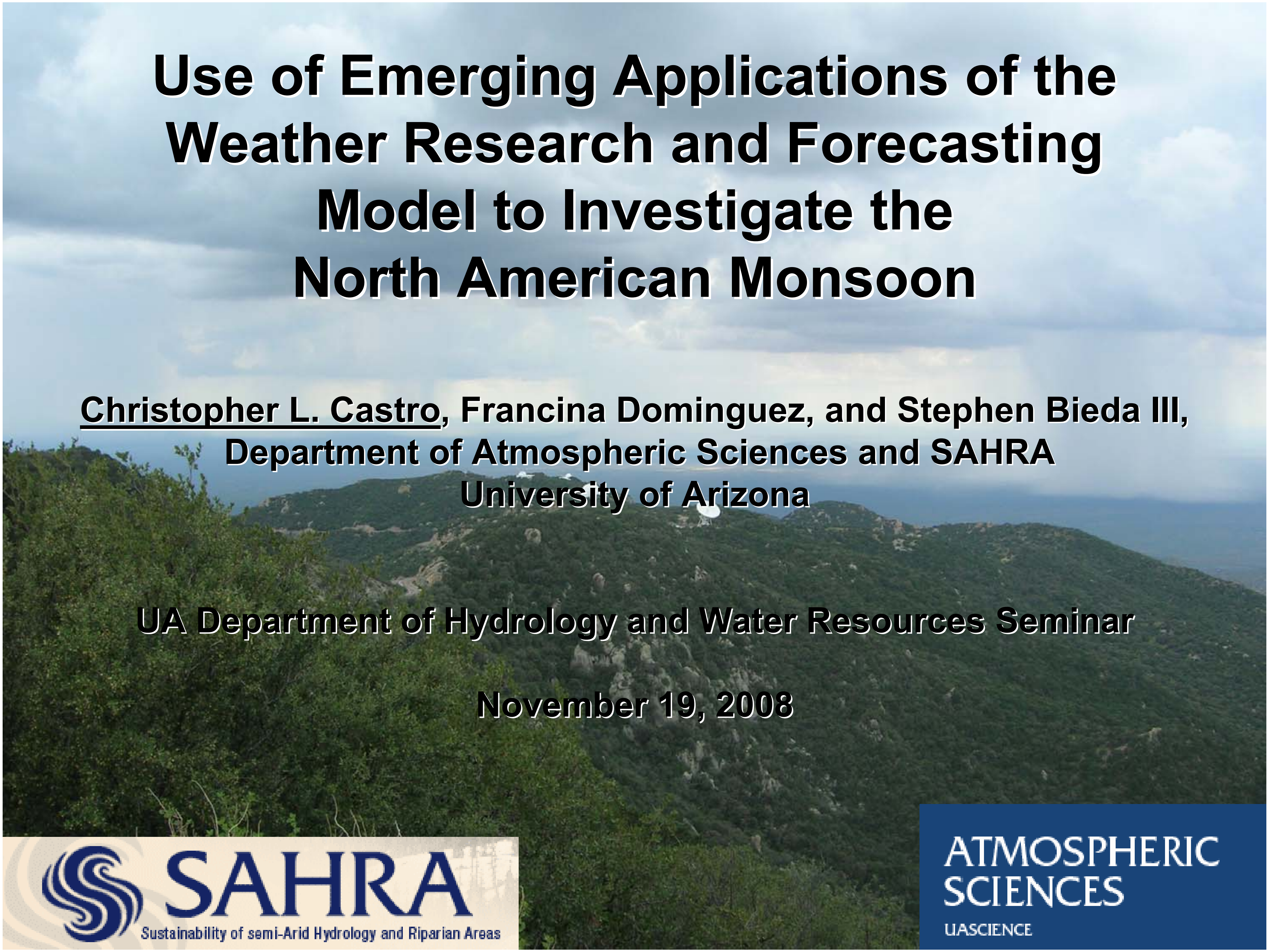

Use of Emerging Applications of the Weather Research and Forecasting Model to Investigate the North American Monsoon

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Department of Atmospheric Sciences and SAHRA
University of Arizona

UA Department of Hydrology and Water Resources Seminar

November 19, 2008

SAHRA
Sustainability of semi-Arid Hydrology and Riparian Areas

ATMOSPHERIC SCIENCES
UASCIENCE

Presentation Outline

What is a regional atmospheric model and why do we use it for dynamical downscaling?

What is WRF and how is it currently being used operationally here at UA?

Recently funded projects which are using WRF

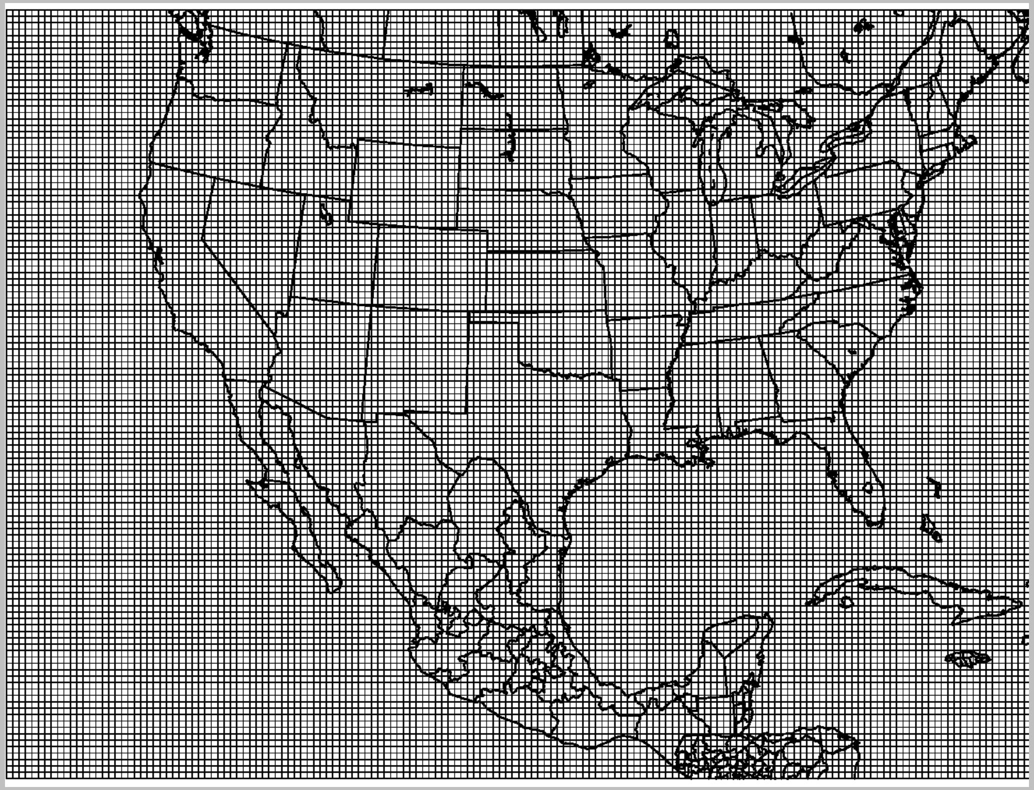
- Short-term monsoon forecasting and adjoint sensitivity (Bieda)
- RCM downscaling of NCEP GCM and IPCC data (Dominguez)

Possible connections to hydrologic applications?

Some slightly modified figures
that I present in my NATS 101 and
graduate modeling courses…

Objective Analysis

Data must be interpolated to some kind of grid so we can run the numerical weather prediction model—this is called the initial analysis.



Grid spacing = 35 km

For a regional model these are equally spaced points.

Structure of atmospheric models

Dynamical Core

Mathematical expressions of

- **Conservation of motion (i.e. Newton's 2nd law $F = ma$)**
- **Conservation of mass**
- **Conservation of energy**
- **Conservation of water**

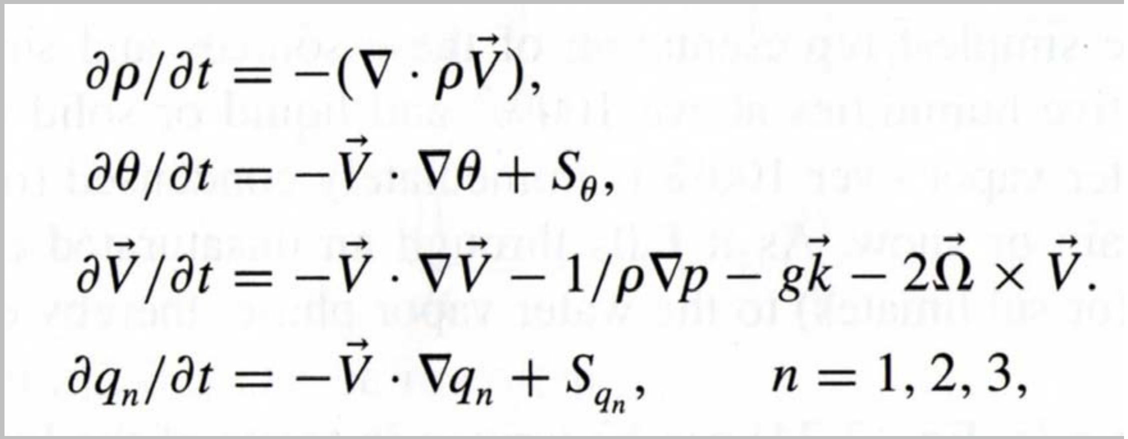
These must be discretized to solve on a grid at given time interval, starting from the initial conditions (analysis).

Parameterizations

One dimensional column models which represent processes that cannot be resolved on the grid.

Called the model "physics"—but it is essentially engineering code.

Equations to represent in dynamic core
MUST SOLVE AT EVERY GRID POINT!



MASS CONSERVATION $\partial\rho/\partial t = -(\nabla \cdot \rho\vec{V}),$

ENERGY CONSERVATION $\partial\theta/\partial t = -\vec{V} \cdot \nabla\theta + S_{\theta},$

CONSERVATION OF MOTION $\partial\vec{V}/\partial t = -\vec{V} \cdot \nabla\vec{V} - 1/\rho\nabla p - g\vec{k} - 2\vec{\Omega} \times \vec{V}.$

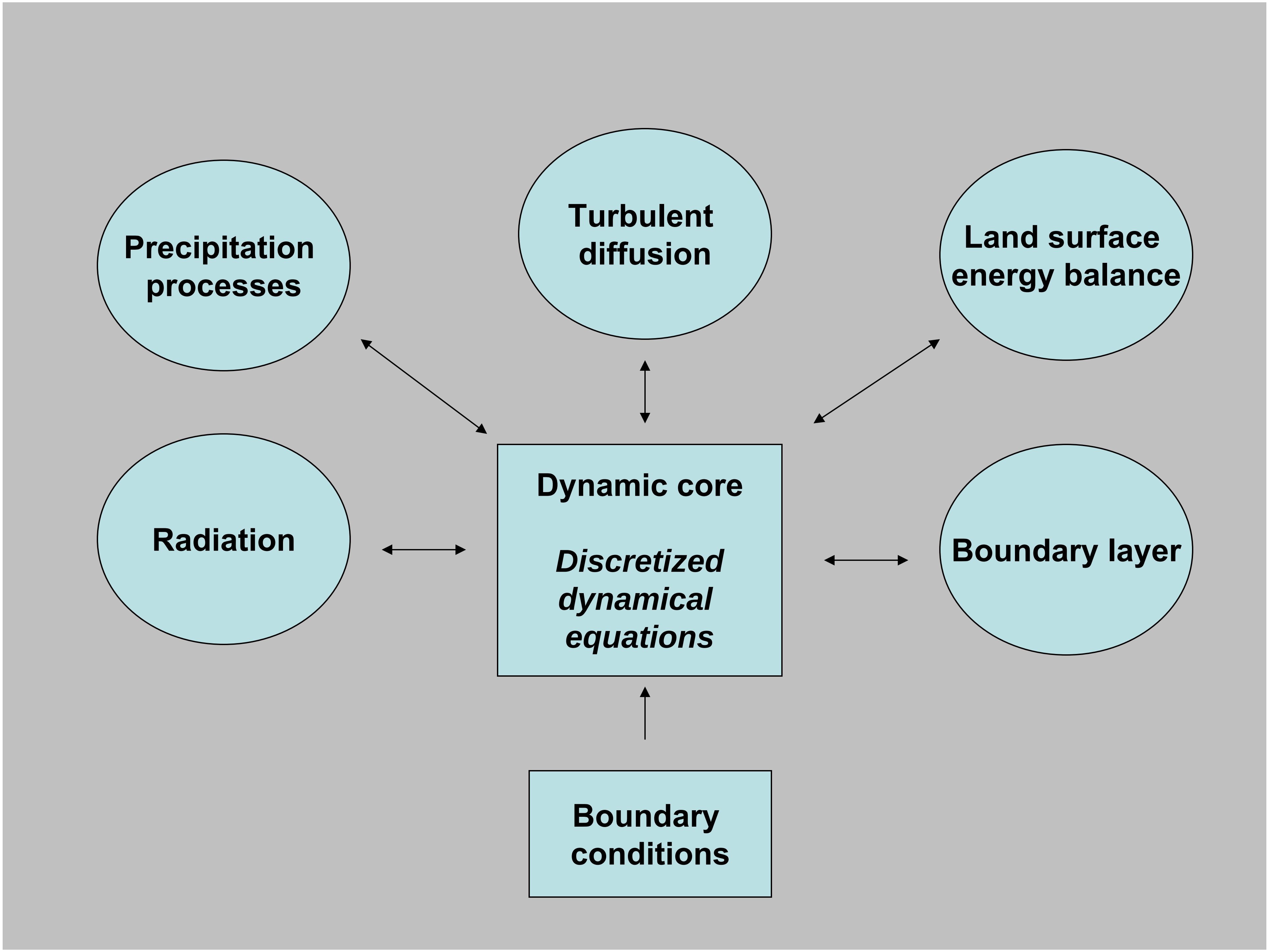
CONSERVATION OF MOISTURE $\partial q_n/\partial t = -\vec{V} \cdot \nabla q_n + S_{q_n}, \qquad n = 1, 2, 3,$

(Pielke 2002)

<u>Why is just doing this REALLY, REALLY HARD?</u>

Have discretize the equations, so they can be solved on a grid.
Equations are non-linear.

We haven't even accounted for parameterizations yet!



Precipitation processes

Turbulent diffusion

Land surface energy balance

Radiation

Dynamic core

Discretized dynamical equations

Boundary layer

Boundary conditions

Dynamical downscaling

Definition: ***Use some kind of numerical model to generate finer-resolution information from courser resolution information. For the atmosphere, this is a limited area model.***

Implicit assumption: A finer resolution and/or improved model physics (parameterizations) gives a "better" representation of weather and climate than the driving coarser resolution model (i.e. GCM).

"Better" may = more fidelity with observations and/or improved representation of physical processes

If this is not satisfied, you're wasting money in terms of computer time to generate simulations and labor to analyze the results!!

Dynamical Downscaling Types
(Castro et al. 2005)

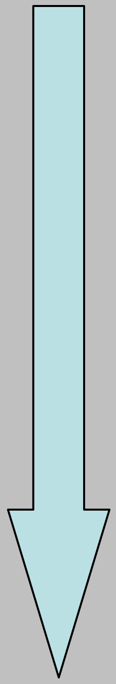
TYPE 1: Short-term numerical weather prediction out to 1-2 weeks.

TYPE 2: Retrospective simulation of past climate by downscaling a atmospheric reanalysis ("perfect" lateral boundary forcing).

TYPE 3: Downscale a atmospheric general circulation model forced with fixed surface boundary condition (e.g. SST) from some observed initial state
→ Seasonal forecast mode.

TYPE 4: Downscale a completely coupled atmosphere-ocean general circulation model for integrated for many years.
→ Climate projection mode

Fairly certain in results and constrained



Very unconstrained and uncertain!

WRF THE WEATHER RESEARCH & FORECASTING MODEL

We Klingons are not just warriors, we develop numerical weather prediction models too as you humans!

WRF THE WEATHER RESEARCH & FORECASTING MODEL

Based largely on the MM5 model, originally developed at Penn State.

Two dynamical cores, NMM (NCEP) and ARW (NCAR). The latter is what is used for most research applications and what we use.

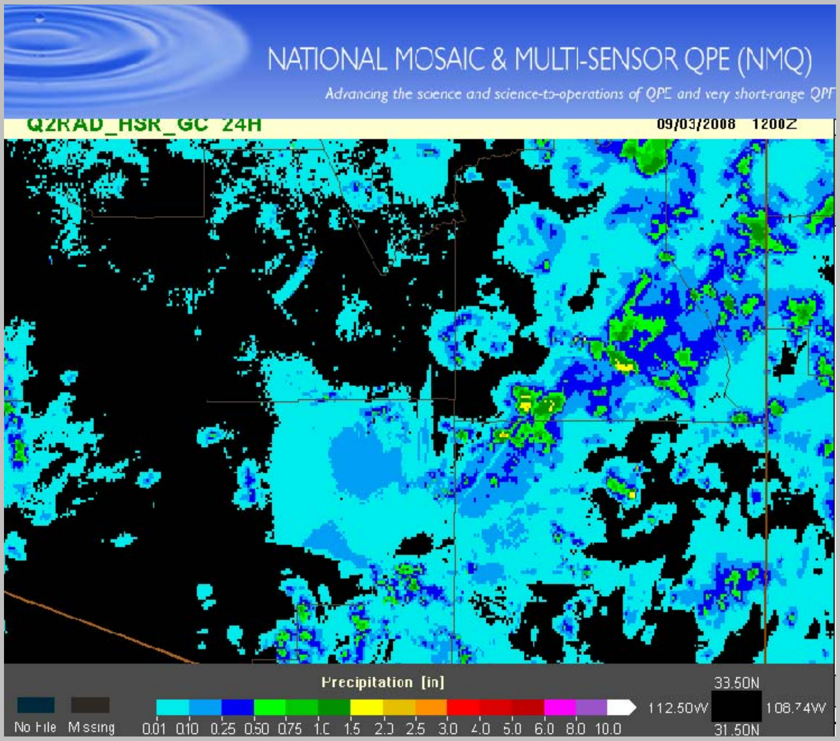
Numerous parameterization options for physical processes.

Though most heavily used for short-term weather prediction, designed for a broad range of scales and applications.

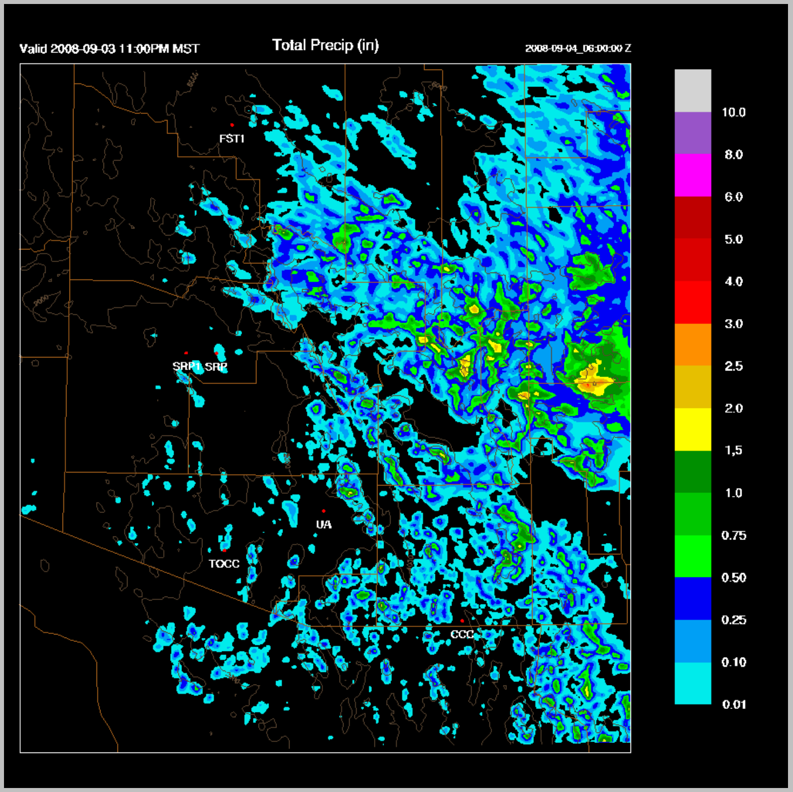
Some advantages to WRF: Model use and development occurring at numerous institutions, user community is large, spin-up time is relatively quick via on-line tutorials or NCAR tutorials, and runs on wide variety of computer platforms.

Real time UA forecasting in the Department of Atmospheric Sciences during monsoon

Radar estimated rainfall



WRF rainfall
(1.8 km grid spacing)



Courtesy Mike Leuthold

Some consistent problems in NWP monsoon forecasts for Arizona

Poor or missing initialization of smaller-scale features, like Gulf surges, outflow boundaries, or clouds.

Model produces thunderstorms, but they occur in the wrong place and/or the intensity is off.

Different GCM forcing data = different model simulation result.

Data to initialize the models is completely missing in Mexico!

What parameterizations to use? Use a trial and error approach to figure out what works “best” operationally.

Severe weather events that affect urban areas are very difficult to simulate skillfully (e.g. Phoenix)

Some recently funded WRF-related projects in my group…

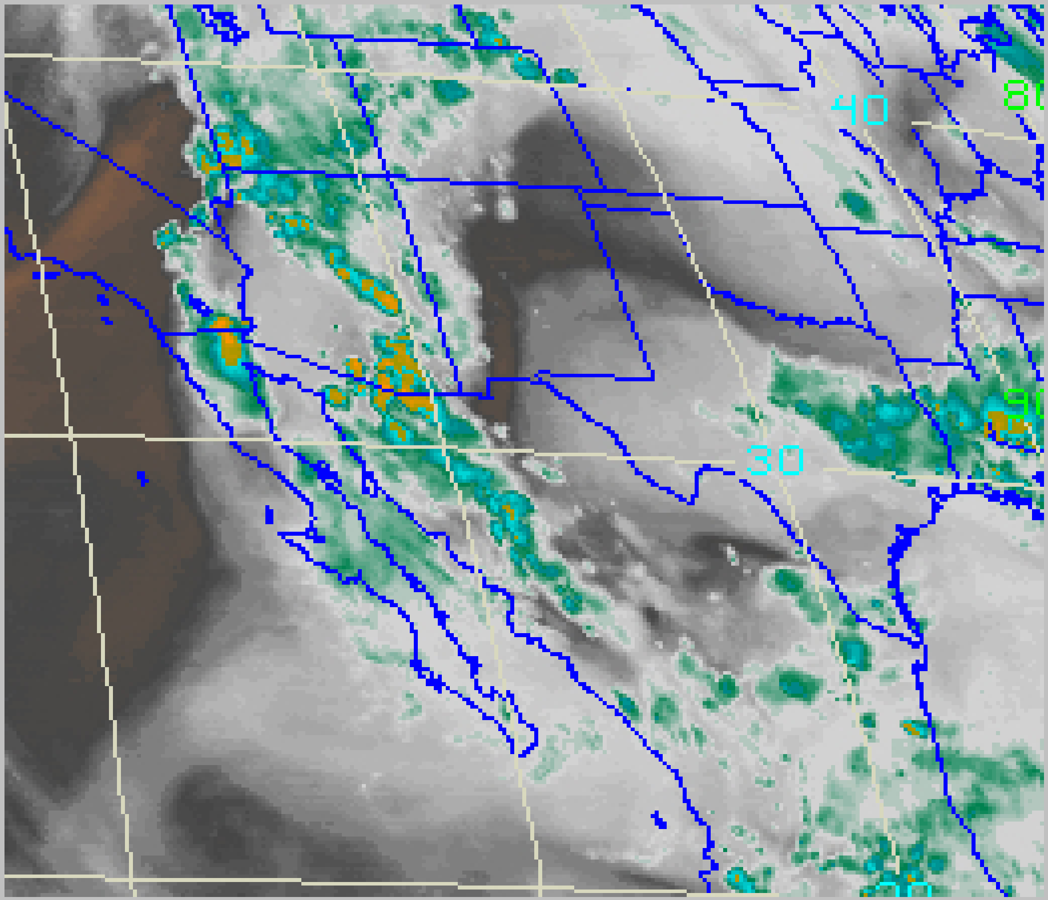
Use of Regional Atmospheric Modeling to Improve Short and Long-term Forecasting Capability of the North American Monsoon System
PIs: C. Castro, F. Dominguez
Sponsoring agency: NSF

Using Regional Atmospheric Modeling to Investigate Heavy Monsoon Rainfall Events in Arizona and Socioeconomic Implications
PIs: C. Castro, S. Grossman-Clarke (ASU)
Sponsoring agency: Science Foundation Arizona

Processes Linking Easterly Waves and the North American Monsoon System
PIs: Y. Serra, C. Castro, E. Ritchie
Sponsoring agency: NSF

Short term monsoon forecasting and adjoint sensitivity

August 2, 2005 Severe Weather Event in Phoenix Metro Area: A "Rim Shot"



Water vapor imagery on Aug. 2, 2005 at 15Z

Had "typical" ingredients

1. **Upper-level inverted trough**

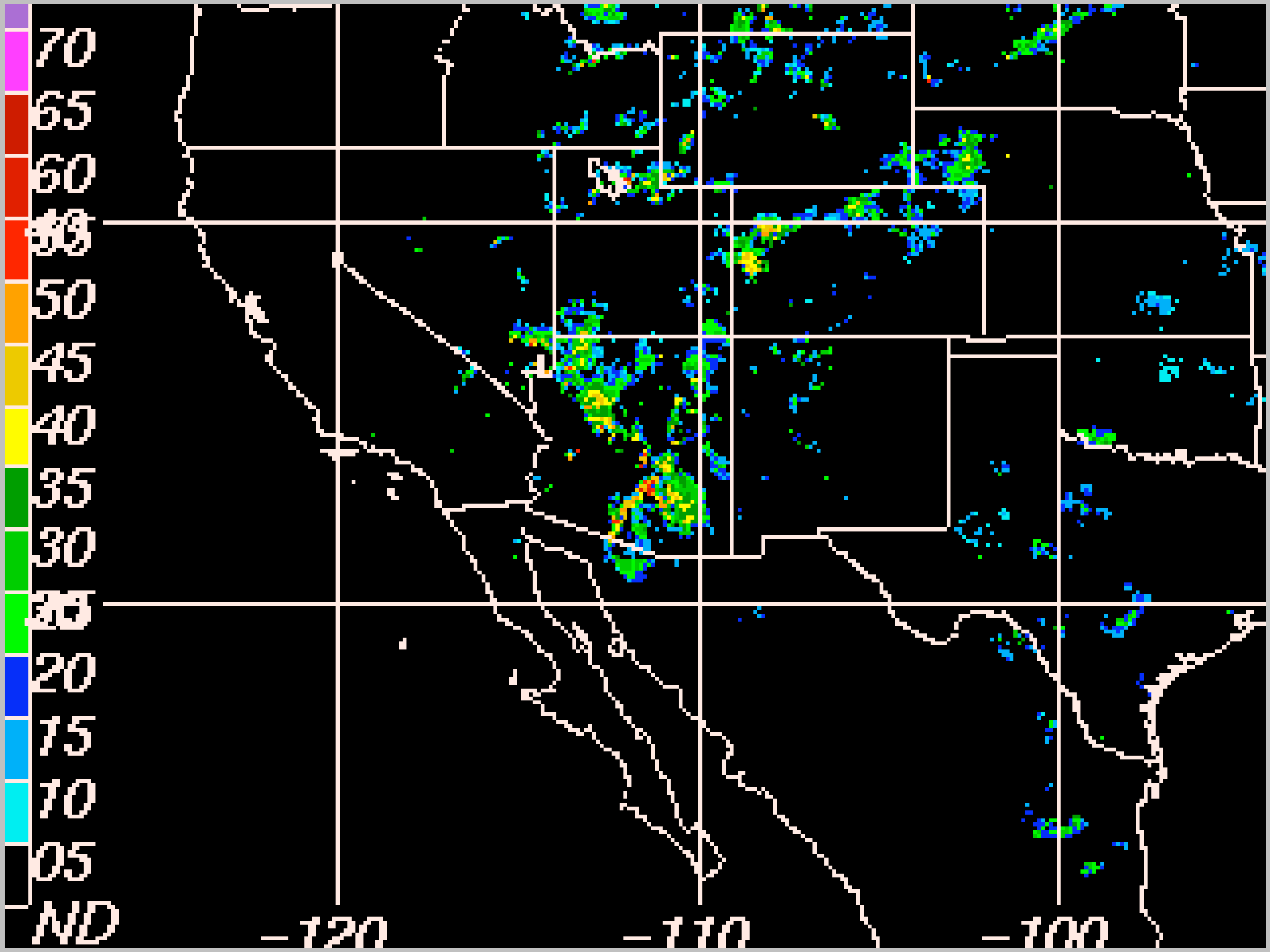
2. **Low-level surge of moisture from the Gulf of California.**

Net result

Vertical wind shear, high θ_e in low levels, upper level divergence, and relatively high CAPE.

Terrain-induced convection can organize into MCSs west of Mogollon Rim.

Corresponding NEXRAD radar imagery



Severe thunderstorm in Phoenix area: Approx. 6Z, 3 Aug. 2005

Produced

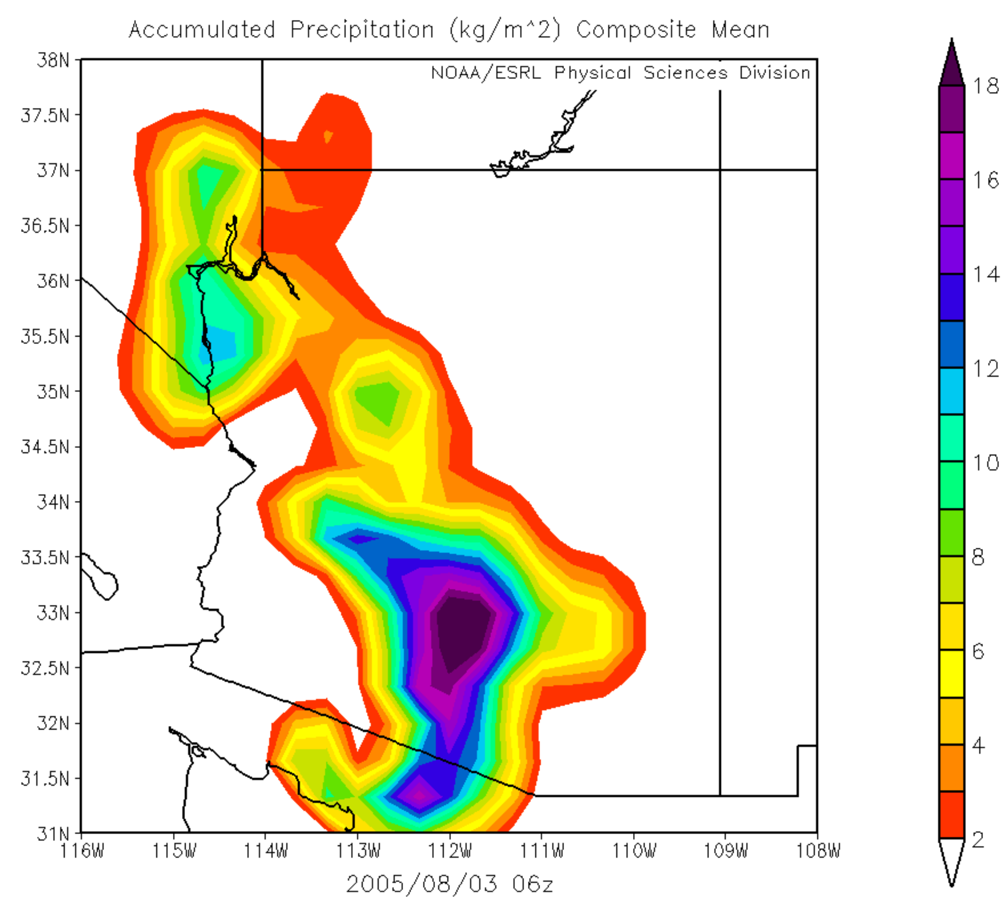
Major dust storm

Golf-ball size hail

Damaging winds

Urban flooding

Close to an inch or two or rain in isolated locations.



3h accumulated rainfall, 3Z to 6Z, 3 Aug. 2005 (NARR product, NOAA ESRL).

WRF (V3) NWP Simulations of Aug. 2005 Event

24 h simulation starting at 12 Z Aug. 2.
48 h simulation starting at 12 Z Aug. 1.

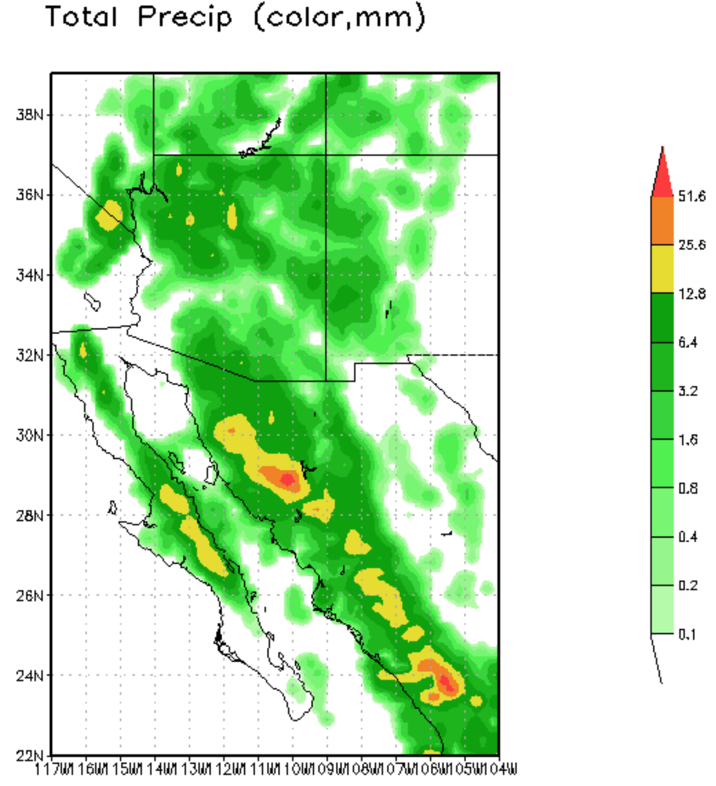
Western U.S. domain

21-27 km grid spacing on coarsest grid

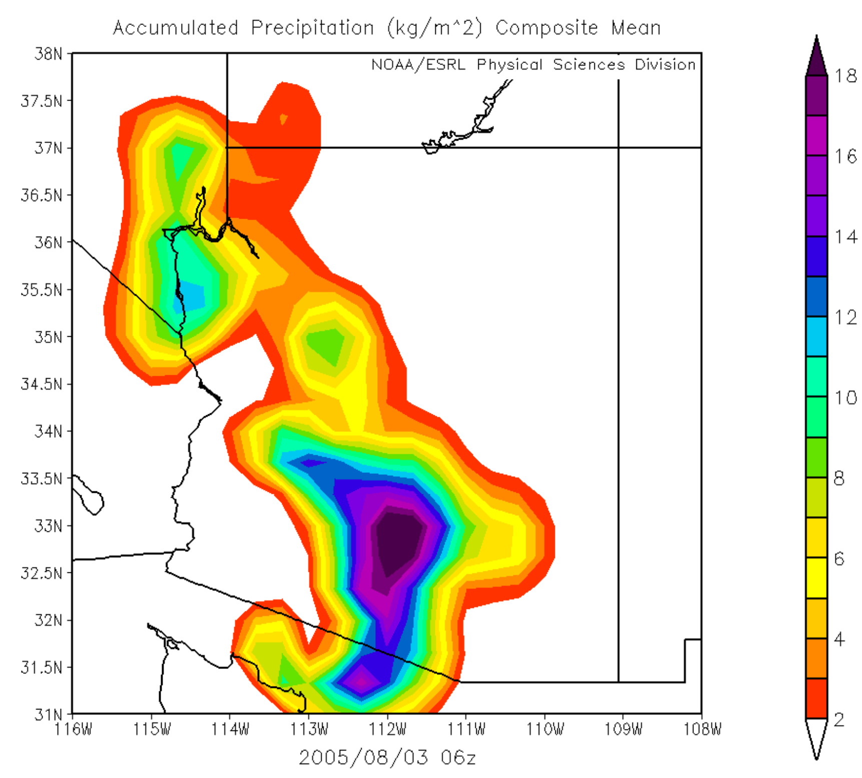
GFS model analysis lateral boundary forcing

“Standard” WRF parameterizations

Forward Integration
August 3, 2005 (18h)

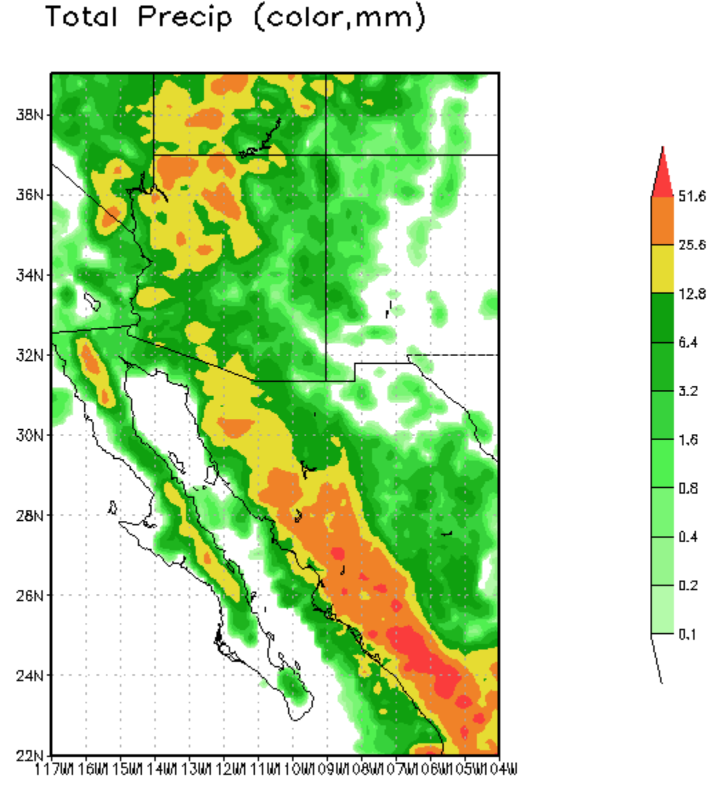


3h accumulated rainfall, 3Z to 6Z, 3 Aug. 2005
WRF Model V3.0

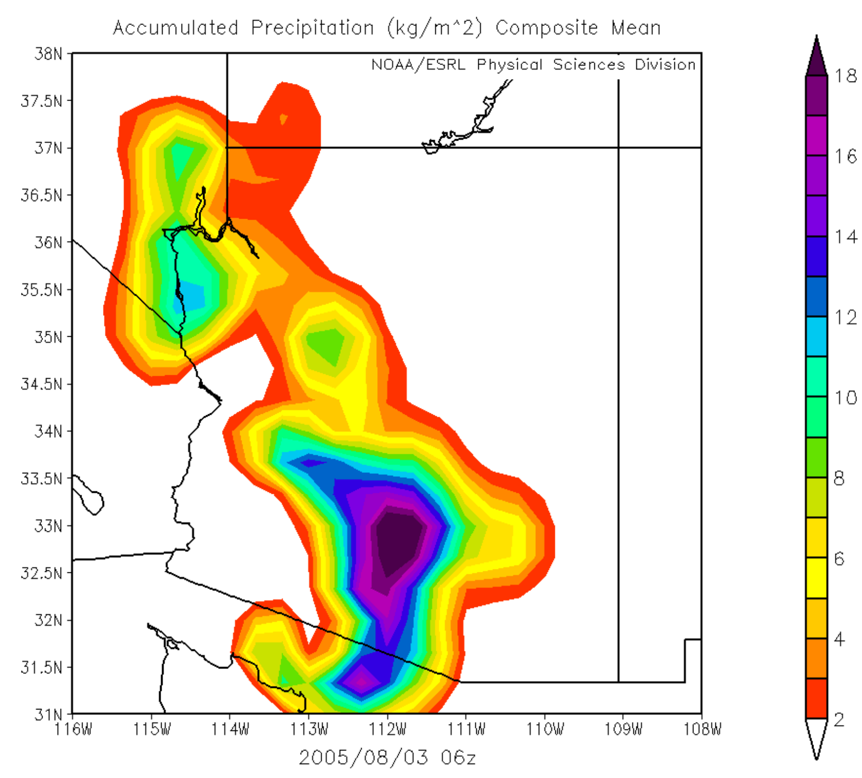


3h accumulated rainfall, 3Z to 6Z, 3 Aug. 2005
(NARR product, NOAA ESRL).

Forward Integration
August 3, 2005 (42h)



3h accumulated rainfall, 3Z to 6Z, 3 Aug. 2005
WRF Model V3.0, 42 hour forecast



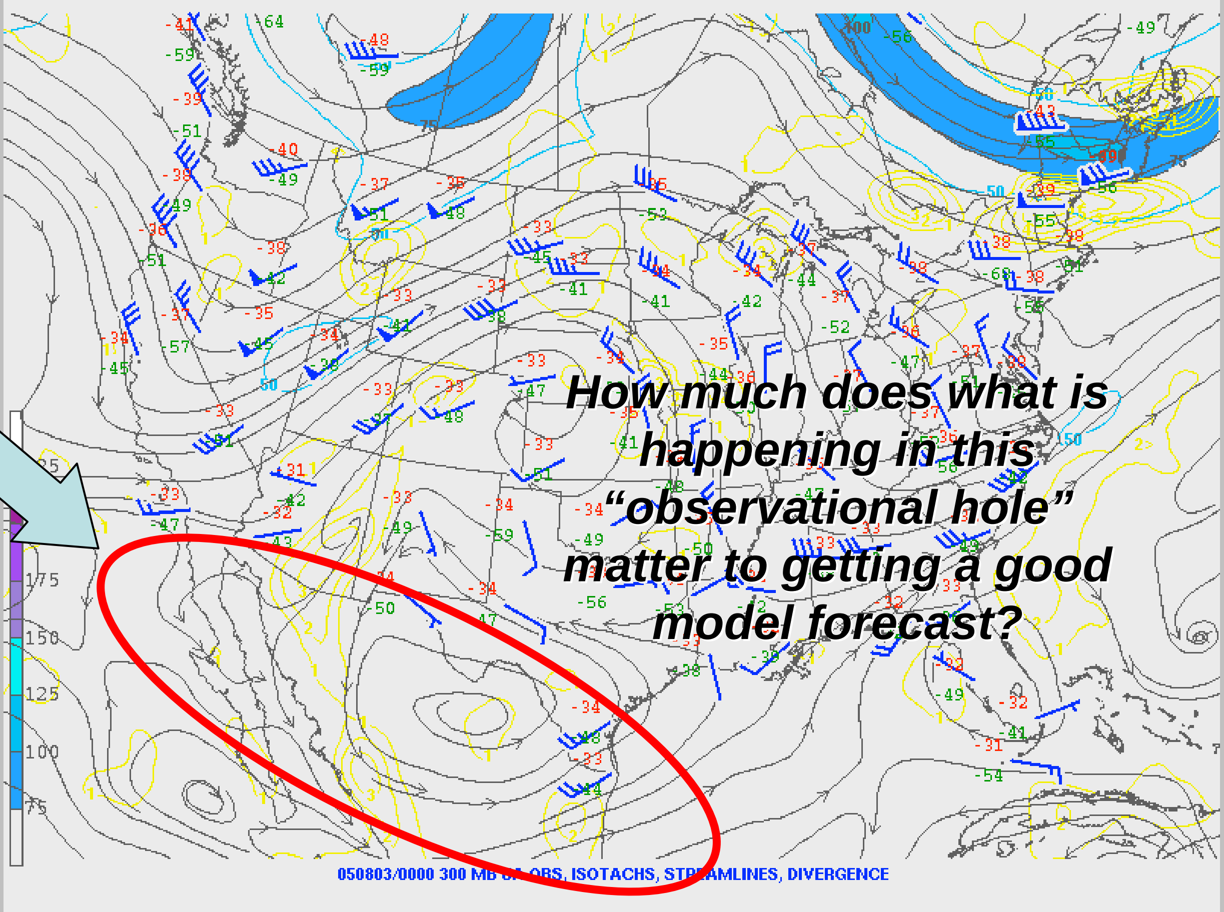
3h accumulated rainfall, 3Z to 6Z, 3 Aug. 2005
(NARR product, NOAA ESRL).

A Lack of Observations in Mexico

There have been virtually no upper air observations in northern Mexico since the end of NAME.

Also no data along the Gulf of California to track gulf surges.

A consistent problem noted by Tucson and Phoenix WSFOs during the monsoon.



How much does what is happening in this “observational hole” matter to getting a good model forecast?

300-mb winds and streamlines

Brief Overview of Adjoint Modeling

Technique to determine the sensitivity of a NWP forecast for a selected target region to specification of initial conditions within the model domain.

High sensitivity regions and atmospheric parameters in which small perturbations can produce large effects on forecast features that can be identified.

Adjoint model is the transpose of the tangent linear operator of the given NWP model. An estimate of a differentiable model forecast state (response function R) defined at a given forecast verification time (t_f) can be produced through a modifiable initial state (X^0).

Adjoint Sensitivity of a Simple Response Function (*R*), defined at verification time (*f*)

$$R = \frac{1}{2}\sum_{i,j}\left[\left(u_{i,j}^{f}\right)^2 + \left(v_{i,j}^{f}\right)^2\right]$$

u, v = **Horizontal winds**

X^{O} = **Model initial state**

X^{f} = **Model final state**

$$\frac{\partial R}{\partial X^{o}} = L^{*}\frac{\partial R}{\partial X^{f}}$$

Gradient of response function at start of model integration (adjoint sensivitity)

Adjoint model

Gradient of response function at forecast verification time

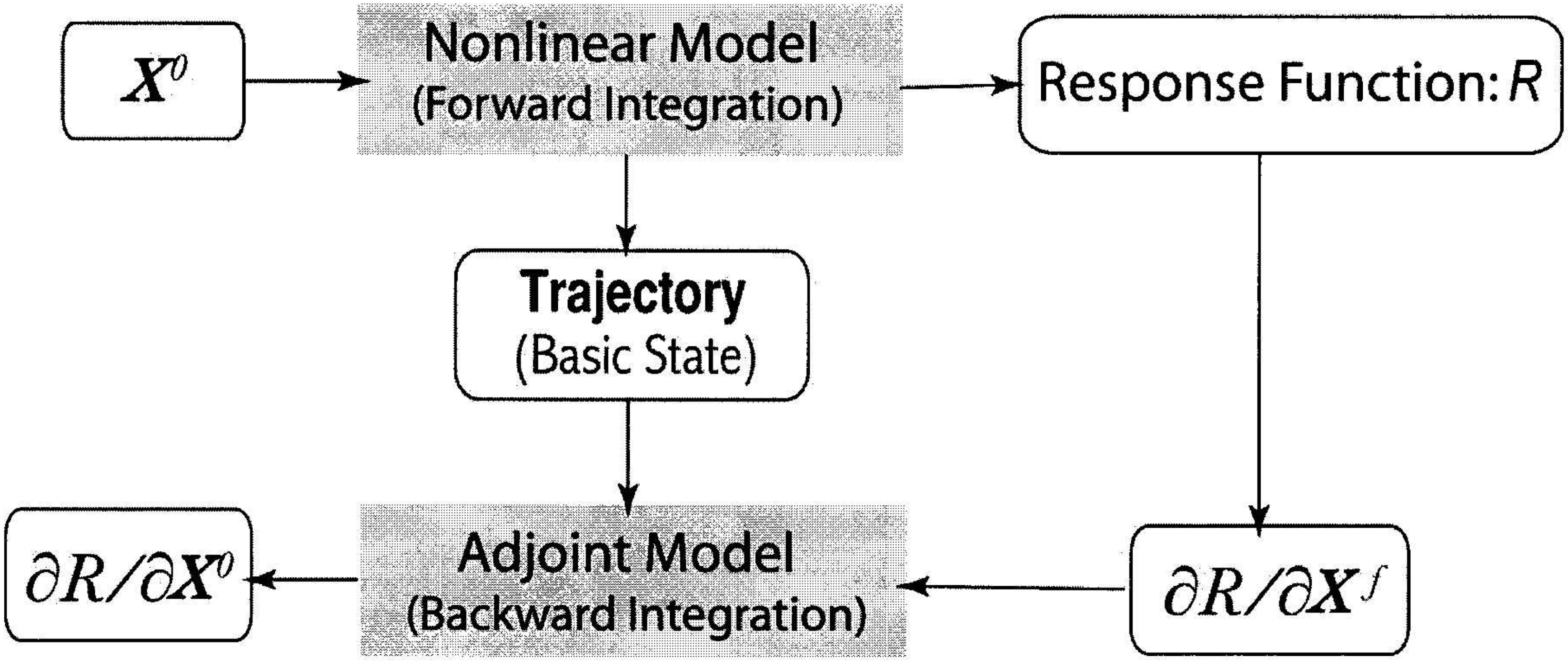


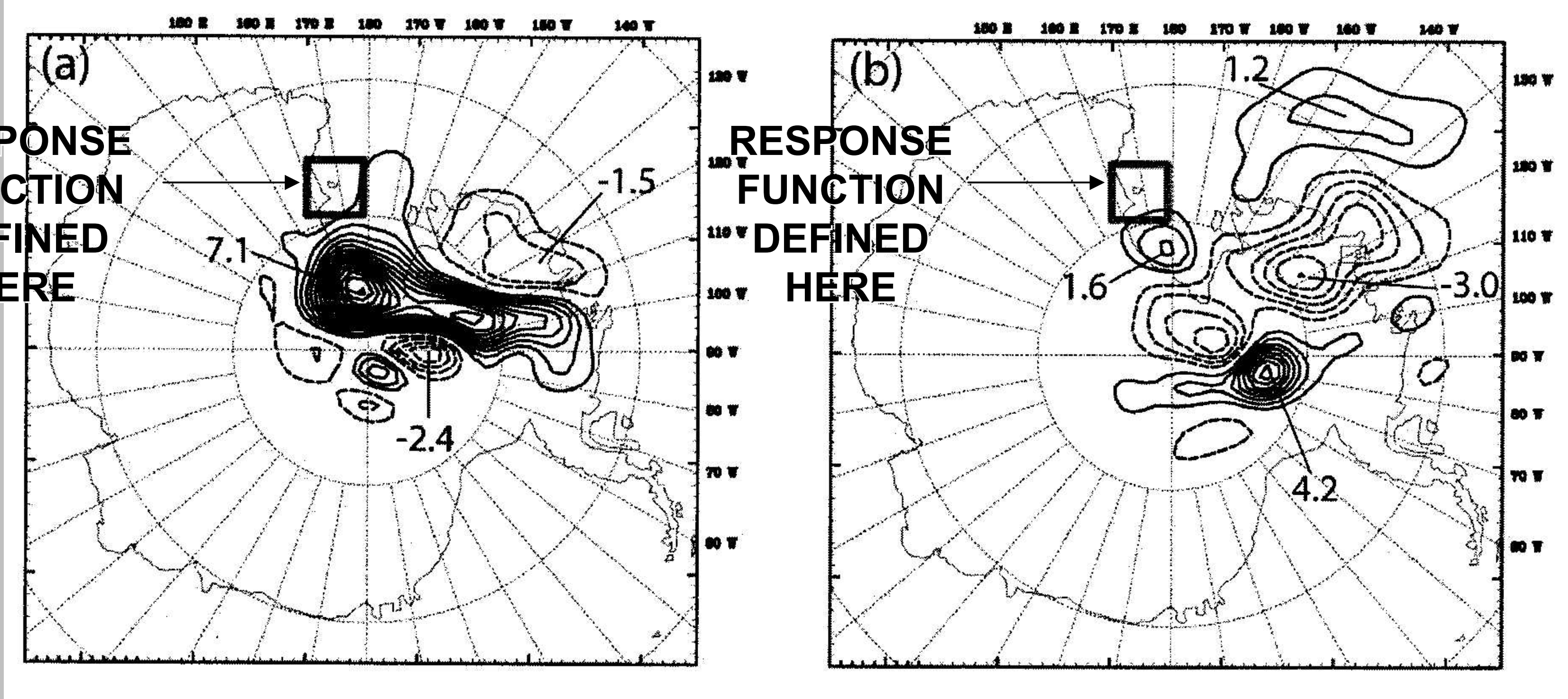
Figure 7: Schematic outlining the flow chart of adjoint sensitivity calculation.

(Xiao et al. 2008)

Antarctic Windstorm Case
First demonstration with WRF-VAR

Adjoint Sensitivity to low level u

Adjoint Sensitivity to low level v



RESPONSE FUNCTION DEFINED HERE

RESPONSE FUNCTION DEFINED HERE

Units: m s^{-1}

(Xiao et al. 2008)

Adjoint model caveats for monsoon convection

1. Does the linearity assumption hold?

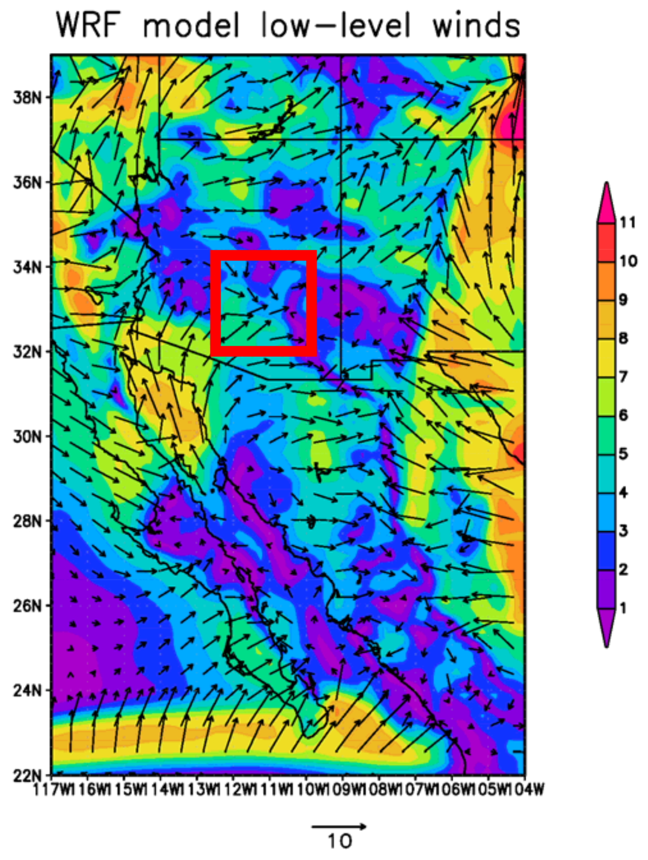
2. Parameterized processes are not accounted for in the adjoint model yet. Sensitivity only to dry dynamics.

Response Function (R)

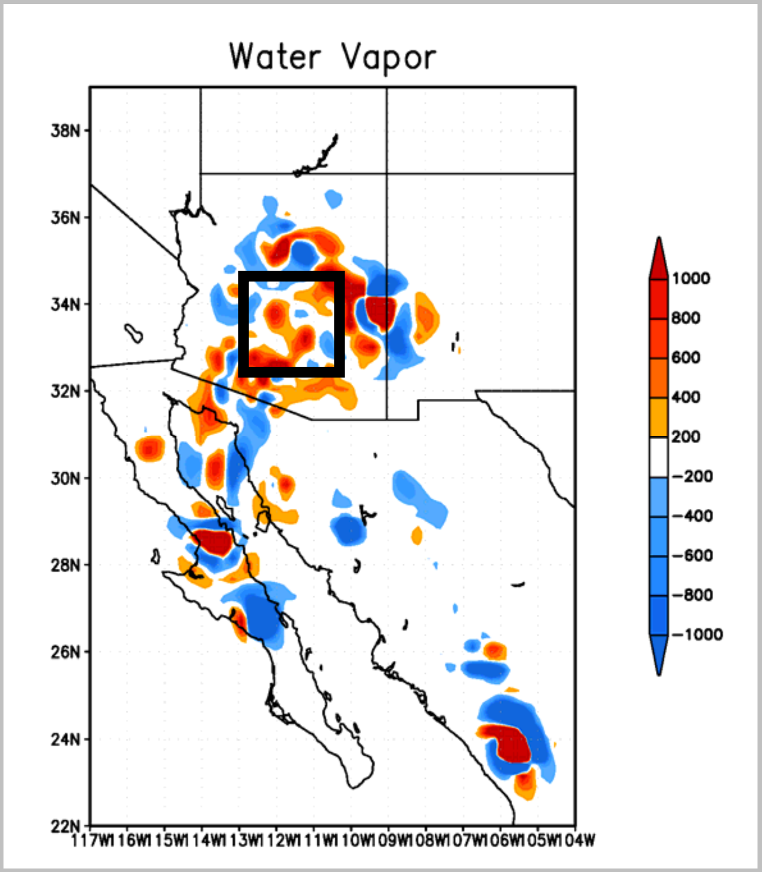
$$R = \frac{1}{2}\sum_{i,j}\left[\left(u_{i,j}^{f}\right)^{2} + \left(v_{i,j}^{f}\right)^{2}\right]$$

Defined in a 10 x 10 grid point box over central Arizona for 27 km grid spacing.

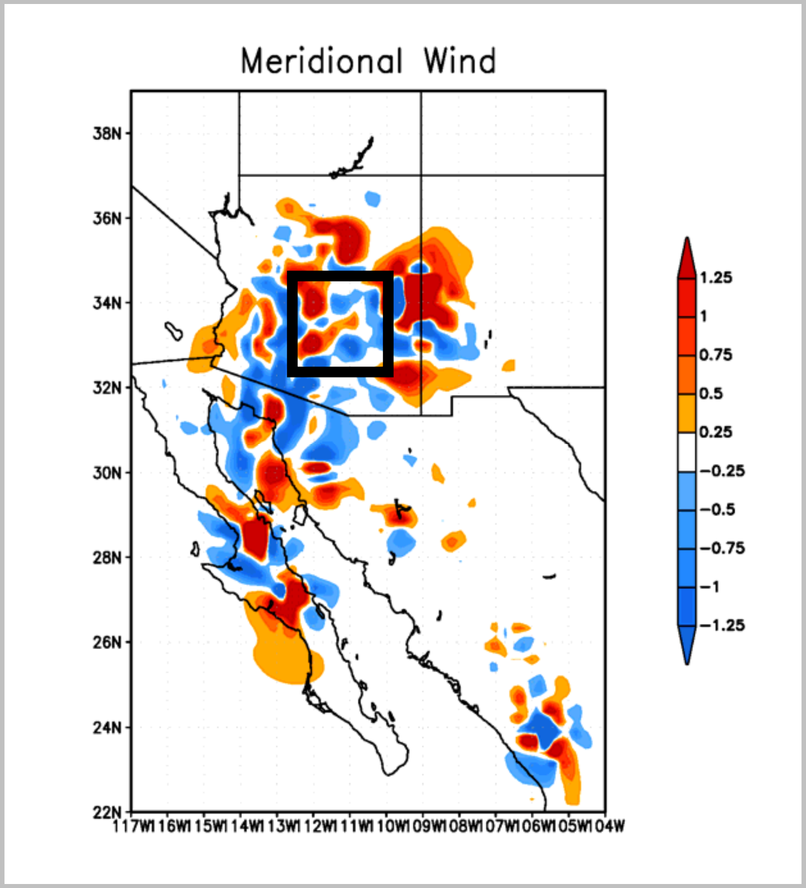
Verification time is 6Z, Aug. 3 (Simulation hour 18)



Adjoint sensitivity to initial conditions: Model level 5

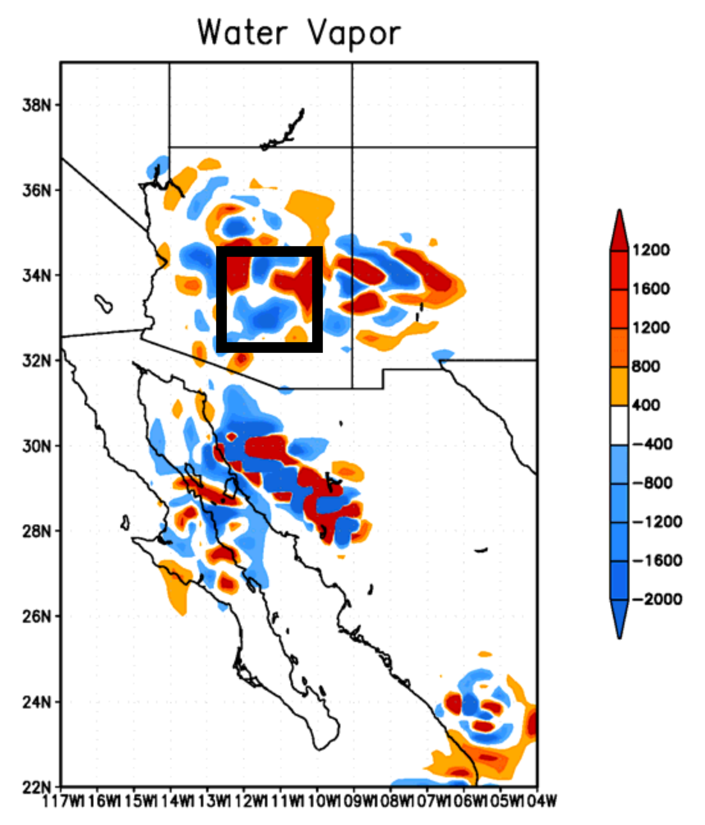


Units: $m^2\ s^{-2}\ kg\ kg^{-1}$

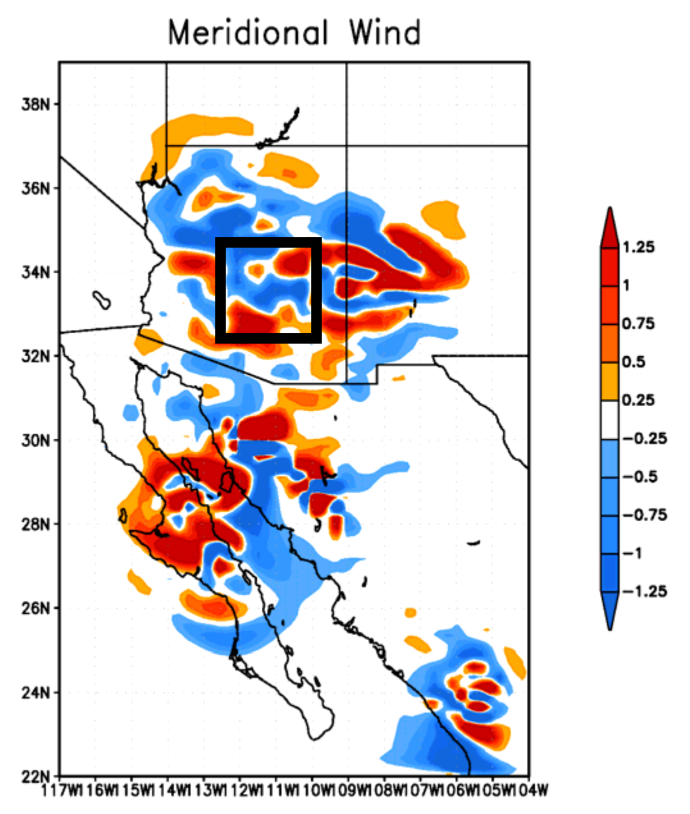


Units: $m\ s^{-1}$

Adjoint sensitivity to initial conditions: Model level 20



Units: m^2 s^{-2} kg kg^{-1}



Units: m s^{-1}

Ongoing work...

Higher resolution simulations comparable to current UA WRF monsoon forecasts.

Testing of additional forecast aspects more directly tied to the development of convection using the adjoint sensitivity method (e.g. CAPE, moisture flux convergence).

Incorporation of adjoints of parameterizations (e.g. convection, microphysics)

Simulation of intensive observing periods (IOPs) during the North American Monsoon Experiment (NAME) in 2004 and corresponding adjoint sensitivity experiment. IOPs corresponded with development of organized convection like the Aug. 2005 case.

Assimilate NAME field campaign data into the aforementioned NAME IOP simulations.

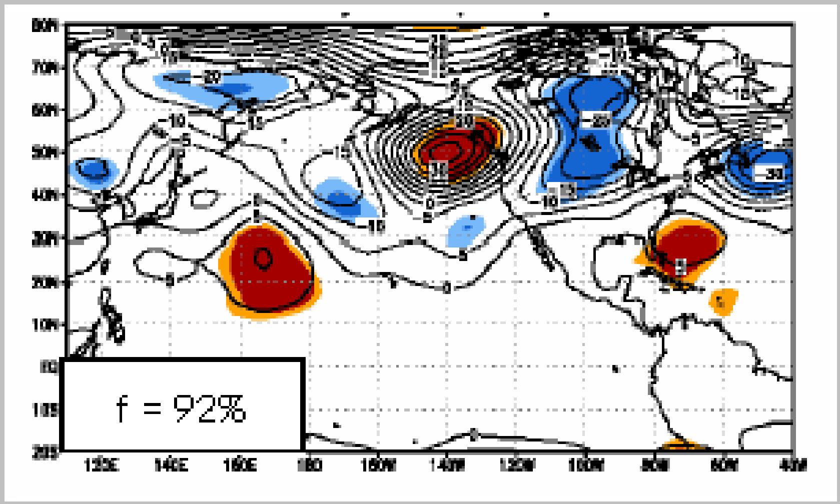
Expected outcome: Identify “hot spots” of forecast sensitivity that will lead to a permanent long-term monsoon observing system for U.S. and Mexico.

Regional climate modeling

Definition: ***A numerical weather prediction model integrated for a period longer than about two weeks, so that the sensitivity to initial conditions is lost.***

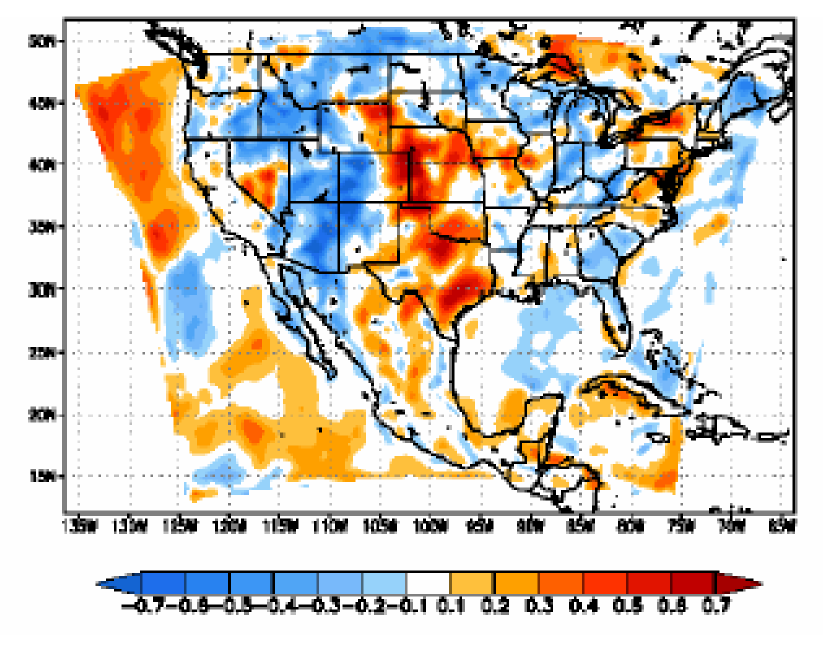
Successful representation of the monsoon in a retrospective sense (Castro et al. 2007)

Summer teleconnection



Observed 500-mb height anomalies (m) in early July associated with one of the dominant modes of Pacific SST variability.

Regional model response



Corresponding difference in diurnal moisture flux convergence as simulated by a regional model (RAMS) downscaling an atmospheric reanalysis.

Well that’s great, but can the same be done for seasonal climate forecasts and climate change projections?

Answer: Yes, with two caveats on the driving GCM:

1. **Does it have a reasonable climatology?**
2. **Summer teleconnections captured?**

If the answer to either is no, wasting computer time…

My opinion on how to proceed with RCM climate forecasting.

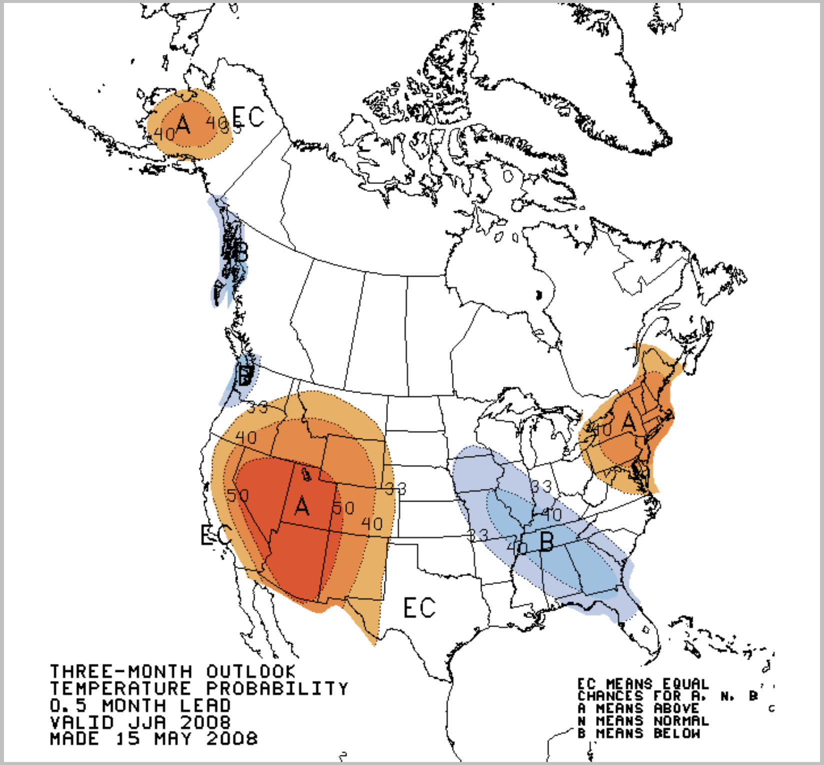
1. Downscaling of seasonal forecasts
2. Downscaling for climate change projection purposes (i.e. IPCC simulations)

Comments:

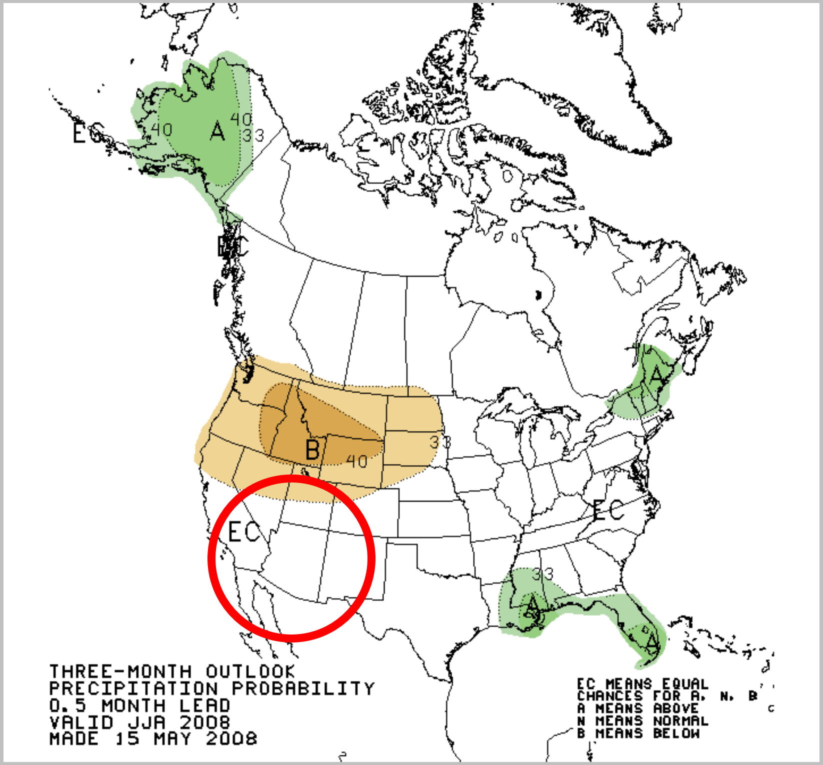
I know we REALLY want to get #2, but must do #1 first. Must assess value added in a seasonal forecast sense before proceeding to climate change projection, which has more degrees of freedom. Use consistent methodology for both.

Additionally, the disconnects between the research communities that do weather and short-term climate forecasting vs. climate change projection don’t help.

2008 Official Climate Prediction Center Forecast for this past summer.



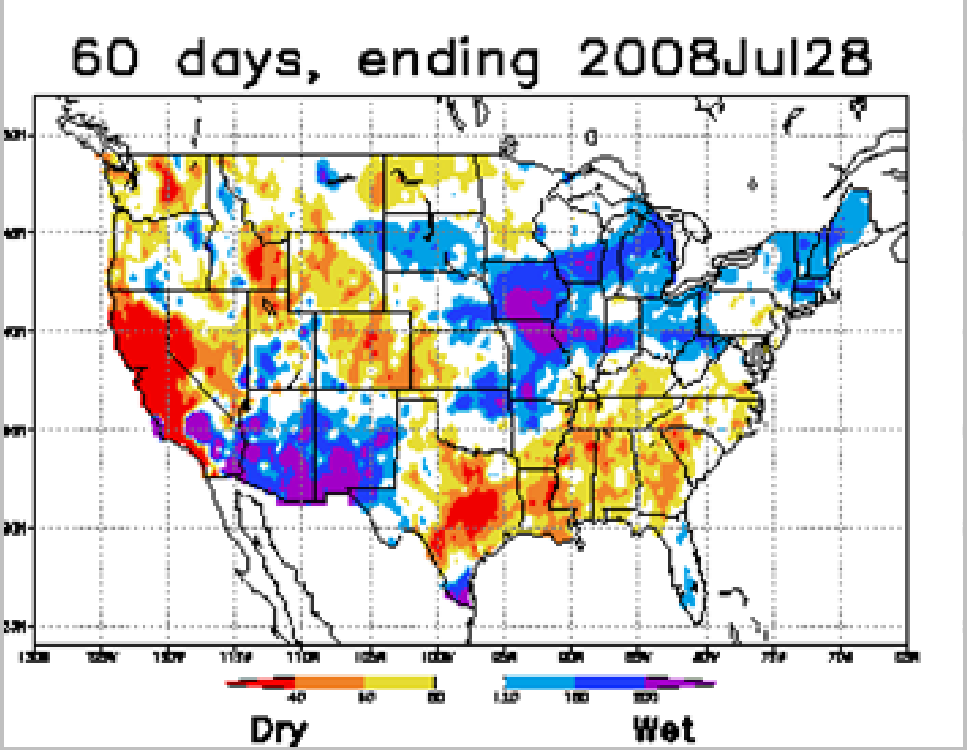
Temperature forecasts are becoming more dominated by long-term trends, probably due to climate change.



“Equal chances” for monsoon precipitation in the Southwest.

http://www.cdc.noaa.gov

Here's what happened. So was the CPC forecast is "good" or not?



(Climate Diagnostics Center)

Precipitation percent above or below normal for past 60 days

Generally wet in the Southwest and dry in the Great Plains.

Note: Northern Mexico also experienced 2nd wettest July on record, with only 1955 being wetter, according to Art Douglas.

Retrospective CFS Seasonal Forecast downscaling

Use a similar domain as Castro et al. (2007) RAMS simulations that covers the contiguous U.S. and Mexico

Simulate retrospective period 1982-2007.

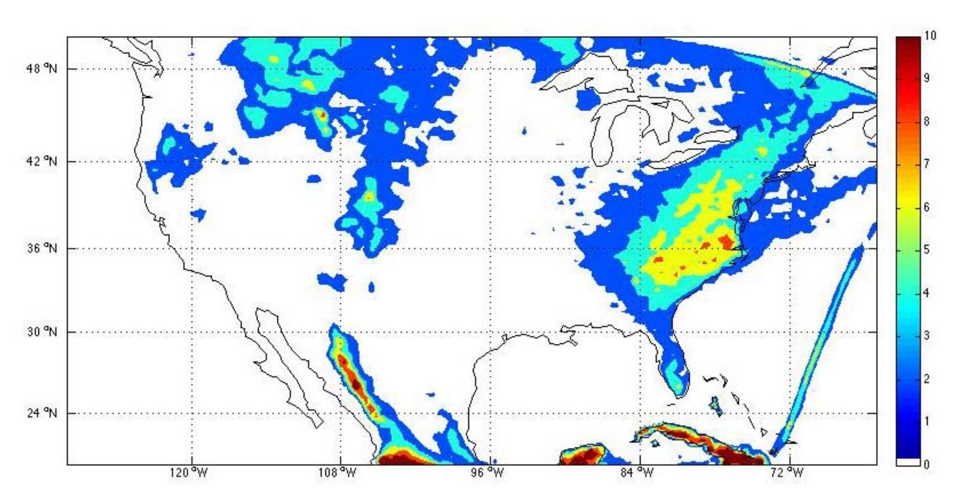
Downscale 5 ensemble members per year, from the date of the May 1 forecast.

Simulation period through at least the end of August to capture the monsoon.

Will eventually employ a spectral nudging technique.

Expected outcome: Improved representation of the monsoon in the regional model that will lead to a more accurate seasonal forecast.

WRF-CFS downscaled precipitation

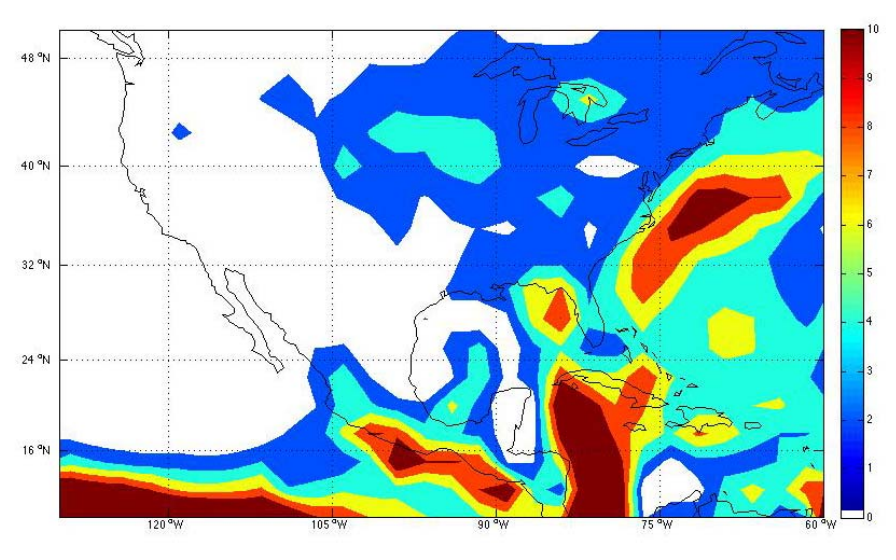


Monsoon precipitation (mm per day) from WRF downscaled CFS ensemble member vs. original GCM data

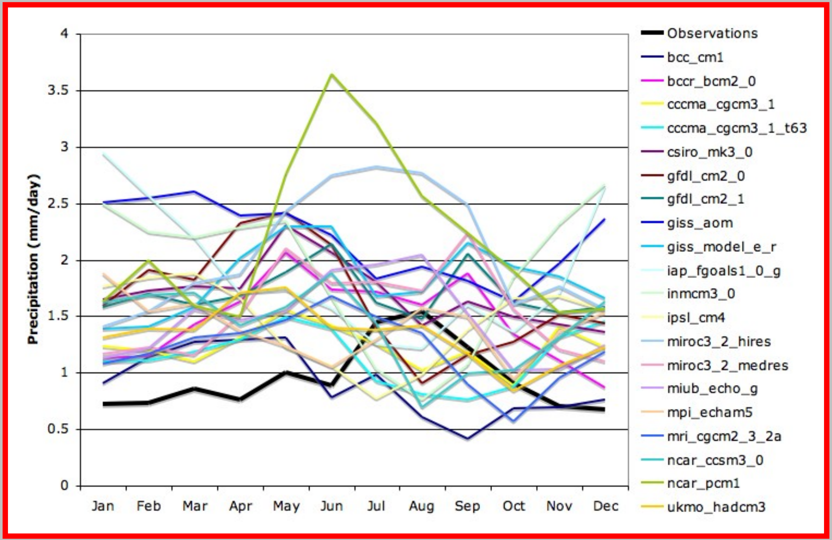
Year: 1993
(dry monsoon)
June-Sep. average

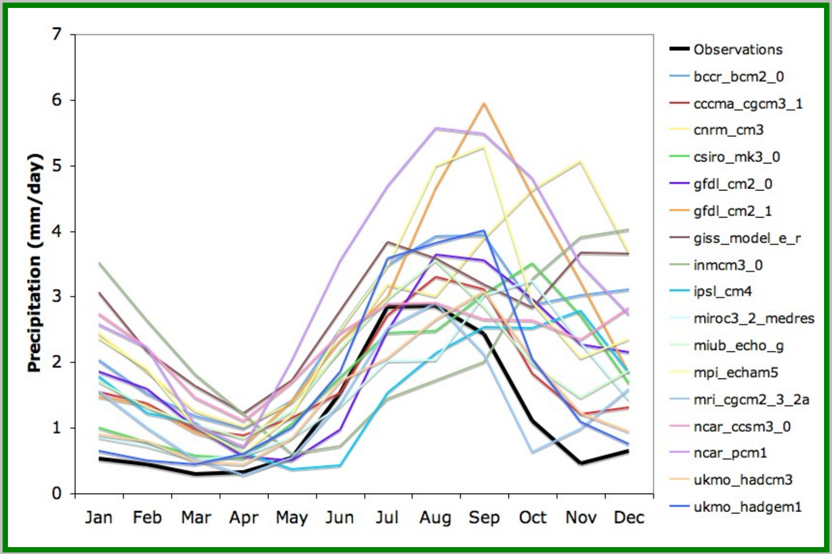
Note: An obvious problem in the spatial distribution of rainfall for this year in this particular member--but the rainfall magnitudes are comparable to what happened with respect to central U.S. flood event.

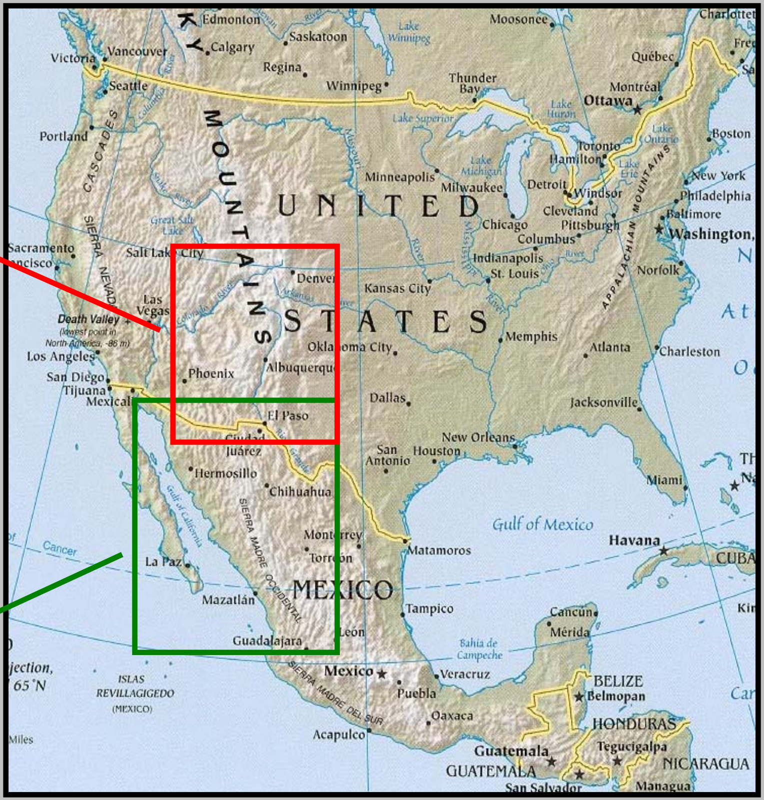
CFS precipitation



IPCC Simulated Rainfall During "Control" Period







Average historical model runs (sres_20c3m) 1970-2000

(Courtesy Francina Dominguez)

Spectral Nudging in WRF

Gonzalo Miguez Macho,

Universidade de Santiago de Compostela, Galicia, Spain

Spectral nudging

Model variables

Observations (reanalysis)

$$\frac{dQ}{dt} = L(Q) - K(x,y)\cdot\left(Q - Q_o\right)$$

Davies nudging

model operator

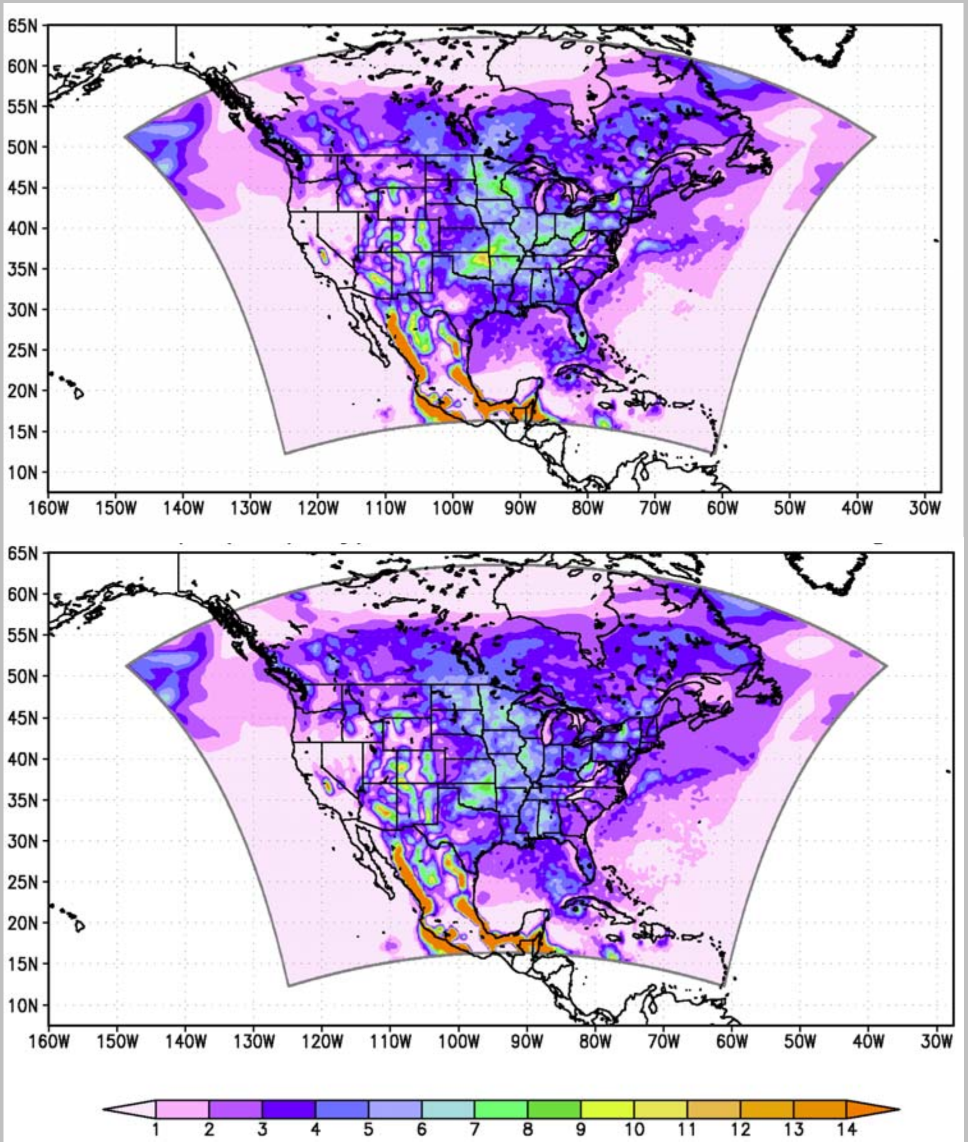
Relaxation coefficient

$$\sum_{|n|\le N}\sum_{|m|\le M}\frac{dQ_{mn}}{dt}\cdot e^{ik_m x}\cdot e^{ik_n y} = L(Q) - \sum_{|n|\le N}\sum_{|m|\le M} K_{mn}\cdot\underbrace{\left(Q_{mn} - Q_{o\,mn}\right)}_{D_{mn}}\cdot e^{ik_m x}\cdot e^{ik_n y}$$

Spectral nudging

- K_{mn} (spectral nudging coefficient) may depend on height
- To nudge longwaves, make it nonzero ONLY for small m and n

RAMS mean June 2000 precipitation (mm/day)



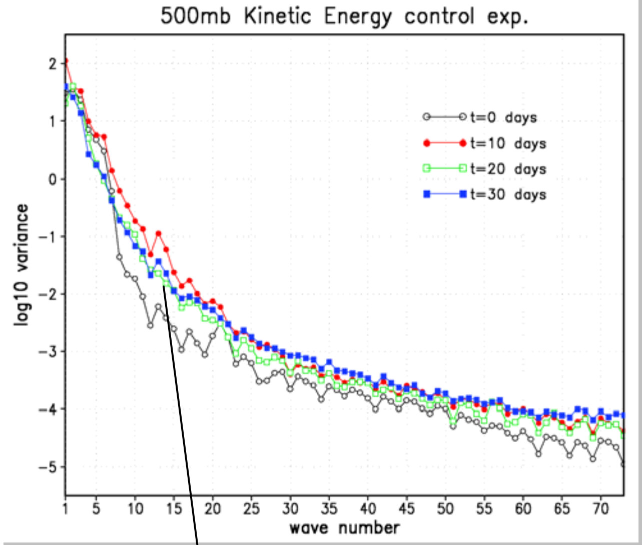
Spectral nudging

Conventional nudging

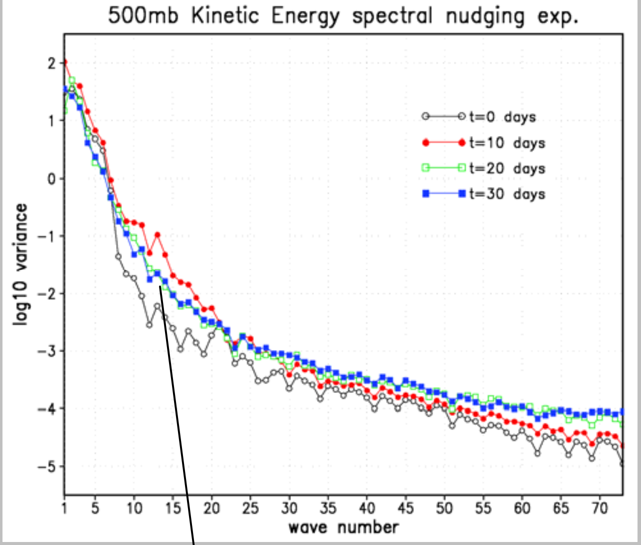
(entire domain)

500 mb Kinetic energy spectra

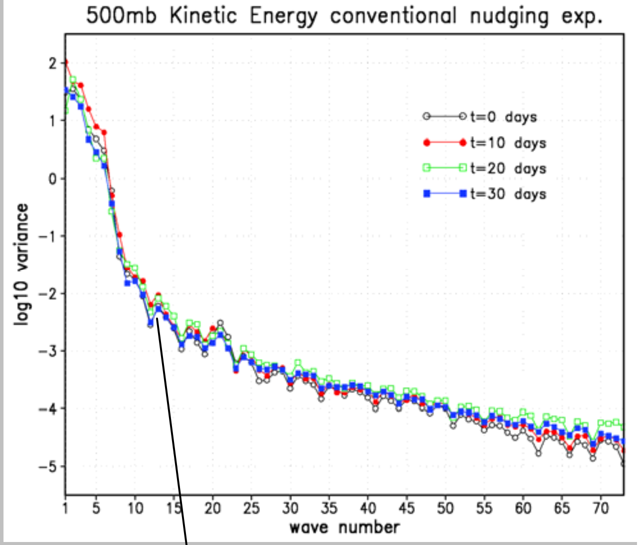
Control
(no nudging)



Spectral nudging



Conventional nudging



Due to higher resolution, the model generates small scales not present at t=0

The model generates small scale structure as in the control

No more structure than in driving fields (reanalysis)

Concluding thoughts

A regional model is potentially a very powerful tool to investigate the monsoon in Arizona—both in a short-term NWP sense and climate forecast and projection sense.

Generating a “good” result with WRF is by no means simple! Sensitivities to the specification of domain size, grid spacing, model parameterizations, length of model simulation. For RCM simulations, some means to control loss of large-scale variability becomes an issue.

Emerging applications of WRF can very pressing problems with repect to the monsoon:
1) How can we develop a long-term monsoon observing system?
2) How can we improve summer seasonal climate forecasts?

How can this work tie to hydrologic applications?

Regional model simulations are approaching the scale at which they can be used as input to hydrologic models.

- Direct input
- Additional statistical downscaling to finer resolution

Moves away from the idea of stochastic forcing to hydrologic models—which is typically used now.

Possible applications in Arizona and beyond?

- Flash Flood forecasting
- Long-term streamflow projections
- Soil moisture forecasts

Do you all have ideas? I’d like to know!