Using Short-Range Weather Forecasting Techniques to Evaluate Moist Physical Processes in Climate Models

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Outline

- **Why Weather Forecasting Techniques?**

- **3 Examples:**

  - Summertime convection over the central U.S.
  - Mid-latitude frontal clouds
  - Tropical convection during TOGA-COARE

Why weather forecasting techniques?

- Climate modelers have long experience examining climate errors without really understanding how they occur

- If one can initialize a climate model satisfactorily, weather forecasting techniques allow you to examine errors in the model simulation before the state of the atmosphere and land surface has drifted to its preferred bias state

- Life cycles of clouds and other moist processes have characteristic time scales of hours to a few days

Why weather forecasting techniques?

- Climate model ‘improvements’ (e.g. new parameterizations) should be apparent at the weather time scale as well

- Weather forecasting techniques facilitates comparison with observations

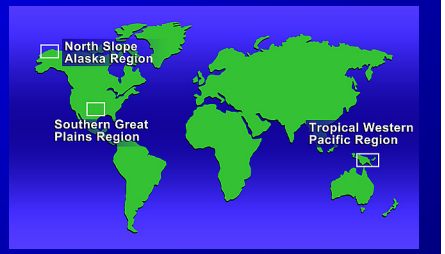
But can initialization of climate models without complicated data assimilation systems be done?

The DOE CAPT project

- *CAPT* = *C*CPP – *A*RM *P*arameterization *T*estbed

  CCPP = Department of Energy's *C*limate *C*hange *P*rediction program which funds the *PCMDI* (*P*rogram for *C*limate *M*odel *D*iagnosis and *I*ntercomparison) at Livermore

  ARM = Department of Energy's *A*tmospheric *R*adiation *M*easurement program



- ARM data provides us with very detailed information from its few sites – but we are expanding our viewpoint with the help of NASA satellite data

Initialization of Climate Models

- We take analysis data (surface pressure, winds, temperature, and water vapor) from ECMWF (or NCEP or any others) and interpolate carefully to the grid of the climate model and go

- The procedures used are those that ECMWF use when ECMWF wants to do a test forecast starting from another NWP center's (e.g. UKMO) analysis

- The forecasts with the climate models we use (NCAR CAM3 & GFDL AM2) do produce credible 500 hPa height and sea level pressure metrics – this can be done because climate models have more resolution than in the past

Initialization of Climate Models

- The forecasts of the climate models we use in CAPT) do have some initial noise and spin-up but the errors we focus on are those that are robust to the choice of analysis data or modeling technique

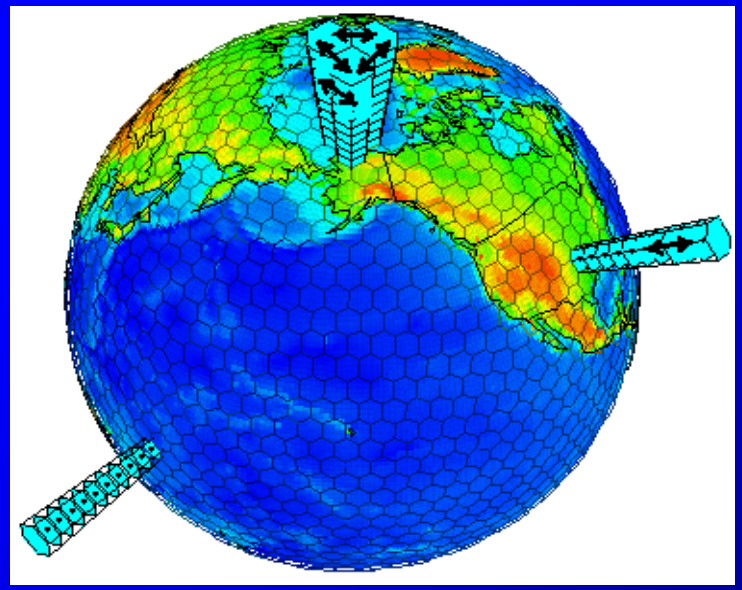
- An alternative to performing a weather forecast with a full climate model is to perform short-range forecasts at geographical point on Earth with the single-column model that accompanies the climate model

What is a Single Column Model?

- A Single Column Model is a one-dimensional simulation of the atmosphere using only the "column physics" from the global model

- A SCM can be initialized with the observed profile of temperature and water vapor and integrated forward with the time history of transport of energy and water vapor in or out of the SCM domain to simulate an observed period

Single Column Model (SCM)



- The data needed to accurately compute the horizontal transport is usually limited to periods of field experiments when a network of sounding stations exists (e.g. ARM Intensive Observing Periods or TOGA-COARE)

The SCM/CRM Forcing Approach

"Advective Forcing" computed from observations

"Physics" computed from:

- **CRM "explicitly"**
- **SCM parameterizations**

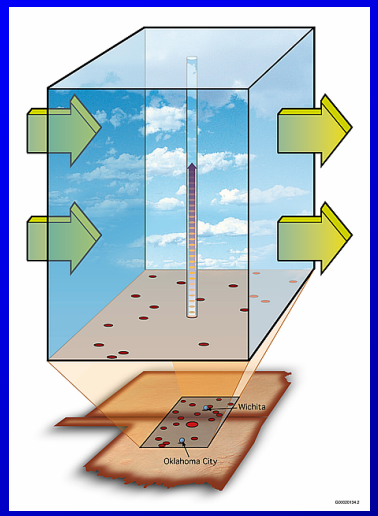
$$\frac{\partial s}{\partial t} = -V \bullet \nabla s - \omega \frac{\partial s}{\partial p} + L(c-e) - \frac{\partial \overline{\omega' s'}}{\partial p} + Q_{rad}$$

$$\frac{\partial q}{\partial t} = -V \bullet \nabla q - \omega \frac{\partial q}{\partial p} + (e-c) - \frac{\partial \overline{\omega' q'}}{\partial p}$$

Example 1

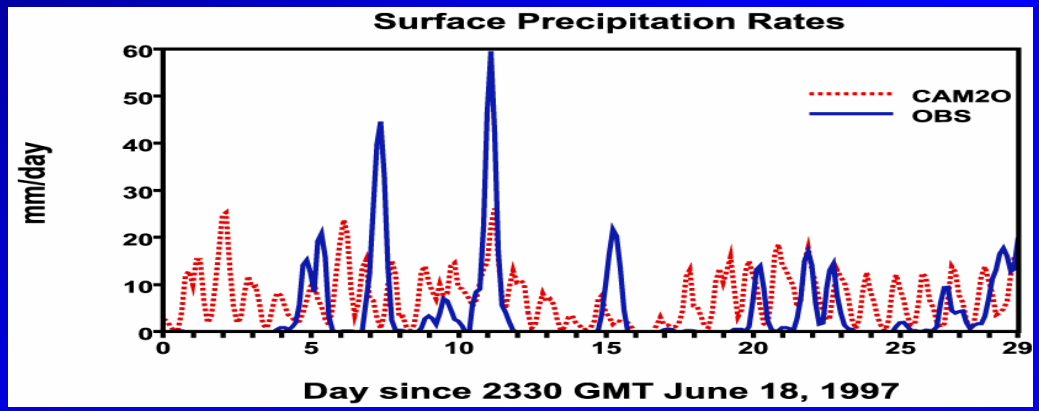
Summertime Convection over the ARM Southern Great Plains site

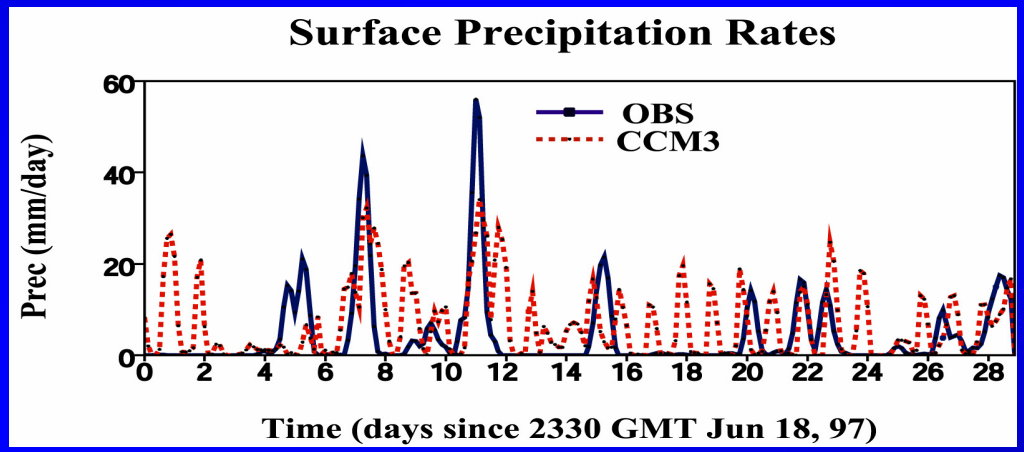
- Simulations with the NCAR and GFDL GCM forecasts and SCM forecasts are performed for the June-July 1997 ARM Intensive Observing Period



- A series of forecasts are initialized at 00Z and results for hours 12 to 36 are concatenated to form a time series to compare to the observations

NCAR results





GCM Forecasts

Daily precipitation in the mid-afternoon

Physics problem!

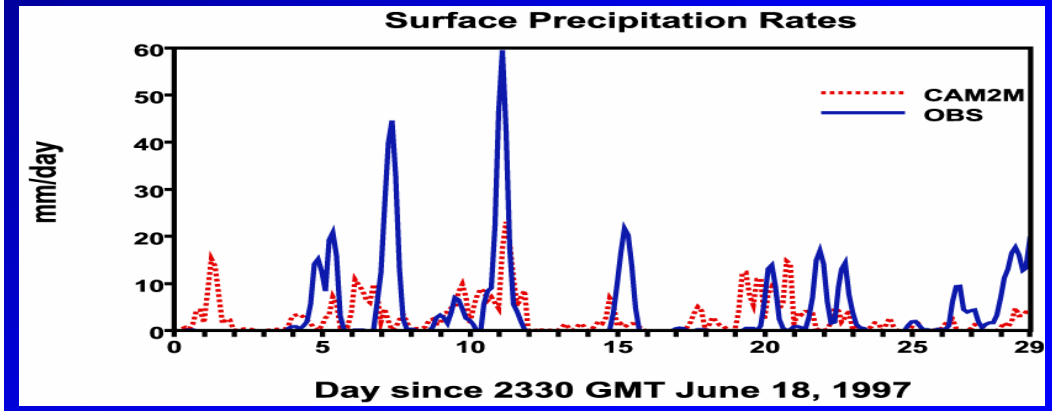
SCM Forecasts

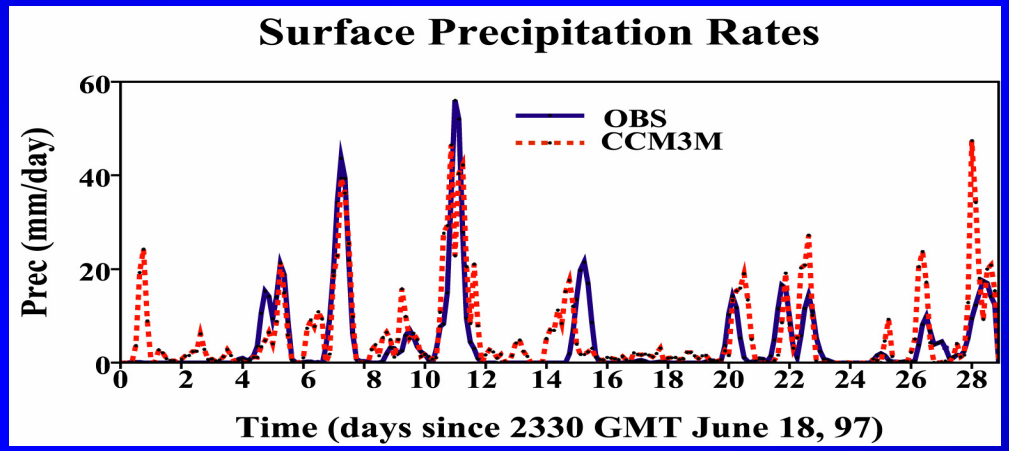
Why is there precipitation every day?

- The default convection scheme (Zhang-McFarlane 1995) has a Convective Available Potential Energy (CAPE) closure which doesn't have any allowance for convective inhibition or convective triggers

- Xie and Zhang (2000) proposed that deep convection should require that DCAPE > 0 in addition to CAPE > 0. DCAPE is the change in CAPE due to large-scale advection and vertical motion. (i.e. the large-scale circulation should be supportive of convection)

Impact of DCAPE trigger





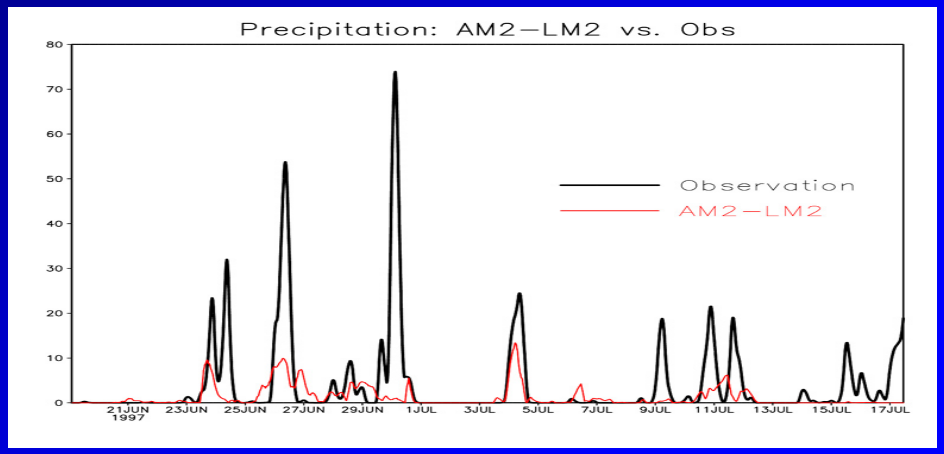
GCM Forecasts

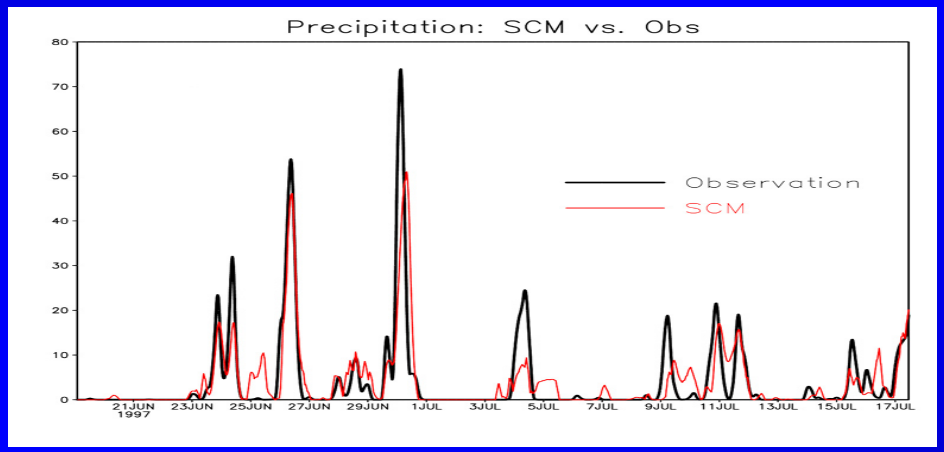
Daily precipitation problem gone!

SCM has good agreement but events too weak in GCM.

SCM Forecasts

GFDL Results





GCM Forecasts

SCM has good agreement but events too weak in GCM

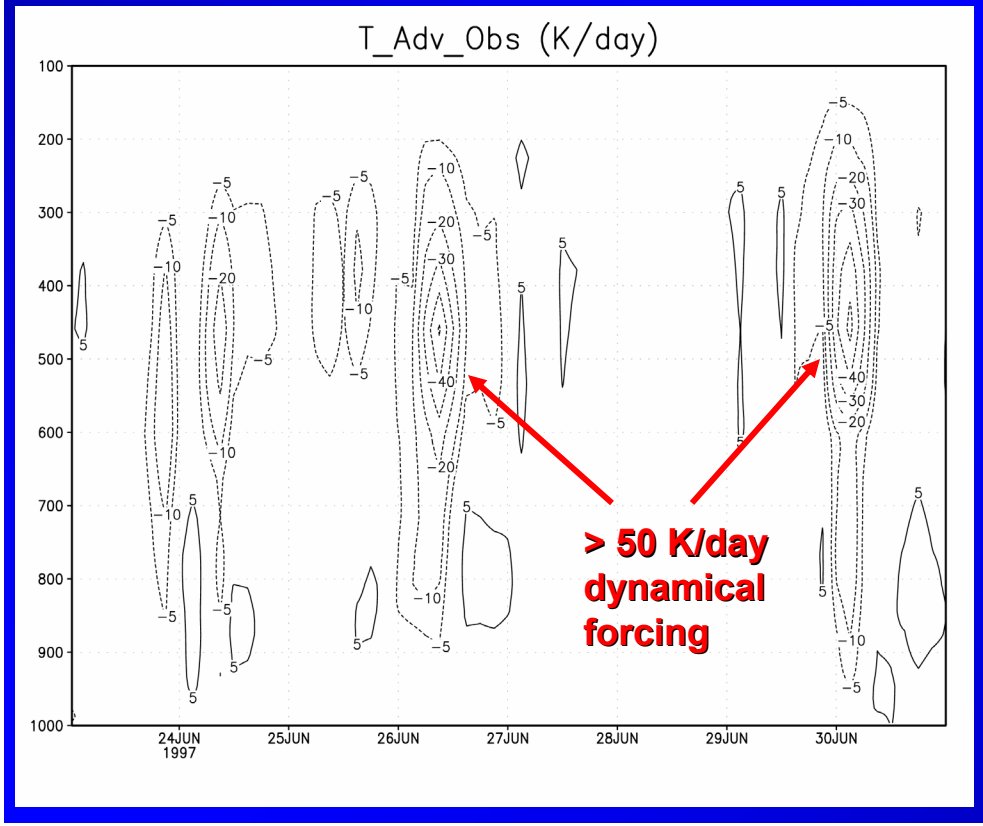
Physics problem?

SCM Forecasts

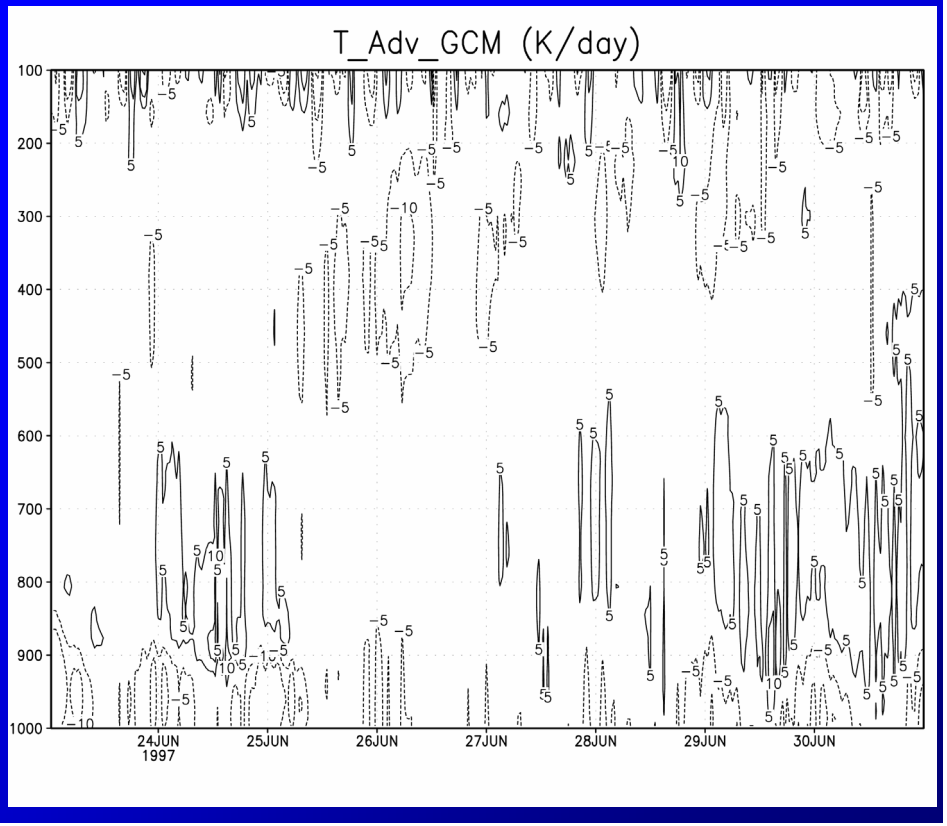
Advective Forcing is Considerably Different!

Large-scale Temperature Advection: $-V \bullet \nabla s - \omega \frac{\partial s}{\partial p}$

Variational Analysis (given to SCM)



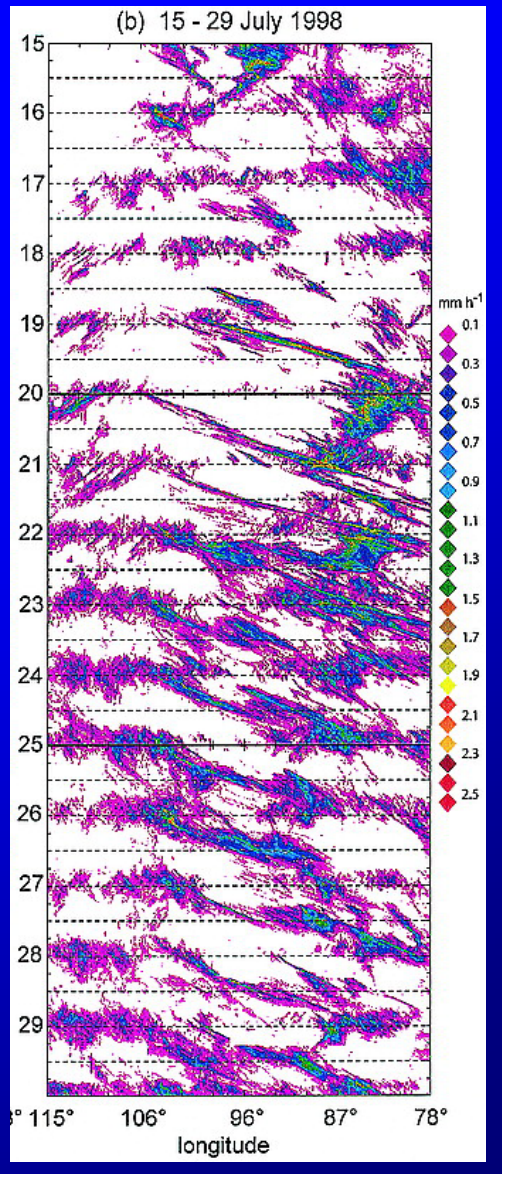
GCM dynamics



Why doesn't the GCM produce the same forcing?

- The strong advective forcing is associated with nighttime deep convection which is stimulated by a fast (~15 m/s) eastward moving deep tropospheric gravity wave (Carbone et al. 2002) itself which is initiated by the early evening convection at the front range of the U. S. Rockies

- The serious underestimate of precipitation causes the AM2 model to drift to a climate which is biased warm (~6 K in JJA averages) and dry

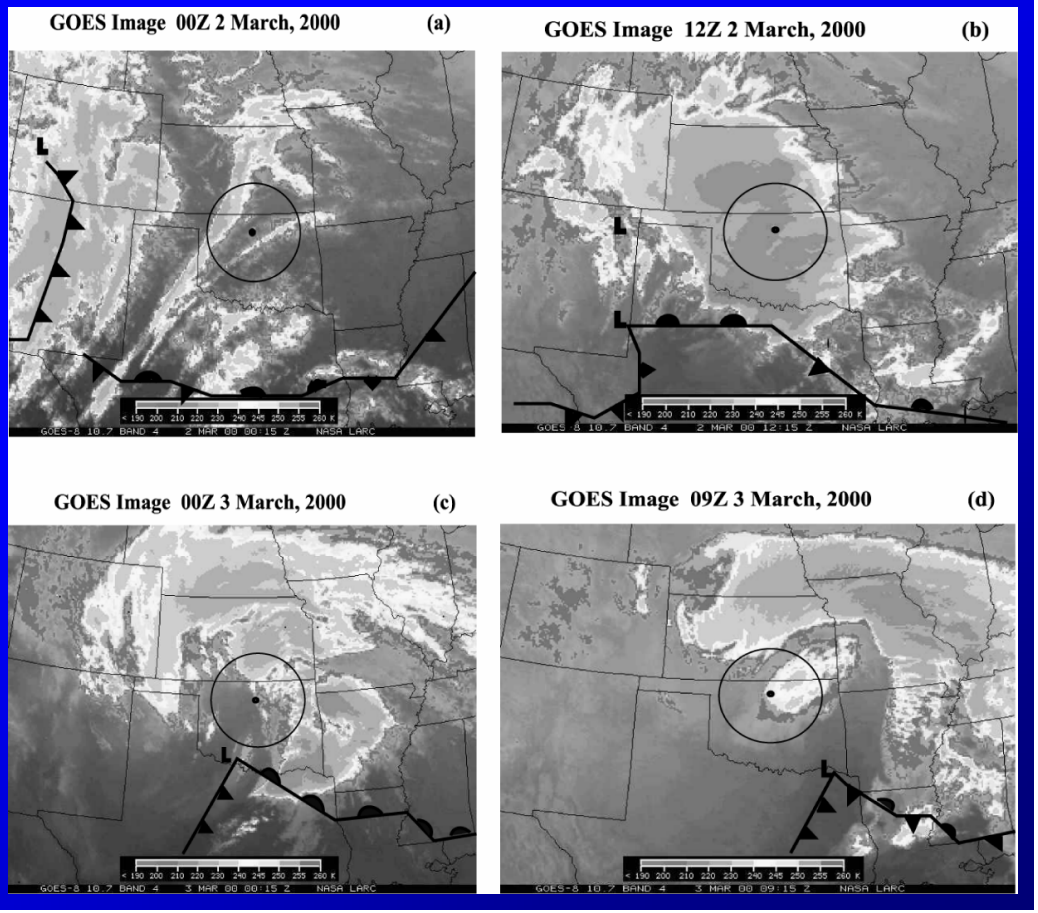


Radar Precipitation Hovmoller (Carbone et al. 2002)

Example 2

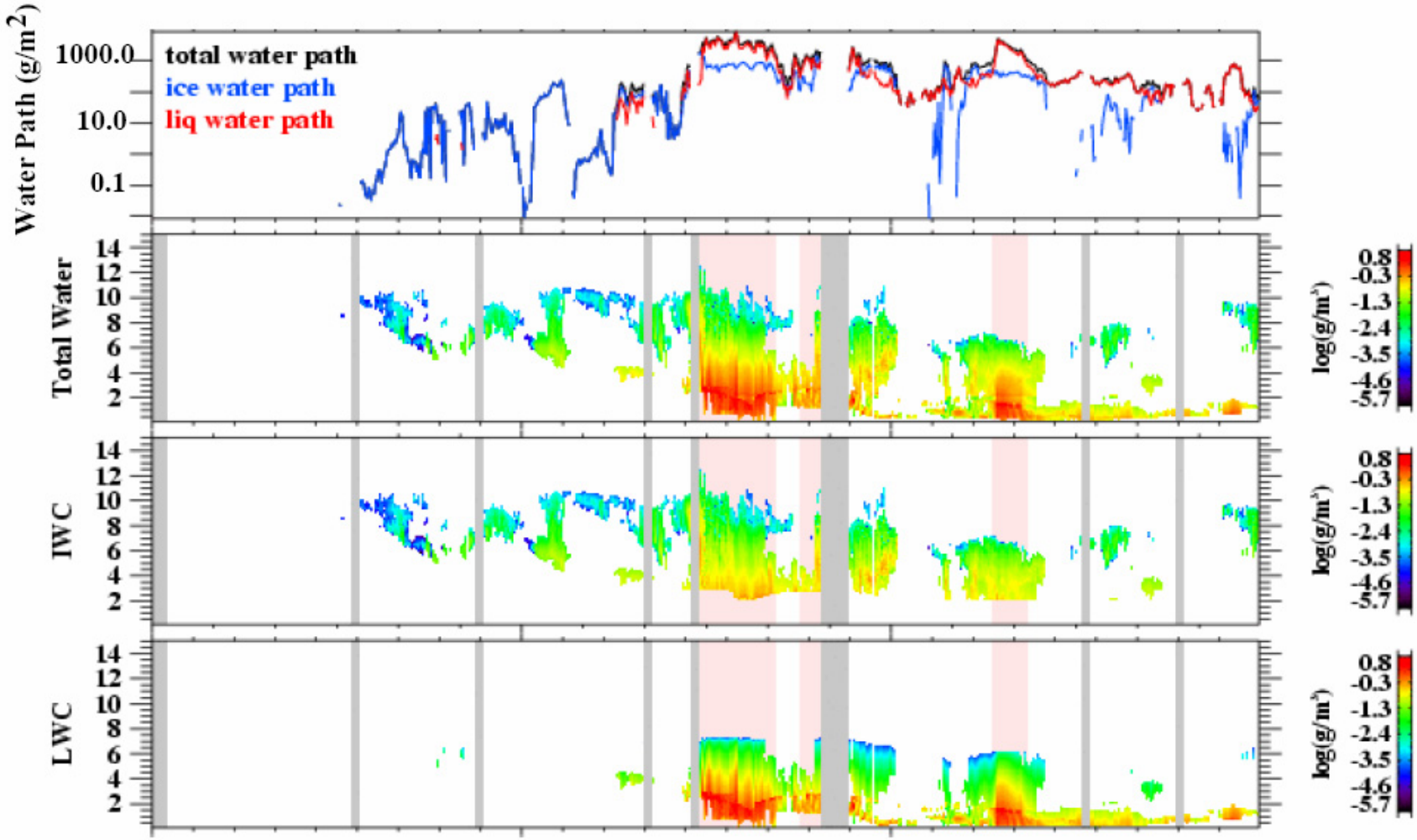
Clouds associated with a cold front passage over the ARM Southern Great Plains site

- A very strong cyclone passed over the ARM SGP site on March 2-3, 2000
- This was during the ARM "Cloud" Intensive Observing Period

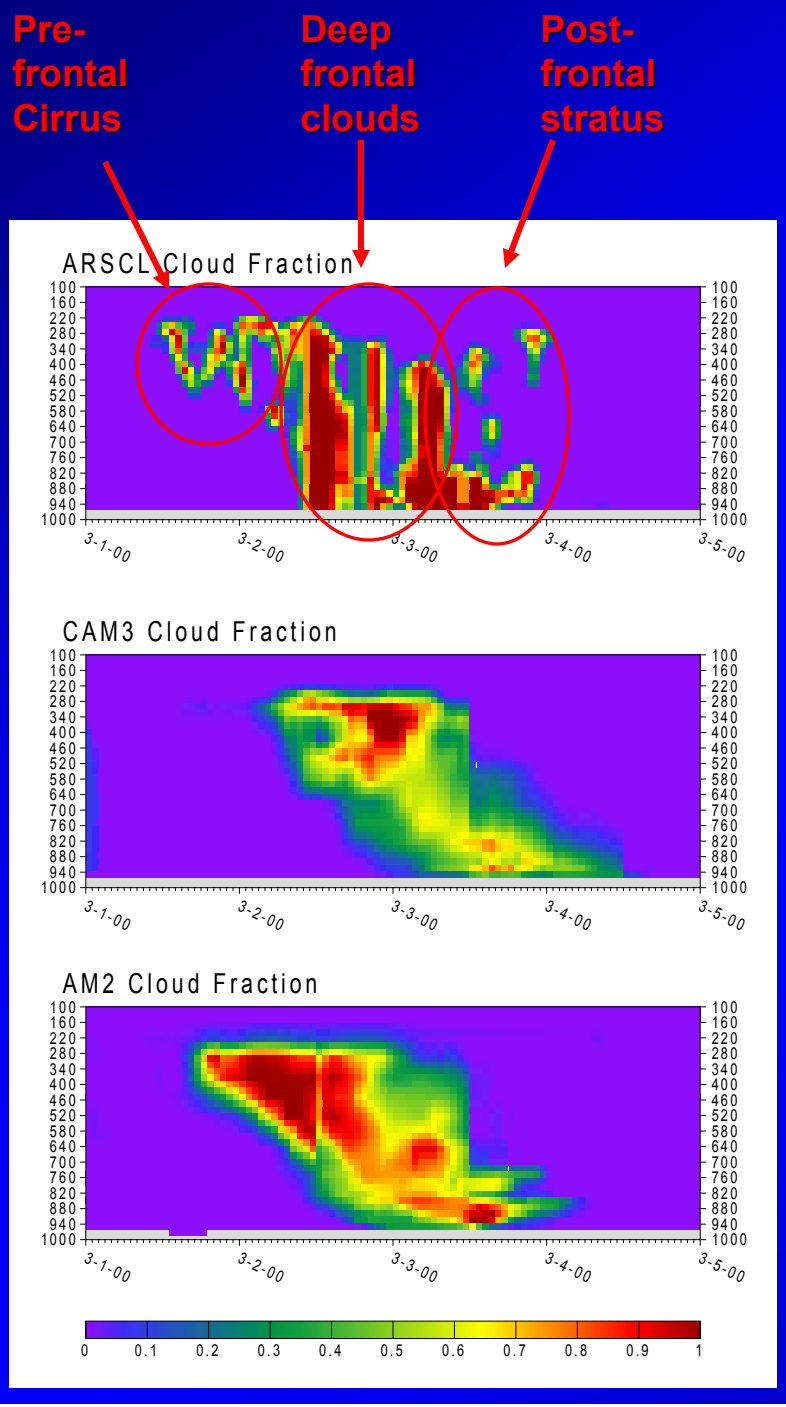


Cloud Retrievals from the ARM Millimeter Wavelength Cloud Radar

(courtesy from Jay Mace, U. Utah)



Cloud Fraction

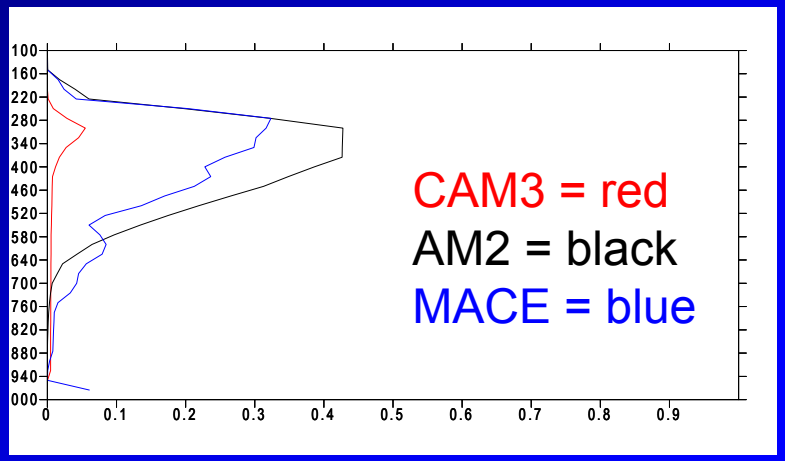


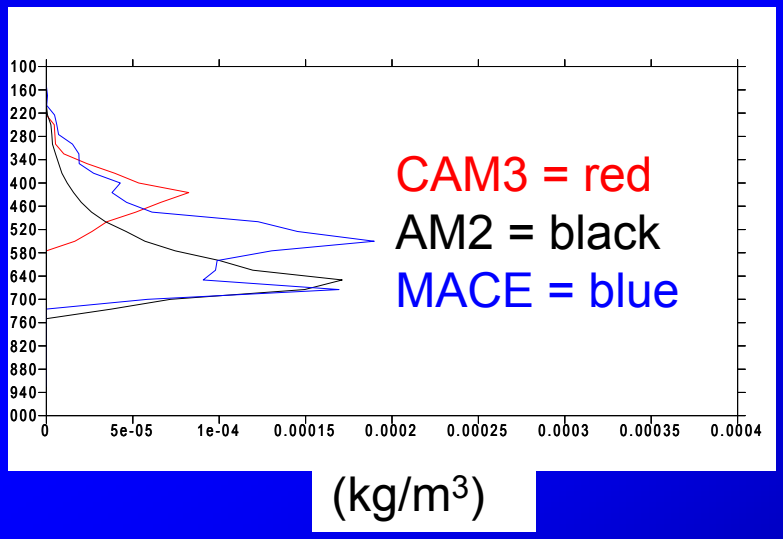
Observation

NCAR CAM3

GFDL AM2

High Cloud Period Average





Cloud Fraction

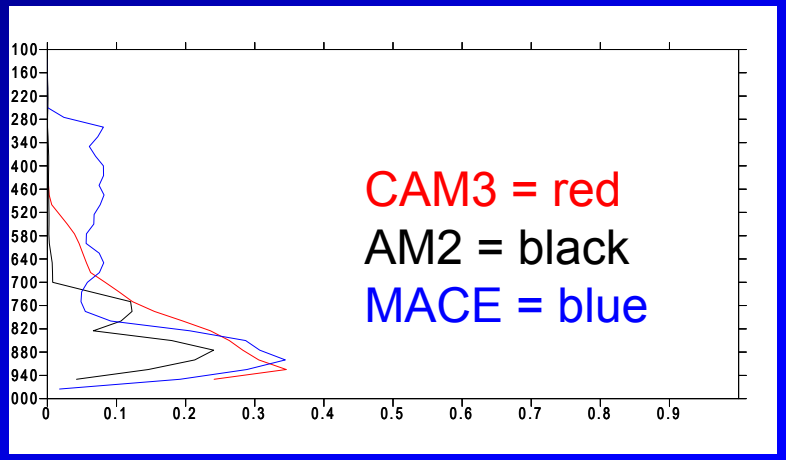
Ice Water Content (in-cloud)

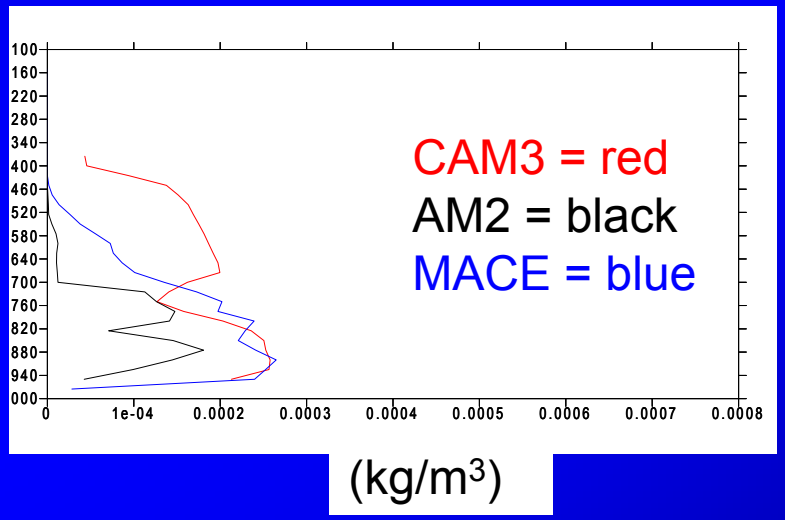
(+/- 50% estimated accuracy)

NCAR's cirrus is too small in extent but with about the right amount of ice water in cloud

GFDL's cirrus has about the right extent but with too little ice water

Low Cloud Period Average





Cloud Fraction

Liquid Water Content (in-cloud)

(+/- 50% estimated accuracy)

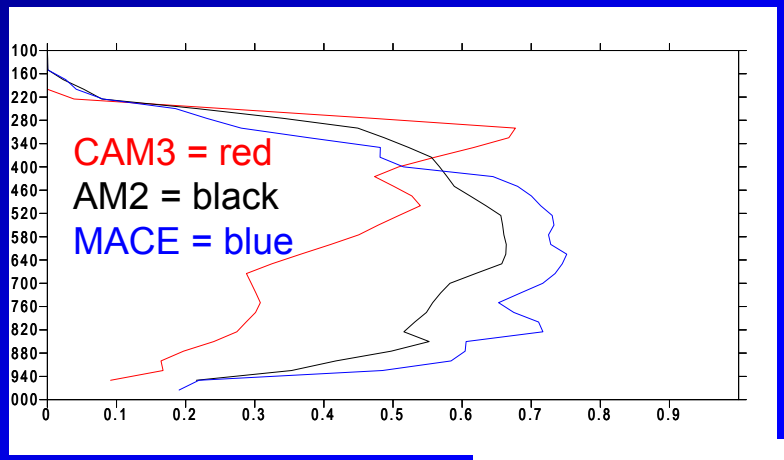
NCAR's low cloud fraction and in-cloud liquid water are in good agreement

GFDL's low cloud fraction and in-cloud liquid water are both too small

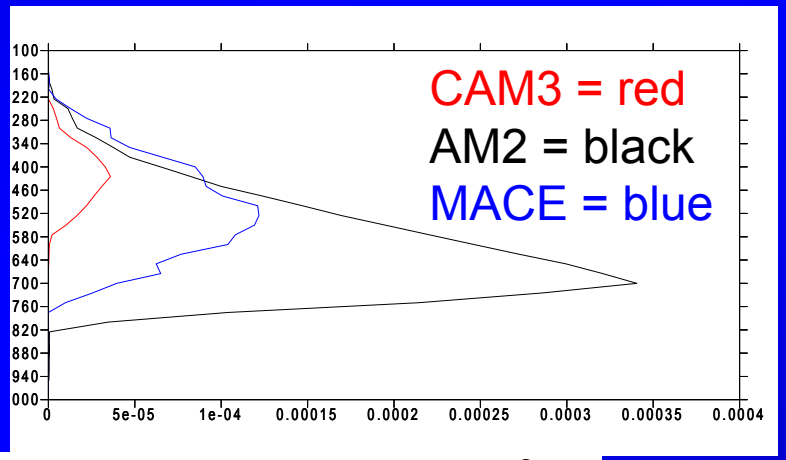
Note both models miss the scattered post-frontal cirrus!

Deep Cloud Period Averages

Cloud Fraction

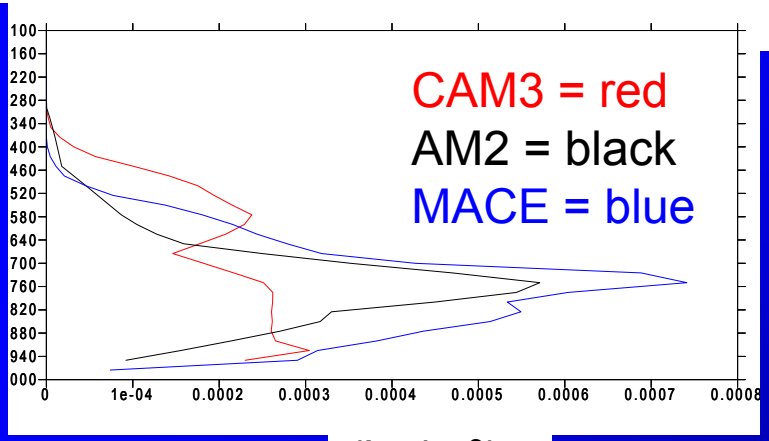


Ice Water Content (in-cloud)



(kg/m^3)

GFDL has much more condensate than NCAR but it simulates a much stronger storm



(kg/m^3)

Liquid Water Content (in-cloud)

N. B. Observations of cloud ice and liquid are highly uncertain at times of precipitation and in mixed-phase clouds!

Next Steps

- Need to build up statistics since many case studies will needed to compare single point cloud radar retrievals to GCM grid-box averages
- Need to consider the relationship of cloud properties to dynamics
- Wish to look beyond single point → CloudSat

Example 3

Tropical Deep Convection – TOGA-COARE

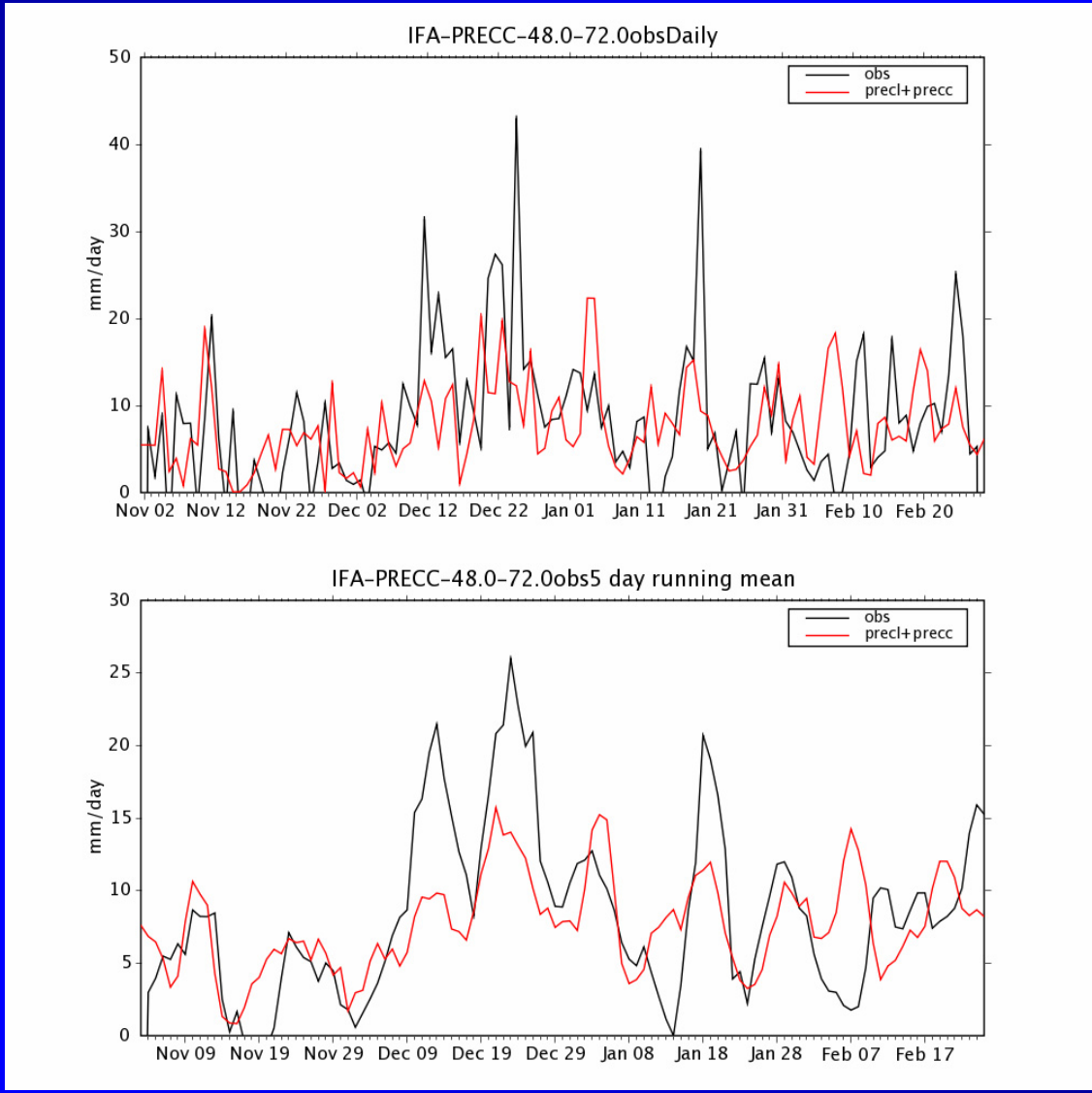
- TOGA-COARE was an experiment that took place over the Tropical Pacific Warm Pool during November 1992-February 1993
- During this period several active and inactive phases of the Madden-Julian Oscillation were observed
- Climate models have large problems with tropical convection and MJO

Can a forecasting approach be useful?

Are the ECMWF ERA-40 analyses good enough?

Do issues of precipitation spin-up (or spin-down) get in the way?

Precipitation over the Intensive Flux Array (IFA)

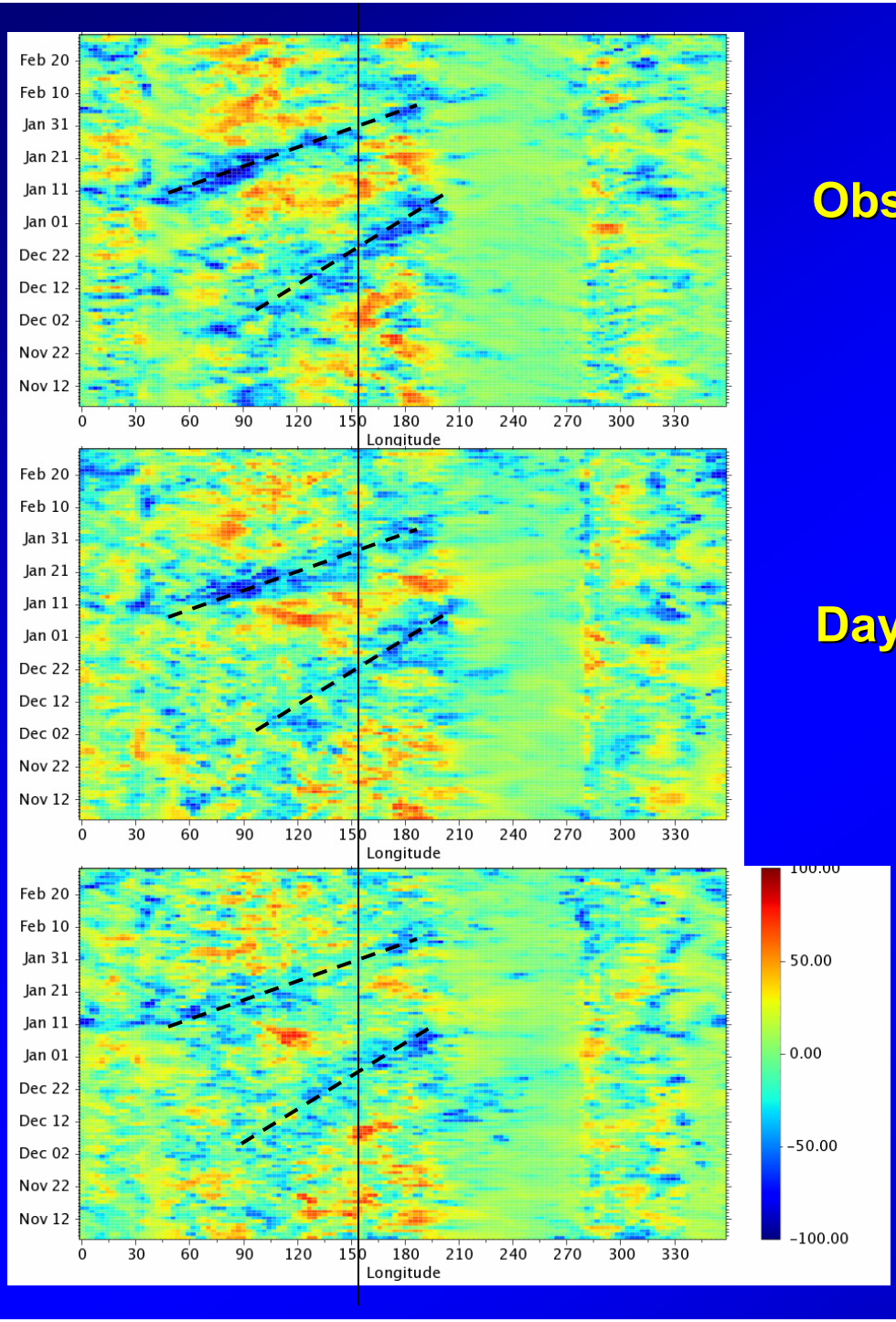


NCAR CAM3 Day 3 Precip

Daily mean

5-day running mean

OLR Anomaly Hovmollers (5N-5S)



Observations

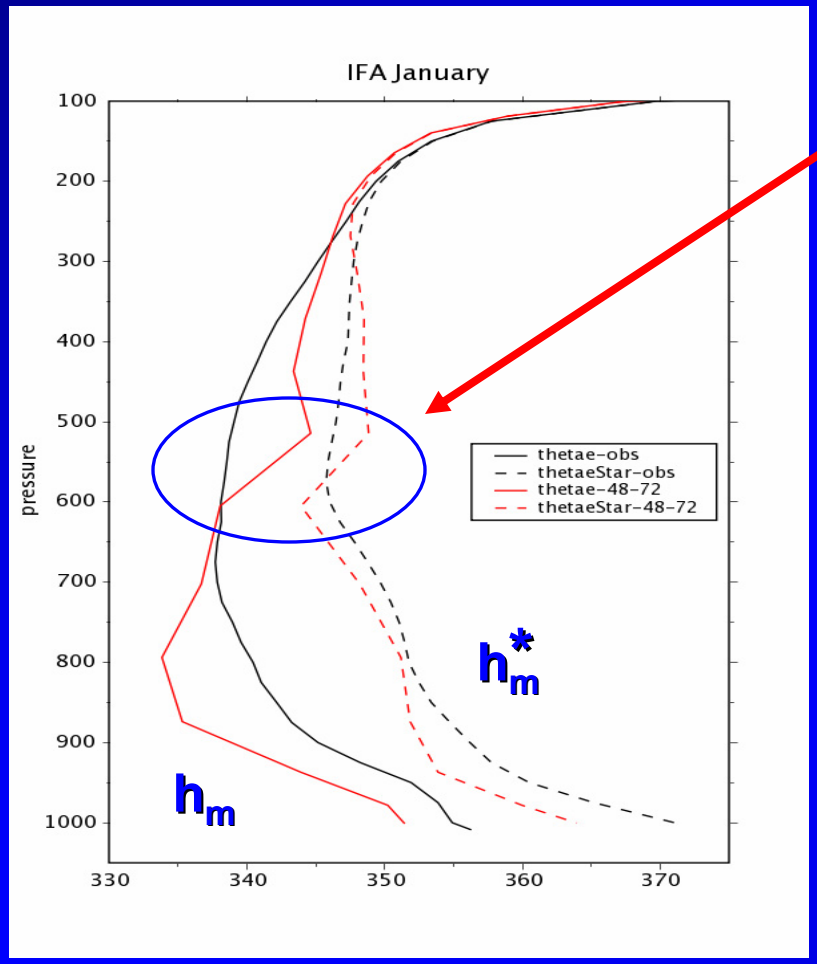
Day 2 Forecasts

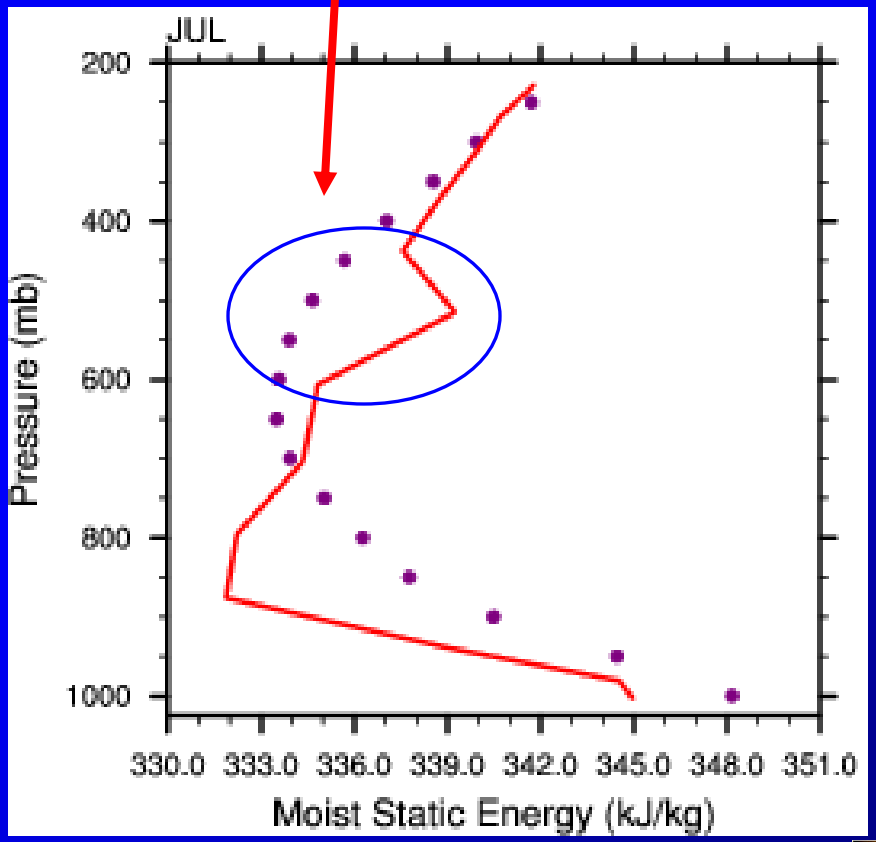
Day 6 Forecasts

NCAR CAM3 has some semblance of MJO in day 2, but is very weak by day 6!

Thermodynamic Drift of Moist Static Energy

Day 3 forecasts show the same unrealistic profile of moist static energy that persists in model's climate!





Day 3 Forecasts for IFA

AMIP July Climate for Truk

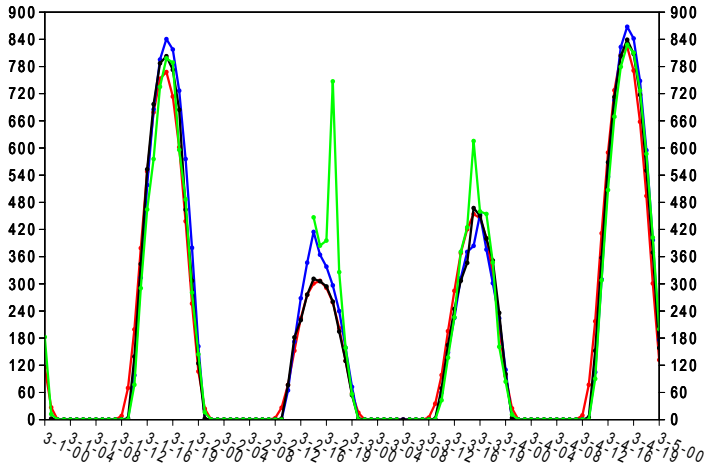
Final Thoughts

- I hope I have convinced you that a short-range weather forecasting approach can be a useful technique to diagnose some of the sources of errors before a model drifts to its climate state
- Single Column Model tests can help isolate physics errors from errors in dynamical forcing
- Satellite data is a useful complement to single-point observations taken in field-experiments *(No one dataset has the answers to all of the problems)*

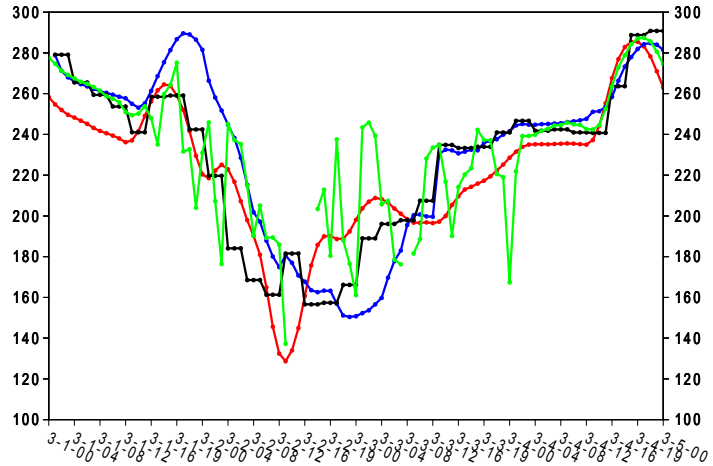
The End

Radiation

SW TOA

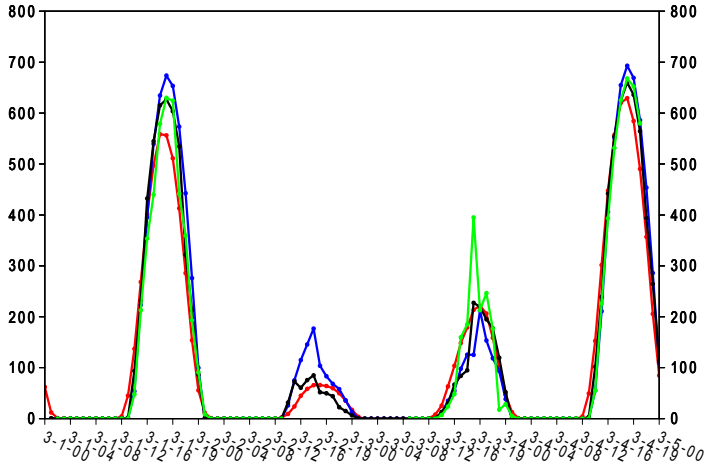


LW TOA

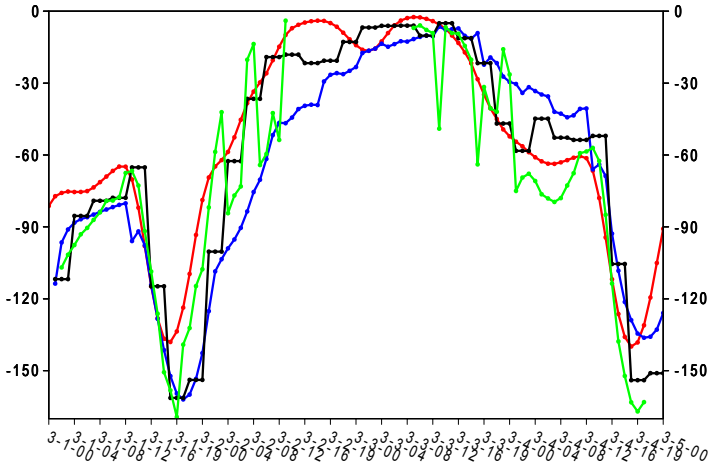


Red = ARM
Black = AM2
Green = MACE
Blue = CAM3

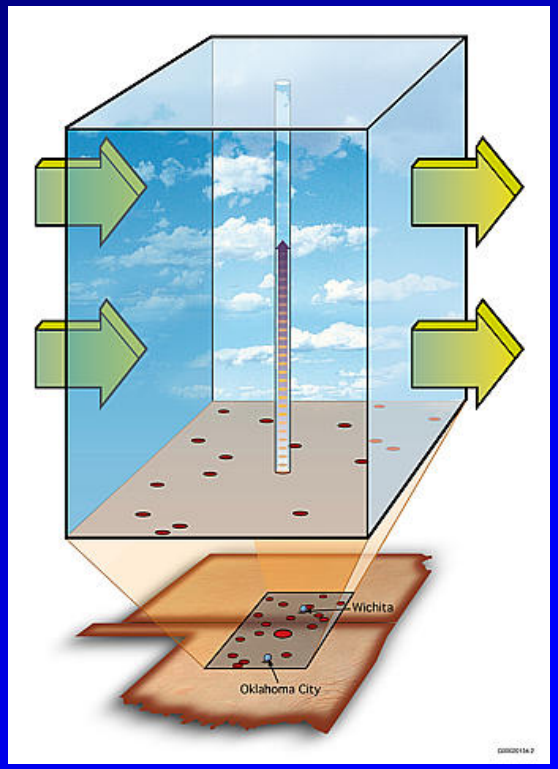
SW SFC



LW SFC



ARM Data



- 5 sounding stations (every 3 hours during IOPs)
- 7 wind profilers
- Surface flux (sensible, latent, CO_2) and radiation estimates from multiple surface stations
- Precipitation estimates from radar calibrated to gauge data
- Satellite estimates of top-of-atmosphere radiation budget (geostationary data calibrated to CERES)

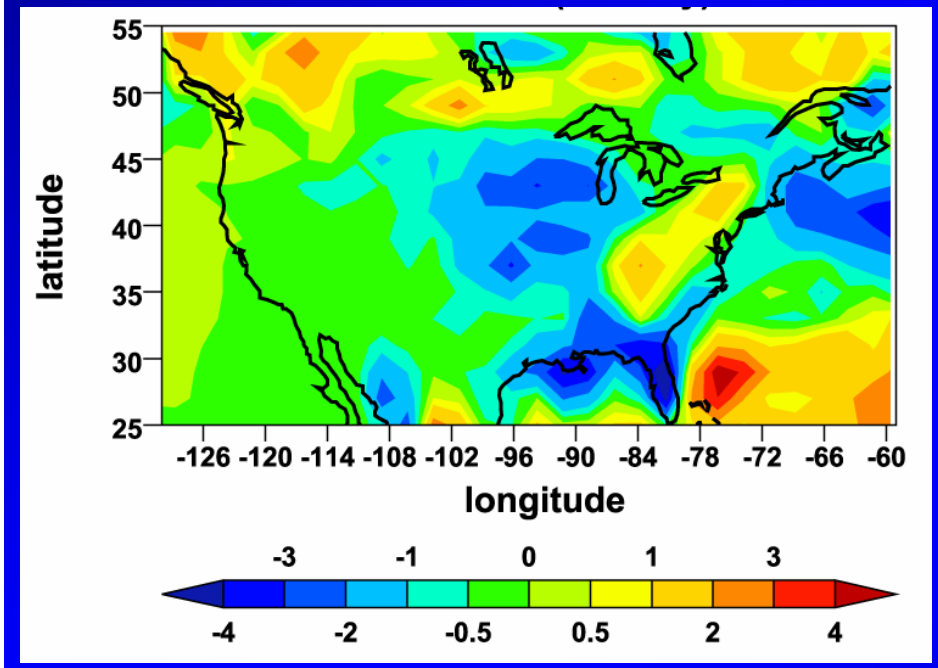
+ NCEP Regional Model (RUC) background fields

Variational Analysis *(Zhang and Lin 1997, Zhang et al. 2001)*

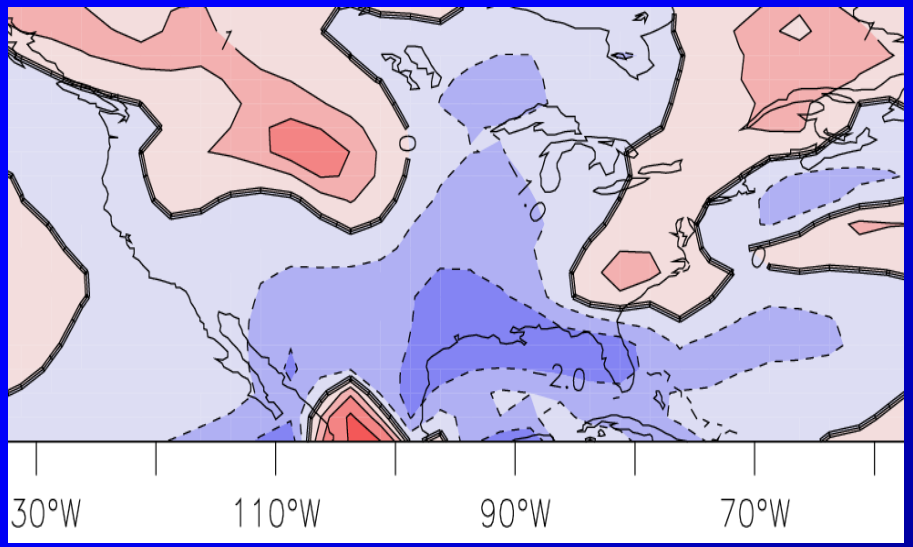
- The profiles of state variables are adjusted until they satisfy column budgets of mass, energy, and moisture
- This provides an estimate of the large-scale flow and the diabatic heat and moisture tendencies

Precipitation Bias
(AM2 Minus Observations)

1st Day Forecast Bias



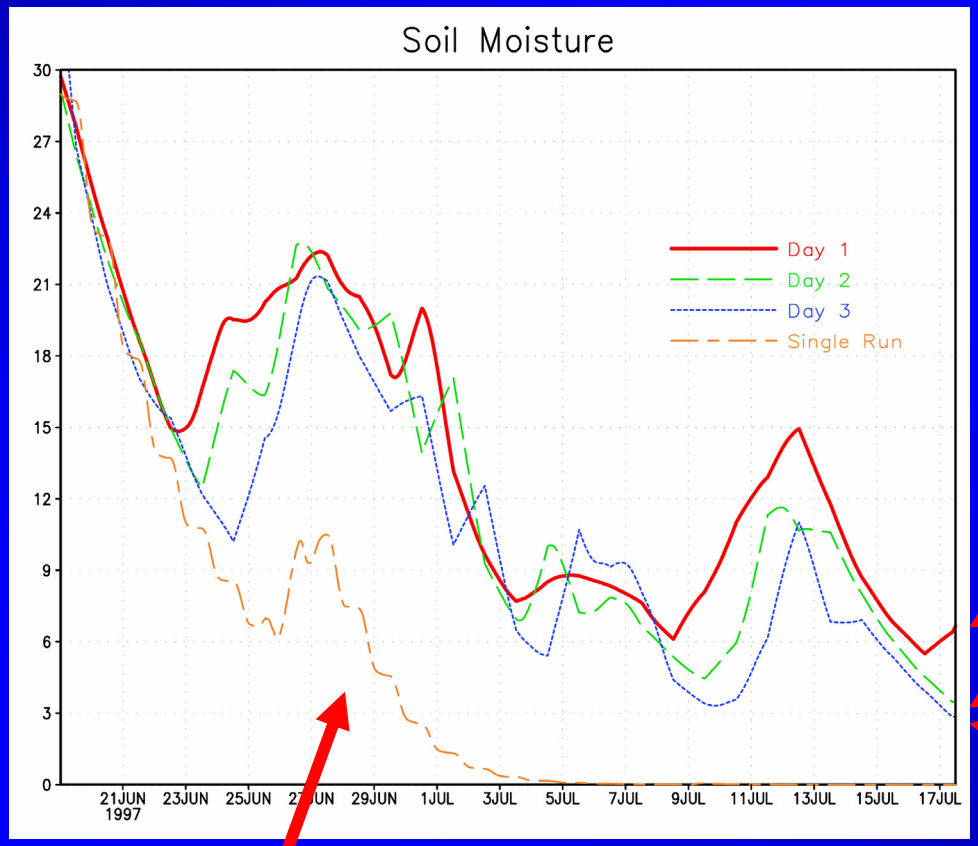
Climate Bias



(mm day^{-1})

Climate bias appears from the very beginning of the forecasts!

Climate drift is tied to the lack of precipitation



Day 1

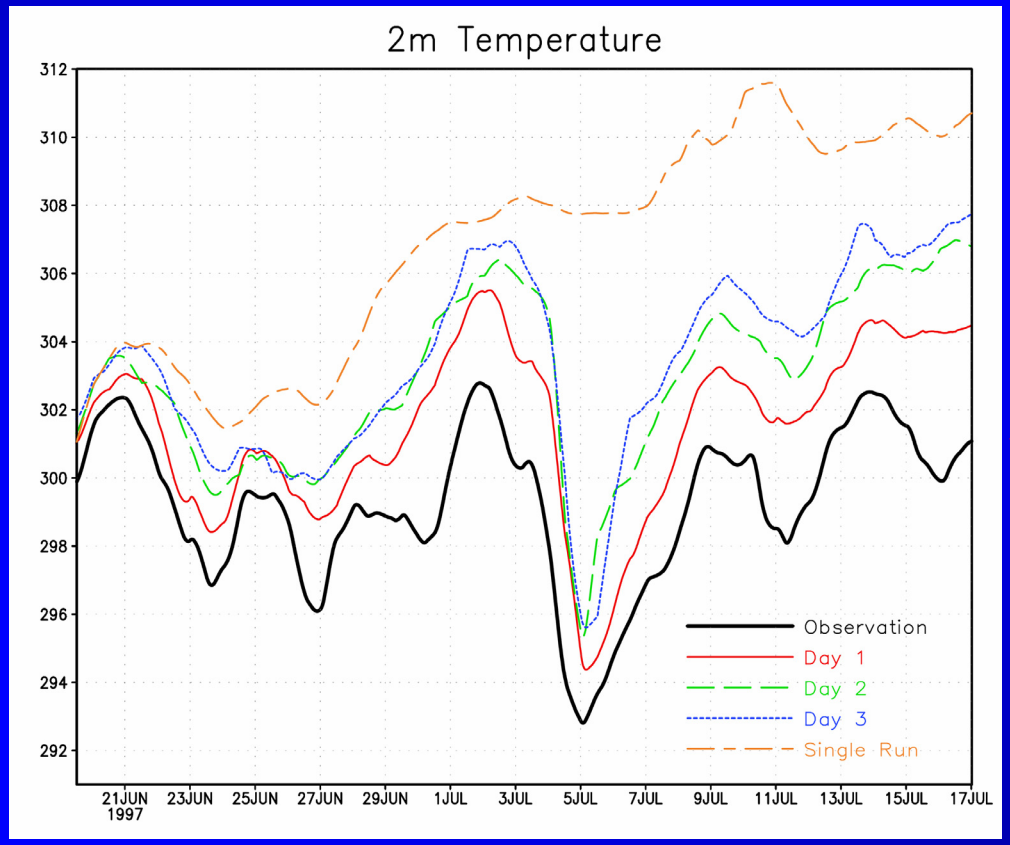
Day 2

Day 3

Single forecast from the start of the IOP

Climate Drift

24-hour running mean 2-meter temperature



Single forecast from the start of the IOP

Day 3

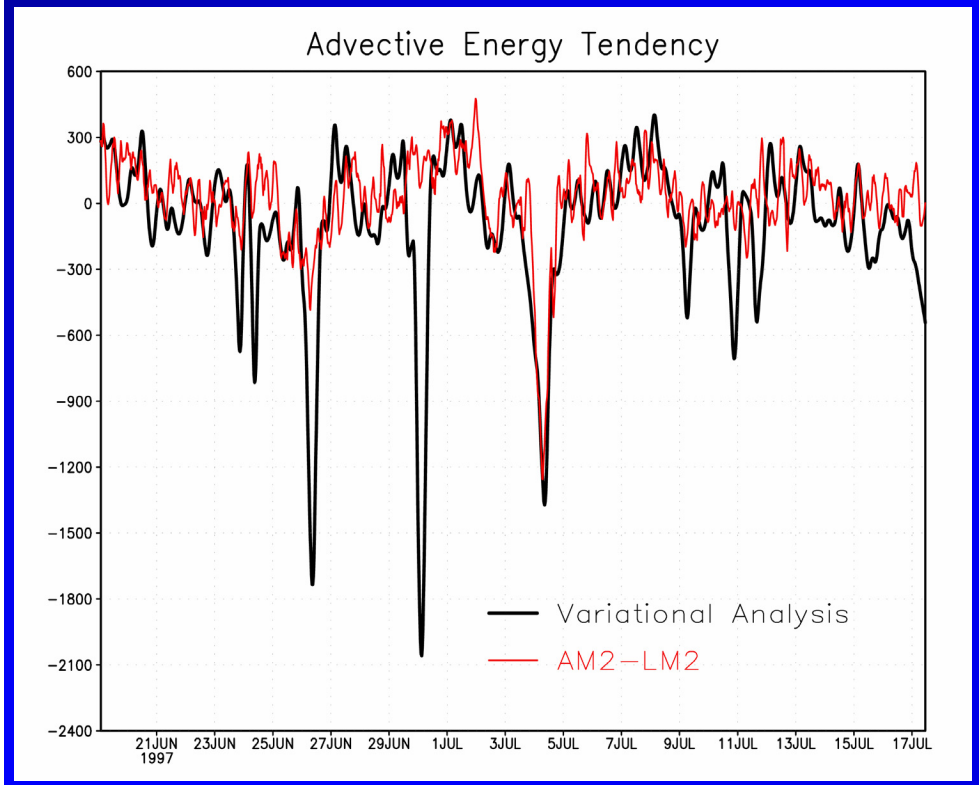
Day 2

Day 1

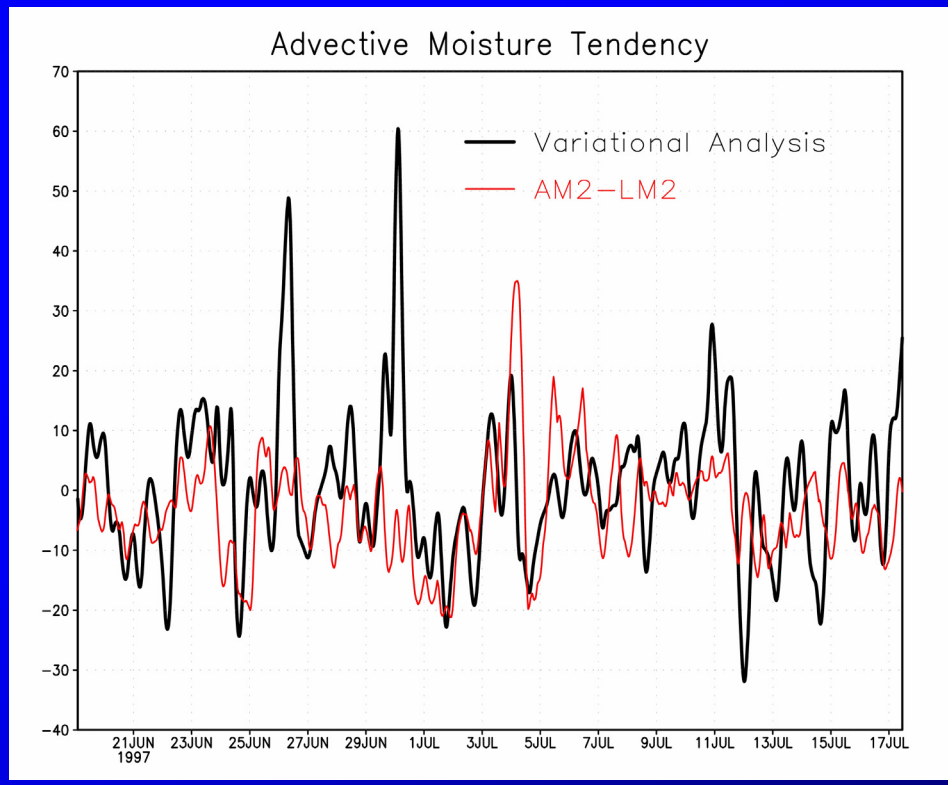
Observation

Column Integrated Advective Tendencies

Energy (W m^{-2})



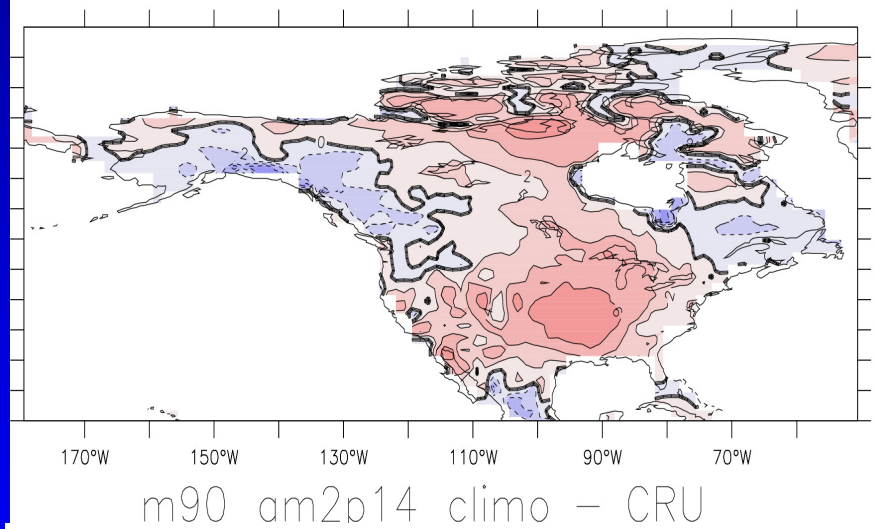
Moisture (mm day^{-1})

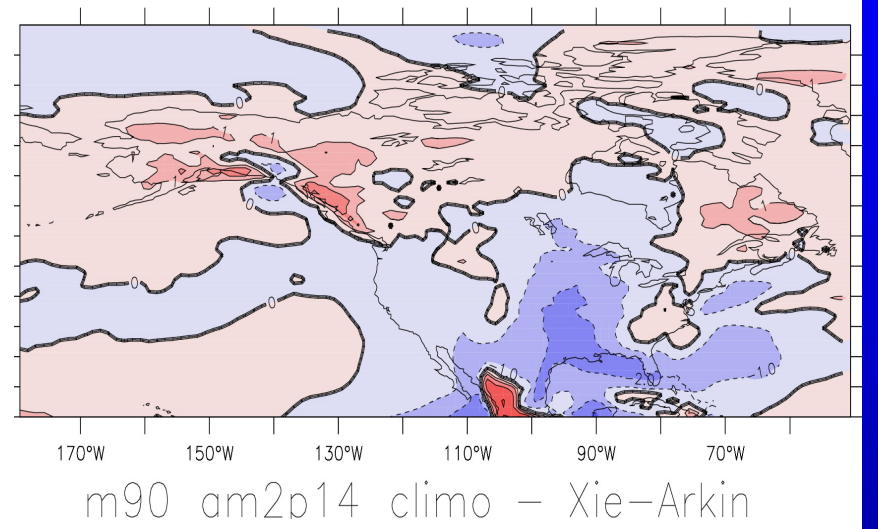


Increased horizontal resolution is apparently not the answer (at least not yet)

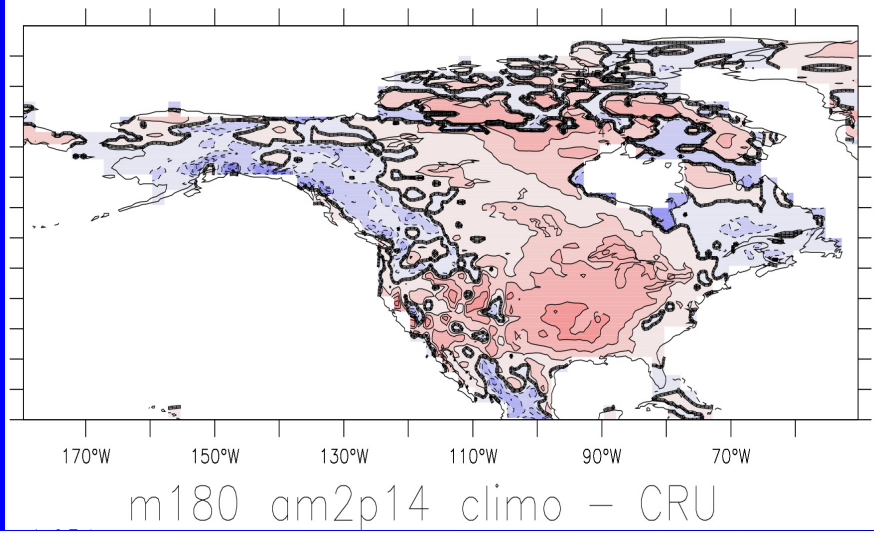
2 meter temperature bias (K) **Precipitation bias (mm day^{-1})**

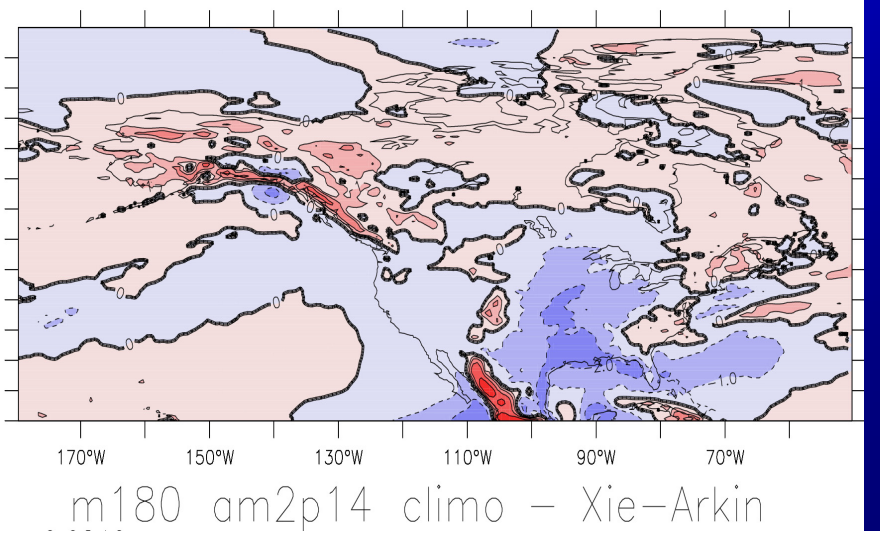
1 degree





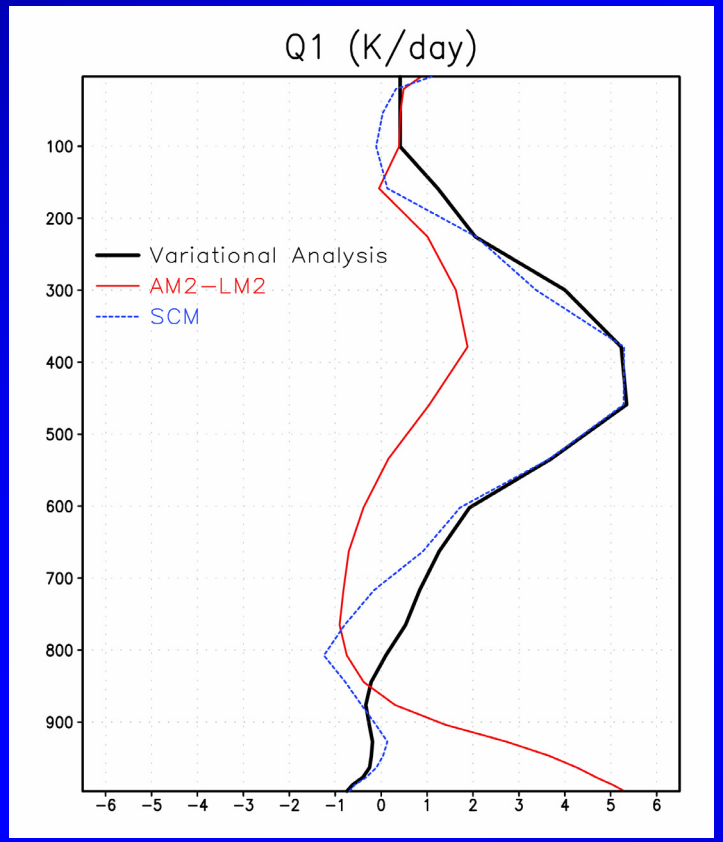
0.5 degree

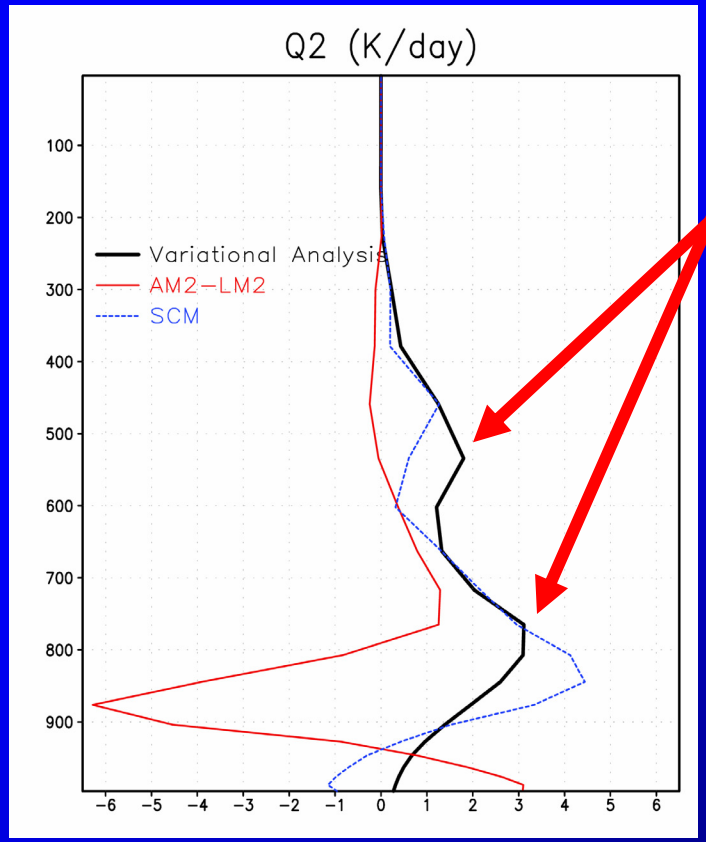




Is the physics good enough?

Heat & Moisture Source/sinks on Wet Days

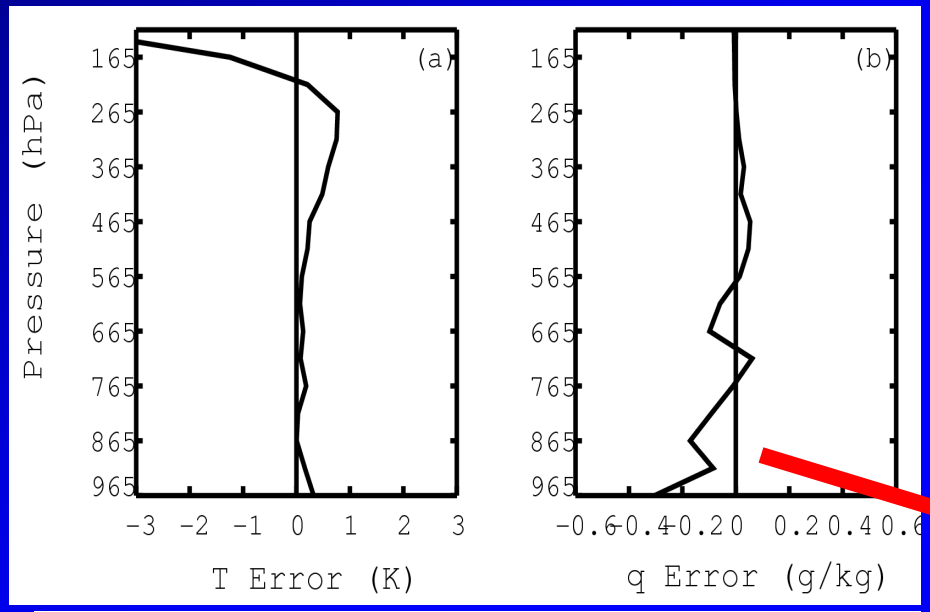




Convective precipitation evaporation at too high a level or lack of stratiform precip-itation?

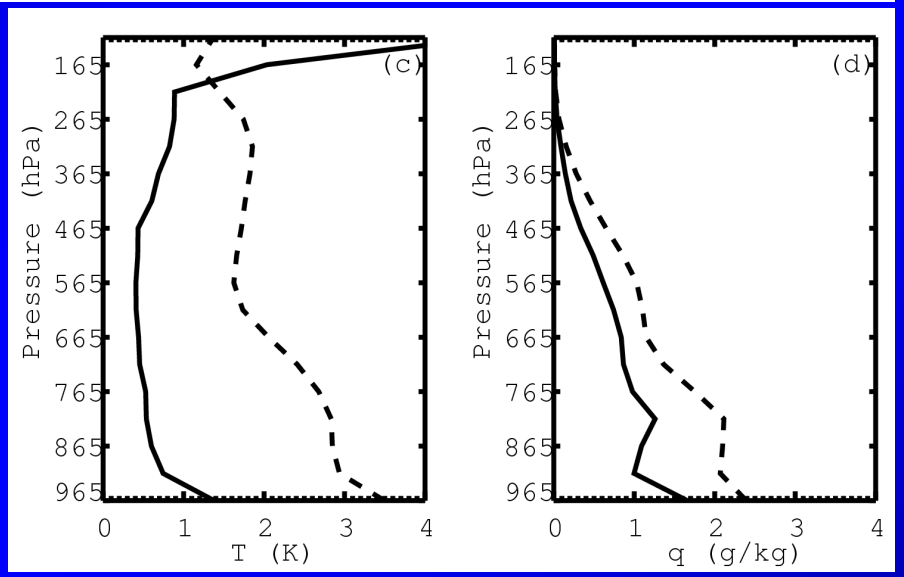
Accuracy of ERA-40 data at the ARM SGP site

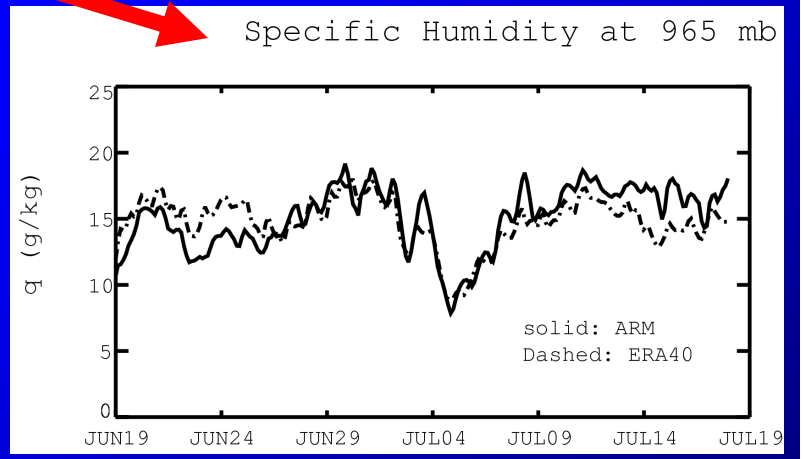
Mean Bias Error (ERA40 – ARM)

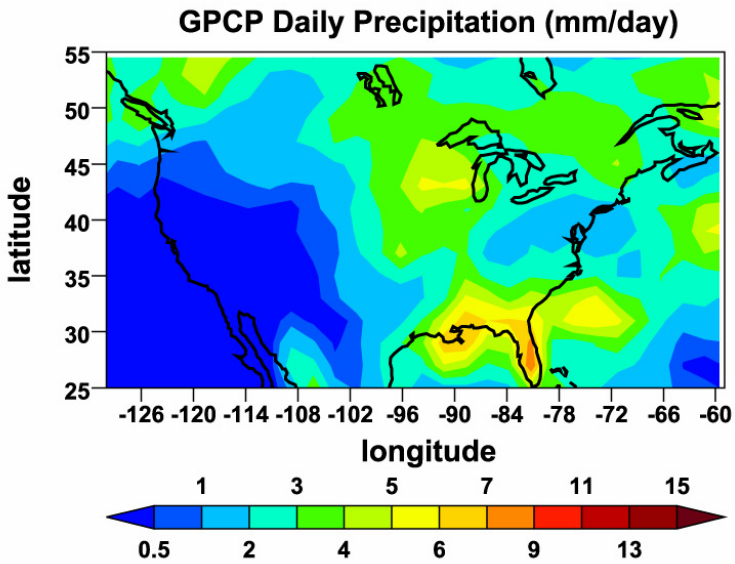


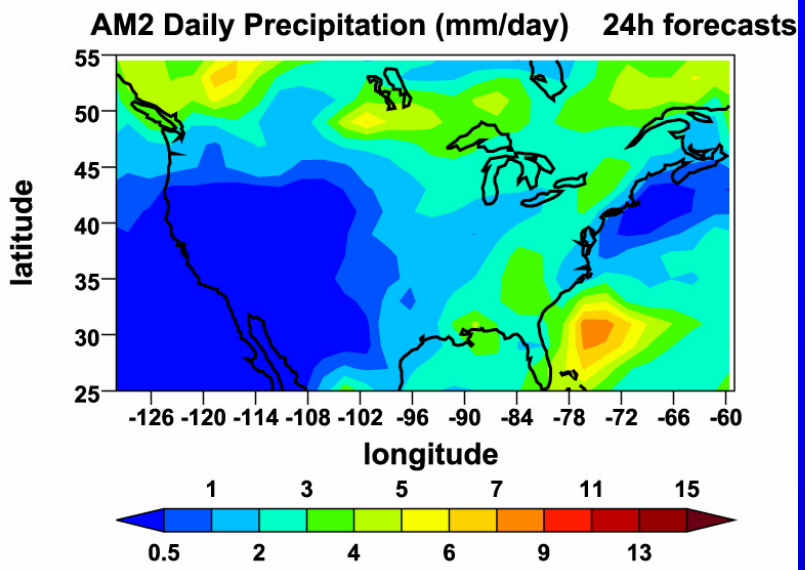
RMS Error (solid)

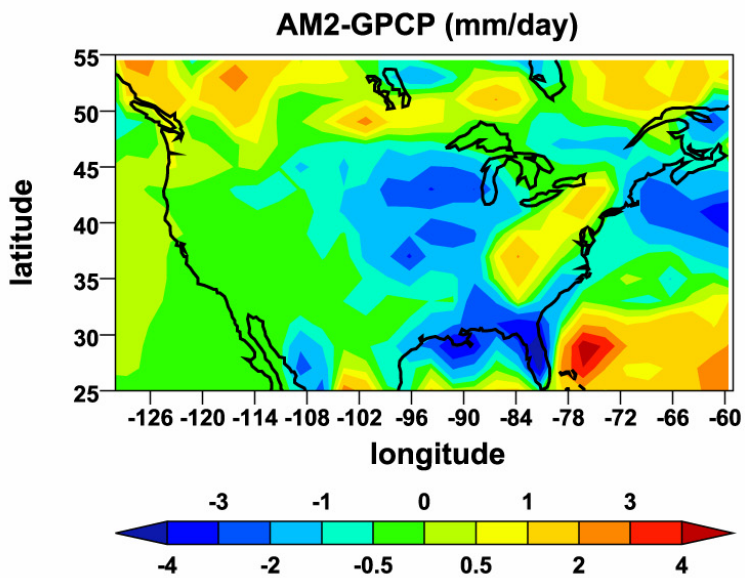
Std. Dev. Obs (dashed)

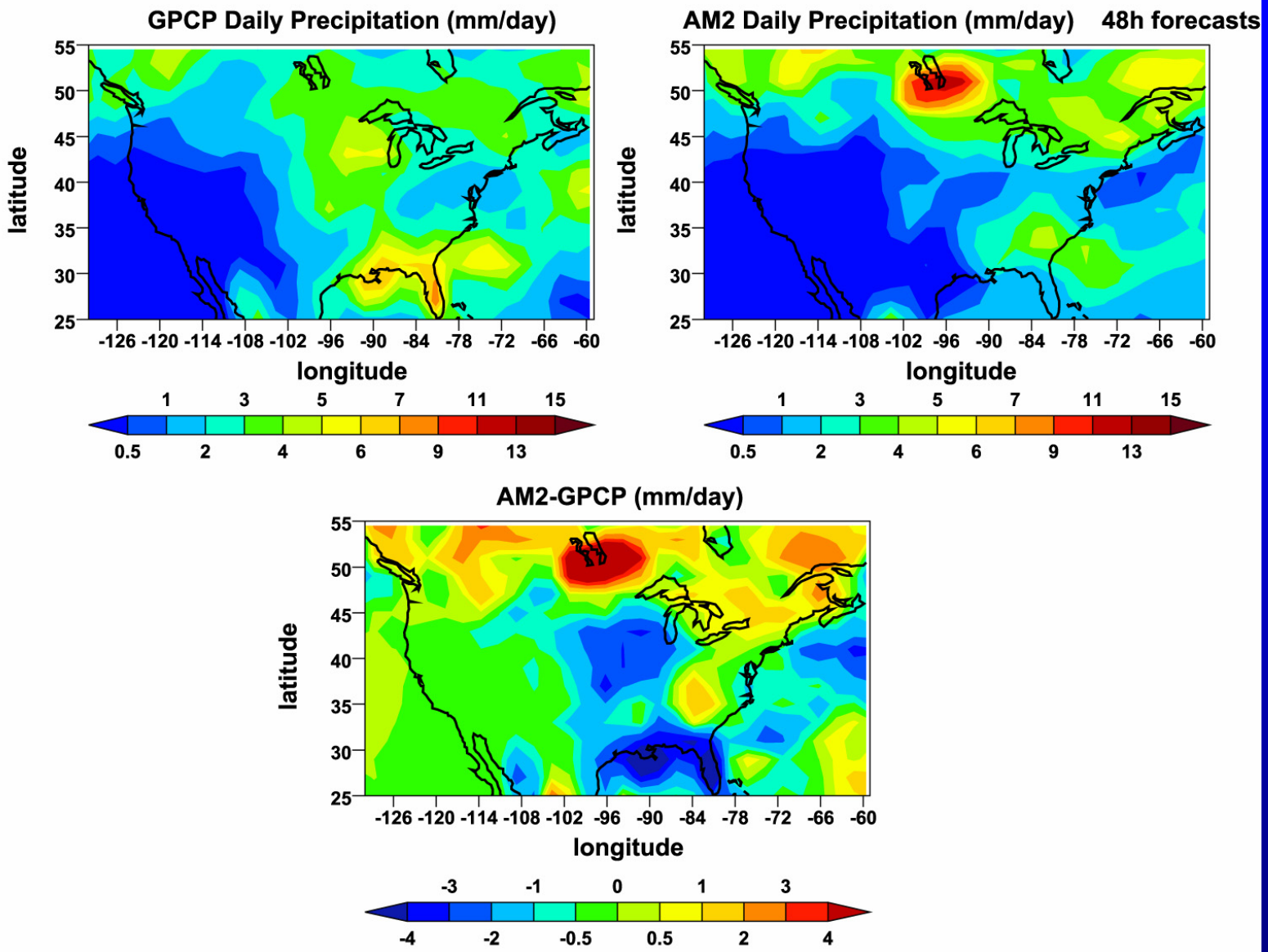


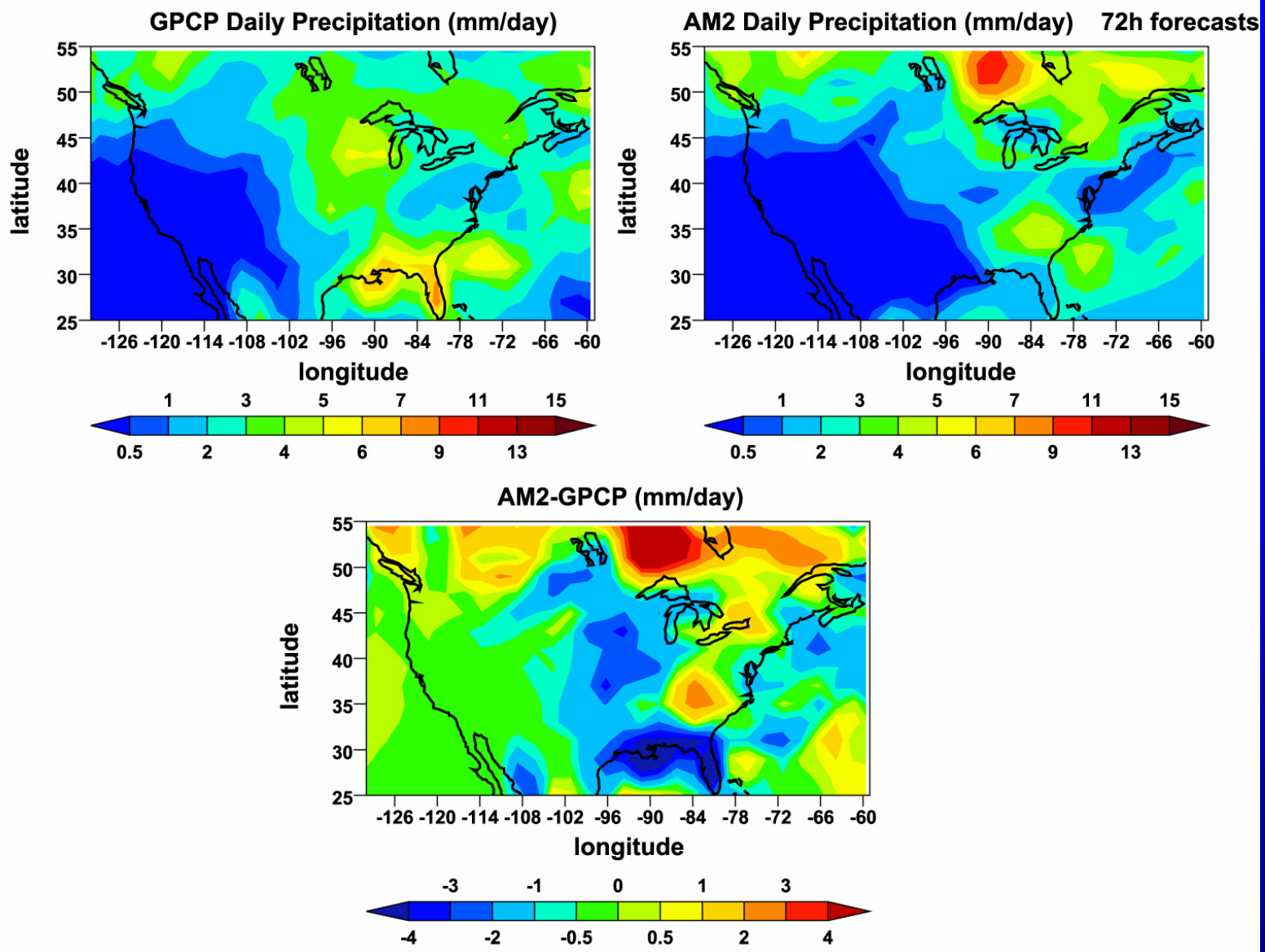



GPCP Daily Precipitation (mm/day)
latitude
55
50
45
40
35
30
25
-126 -120 -114 -108 -102 -96 -90 -84 -78 -72 -66 -60
longitude
1 3 5 7 11 15
0.5 2 4 6 9 13


AM2 Daily Precipitation (mm/day) 24h forecasts
latitude
55
50
45
40
35
30
25
-126 -120 -114 -108 -102 -96 -90 -84 -78 -72 -66 -60
longitude
1 3 5 7 11 15
0.5 2 4 6 9 13


AM2-GPCP (mm/day)
latitude
55
50
45
40
35
30
25
-126 -120 -114 -108 -102 -96 -90 -84 -78 -72 -66 -60
longitude
-3 -1 0 1 3
-4 -2 -0.5 0.5 2 4


GPCP Daily Precipitation (mm/day)
AM2 Daily Precipitation (mm/day) 48h forecasts
AM2-GPCP (mm/day)
latitude
longitude
55
50
45
40
35
30
25
-126 -120 -114 -108 -102 -96 -90 -84 -78 -72 -66 -60
1 3 5 7 11 15
0.5 2 4 6 9 13
-3 -1 0 1 3
-4 -2 -0.5 0.5 2 4


GPCP Daily Precipitation (mm/day)
AM2 Daily Precipitation (mm/day) 72h forecasts
AM2-GPCP (mm/day)
latitude
longitude
55
50
45
40
35
30
25
-126 -120 -114 -108 -102 -96 -90 -84 -78 -72 -66 -60
1 3 5 7 11 15
0.5 2 4 6 9 13
-3 -1 0 1 3
-4 -2 -0.5 0.5 2 4