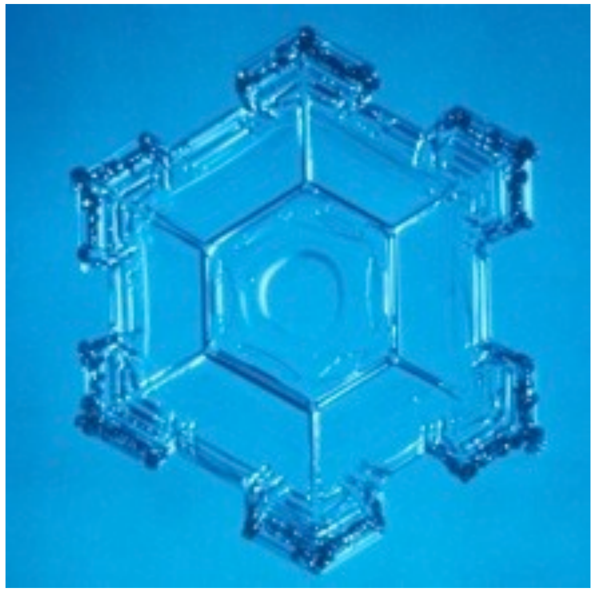
Quantifying the limits of convection parameterization

Modeling Across Scales

Global circulation

Cloud-scale &mesoscale processes



Radiation, Microphysics, Turbulence

Modeling Across Scales

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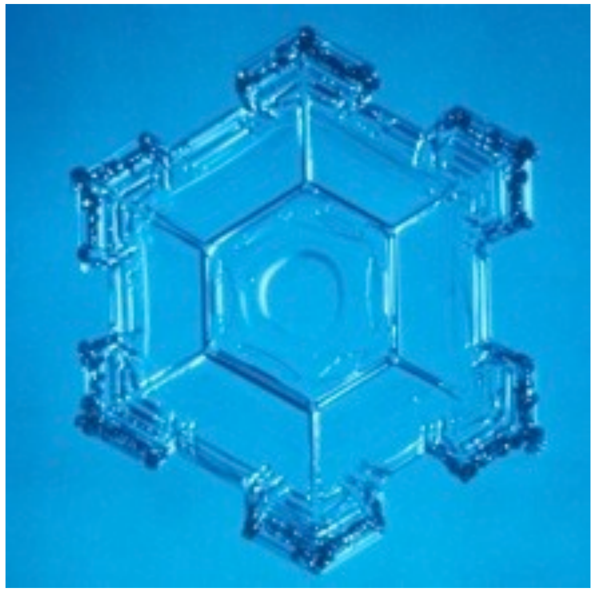
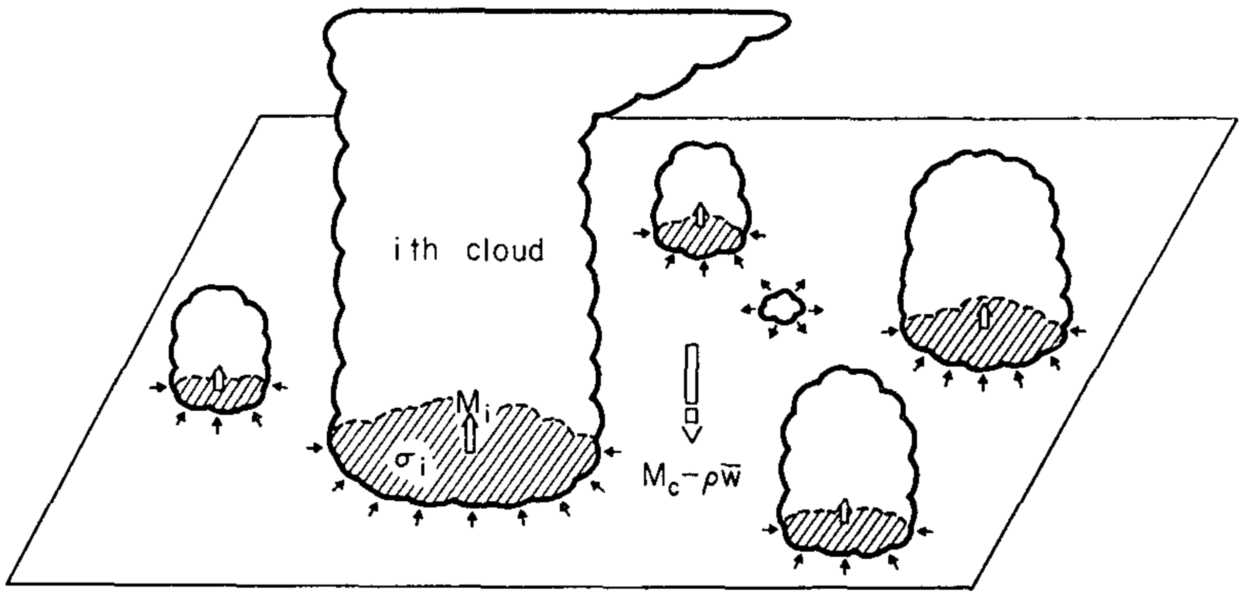
Cloud-scale &mesoscale processes



Radiation, Microphysics, Turbulence

Parameterized

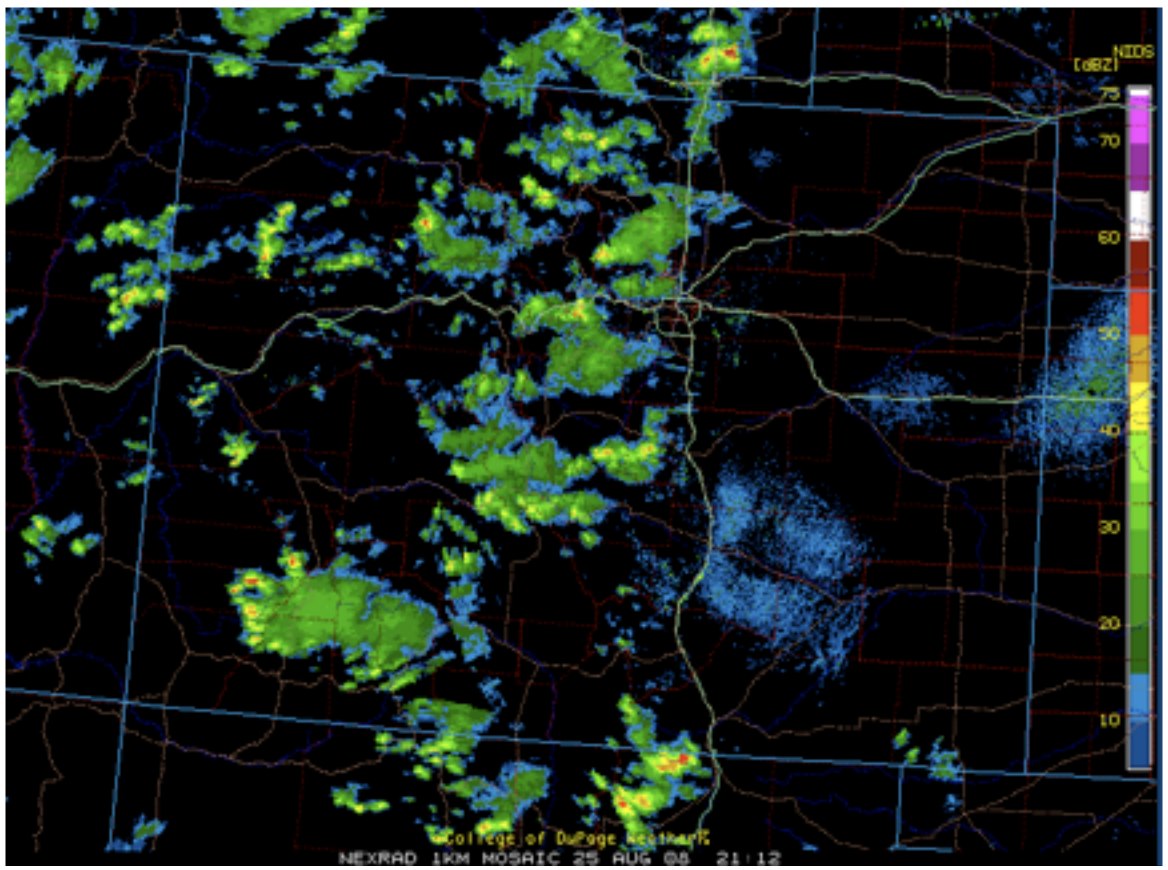
Scale Separation



“Consider a horizontal area … large enough to contain an ensemble of cumulus clouds, but small enough to cover only a fraction of a large-scale disturbance. The existence of such an area is one of the basic assumptions of this paper.”

-- AS 74

A summer afternoon in Colorado

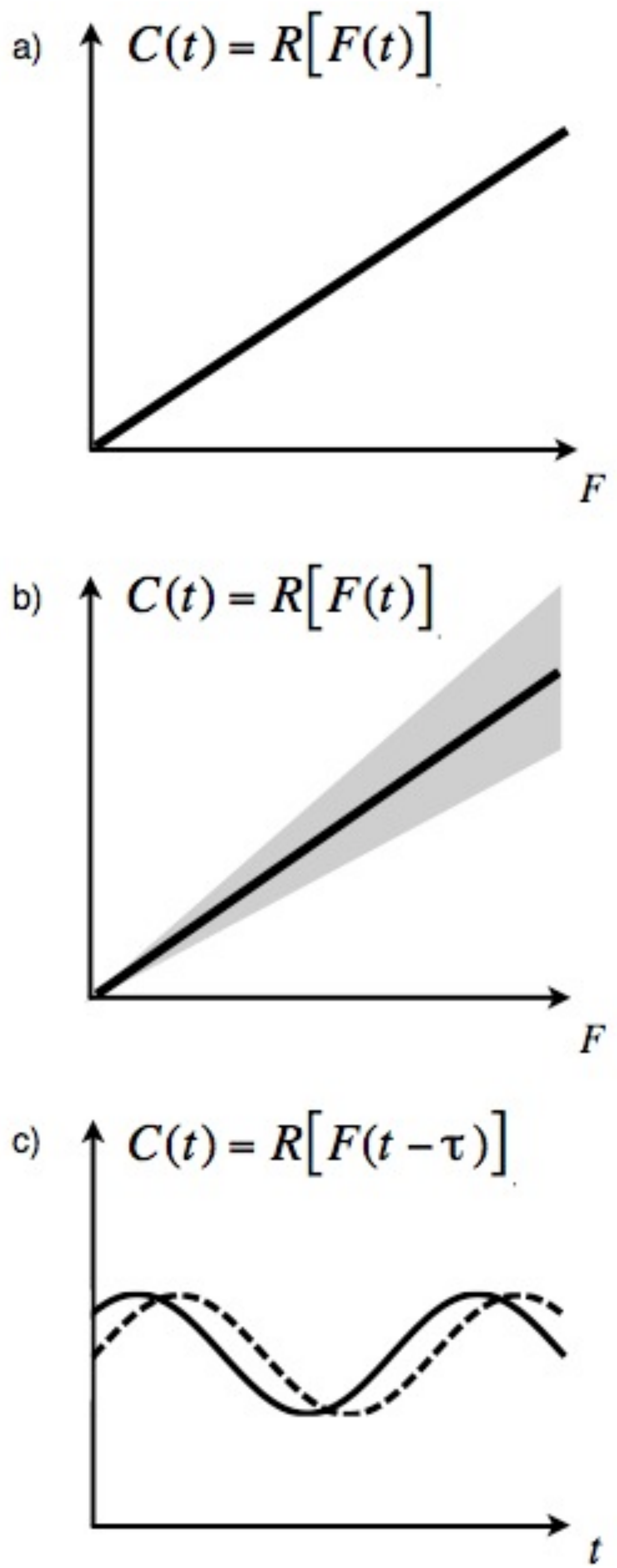


A parameterization determines the "expected" collective effects of many clouds over a large area.

One of the issues is that the sample size is not very large.

The space scales are not sufficiently separated.

Limiting Cases



Quasi-Equilibrium Convection

Non-Deterministic Convection

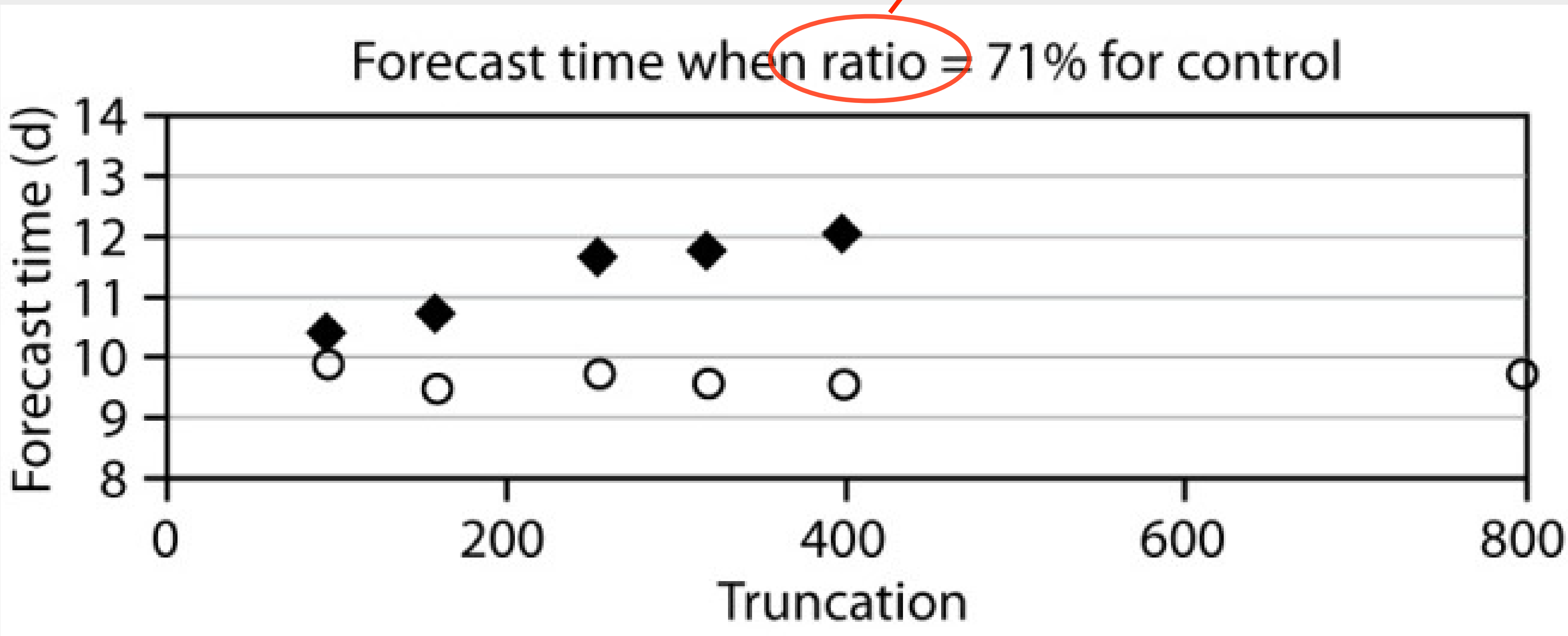
Deterministic but Non-Equilibrium Convection

Higher resolution

- Gradualist approach: dx gradually decreases, without changing parameterizations
  - OK for NWP, not so good for climate
  - No qualitative change until dx~5 km
- Aggressive approach: dx~5 km right now
  - Currently too expensive for climate
  - Super-parameterization as a compromise

Does increased resolution improve the results?

"Ratio" refers to the ratio of forecast error to its saturation value. Black diamonds for the T799 "perfect model," white circles for real forecasts.

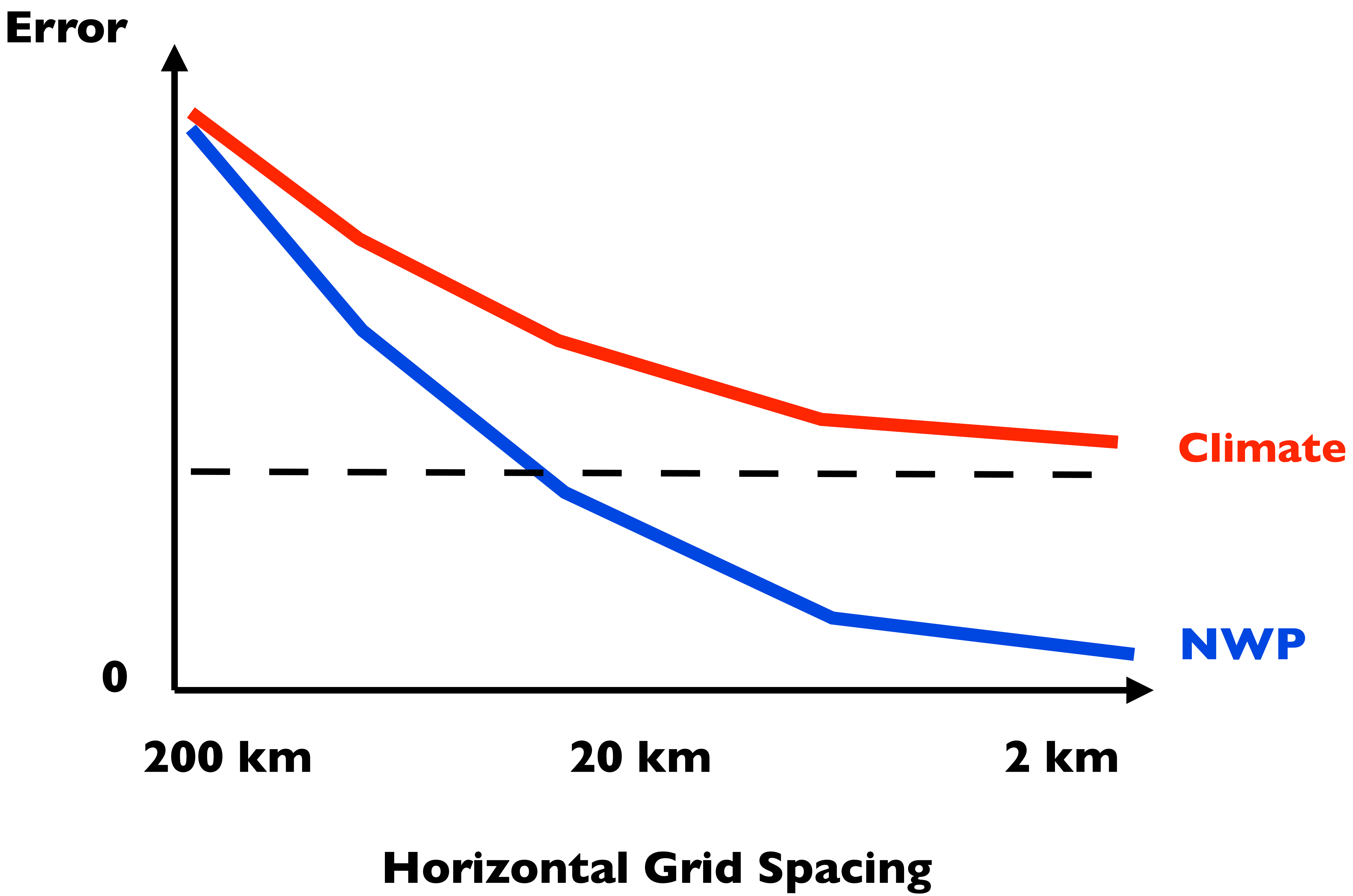


Buizza 2010:

"…although further increases in resolution are expected to improve the forecast skill in the short and medium forecast range, simple resolution increases without model improvements would bring only very limited improvements in the long forecast range."

Error versus resolution

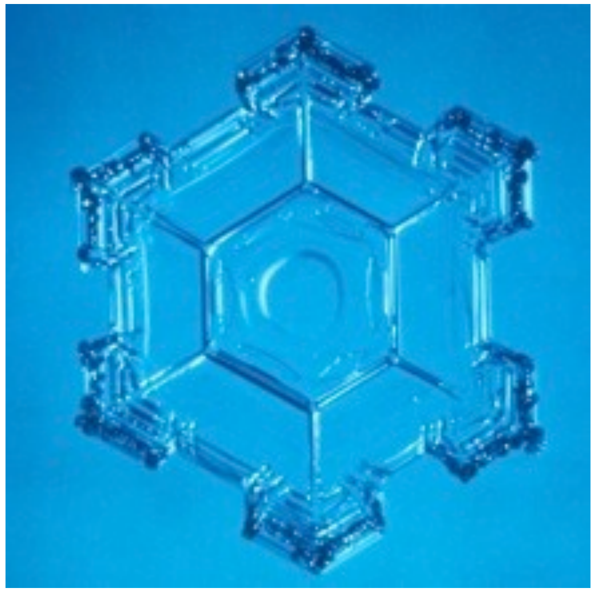
without changing the parameterizations



Parameterize less.

Global circulation

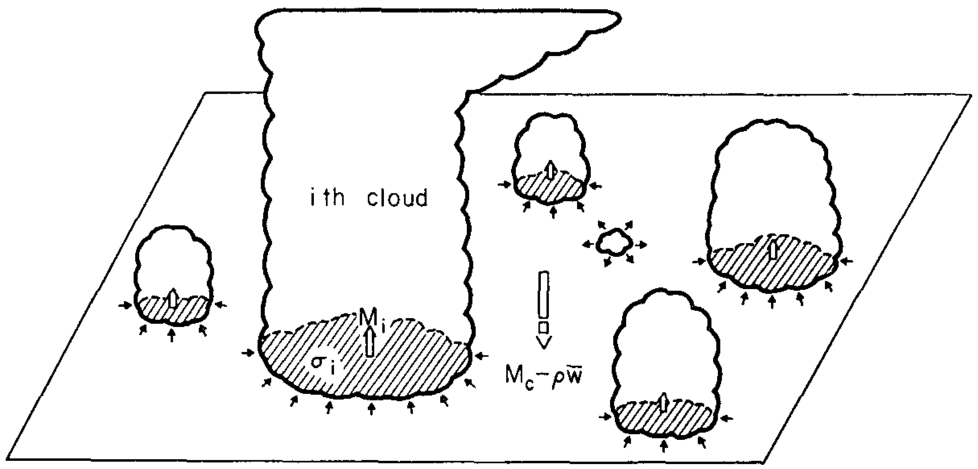
Cloud-scale
&mesoscale
processes



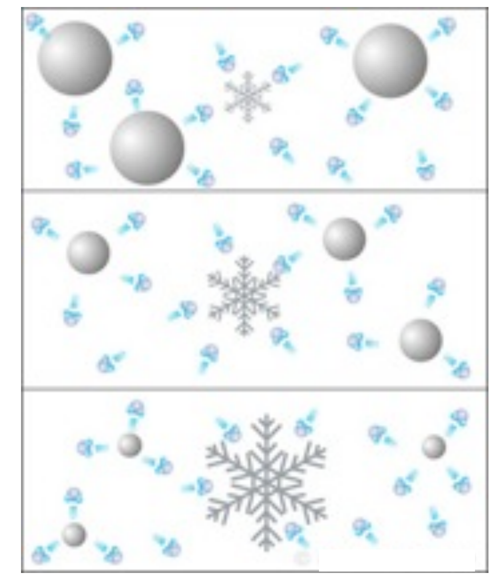
Radiation,
Microphysics,
Turbulence

Parameterized

Parameterize different.



Increasing resolution



GCM

Parameterizations for low-resolution models are designed to describe the collective effects of ensembles of clouds.

CRM

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

Expected values --> Individual realizations

Todd Jones

Ensembles of CRM runs

An extension of

Xu, Kuan-Man, Akio Arakawa, Steven K. Krueger, 1992: The Macroscopic Behavior of Cumulus Ensembles Simulated by a Cumulus Ensemble Model. *J. Atmos. Sci.*, **49**, 2402-2420.

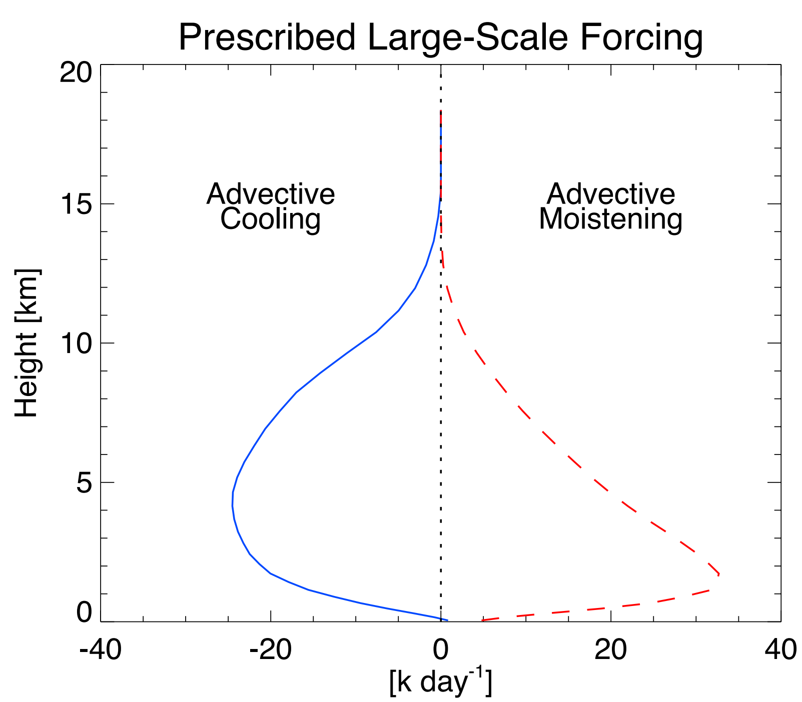
Extended how?

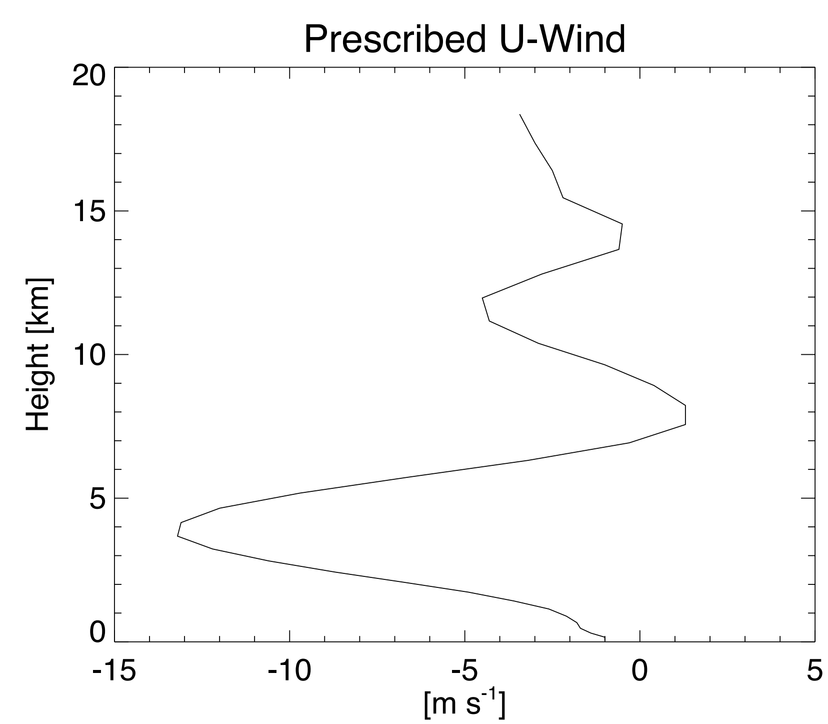
- **Three-dimensional model (important for sample size)**
- **Sensitivity to forcing period**
- **Sensitivity to domain size**

Experiment Design

- Constant SST
- Prescribed radiation
- 256 km square domain
- ~18 km depth
- 2-km horizontal grid spacing

- Large-scale forcing by advective cooling and moistening
- Some wind shear
- Domain-averaged wind relaxed to “obs”



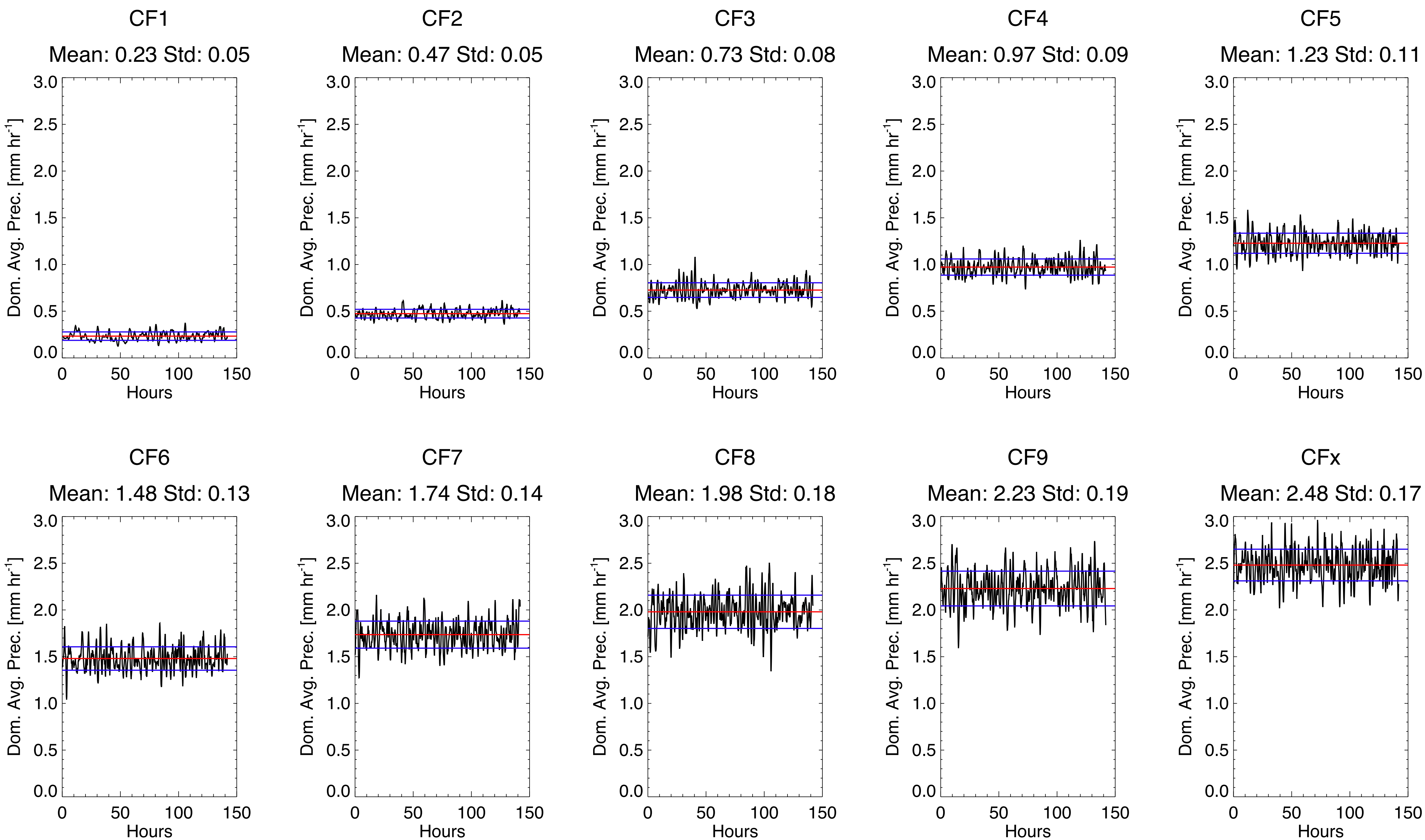


Experiment Design

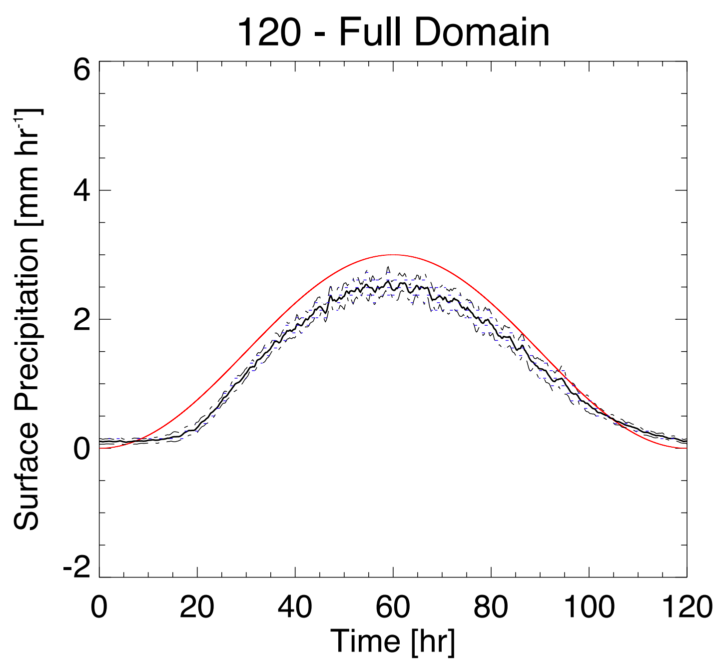
- **Series of constant forcing simulations**
- **Series of periodically forced simulations**
  - **Periods range from 120 hours down to 2 hours**
  - **15 cycles each**
- **Subdomains:**

Fraction	Whole	Quarter	16th	64th	256th
Width, km	256	128	64	32	16

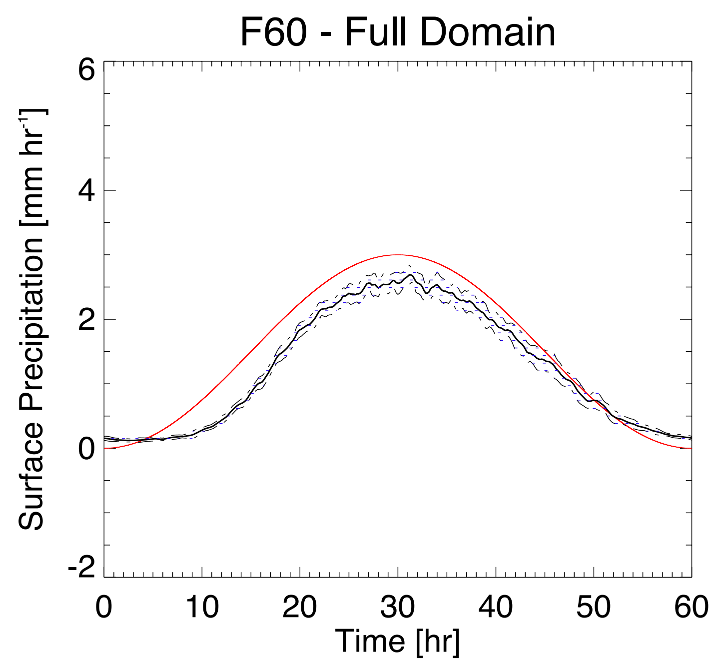
Constant Forcing



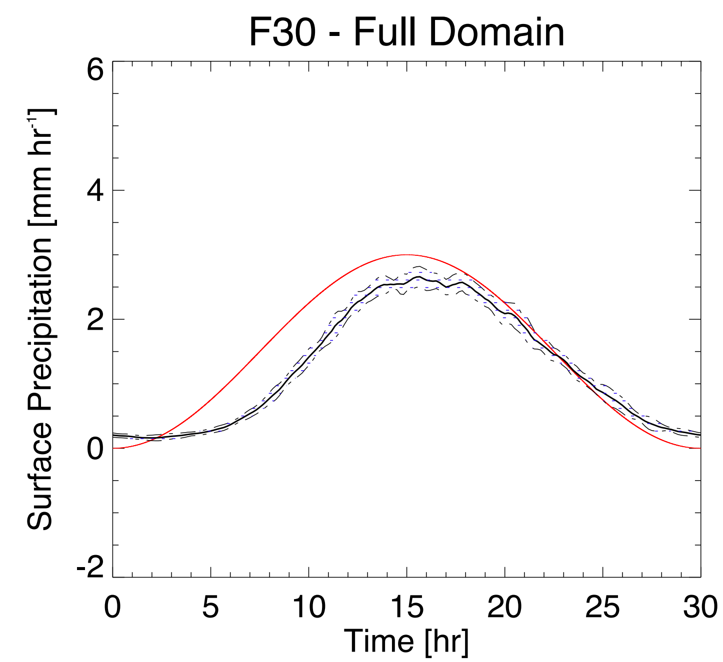
Dependence on Period



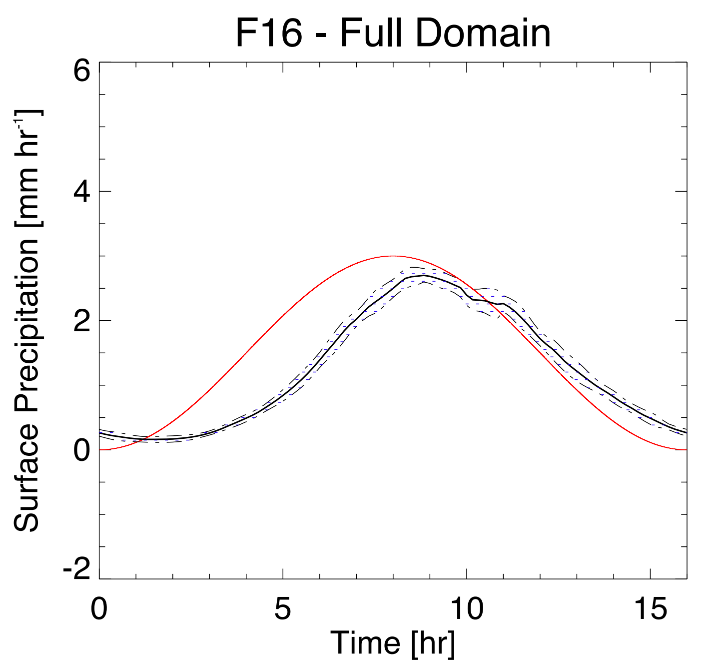
Forcing leads Precip by:
70.0 minutes (0.97 % of the forcing period)



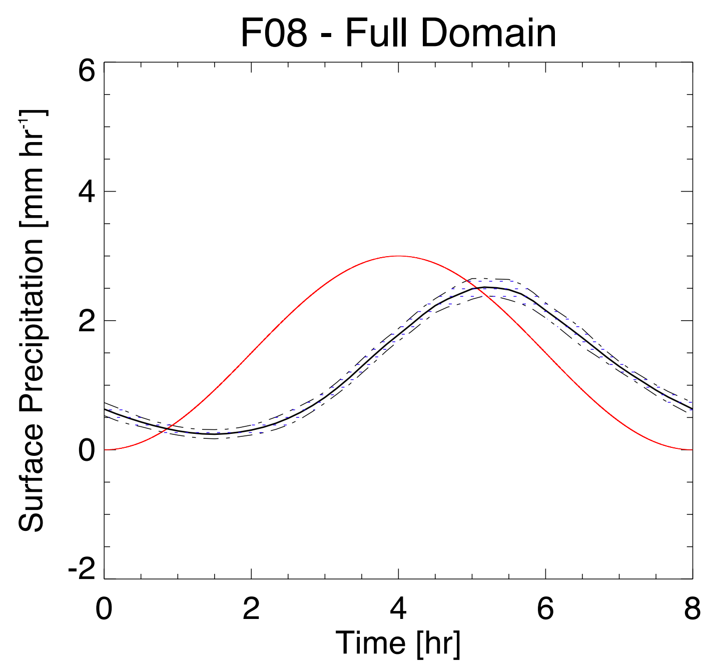
Forcing leads Precip by:
80.0 minutes (2.22 % of the forcing period)



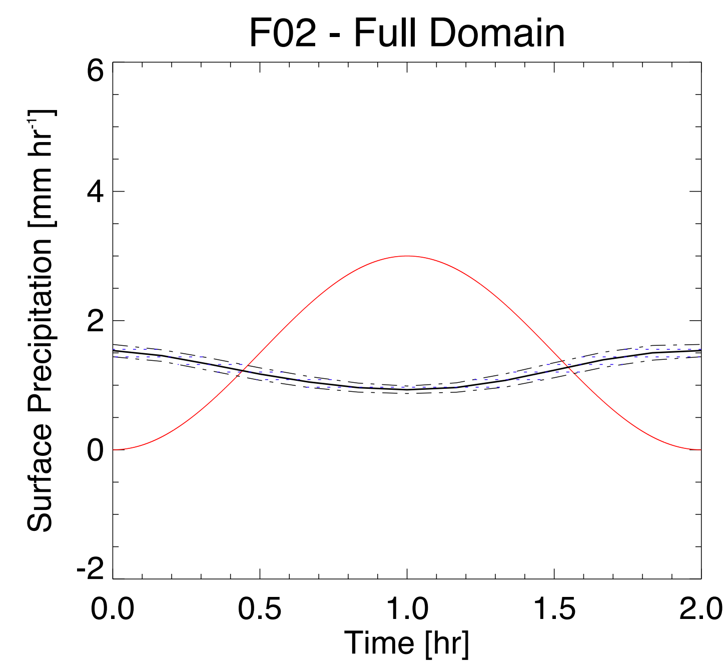
Forcing leads Precip by:
80.0 minutes (4.44 % of the forcing period)



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

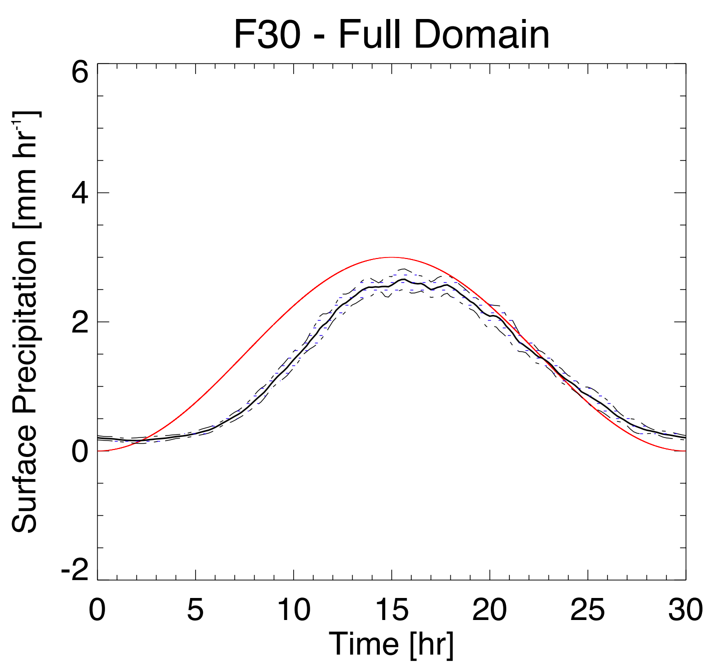


Forcing leads Precip by:
80.0 minutes (16.67 % of the forcing period)



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

Dependence on Domain Size



Forcing leads Precip by:
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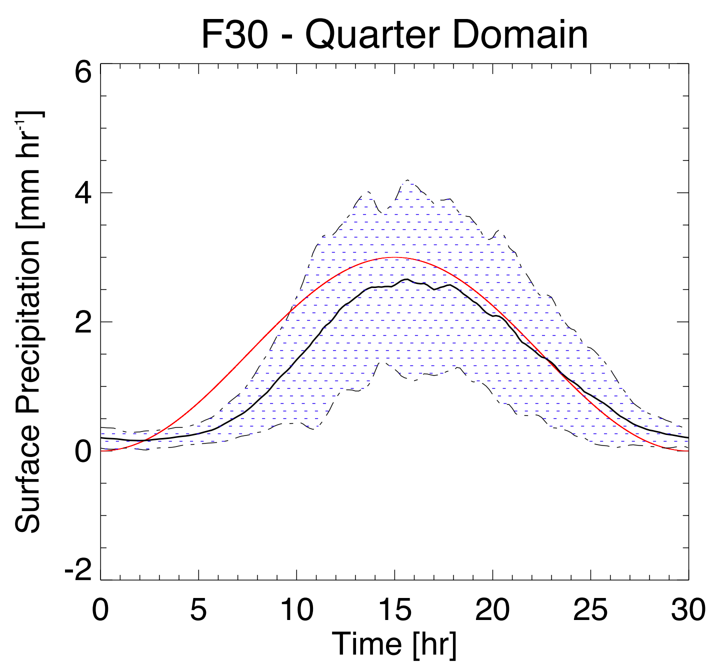
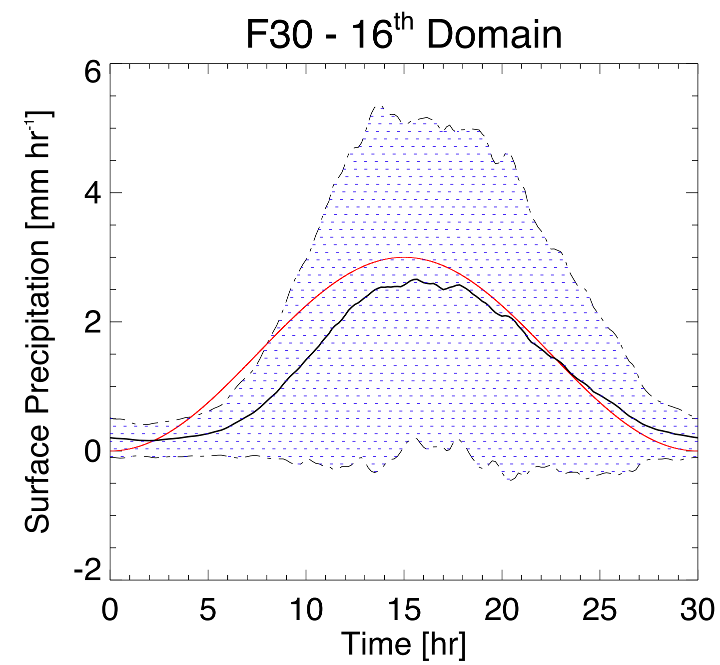
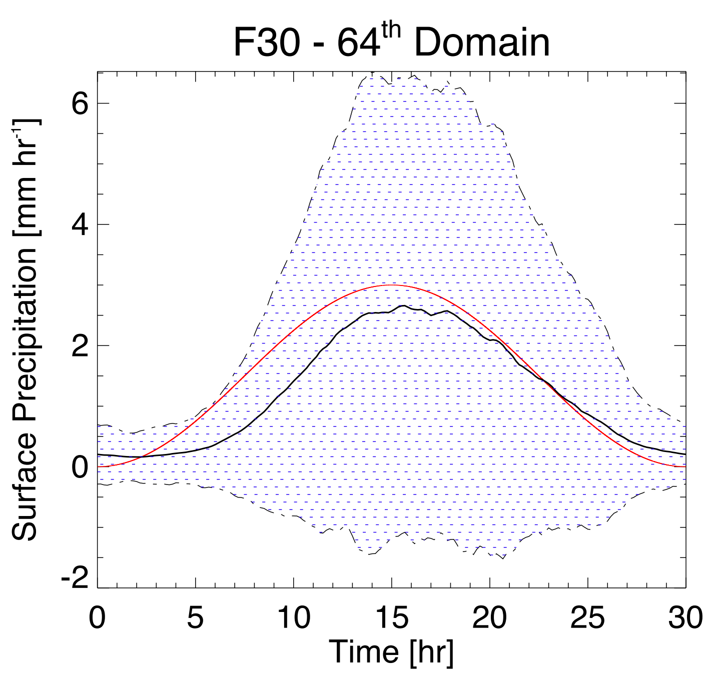


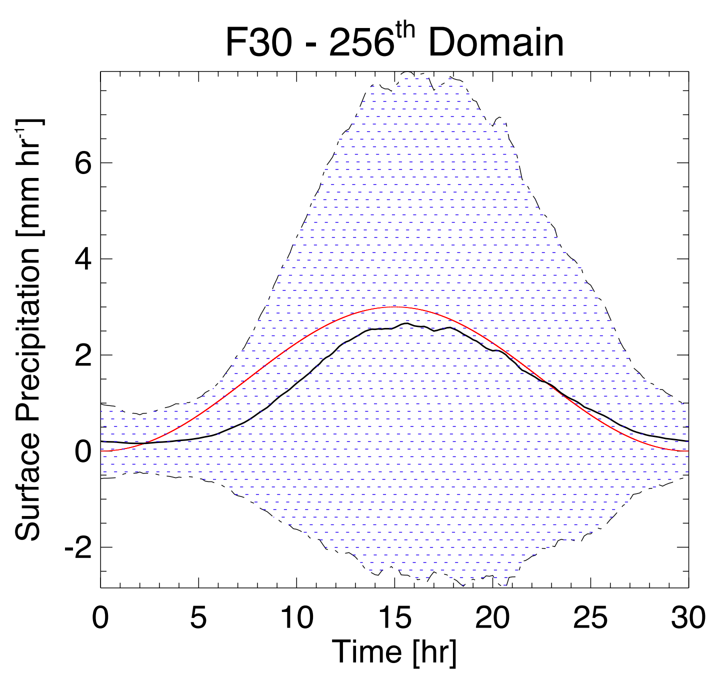
Forcing leads Precip by:
82.5 minutes (4.58 % of the forcing period)



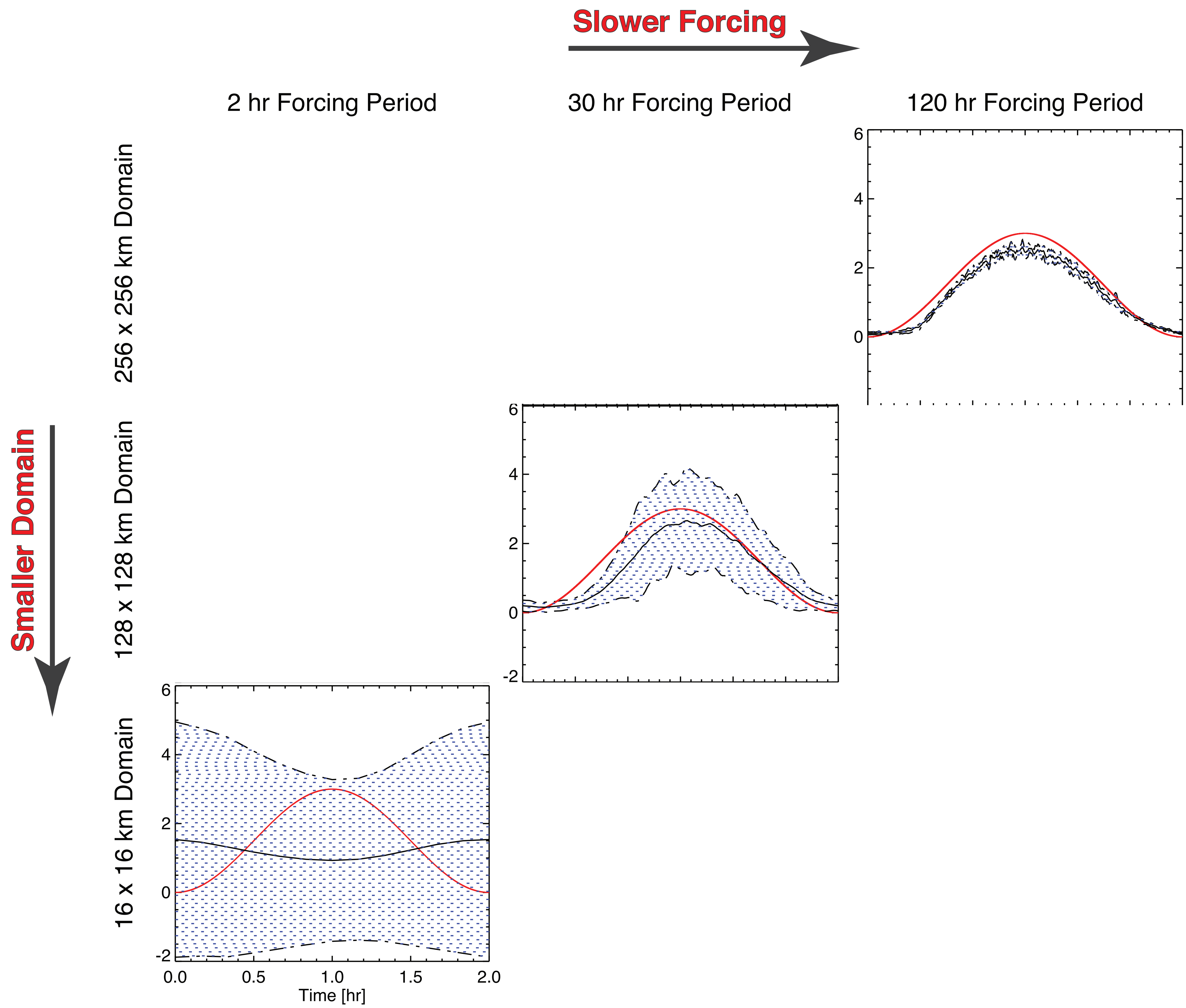
Forcing leads Precip by:
86.9 minutes (4.83 % of the forcing period)



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)

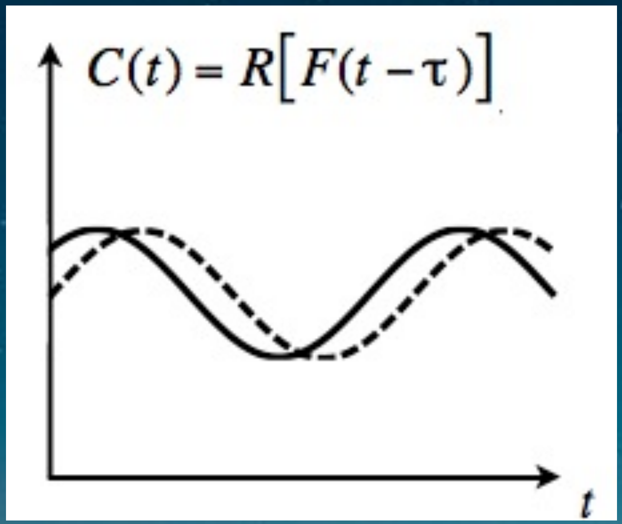

Slower Forcing
2 hr Forcing Period
30 hr Forcing Period
120 hr Forcing Period
256 x 256 km Domain
128 x 128 km Domain
16 x 16 km Domain
Smaller Domain
6
4
2
0
-2
0.0
0.5
1.0
1.5
2.0
Time [hr]

A perfect parameterization

The ensemble mean of the CRM results represents

a perfect deterministic non-equilibrium parmeterization.

It is, of course, a perfect parameterization *of the CRM*, not of the real world.



Stochastic Parameterization

A deterministic parameterization simulates ensemble means.

A stochastic parameterization simulates individual realizations.

Standard Deviation / Mean

What is the best we can do?

	Subdomain Side Length (km)				
Period (hr)	**256**	**128**	**64**	**32**	**16**
15	**0.125**	**0.698**	**1.205**	**1.745**	**2.215**
30	**0.113**	**0.656**	**1.177**	**1.693**	**2.185**
60	**0.116**	**0.664**	**1.222**	**1.760**	**2.227**
120	**0.147**	**0.707**	**1.282**	**1.815**	**2.257**

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A stochastic parameterization should be able to explain these numbers.

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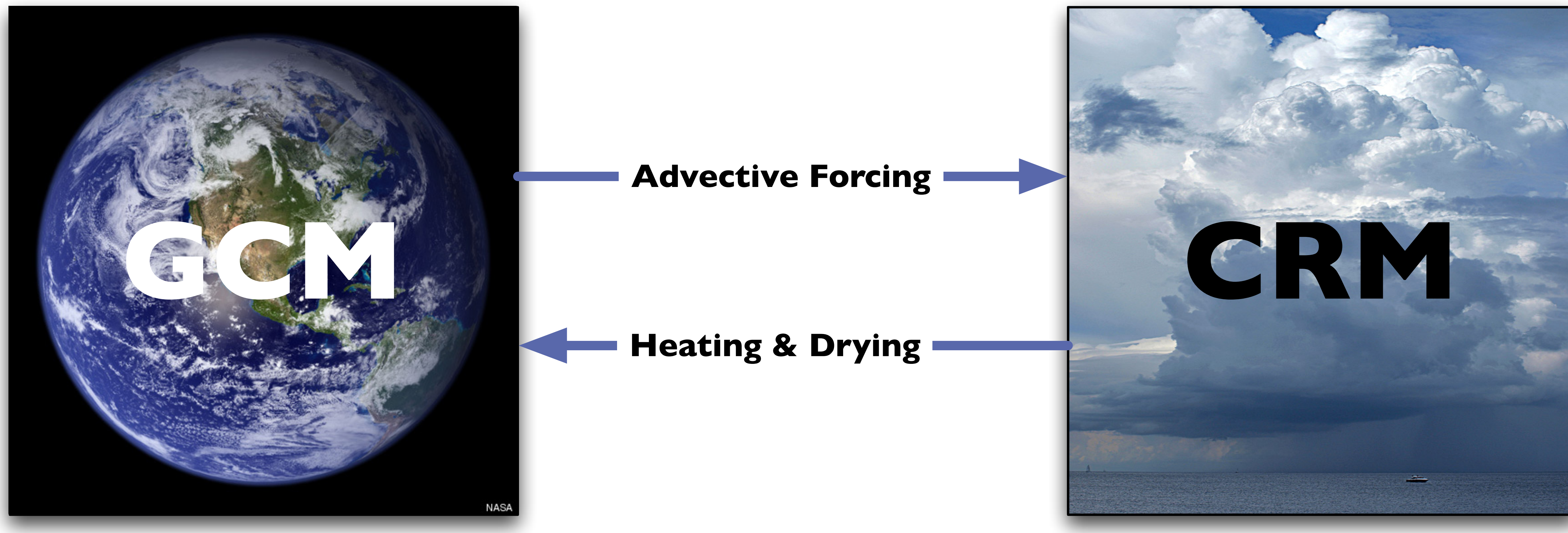
A stochastic parameterization should be able to explain these numbers.

Even with a large domain and slowly varying forcing, *a perfect parameterization* will routinely produce ~10% errors, due to inadequate sample size. That is as good as it gets.

The Multiscale Modeling Framework



"Super-Parameterization"

- Each CRM runs continuously.
- The CRMs do not communicate with each other.
- MMFs are much faster than GCRMs.

What's different?

- We use the equation of motion.
  - No closure assumptions
  - No triggers
  - Mesoscale organization
- The CRM has a memory.
  - Delay in convective response
  - Sensitive dependence on past history
- The computational cost is higher.
  - The MMF is ~200 times more expensive than a conventional model.
  - The MMF works well on parallel machines.

The MMF produces improved variability on a wide range of time scales.

- Diurnal cycle
- MJO
- Seasonal monsoons
- ENSO

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

Super-Parameterization

A super-parameterization is a stochastic parameterization, because it exhibits sensitive dependence on its past history.

Because of the CRM's two-dimensionality, the MMF probably exaggerates the stochastic component of convection.

A super-parameterization can simulate the lag between the forcing and the convective response.

We don't know whether or to what extent the successes of super-parameterization are due to these attributes.

Take-Home Messages

- A CRM can be used to quantify the limits of deterministic parameterization.
- Domain-averaged heating has 10% uncertainty even with wide (256 km) grid cells. The uncertainty increases dramatically as the grid cells become smaller.
- Because a super-parameterization has built-in memory and exhibits sensitive dependence on its past history, it can represent non-equilibrium, non-deterministic convection.