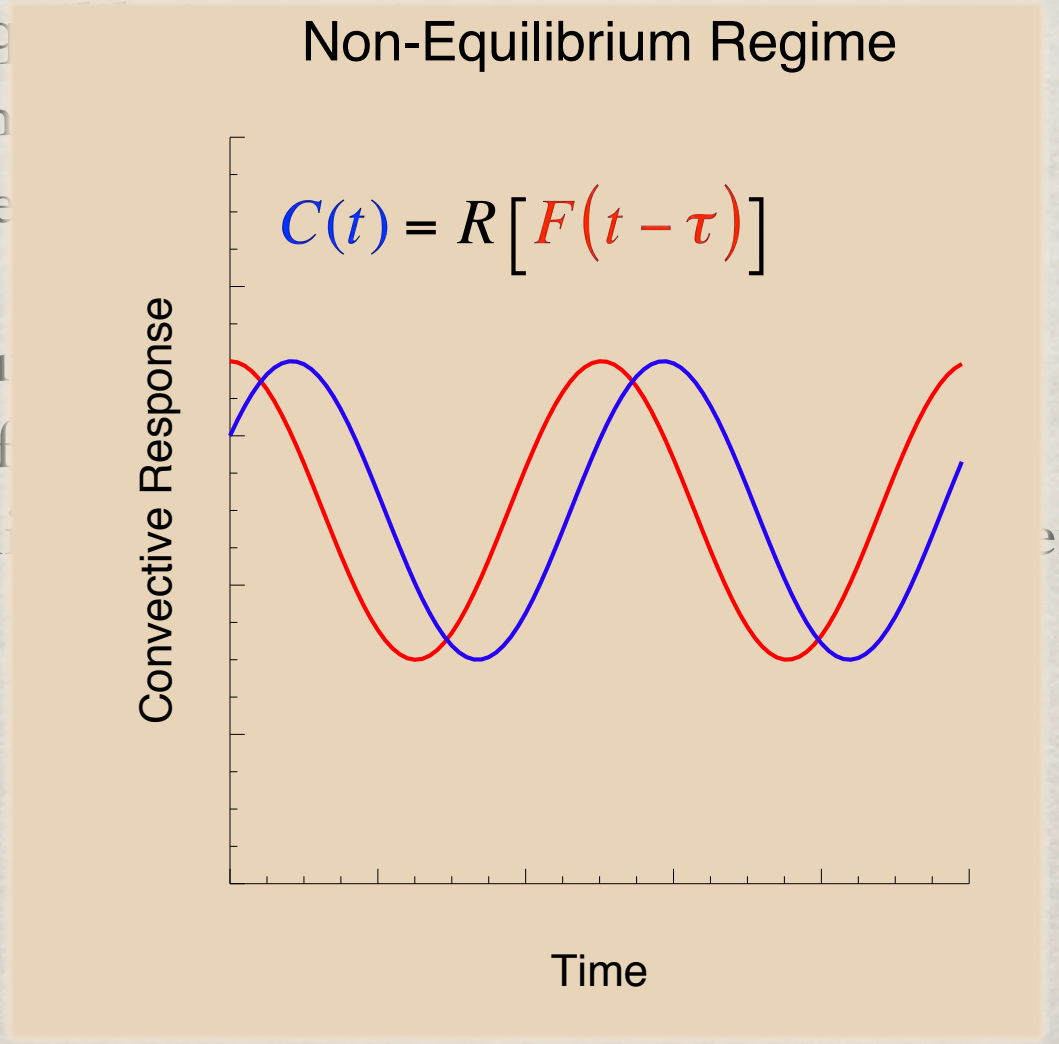
How QE Breaks Down

- Quasi-eq
  - Forcin
  - No me



How QE Breaks Down

- Quasi-eq
  - Forcin
  - No me
- Non-equ
  - Out of
  - Past hi



How QE Breaks Down

- **Quasi-eq**
  - Forcin
  - No me
- **Non-equi**
  - Out of
  - Past hi
- **Non-dete**
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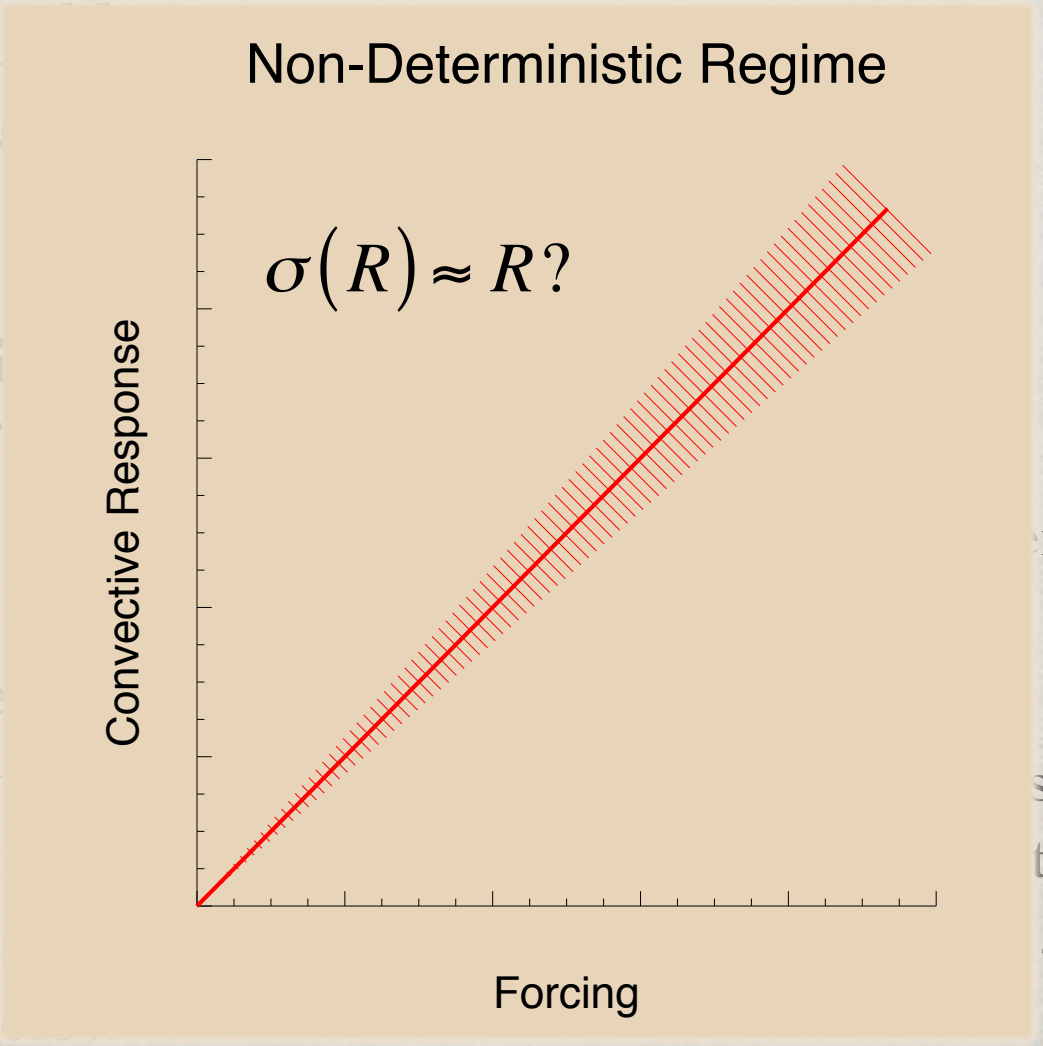
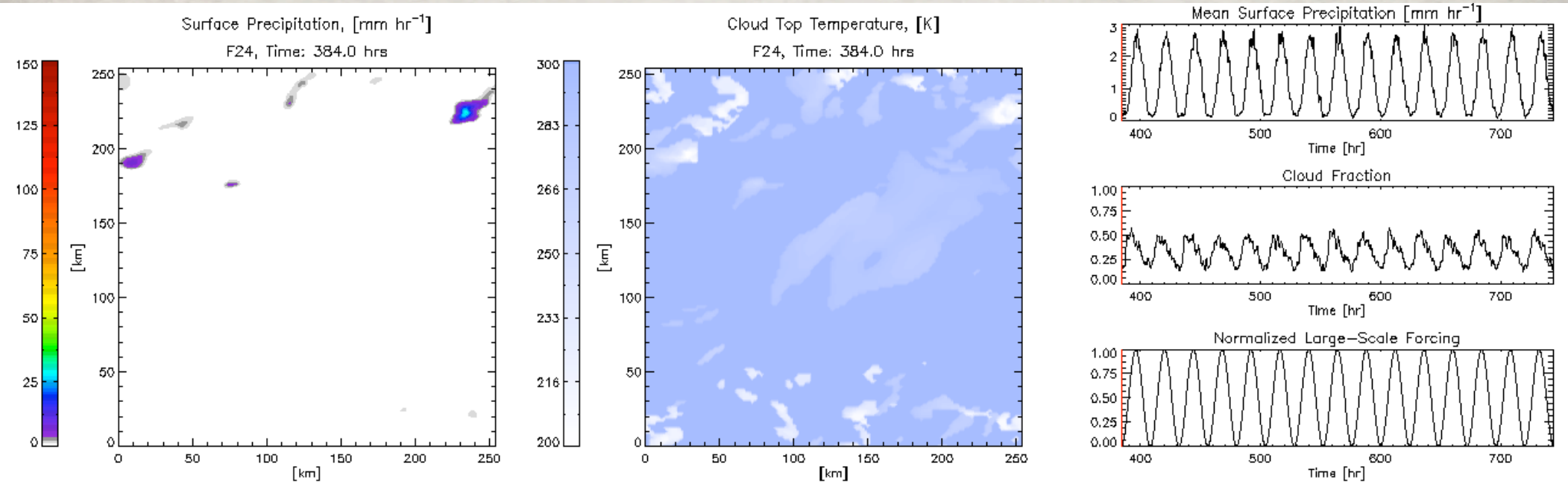


rs

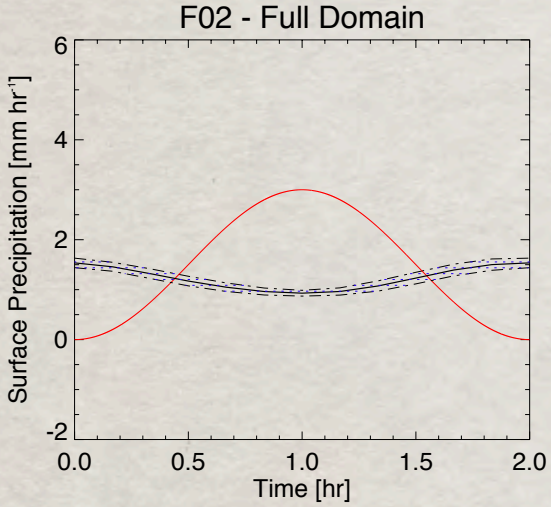
stochastic
t.
-- noise

3D Numerical Simulation

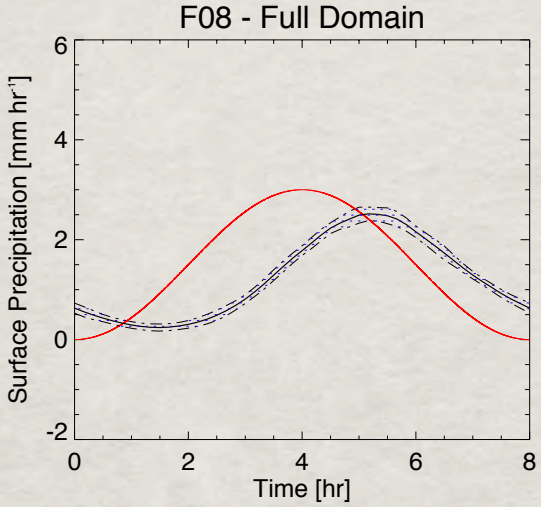


Following Xu et al. 1992

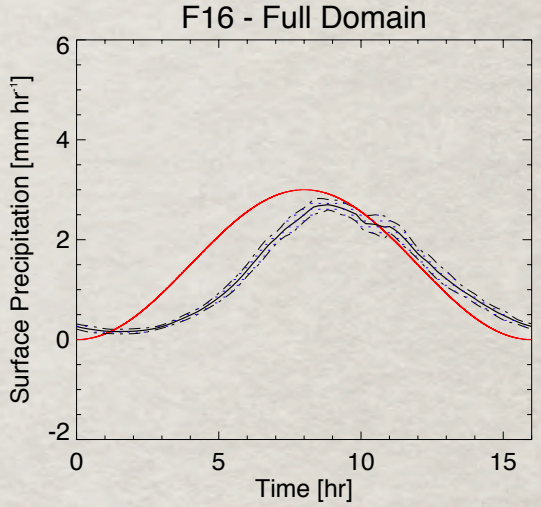
Rain Rate



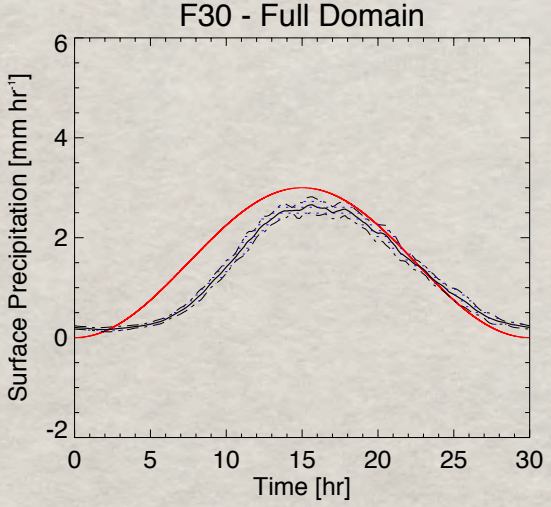
Forcing leads Precip by:
60.0 minutes (50.00 % of the forcing period)



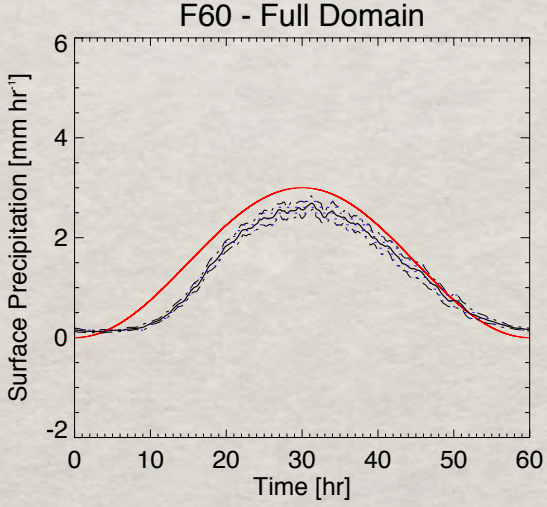
Forcing leads Precip by:
80.0 minutes (16.67 % of the forcing period)



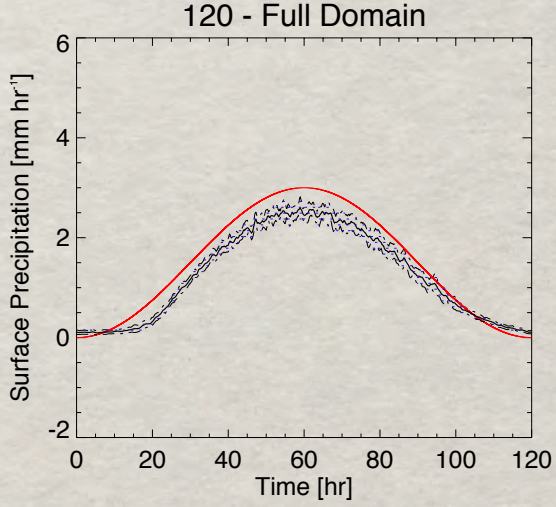
Forcing leads Precip by:
80.0 minutes (8.33 % of the forcing period)



Forcing leads Precip by:
80.0 minutes (4.44 % of the forcing period)

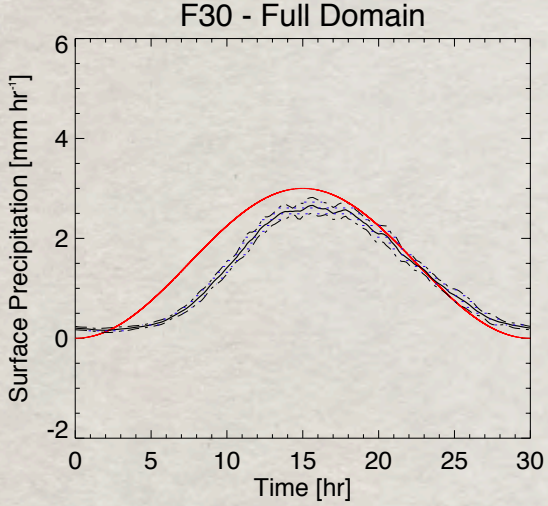


Forcing leads Precip by:
80.0 minutes (2.22 % of the forcing period)

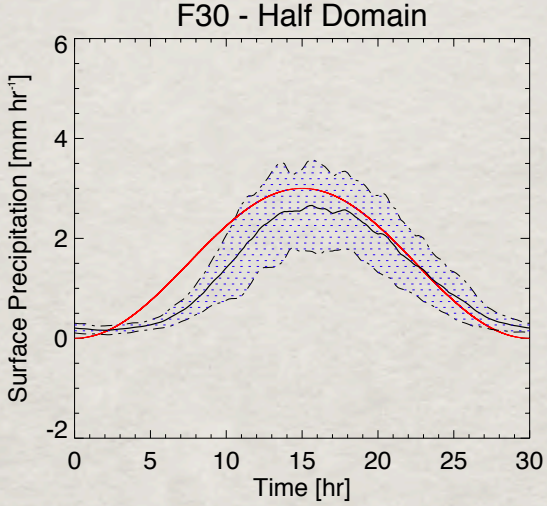


Forcing leads Precip by:
70.0 minutes (0.97 % of the forcing period)

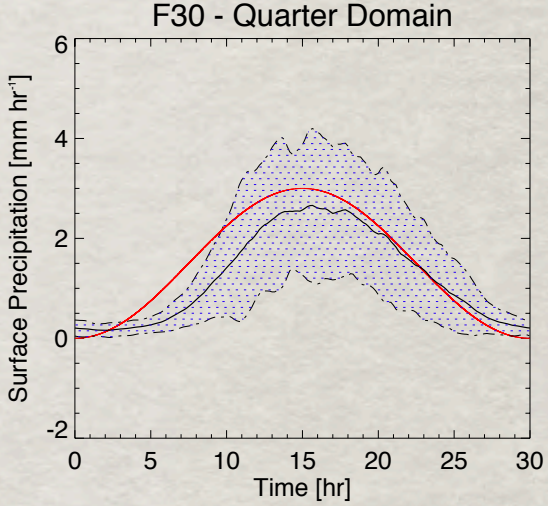
Rain Rate



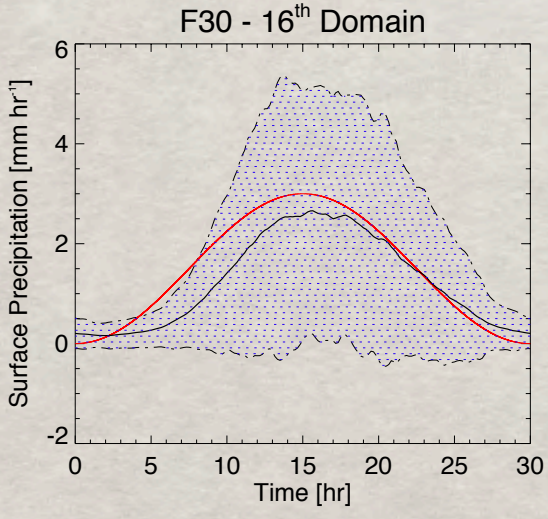
Forcing leads Precip by:
80.0 minutes (4.44 % of the forcing period)



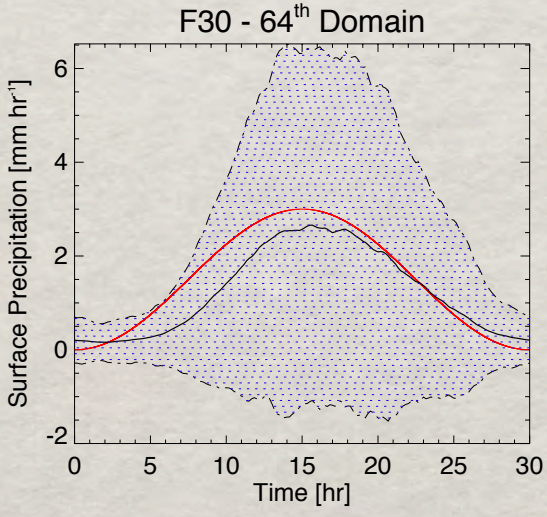
Forcing leads Precip by:
85.0 minutes (4.72 % of the forcing period)



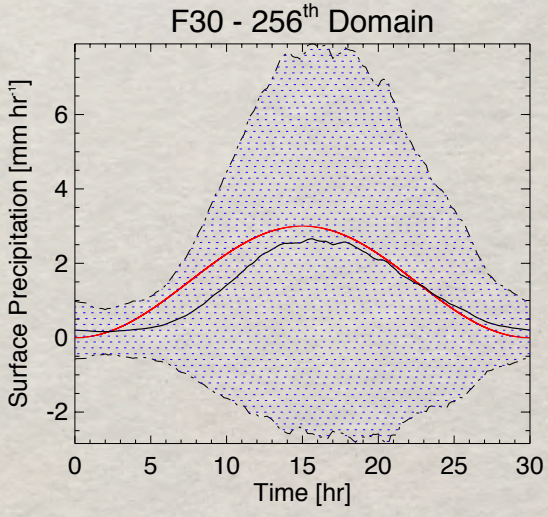
Forcing leads Precip by:
82.5 minutes (4.58 % of the forcing period)



Forcing leads Precip by:
86.9 minutes (4.83 % of the forcing period)

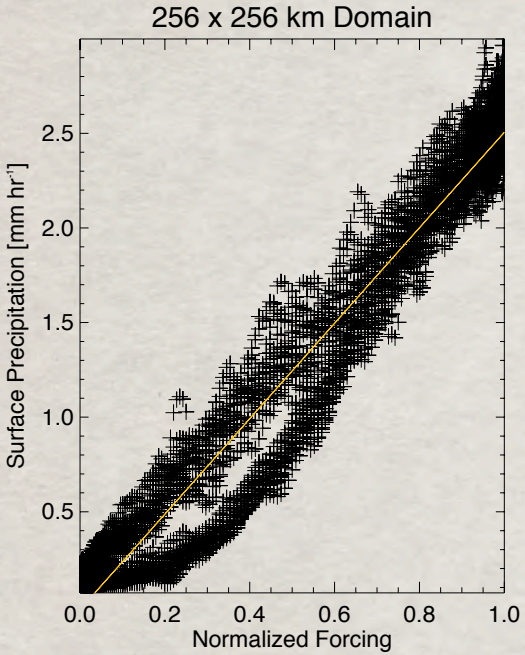


Forcing leads Precip by:
113.8 minutes (6.32 % of the forcing period)

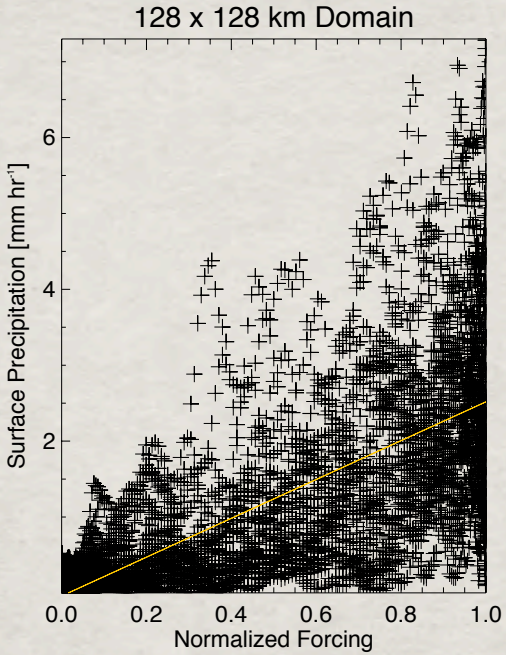


Forcing leads Precip by:
149.0 minutes (8.28 % of the forcing period)

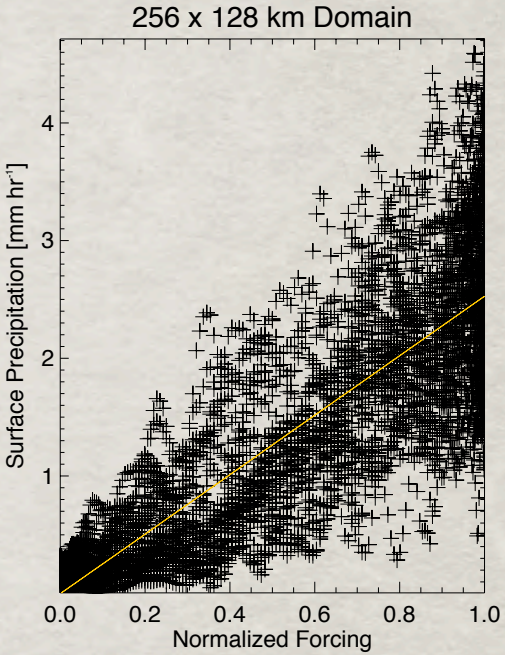
F60



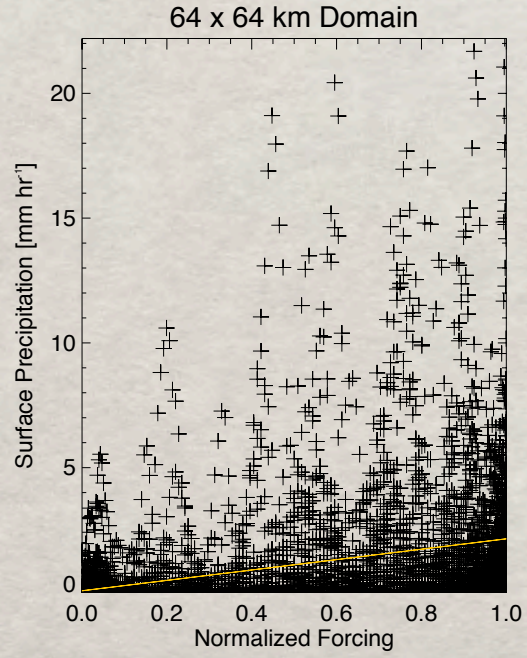
r^2 = 0.948
Slope = 2.522



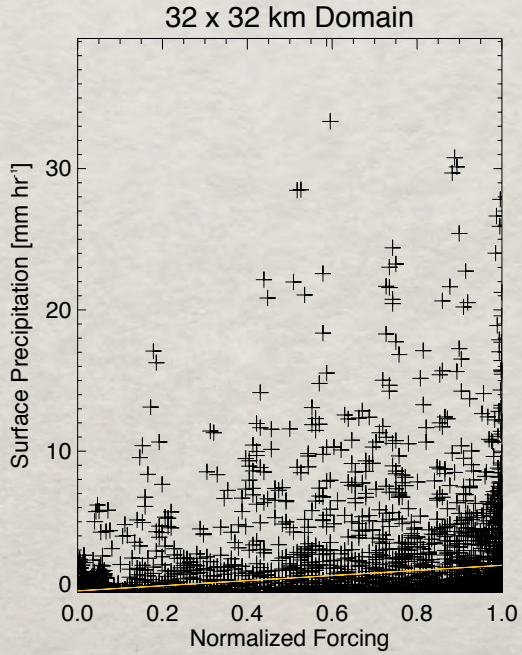
r^2 = 0.473
Slope = 2.558



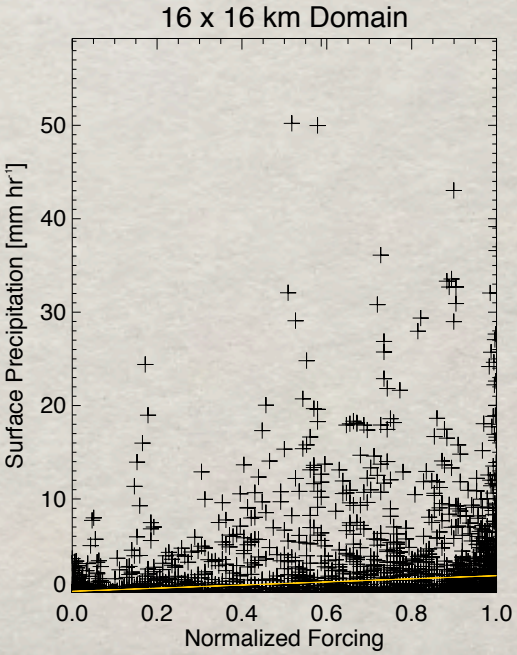
r^2 = 0.723
Slope = 2.527



r^2 = 0.095
Slope = 2.082



r^2 = 0.049
Slope = 1.809

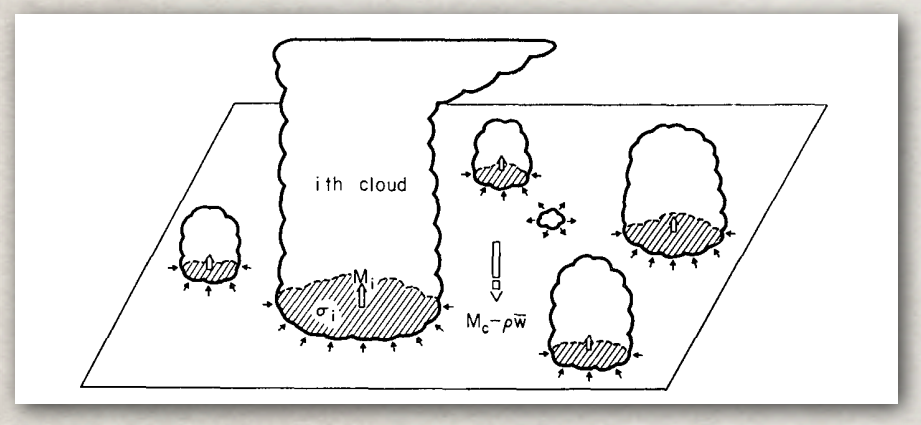


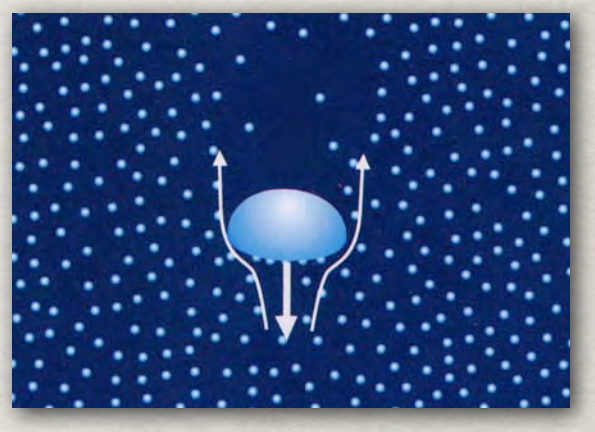
r^2 = 0.030
Slope = 1.673

Limits of Equilibrium

- QE purports to describe "expected values" of Q_1 and Q_2.
- A cloud-resolving model generates a "realization" of Q_1 and Q_2.
- A stochastic parameterization aims to generate a "realization" of Q_1 and Q_2.
- For weather prediction, we will need ensembles of realizations.
- We can imagine a generalization of QE that predicts pdfs of Q_1 and Q_2. This is an interesting but difficult challenge.

Heating and Drying on Fine and Coarse Grids





- Parameterizations for low-resolution models are designed to describe the collective effects of ensembles of clouds.
- Parameterizations for high-resolution models are designed to describe what happens inside individual clouds.

Scale-dependence of heating & drying

$$Q_1 \equiv LC - \frac{1}{\rho}\frac{\partial}{\partial z}(\rho\overline{w's'}) - \frac{1}{\rho}\nabla_H \cdot (\rho\overline{\mathbf{V}_H{}' s'}) + Q_R$$

$$Q_2 \equiv LC + \frac{L}{\rho}\frac{\partial}{\partial z}(\rho\overline{w'q_v{}'}) + \frac{L}{\rho}\nabla_H \cdot (\rho\overline{\mathbf{V}_H{}' q_v{}'})$$

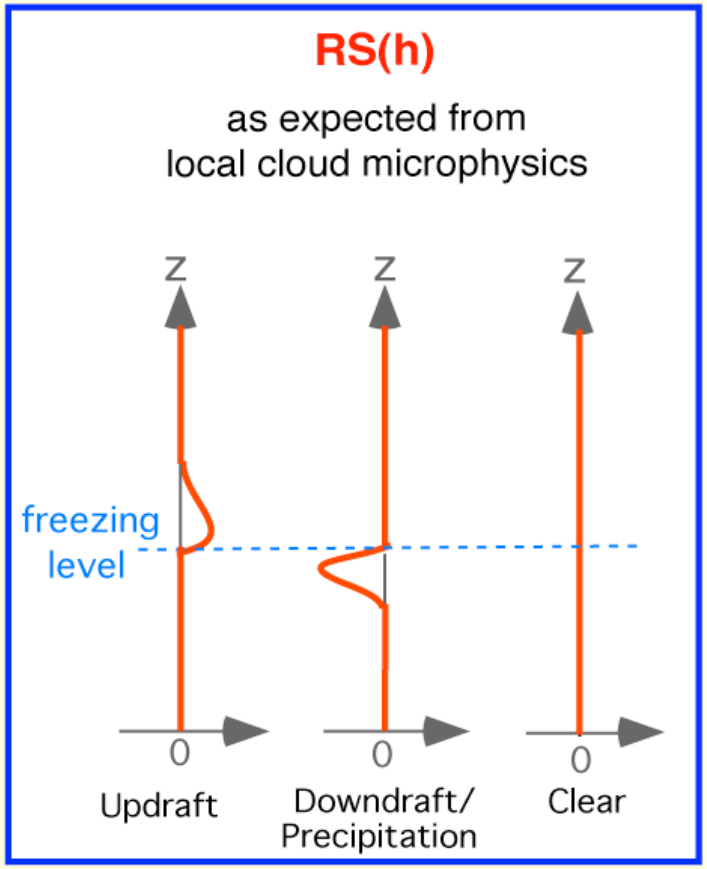
These quantities are defined in terms of spatial averages.

As the averaging length becomes smaller:

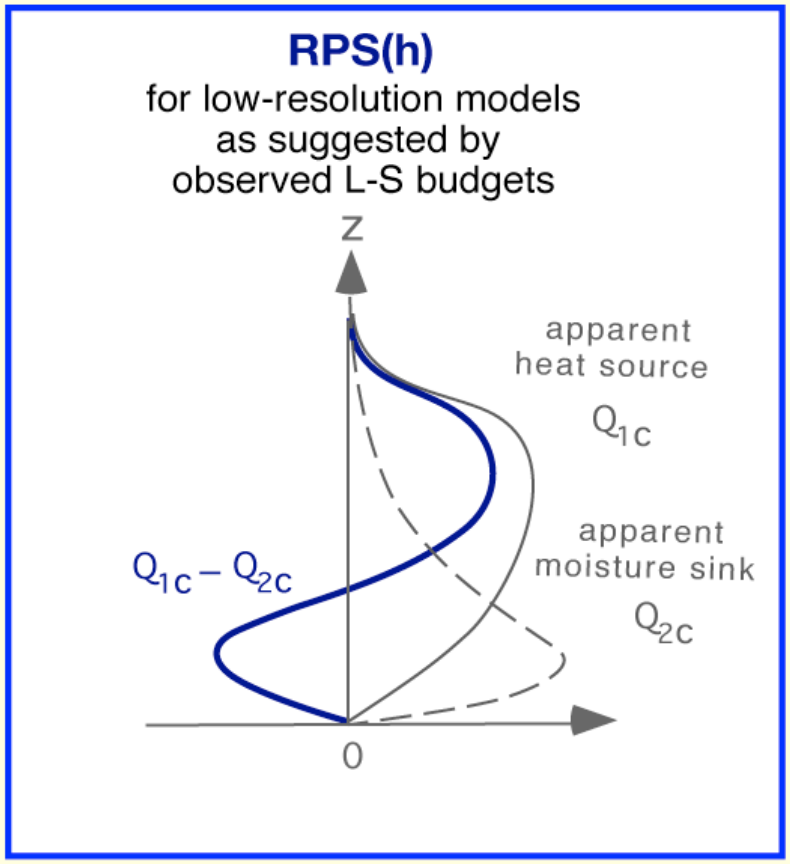
- **The vertical transport terms become less important. Later horizontal averaging does not change this.**
- **The horizontal transport terms become more important locally. Horizontal averaging kills them, though.**
- **The phase-change terms become dominant.**

Typical vertical profiles of the apparent moist static energy source due to convective actvity

Fine mesh



Coarse mesh



Any space/time/ensemble averages of the profiles in the left panel do NOT give the profile in the right panel.

Slide from A. Arakawa

Three problems with parameterizations at high resolution:

- **The sample size is too small.**
- **The "resolved-scale forcing" varies too quickly.**
- **Convective transports should give way to microphysics, but we have no quantitative theory for this transition.**

Expected values --> Individual realizations
--> Global CRMs

You can run a high-resolution model with a cumulus parameterization.

- The model won't blow up.
- Numbers will come out.
- You can make a plot.
- You can publish a paper.
- You can get a grant.
- You won't be arrested.