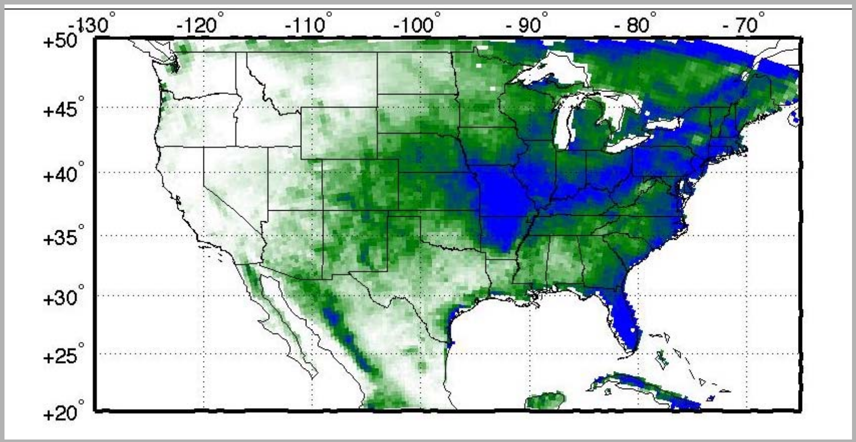
On the Appropriateness of Spectral Nudging in Regional Climate Models



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Dynamically Downscaled IPCC model (HadCM3) July precipitation using WRF with spectral nudging

Seminar
Arizona State University
Tempe, Arizona
April 7, 2010

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Presentation Outline

Motivation and background

Original lessons from a RCM experiment investigating the summer of 1993 with RAMS and CLM

How we have applied these results to our current RCM dynamical downscaling activities to produce seasonal climate forecasts and climate change projections with WRF

Conclusions and general implications for RCM experimental design

<u>Acknowledgments</u>:

Collaborators: Francina Dominguez and Hsin-I Chang (U. Arizona), Burkhardt Rockel and Hans von Storch (GKSS), Giovanni Leoncini (U. of Reading), Roger A. Pielke Sr. (U. of Colorado) and Gonzalo Miguez-Macho (U. of Santiago de Compostela).

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We are being charged to use modeling tools to address issues of major societal importance!

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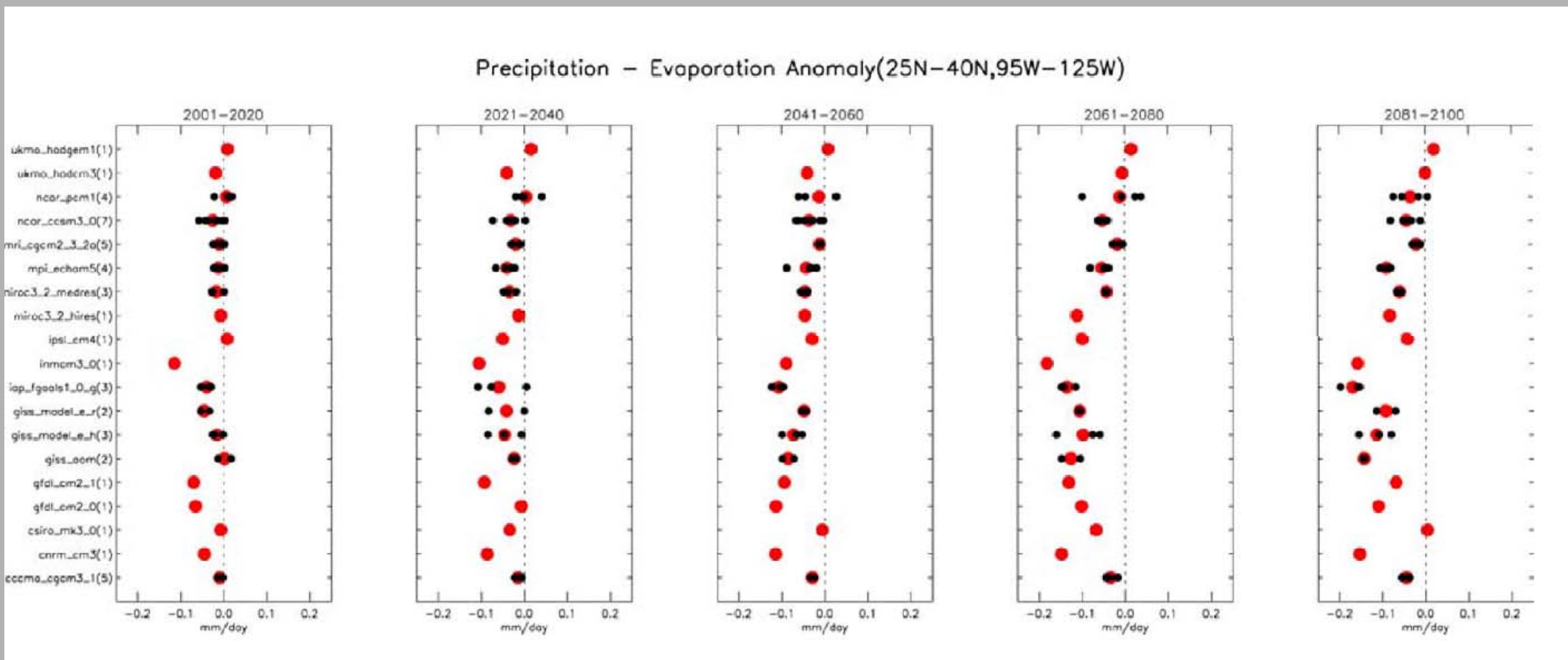
Scientists predict Southwest mega-drought

Climate models indicate region will be as dry as Dust Bowl for decades

David Mcnew / Getty Images

A bleached "bathtub ring," the result of a six-year drought that has dramatically dropped the level of the reservoir, shows on red Navajo sandstone formations near Last Chance Bay at Lake Powell near Page, Ariz. Lake Powell and the next biggest Colorado River reservoir, the nearly 100-year-old Lake Mead, are at the lowest levels ever recorded.

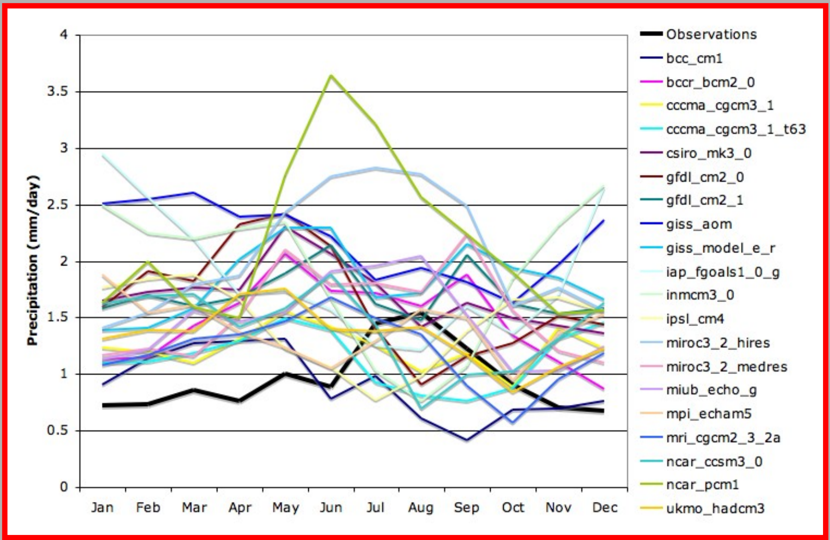
IPCC GCM P-E results for the Southwest United States (relative to model climatologies)

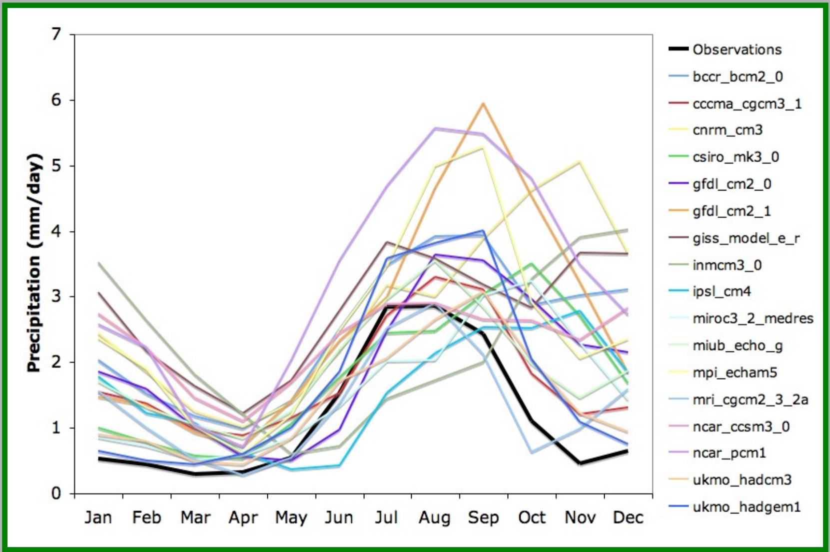


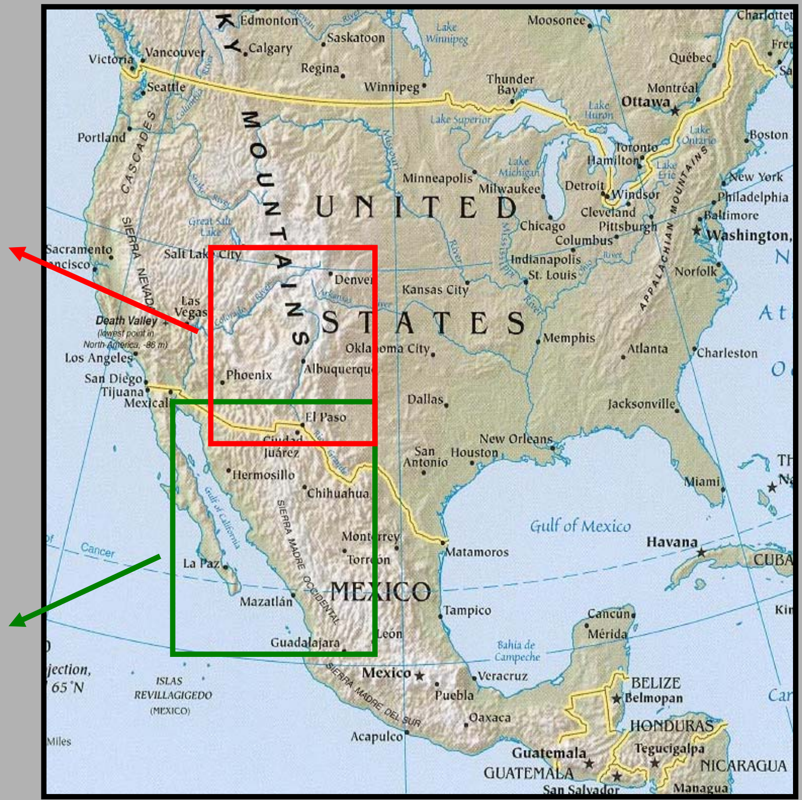
Seager et al. (2007)

My question: How can we trust these results when virtually all these models have little or no representation of summer rainfall?

Monthly average precipitation from IPCC models during the previous century







Historical average of simulations (sres_20c3m) 1970-2000

(Francina Dominguez)

Dynamical Downscaling Types

from *Castro et al.* (2005)

	Examples
TYPE 1: remembers real-world conditions through the initial and lateral boundary conditions	Numerical weather prediction
TYPE 2: initial conditions in the interior of the model are "forgotten" but the lateral boundary conditions feed real-world data into the regional model	Retrospective sensitivity or process studies using global reanalyses
TYPE 3: global model prediction is used to create lateral boundary conditions. The global model prediction includes real-world surface data	Seasonal climate forecasting
TYPE 4: Global model run with no prescribed internal forcings. Couplings among the ocean-land-continental ice-atmosphere are all predicted	Climate change projection

Definition of RCM:

Initial conditions in the interior of the model are "forgotten" but the lateral boundary conditions feed data into the regional model

Type 2 dynamical downscaling and above

Some a priori expectations for RCM dynamical downscaling (Type 2 and above)

<u>**A RCM should:**</u>

1. **Retain or enhance variability of larger-scale features provided by the driving global model (i.e. those on the synoptic scale)**

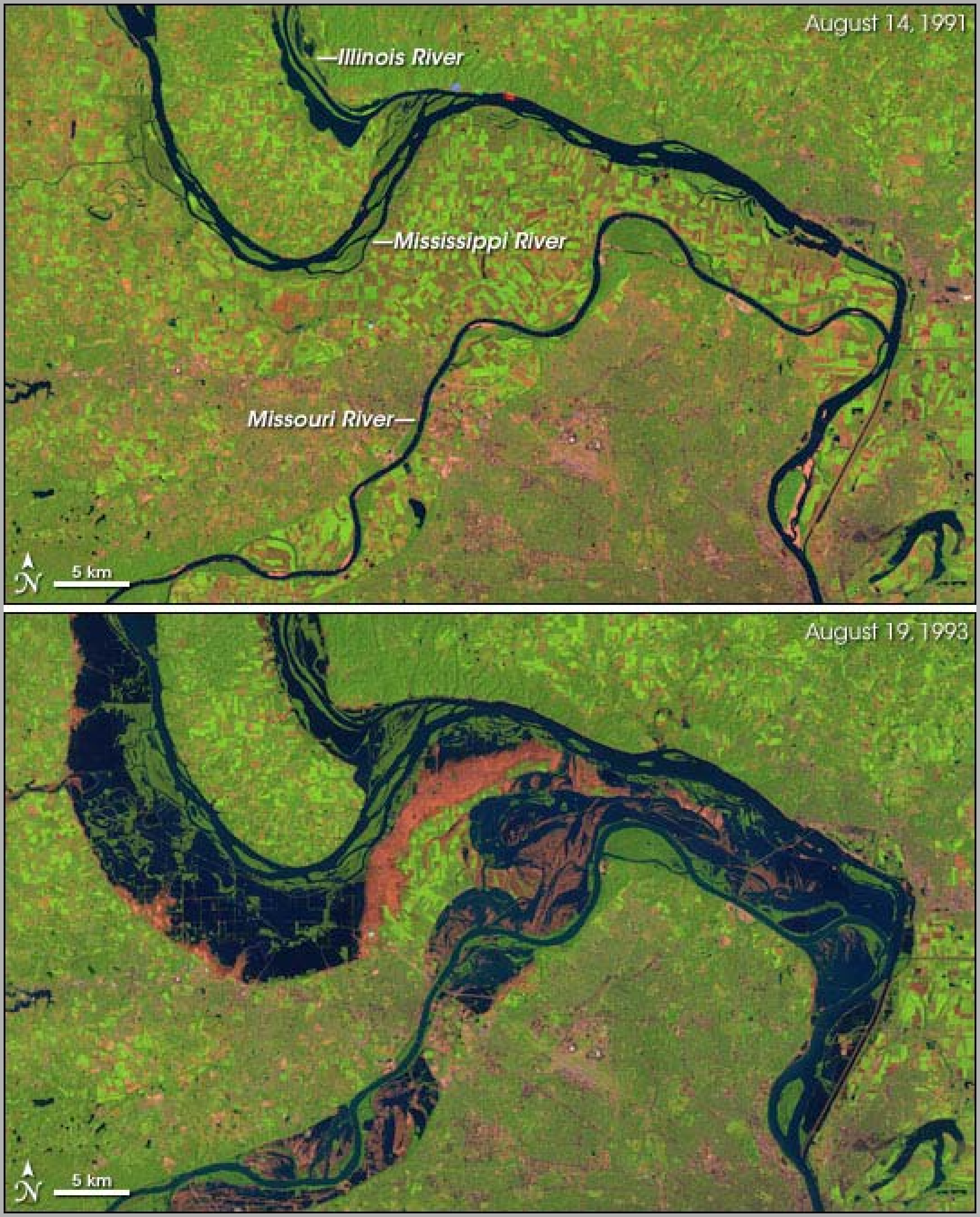
2. **Add information on the smaller scale because of increase in grid spacing, finer spatial scale data (e.g. terrain, landscape) and possibly differences in model parameterized physics.**

3. **Add information that is actually of value, as demonstrated by comparing RCM results with independent metrics (e.g. observations for Type 2)**

Original lessons learned from RCM experiments with RAMS and CLM

A good test case for a RCM… The Great Flood of 1993 in central U.S.

Our RCM experiments focused on the month of May…look at results after two weeks of integration.



Regional Climate Model Experiments and Methods

Castro et al. (2005)

Regional Atmospheric Modeling System (RAMS)

NCEP Reanalysis lateral boundary forcing.

Basic model experiments that investigated sensitivity to domain size and grid spacing with standard lateral boundary nudging only.

Follow on experiments that investigated sensitivity to 4DDA internal nudging.

Rockel et al. (2008)

CLM (or CCLM), climate version of German weather service COSMO model.

ECMWF ERA-40 Reanalysis lateral boundary forcing

Repeat basic model experiments of Castro et al. (2005)

Follow on experiments with spectral nudging.

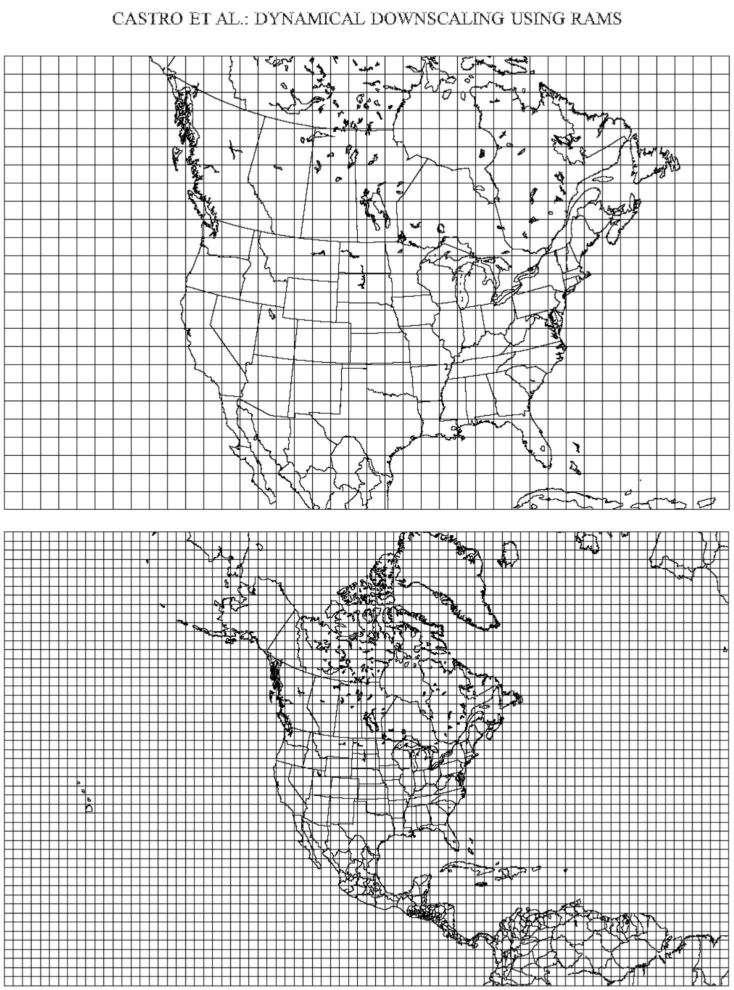


Figure 1. RAMS domains for model sensitivity experiments for Δx = 200 km.

Small Domain

Large Domain

3 nudging points used at lateral boundaries

Degradation of large-scale circulation features

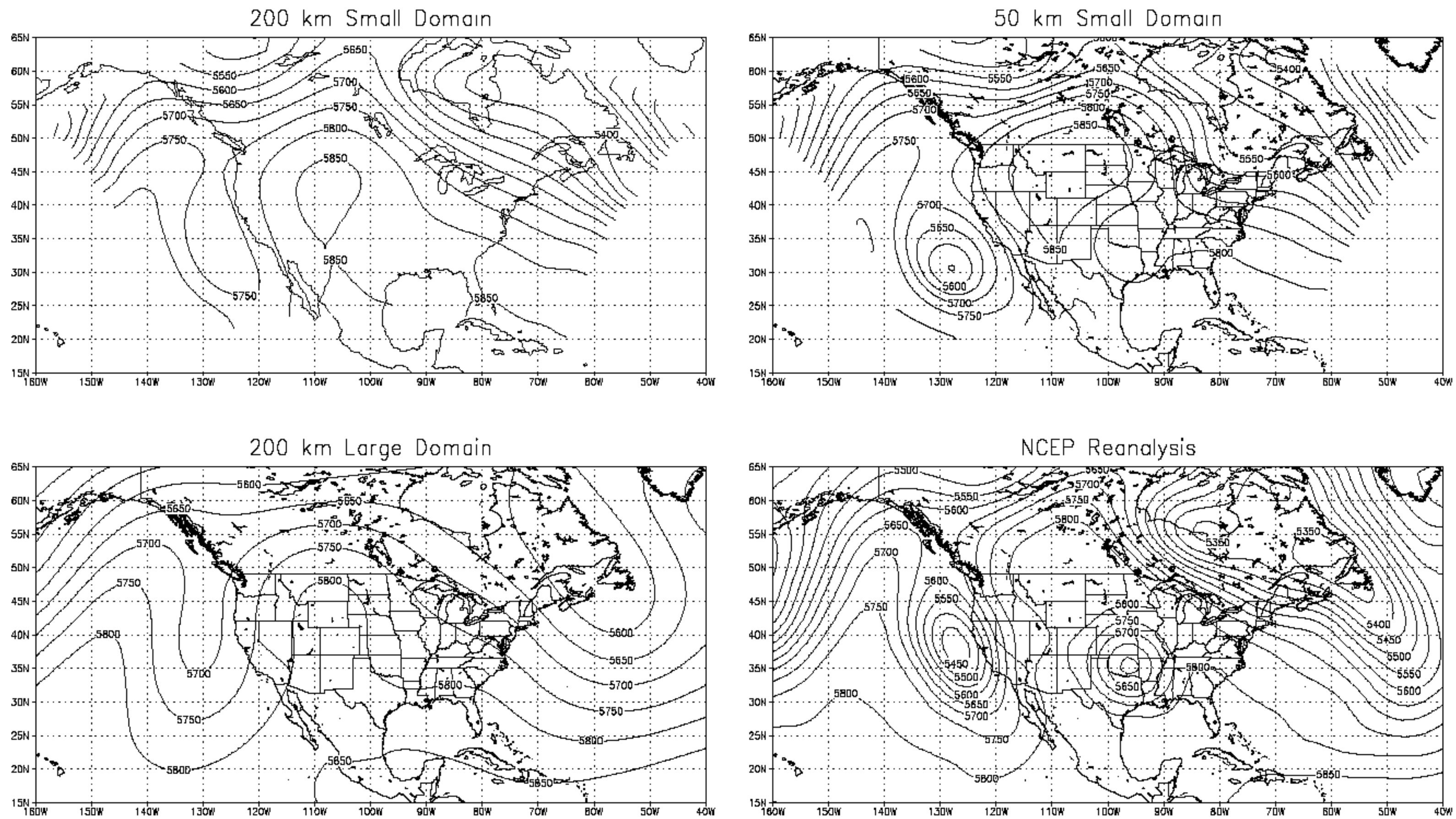
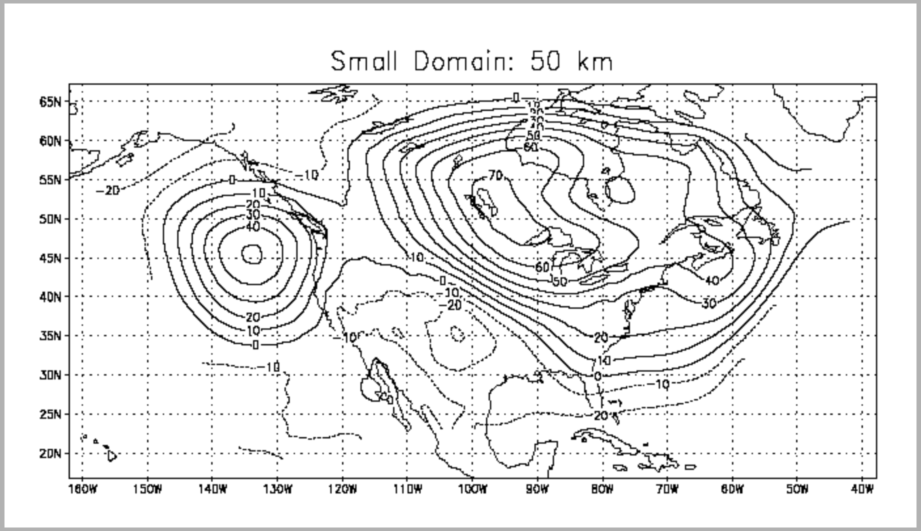


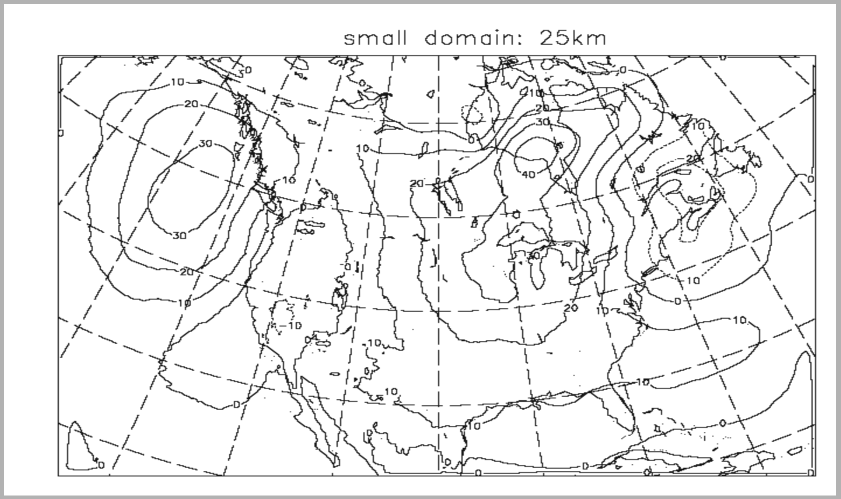
Figure 2. The 500-mbar height (m) on 0Z UTC, 12 May 1993, for indicated model basic experiments and NCEP Reanalysis.

Average 500-mb height difference (m) from driving reanalyses (last 15 days of simulation)

RAMS



CLM



Quantitative analysis of value retained by RCM at large scales

Compute 2-D power spectrum for a given model variable as a function of wavelength (Errico 1985). Do for both RCM and driving reanalysis.

Appropriate variable for large-scale: kinetic energy

Average power spectra of last 15 days of simulation.

Compute the ratio of average of the power spectra of RCM vs. driving reanalysis.

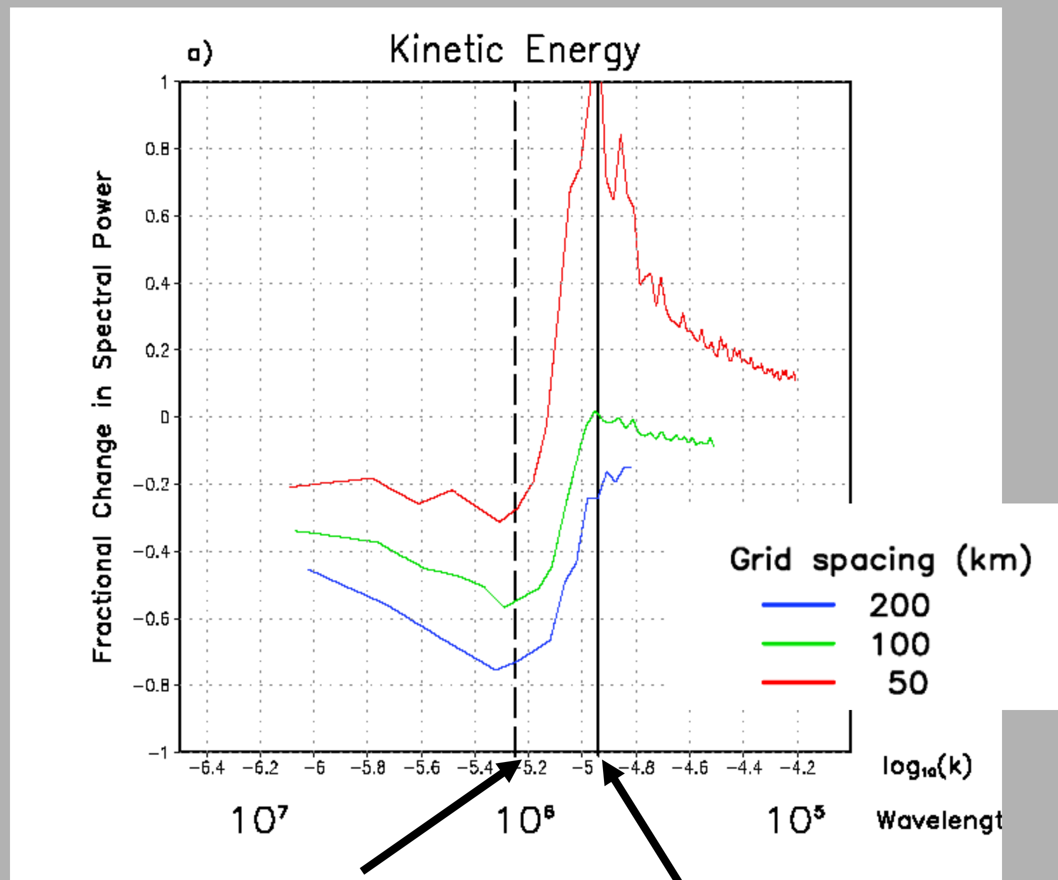
Desired: RCM retains or adds value at the largest scales where the driving GCM or reanalysis has information.

Undesired: RCM loses variability at the largest scales provided by the driving GCM or reanalysis.

Fractional change in spectral power of kinetic energy: RAMS Model

RCM variability MORE than driving reanalysis. VALUE RETAINED OR ADDED

RCM variability LESS than driving reanalysis. VALUE LOST

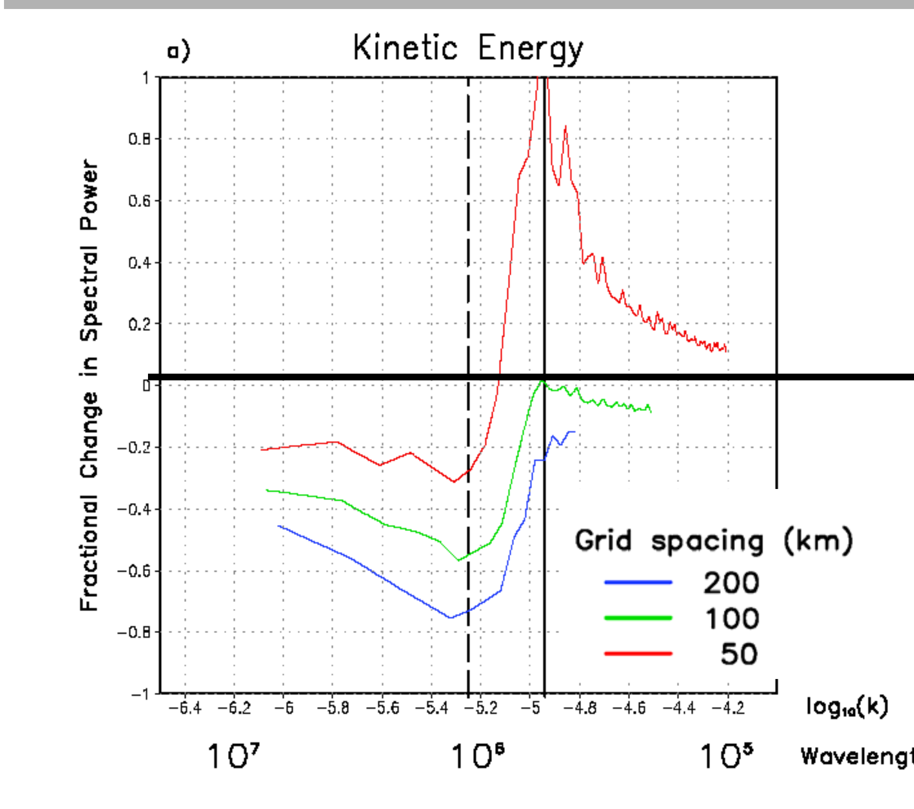


Shortest physically resolved wavelength in reanalysis (4Δx)

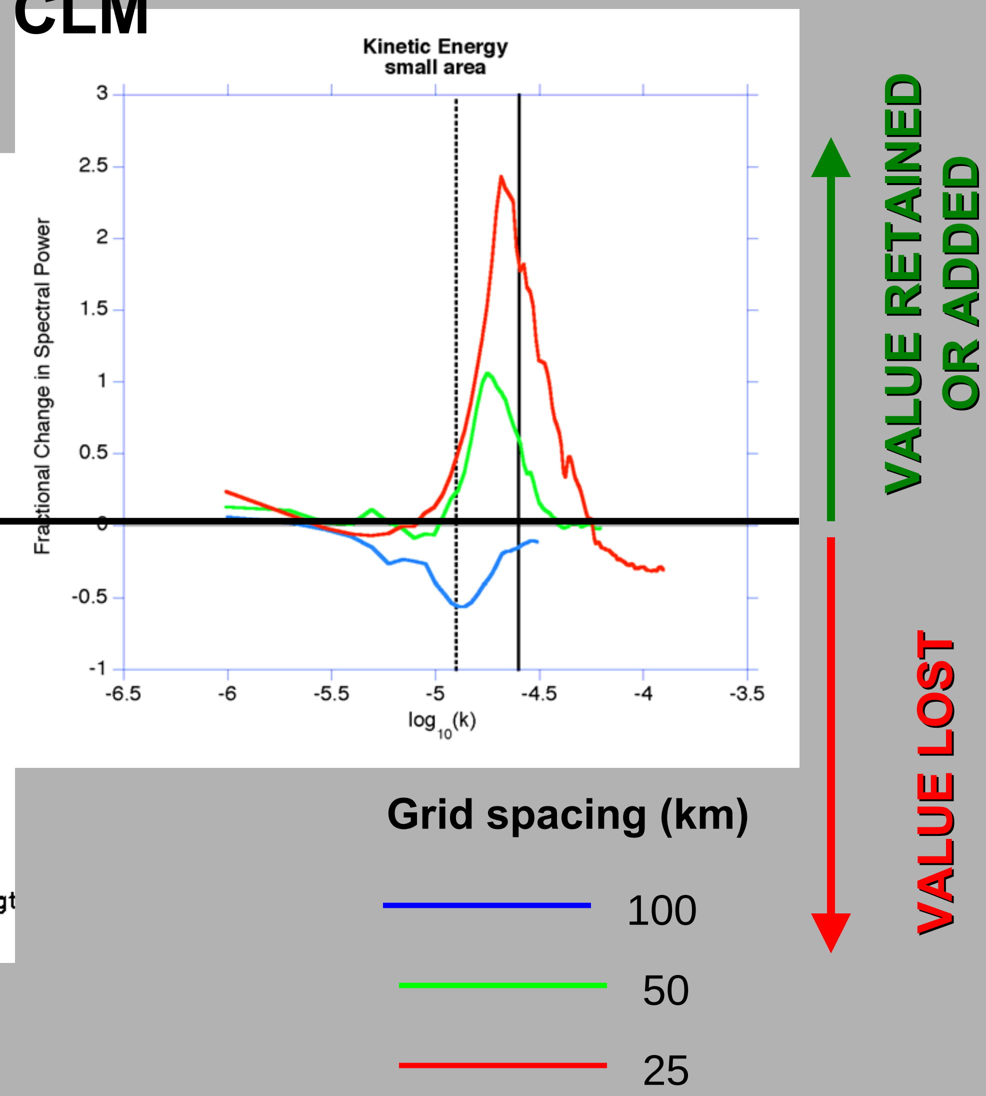
Nyquist frequency of reanalysis (2Δx)

Is the same behavior present in CLM?

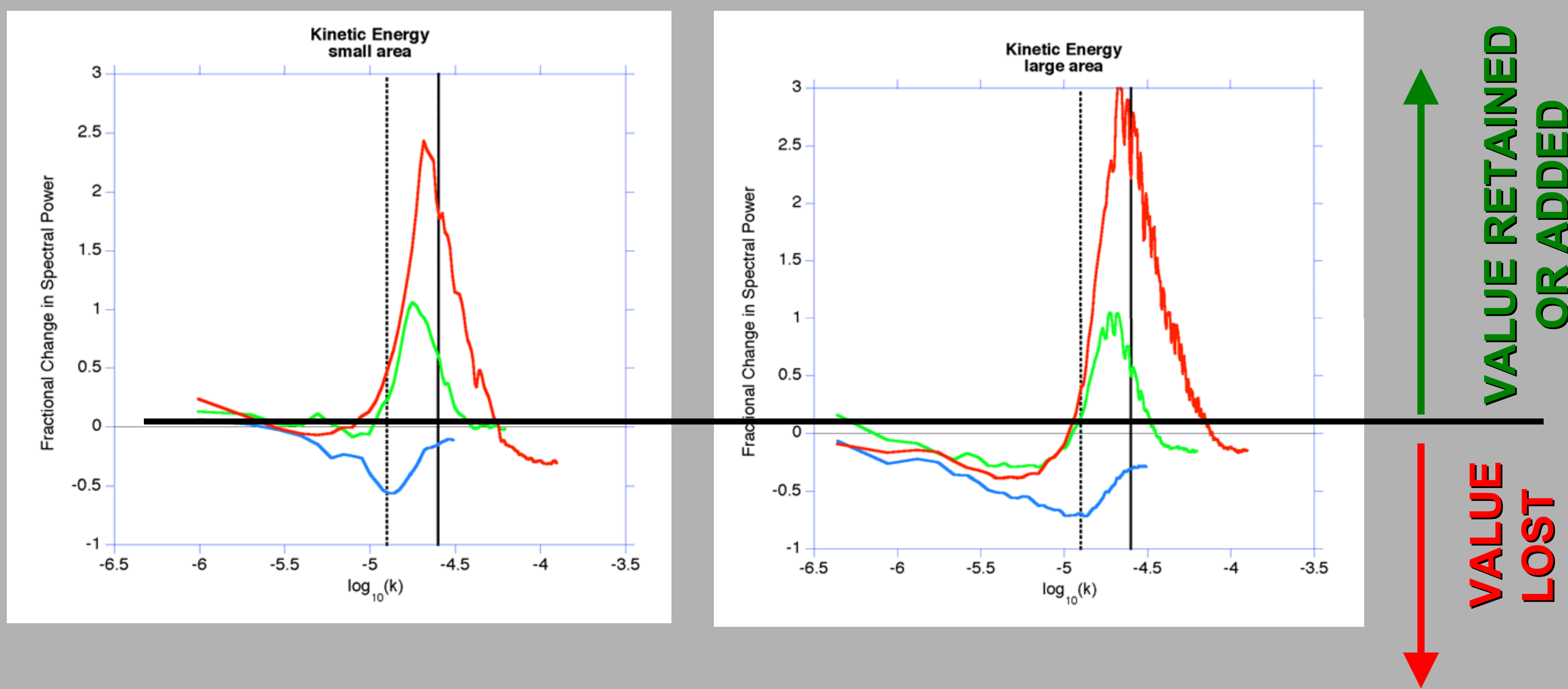
RAMS



CLM



CLM: Small vs. Large Domains



Grid spacing (km)

100

50

25

Even greater loss of large-scale variability with a larger domain. RAMS generates identical result.

Quantitative analysis of value added by RCM at small scales

Compute 2-D power spectrum for a given model variable as a function of wavelength (Errico 1985). Do for RCM with and without interior nudging.

Appropriate variable for small-scale: moisture flux convergence

Average power spectra of last 15 days of simulation.

Compute the ratio of average of the power spectra of RCM with interior nudging vs. RCM with no interior nudging.

RAMS: Interior nudging at all wavelengths

CLM: Spectral nudging for largest wavelengths only

Desired: Interior nudging does not reduce variability at the smaller scales where the RCM is adding information.

Undesired: Interior nudging reduces variability at the smaller scales.

Spectral nudging in brief

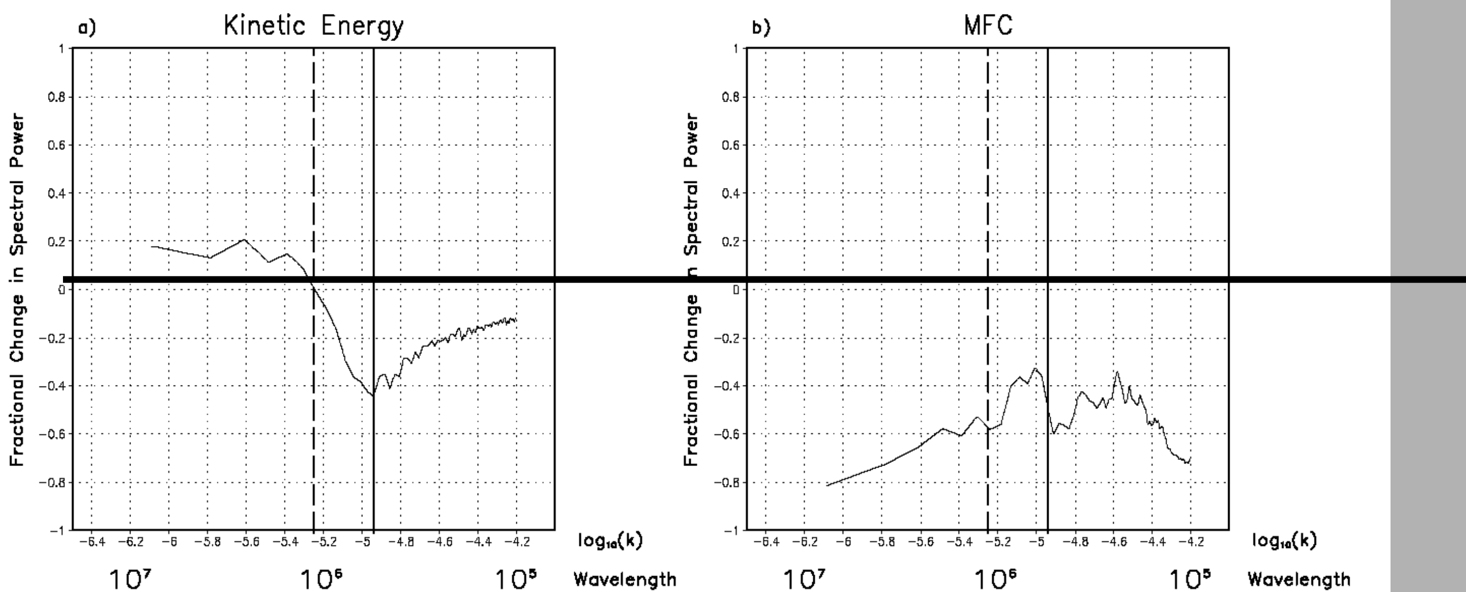
We apply at scales greater than 4Δx of driving global model

Form of nudging coefficients for a given model variable in spectral domain:

$$\sum_{j=-J_a,k=-K_a}^{J_a,K_a} \eta_{j,k}\left(\alpha_{j,k}^{a}(t)-\alpha_{j,k}^{m}(t)\right)e^{ij\lambda/L_\lambda}e^{ik\phi/L_\phi}$$

$\alpha_{j,k}^{a}(t)$	**Fourier expansion coefficients of variable in driving larger-scale model (*a*)**
$\alpha_{j,k}^{m}(t)$	**Fourier expansion coefficients of variable in the regional model (*m*)**
$\eta_{j,k}$	**Nudging coefficient. Larger with increasing height.**

Change in spectral power of KE and MFC with internal nudging in RAMS



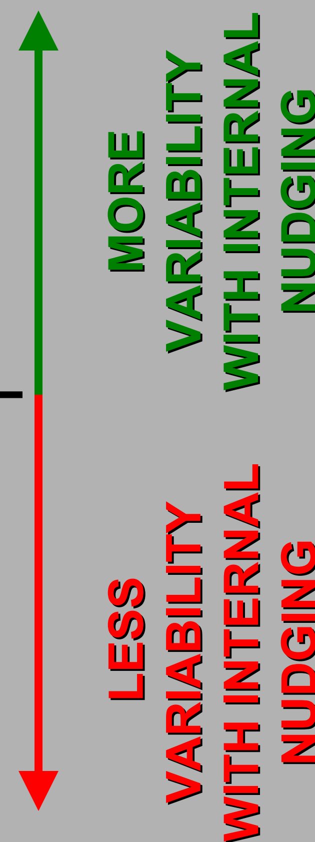
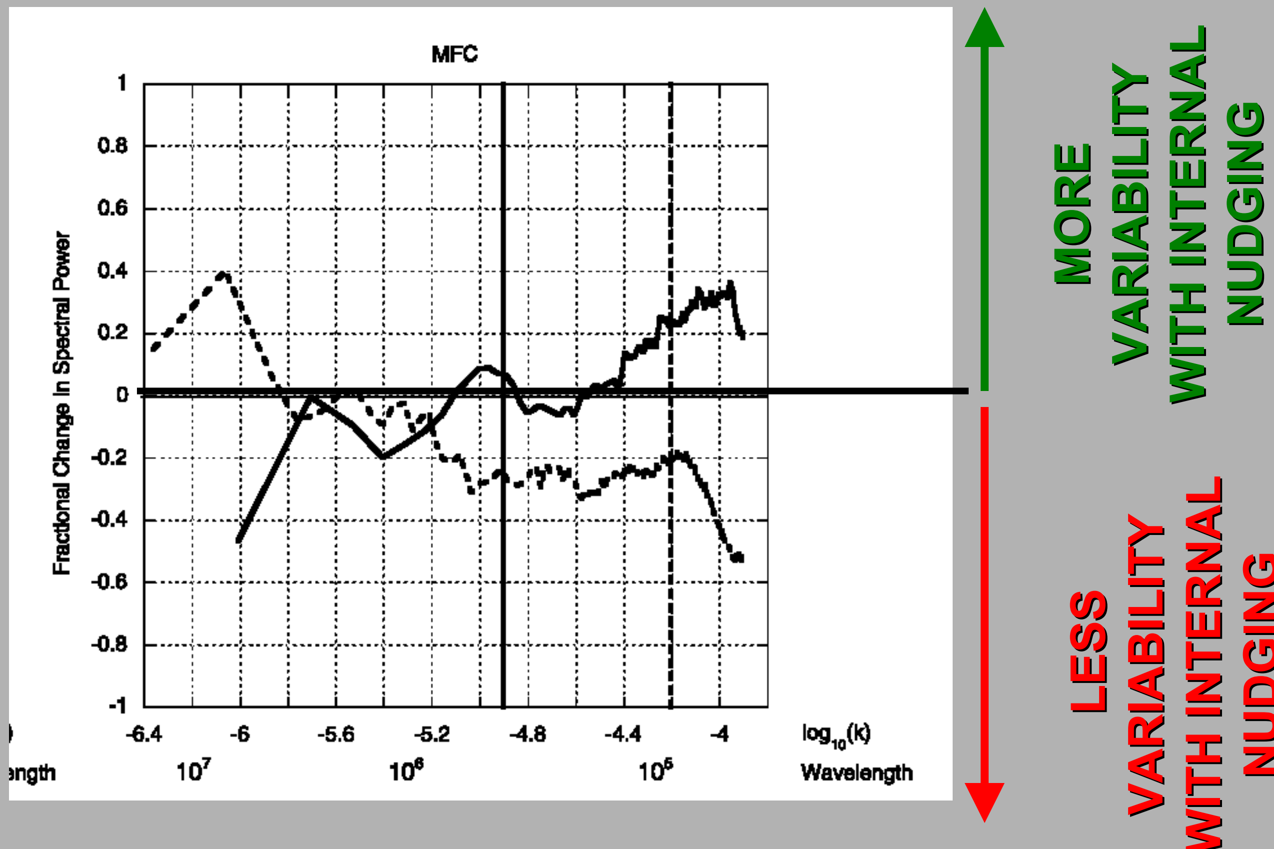


Figure 9. Average fractional change in spectral power ($\Delta S(k)_{frac}$) versus $\log_{10}(k)$ and wavelength for (a) column-averaged kinetic energy and (b) column integrated moisture flux convergence (MFC), Follow-on 1 (internal nudging). The dashed black line indicates k^*_{max}, and the solid black line indicates $k^*_{Nyquist}$. k in units of m^{-1}. Wavelength in units of m.

Tradeoff of internal nudging at all wavelengths: weaken variability at small scales where we want the regional model to add information.

Spectral nudging in CLM preserves the small-scale variability, so it's better!

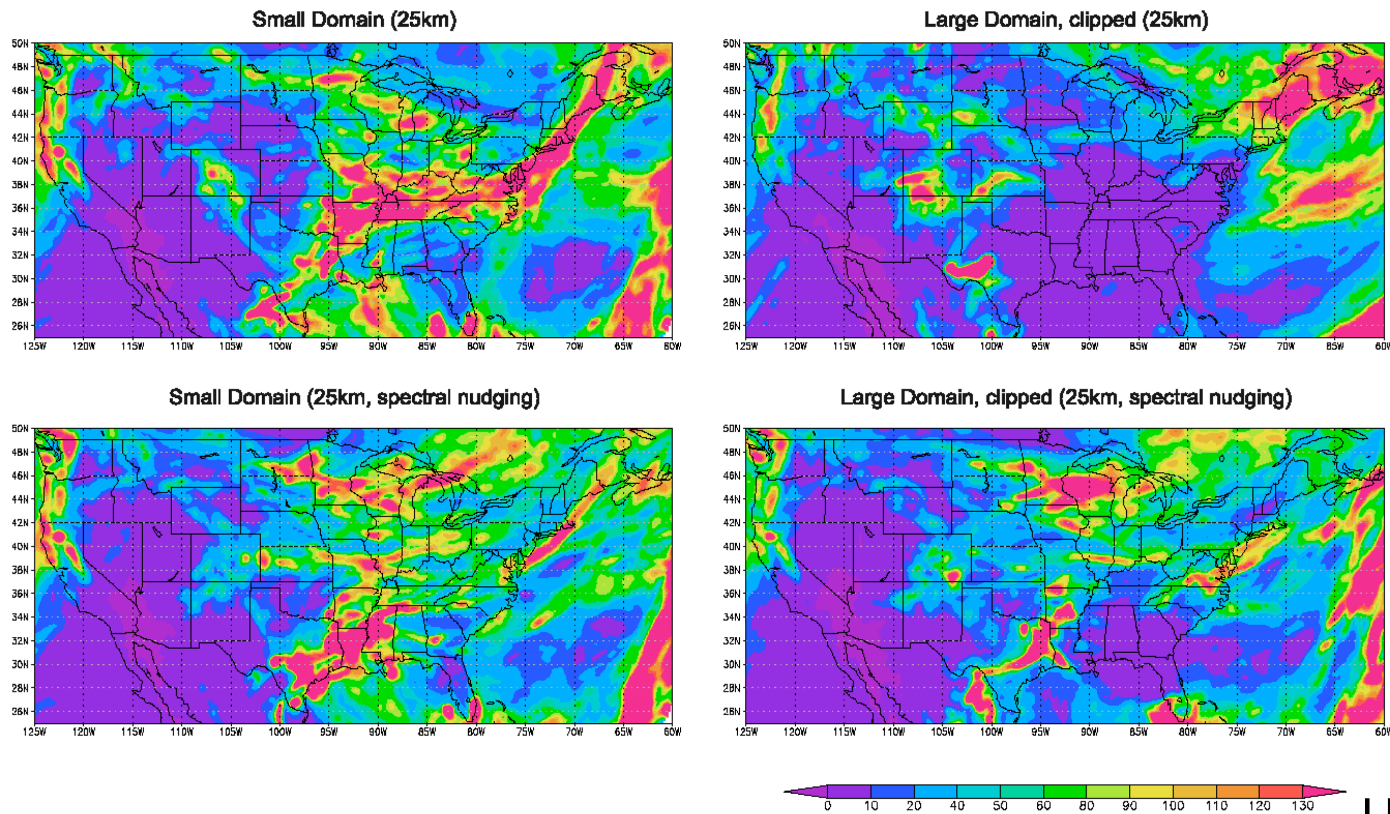


Small domain

Large domain

Δx = 25km

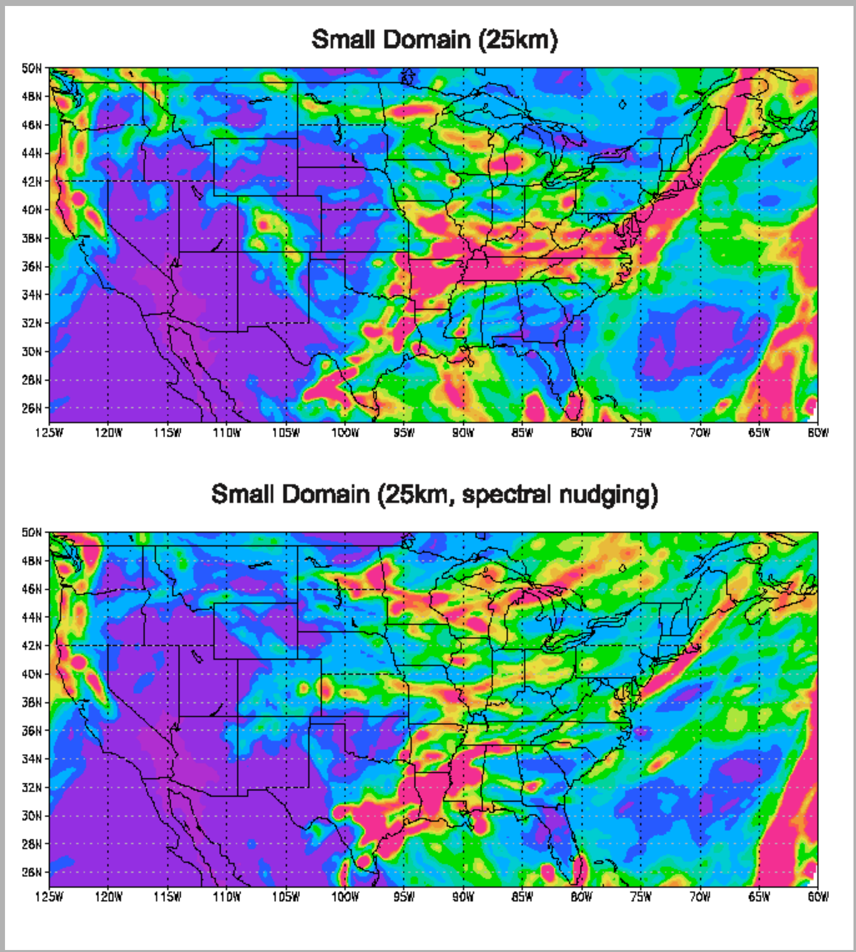
CLM Precipitation for various model configurations

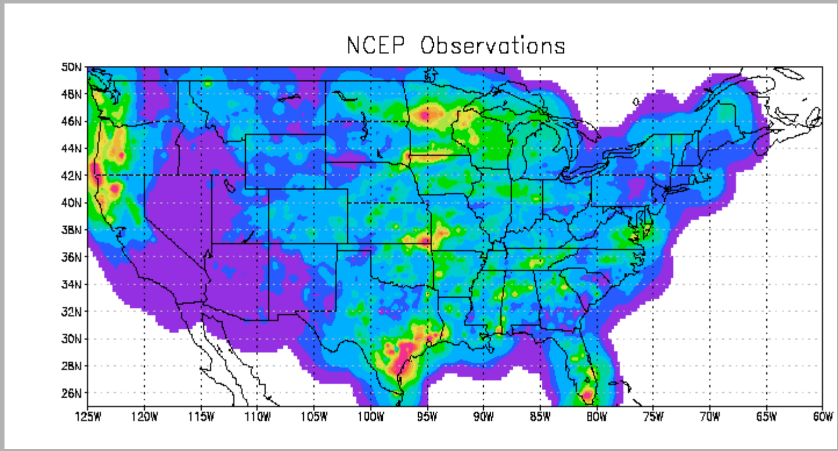


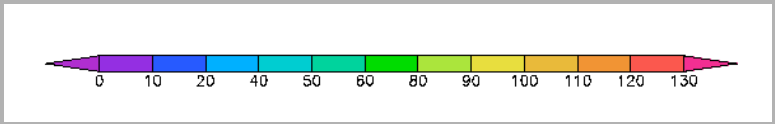
Units: mm

Figure 6. Precipitation results from CLM simulations for the second half of May 1993 without and with spectral nudging in the top and bottom rows, respectively.

CLM Precipitation comparison with observations for small domain







Units: mm

How have we applied these lessons to produce seasonal climate forecasts and climate change projections using WRF?

Assumption: exactly the same behavior will exist for Type III and Type IV dynamical downscaling

Use of WRF for Downscaling of CFS Reforecasts for Warm Season

The version of WRF we use is the Advanced Research WRF (ARW)

Model physical parameterizations consistent with those of the existing WRF NWP System at UA. Use NARR soil moisture as an initial condition.

Summer reforecasts specifically start at the beginning of April, May, or June of the given year for period 1982-2000. WRF simulations start at beginning of May or June and end in August. Only 3 ensemble members available per initialization period, unfortunately!

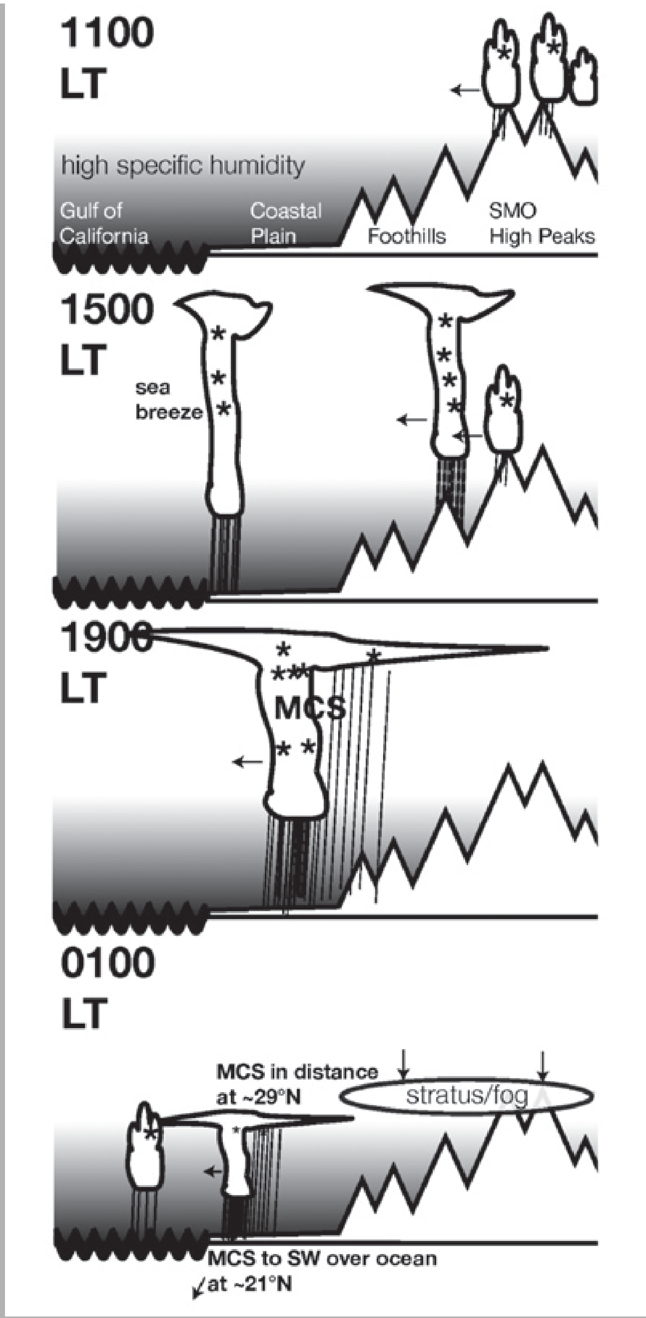
Data from NCEP reanalysis 2 is also being dynamically downscaled to assess the performance of the RCM assuming “perfect” boundary forcing.

The domain for these simulations covers the contiguous U.S. with a grid spacing of 32 km.

A brief digression…

What do we need to get "right" in simulating the warm season in North America, in particular the North American Monsoon?

Short answer:
Physical processes that encompass both "large" and "small" scales



(Nesbitt et al. 2008)

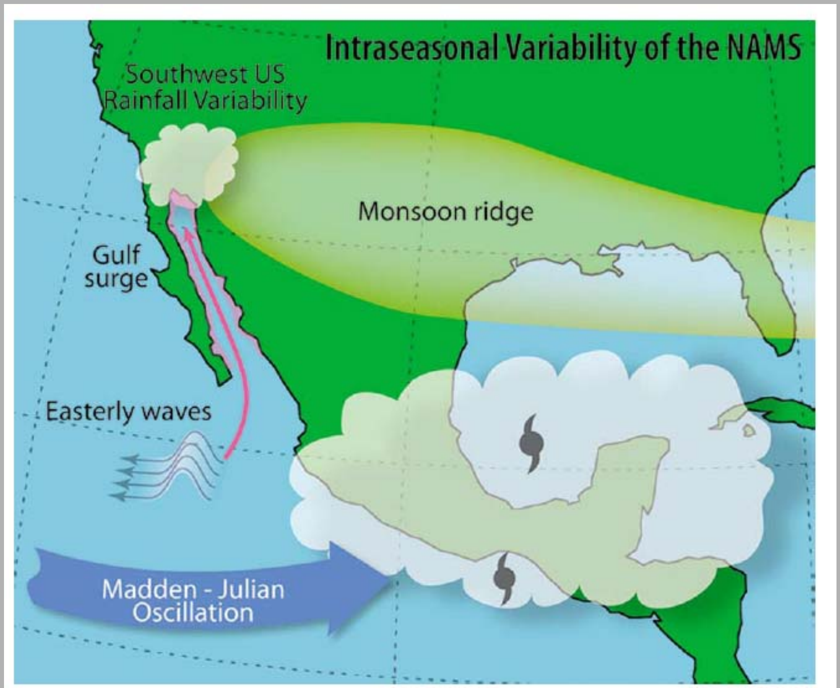
Diurnal Cycle of Convection
Most important

Convective clouds form over the mountains in the morning.

By afternoon and everning storms propagate to the west towards the Gulf of California where they can organize into mesoscale convective systems if there is sufficient moisture and instability.

It's likely that a resolution less than 5 km is necessary to represent this process correctly in regional models. Global models pretty much fail.

Intraseasonal variability



(Moloney et al. 2008)

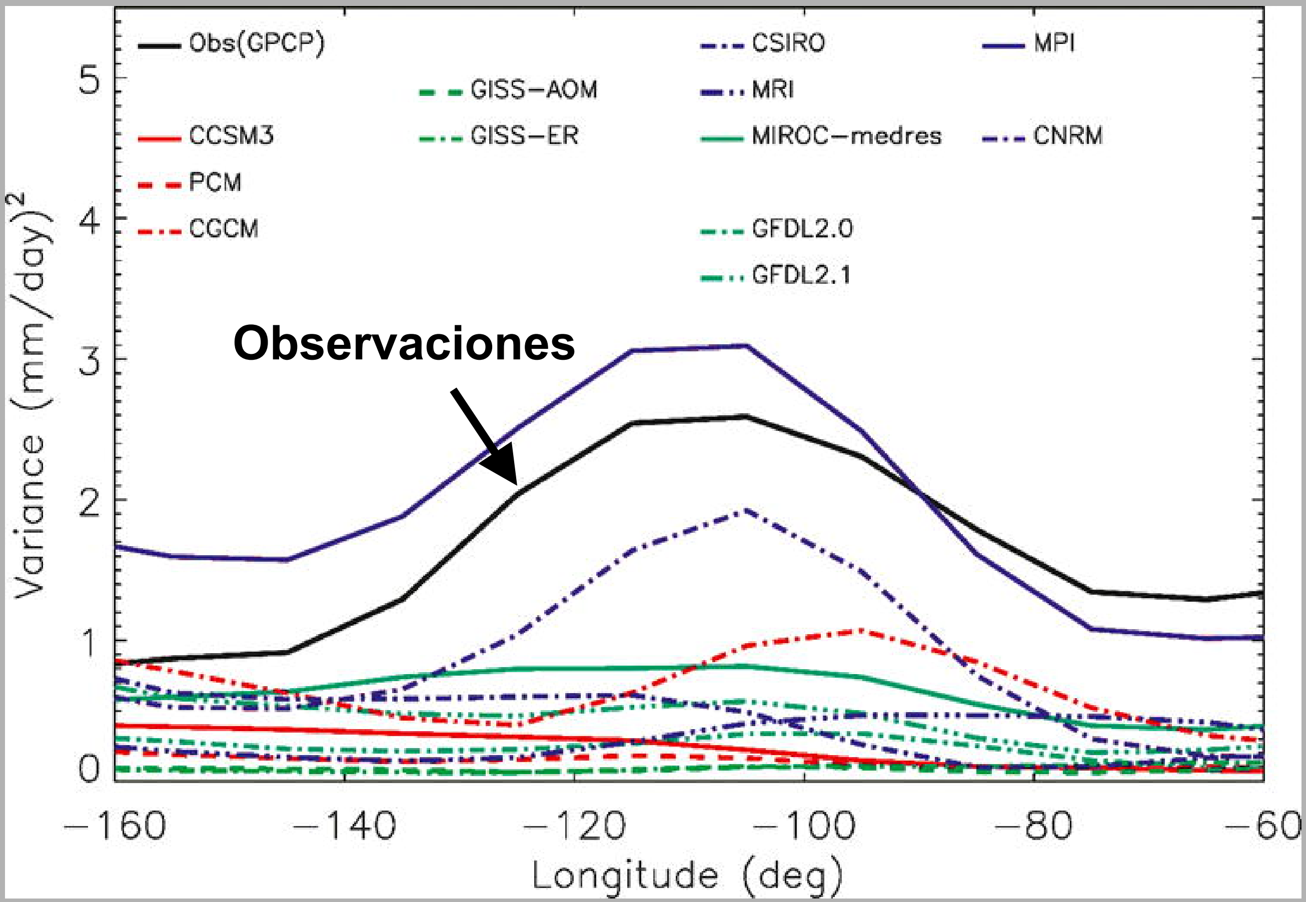
Includes:

- **Easterly waves**
- **Tropical cyclones**
- **Low level moisture surges**
- **Upper level disturbances**
- **Madden Julian Oscillation**

All these factors can help convection organize and intensify.

Can IPCC models represent easterly waves?

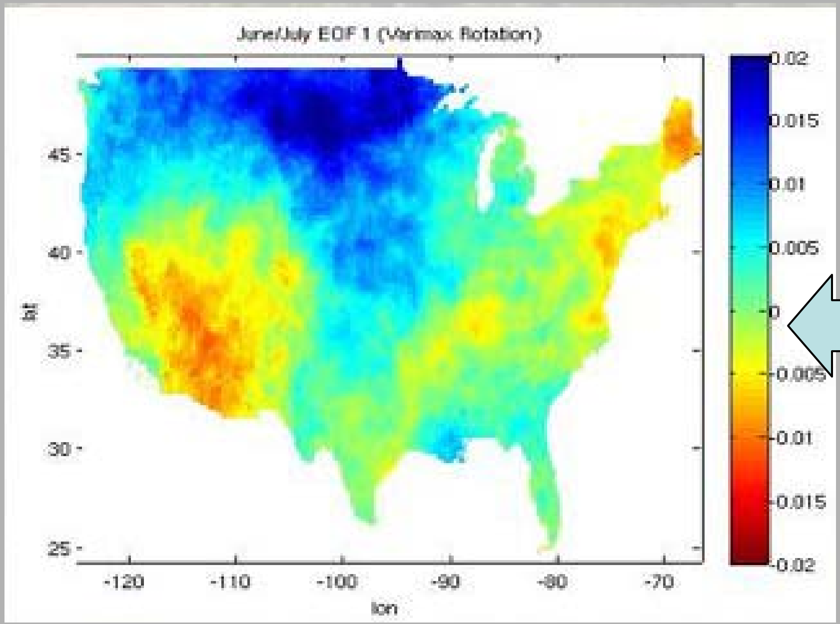
Their variability from 10 to 20º N during the warm season



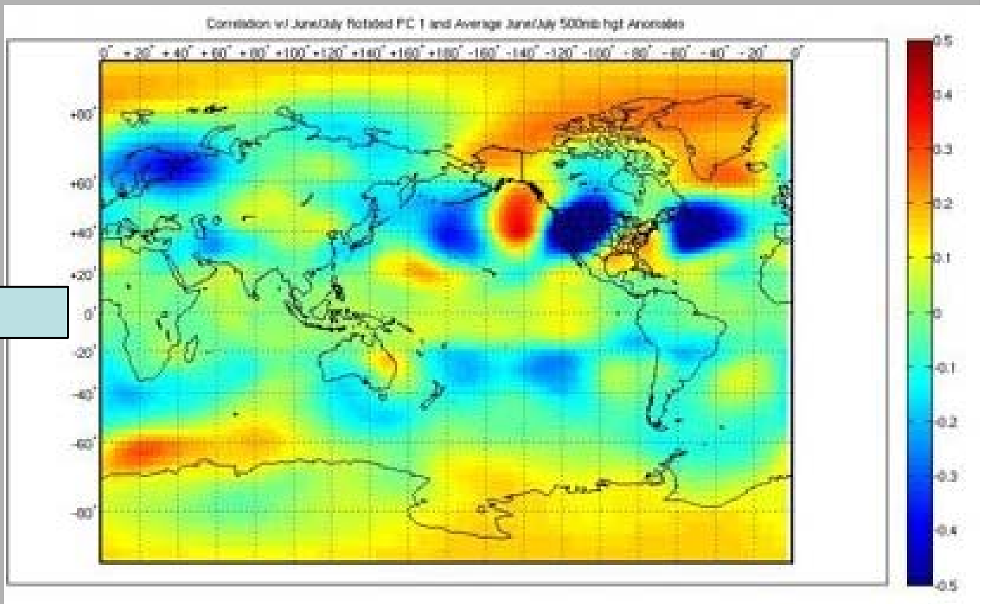
Lin et al. (2009)

Monsoon Interannual Variability

<u>Idea</u>: Atmospheric teleconnections that originate in the western Pacific (and maybe other places) affect the distribution and amount of rainfall, especially in the early part of the summer.



The dominant spatial pattern of precipitation anomalies (SPI) in early summer.



Its relationship to large-scale circulation (500-mb height anomalies).

Ciancarelli et al. (2009)

So how does WRF perform for the 1993 case, with respect to type II and III dynamical downscaling?

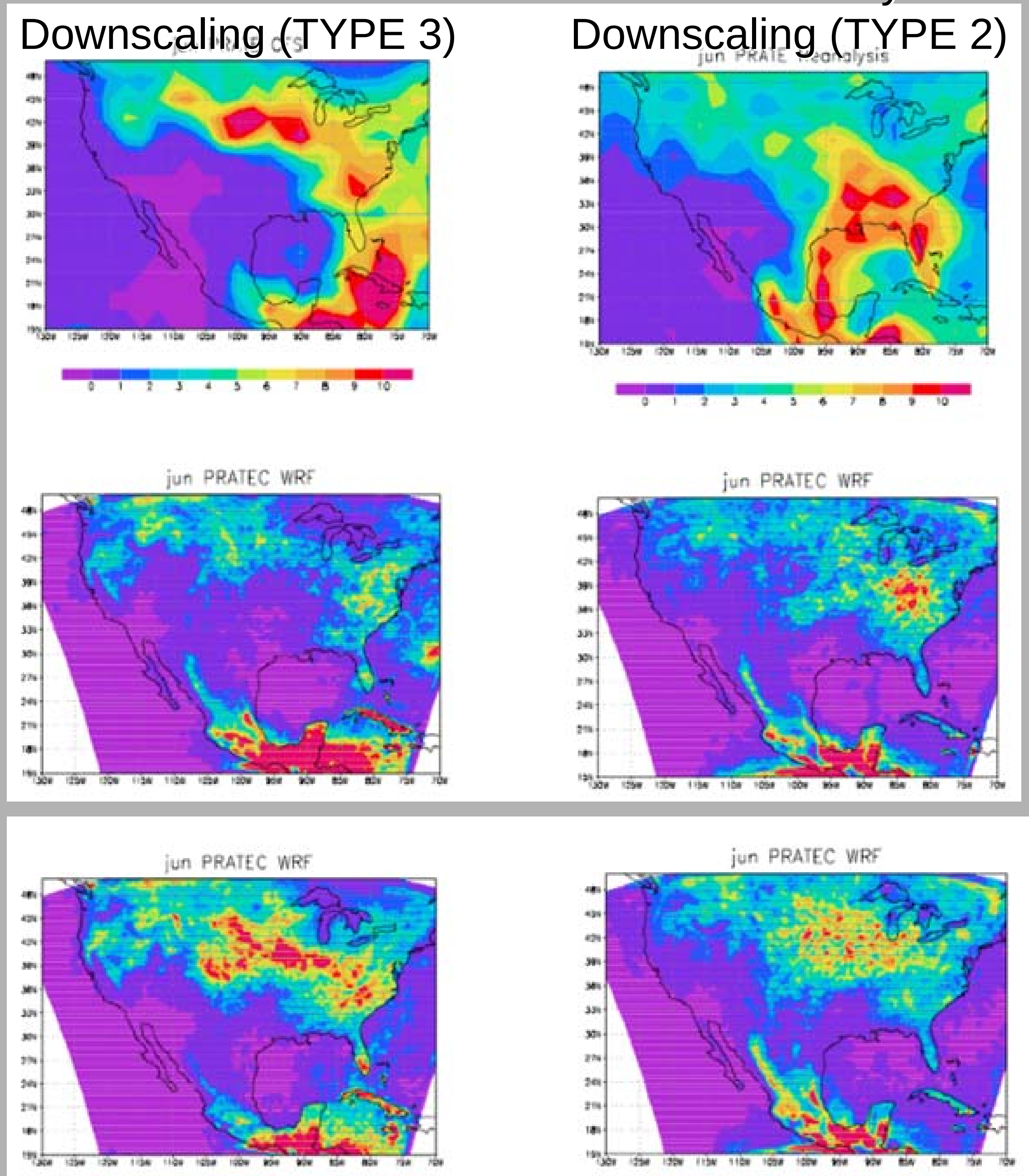
CFS member
Downscaling (TYPE 3)

NCEP Reanalysis:
Downscaling (TYPE 2)

Original
Global model

WRF
Lateral boundary
nudging only

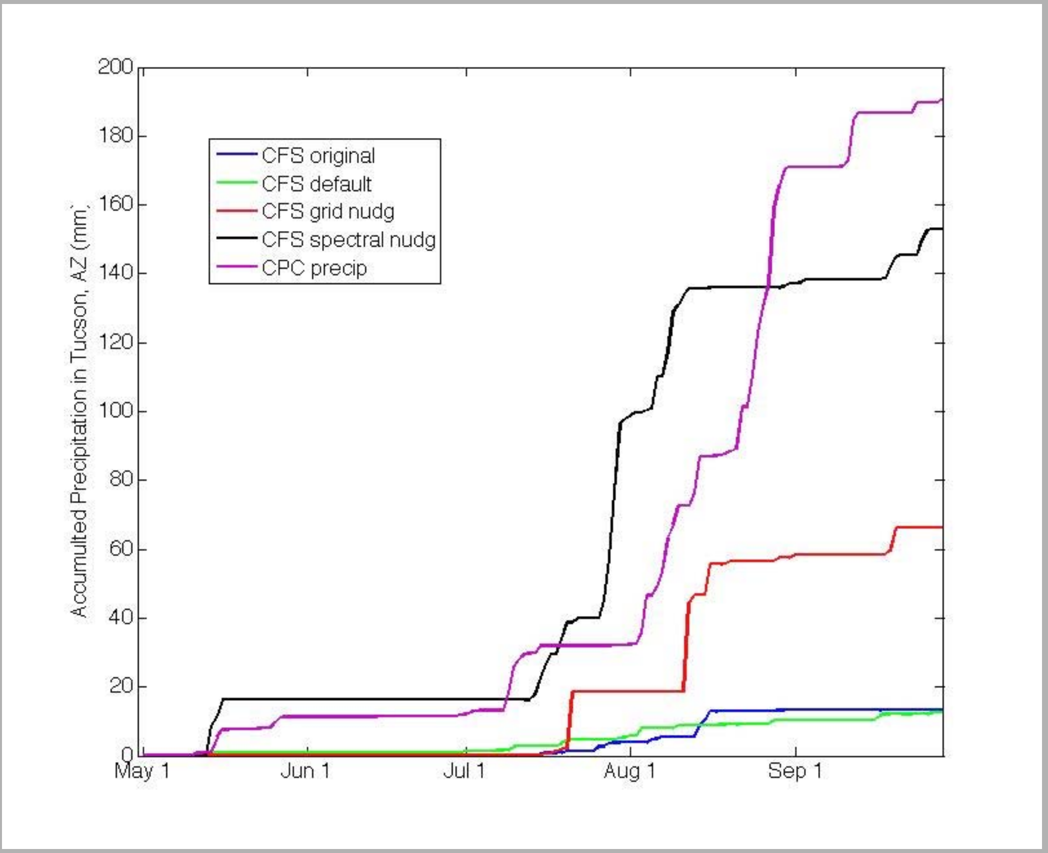
WRF
Spectral nudging



June precipitation solutions for one ensemble member (mm day^{-1})

1993 Summer precipitation Tucson, AZ

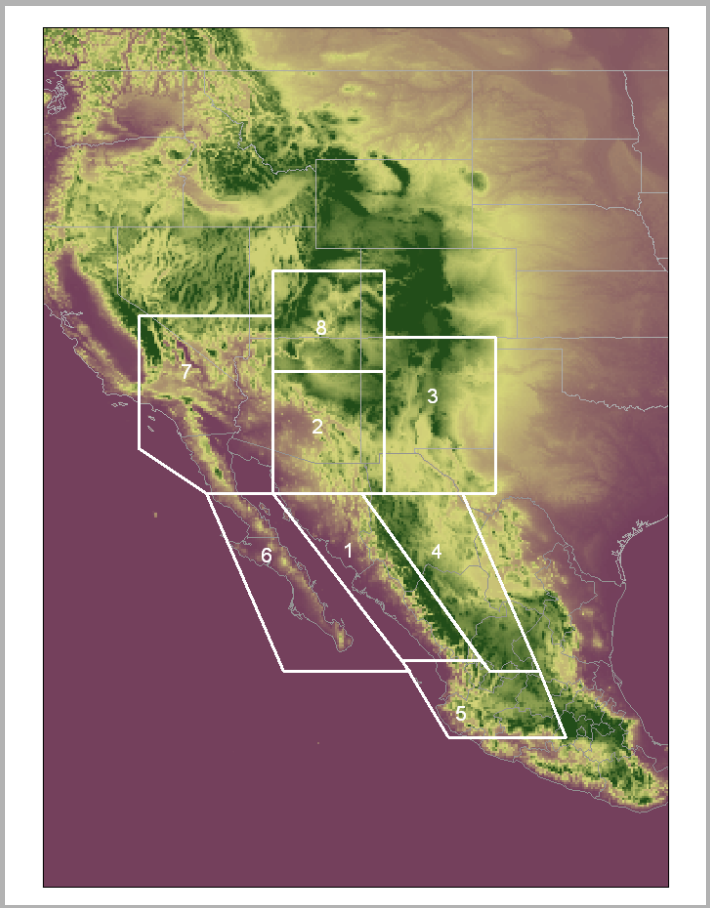
Single CFS ensemble member initialized in May

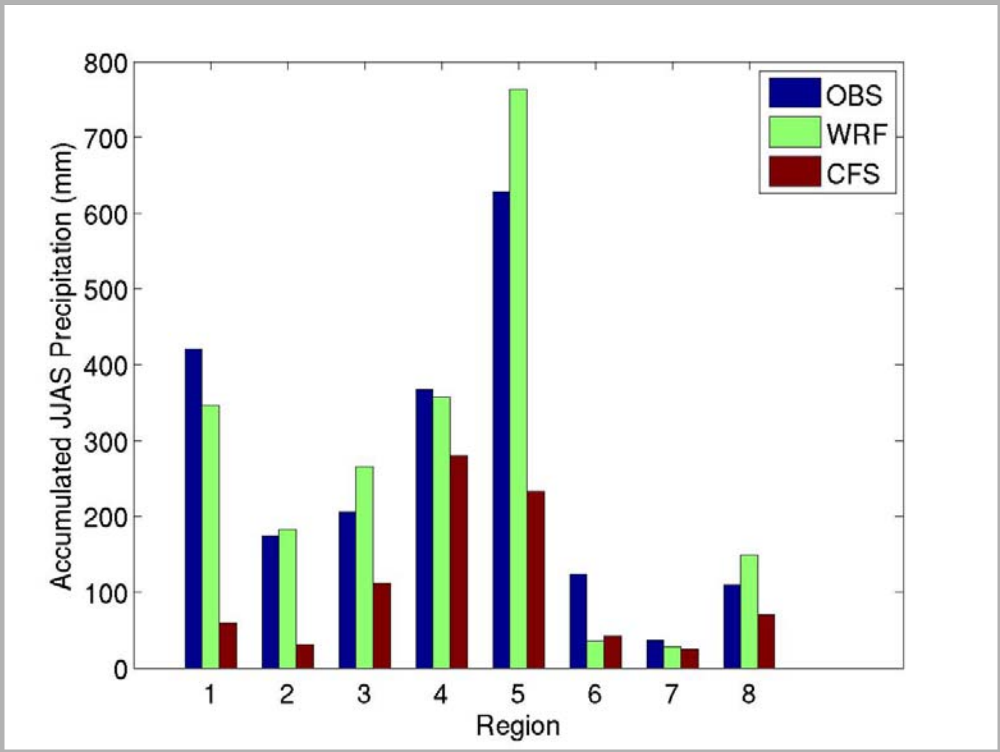


WRF downscaled simulation with spectral nudging gives best result!

Original CFS model <u>and</u> WRF-CFS downscaled with no interior nudging HAVE NO MONSOON!

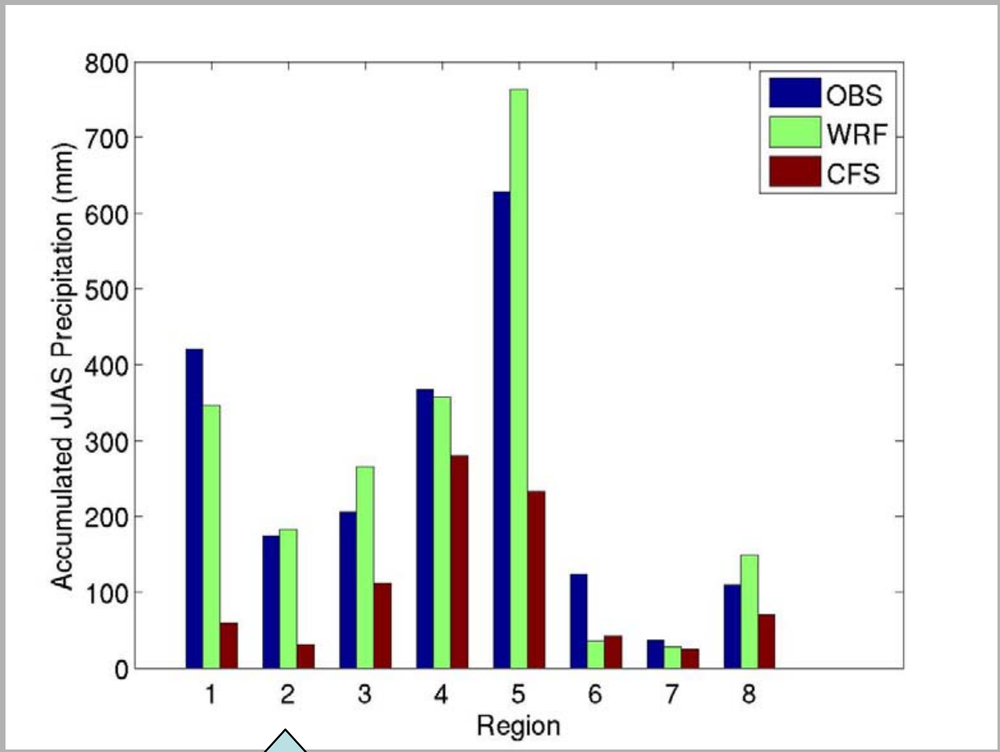
Climatology of WRF-CFS downscaled simulations with spectral nudging vs. original CFS and observations





A better representation of the diurnal cycle of convection explains the dramatic improvement in precipitation by the RCM

Climatology of WRF-CFS downscaled simulations with spectral nudging vs. original CFS and observations



Southeast Arizona

Monsoon Ridge Position at Onset (Late June, July)

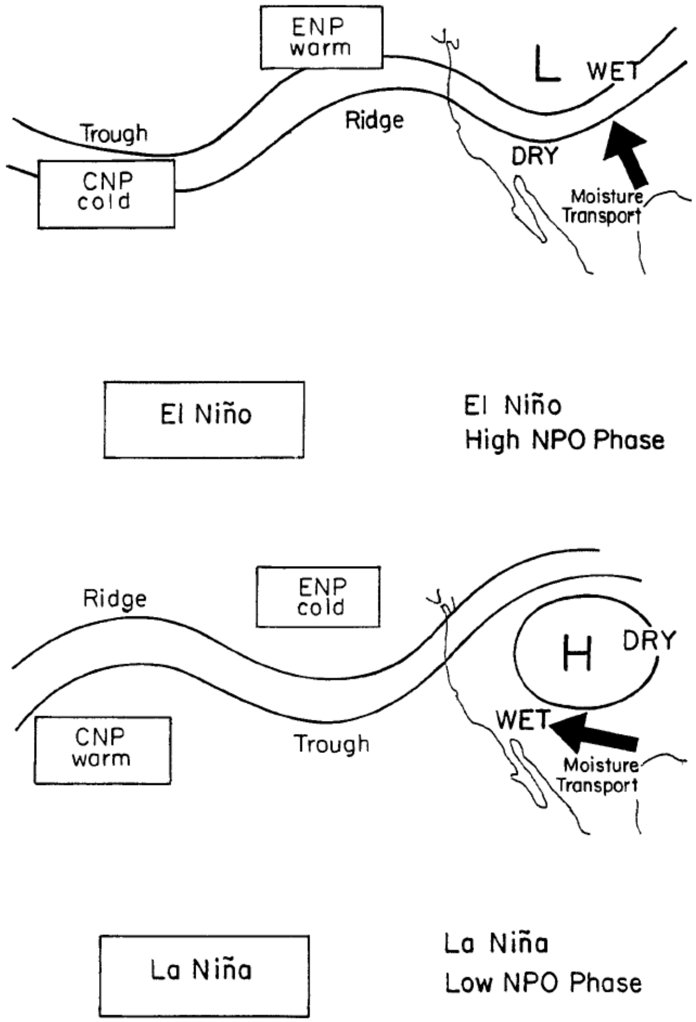


FIG. 14. Idealized relationship of monsoon ridge position and midlevel moisture transport to Pacific SSTs at monsoon onset.

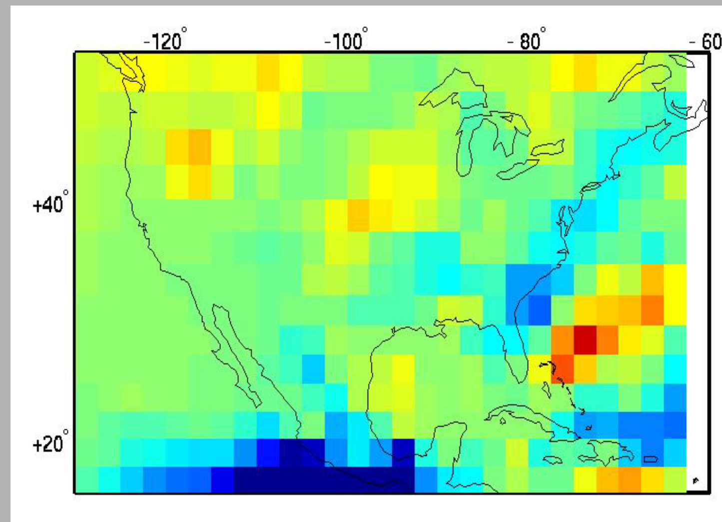
Climatology delayed

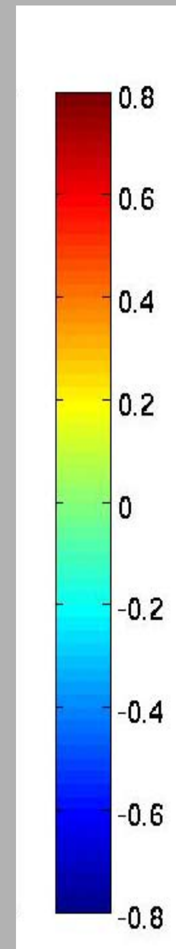
Climatology accelerated

(Castro et al. 2001)

July Precipitation regression coefficient with index based on dominant Pacific SST modes

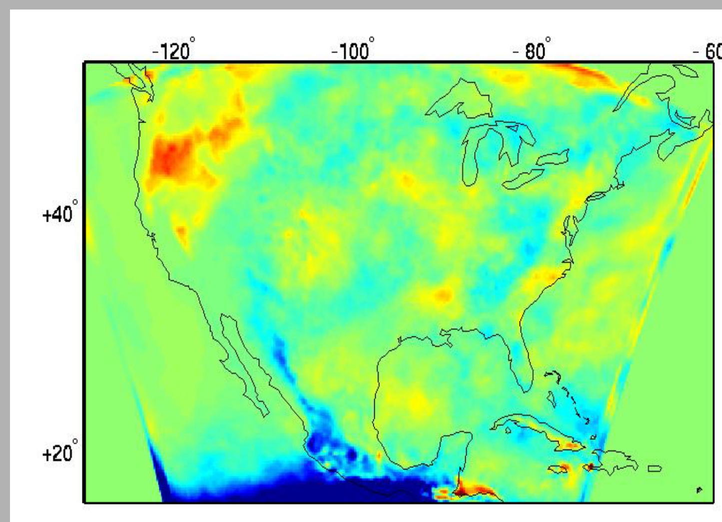
Original CFS Ensemble Average



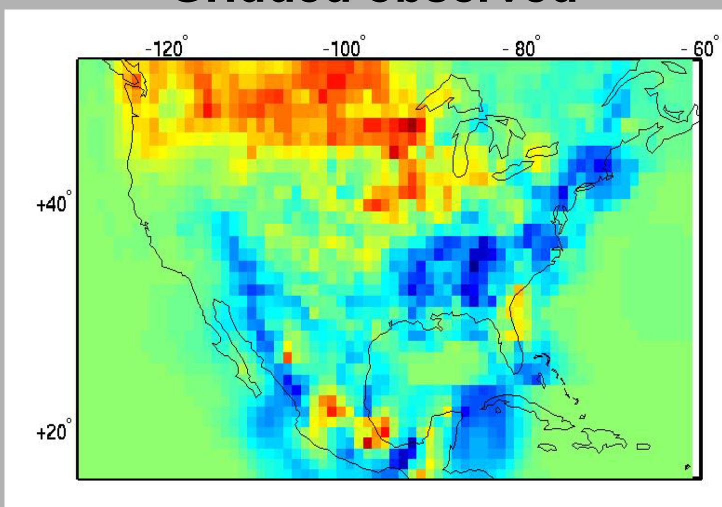


mm day^{-1}

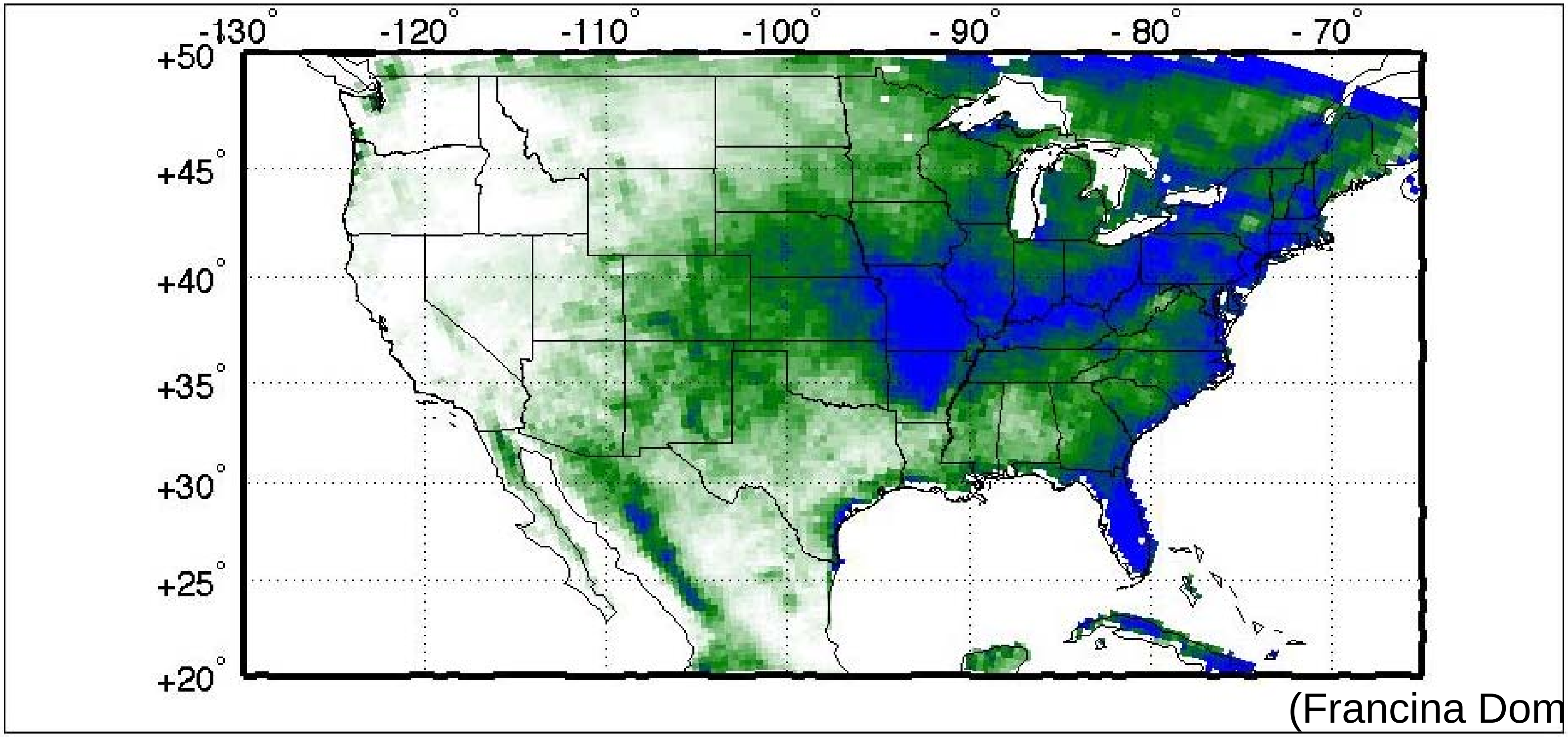
WRF-CFS Downscaled Ensemble Average



Gridded observed



Type 4 dynamical downscaling: Use of WRF to make climate change projections…



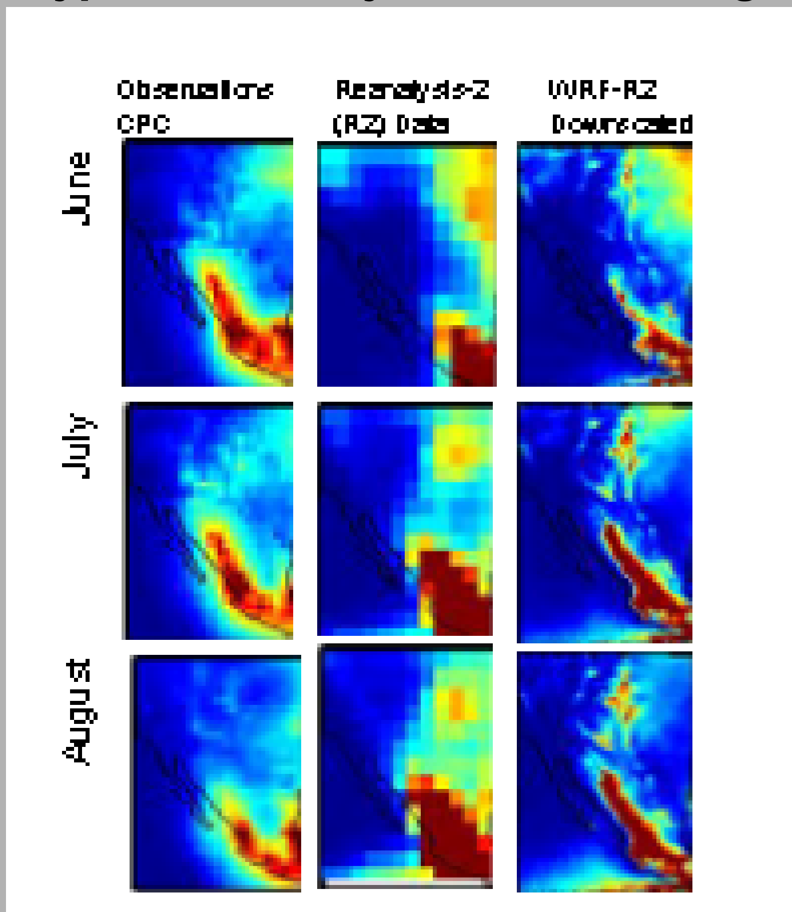
(Francina Dominguez)

Example of WRF-simulated precipitation in July 2010. This simulation uses the HadCM3 model as the driving GCM.

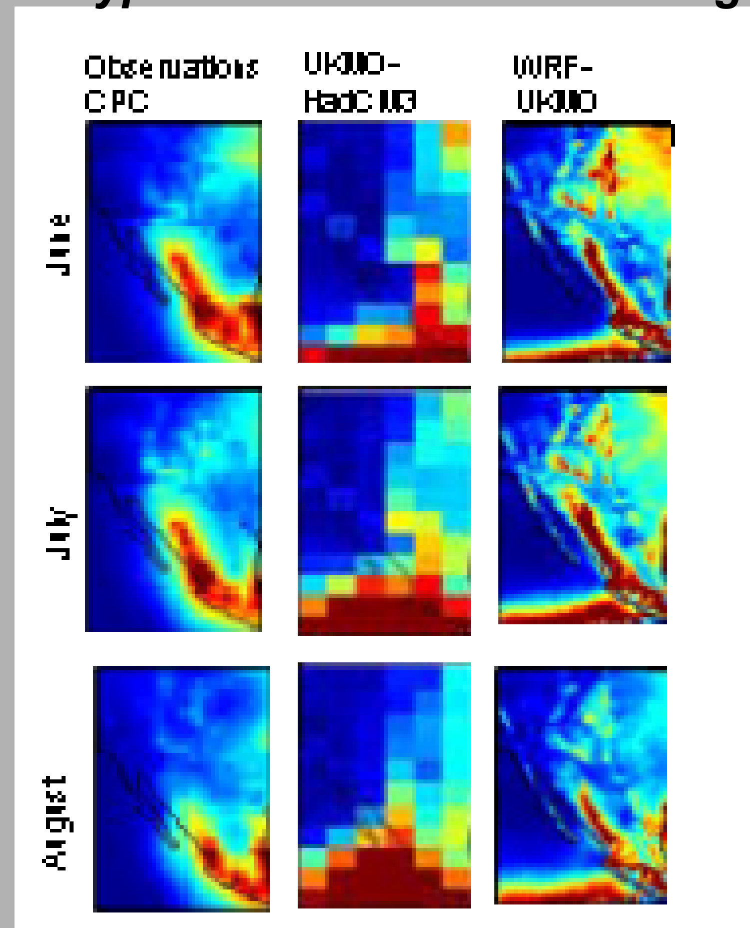
Some recent WRF-HadCM3 results presented DOE PIs meeting last week…

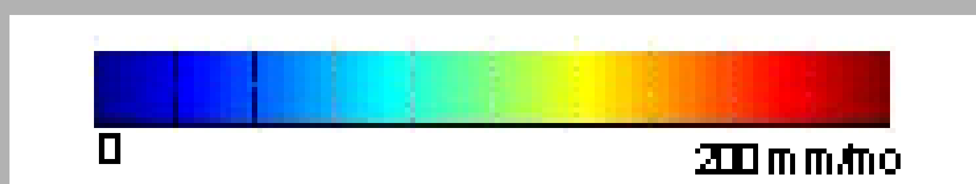
NA Monsoon region summer (JJA) precipitation

Type 2: Reanalysis downscaling

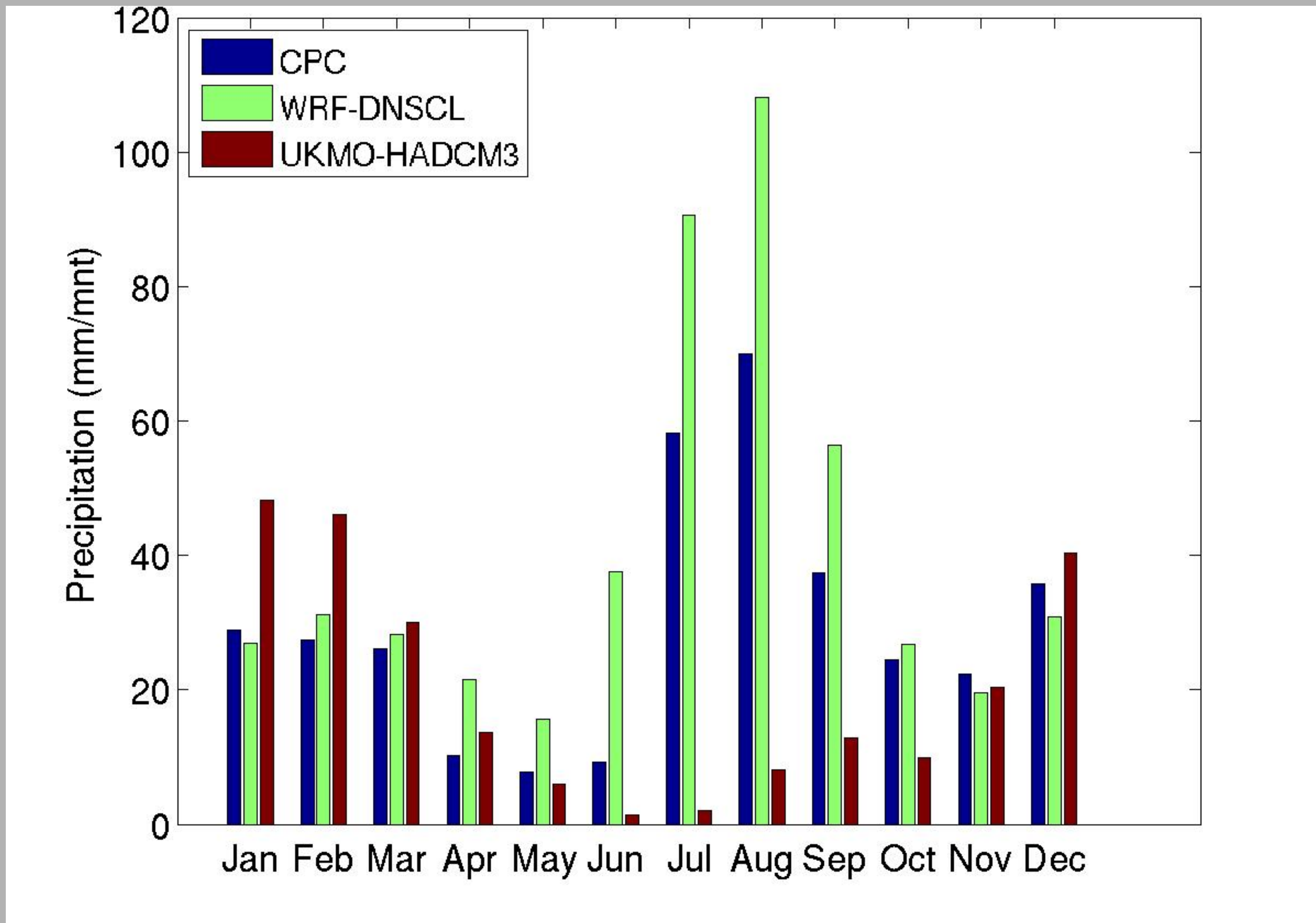


Type 4: HadCM3 downscaling

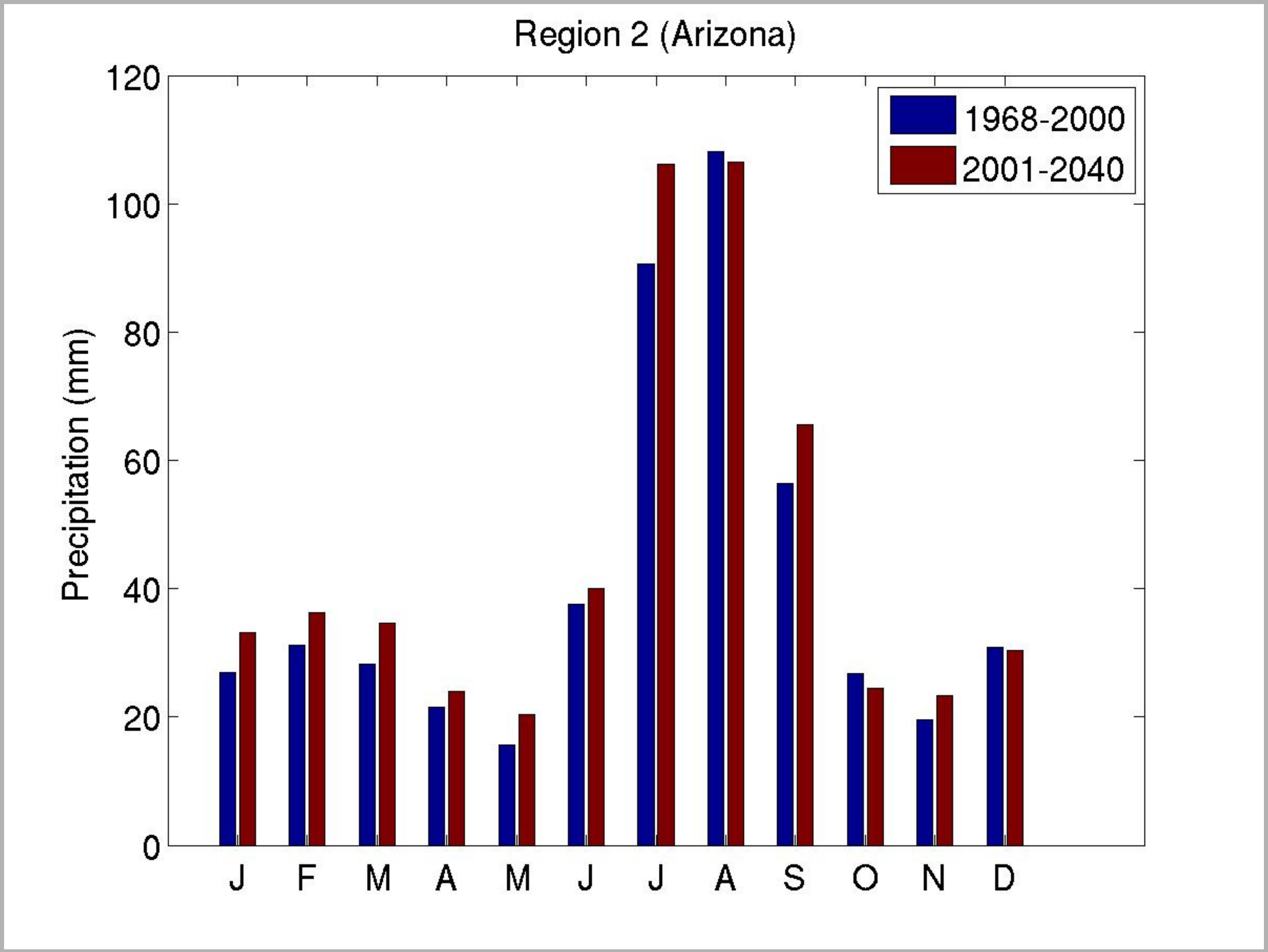




Annual precipitation evolution for Arizona



Change in dynamically downscaled precipitation in Arizona



Conclusions

•The results for CLM reported in *Rockel et al.* (2008) are similar to those found in the RAMS study by *Castro et al.* (2005) for basic experiments using nudging only in a lateral boundary sponge zone. In both models, there is a loss of large-scale variability with increasing domain size and grid spacing.

•Internal nudging can alleviate loss of large-scale variability in both RCMs.

• Spectral nudging yields less reduction in added variability of the smaller scales than grid nudging and is therefore the preferred approach in RCM dynamic downscaling. WRF experiments confirm this for higher order downscaling types (Types III and IV).

•Results suggest the effect to be largest for physical quantities in the lower troposphere (e.g. moisture flux convergence, rainfall)

Additional comments

•The utility of all regional models in downscaling primarily is not to add increased skill to the large-scale in the upper atmosphere, rather the value added is to resolve the smaller-scale features which have a greater dependence on the surface boundary.

•However, the realism of these smaller-scale features needs to be quantified, since they will be altered to the extent that they are influenced by inaccurate downscaling of the larger-scale features.

• Though spectral nudging currently presents the best “solution” to ensure variability is retained on the large-scale, we don’t have good explanations as to what causes the loss of variability at the large-scales without it. Should be an area of future study…