Using Atmospheric Radiation Measurement Observations to *Assess* Climate Models

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January 4, 2005

Many individuals made contributions to this work: Jim Boyle, Ric Cederwall, Jay Hnilo, Mike Fiorino, Steve Klein, Jerry Olson, Tom Phillips, Jerry Potter, Dave Williamson, Shaocheng Xie, and John Yio

ARM
Atmospheric Radiation Measurement

Outline

- The parameterization problem for climate / weather models
- The Atmospheric Radiation Measurement program
- Techniques to use ARM data

  - *Single column modeling*
  - *Weather forecasting and the CAPT project*

- A Case Study

  - *Strong frontal passage at the ARM Southern Great Plains site*

The Parameterization Problem for Climate / Weather Models

Consider the budget equations for s (dry static energy - "temperature"):

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

and q (water vapor mixing ratio) :

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

Atmospheric models discretize these equations with horizontal resolutions of order 100 kilometers (less for weather and regional models), vertical resolutions of order 1 kilometer in the troposphere, and time steps of order 1 hour.

The Parameterization Problem

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

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

"Dynamics" – transport of energy and water vapor by the horizontal winds V and the vertical wind ω

"Resolved" – a lot of confidence that we can model this accurately

"Physics" – Condensation c and evaporation e of water vapor, heating by radiation Q_{rad}, and turbulent transport vertically by sub-grid scale motions

"Parameterized" – relatively lower confidence that we can model this accurately at the scales with which the models are discretized

Parameterization Science

A **parameterization** is something that predicts the grid mean effects of "sub-grid" scale processes by use only of the grid-mean resolved properties.

Atmospheric models use parameterizations for:

- *Radiation* – convergence of radiation energy carried by photons
- *Turbulent transport* – boundary layer turbulence, clear-air turbulence
- *Moist processes* – water vapor phase changes and precipitation formation (cloud processes) at "stratiform" and "convective" scales

Confidence decreases

The Atmospheric Radiation Measurement (ARM) Program

- The *hypothesis* of the DOE ARM program is that a *measurement program* to take detailed atmospheric observations of processes related to radiation and clouds will be useful to assess parameterization errors.
- The ultimate goal of the program is more accurate climate models which will give improved climate change predictions.
- ARM's unique observing strategy to take detailed observations of the atmosphere *continuously* using ground based remote sensing at 3 locales.

ARM
Atmospheric Radiation Measurement

Selected ARM Instruments

Pyranometers

Radiation

Raman Lidar

Vertical profiles of water vapor and aerosols

Millimeter Wavelength Cloud Radar

Vertical profiles of clouds

ARM
Atmospheric Radiation Measurement

Techniques to compare ARM data to models

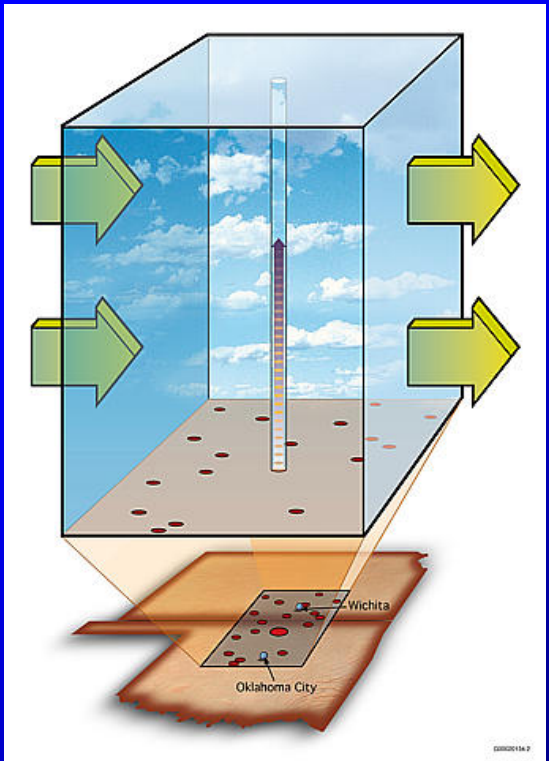
Because of ARM's unique observing strategy, somewhat specialized techniques are needed to use ARM data. In particular one needs a way to predict with models what happens above the ARM sites.

Two primary techniques are used at LLNL:

- Single Column Modeling
- Weather forecasting: CAPT

Single Column Modeling

- Physical parameterizations are one-dimensional (i.e. in the vertical) – for example, they describe the vertical transport of radiation or the falling out from the atmosphere of precipitation
- They generally do not directly depend on what is happening in other grid-columns of the atmospheric model
- Thus one can run the parameterizations in isolation from the rest of the model – provided you give the model the inputs it needs



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

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

"Dynamics" – what is moved in and out of the single column – also called the "Large-scale Forcing"

"Physics" calculated by the SCM's parameterizations

The LLNL ARM group (Shaocheng Xie, John Yio, and Ric Cederwall) has analyzed the ARM data to derive the large-scale forcing for the ARM sites.

This allows SCMs (and cloud resolving models) to simulate the weather that occurs on particular days over the ARM sites.

The Weather Forecasting Approach: CAPT

CAPT = CCPP ARM Parameterization Testbed
(CCPP = Climate Change Prediction Program)

Why not simulate the weather at the ARM sites with a global model as weather prediction models do?

- **This has been difficult for climate models because they don't have the complicated data-assimilation schemes that are needed to provided an initial condition for a forecast**
- **CAPT bypasses this problem by initializing the models directly with atmospheric analyses provided weather prediction centers.**

CAPT (cont.)

- As in the SCM approach, the CAPT approach allows one to assess parameterization errors at time-scales not normally examined by climate-modelers and time scales closer the native time scales of the process

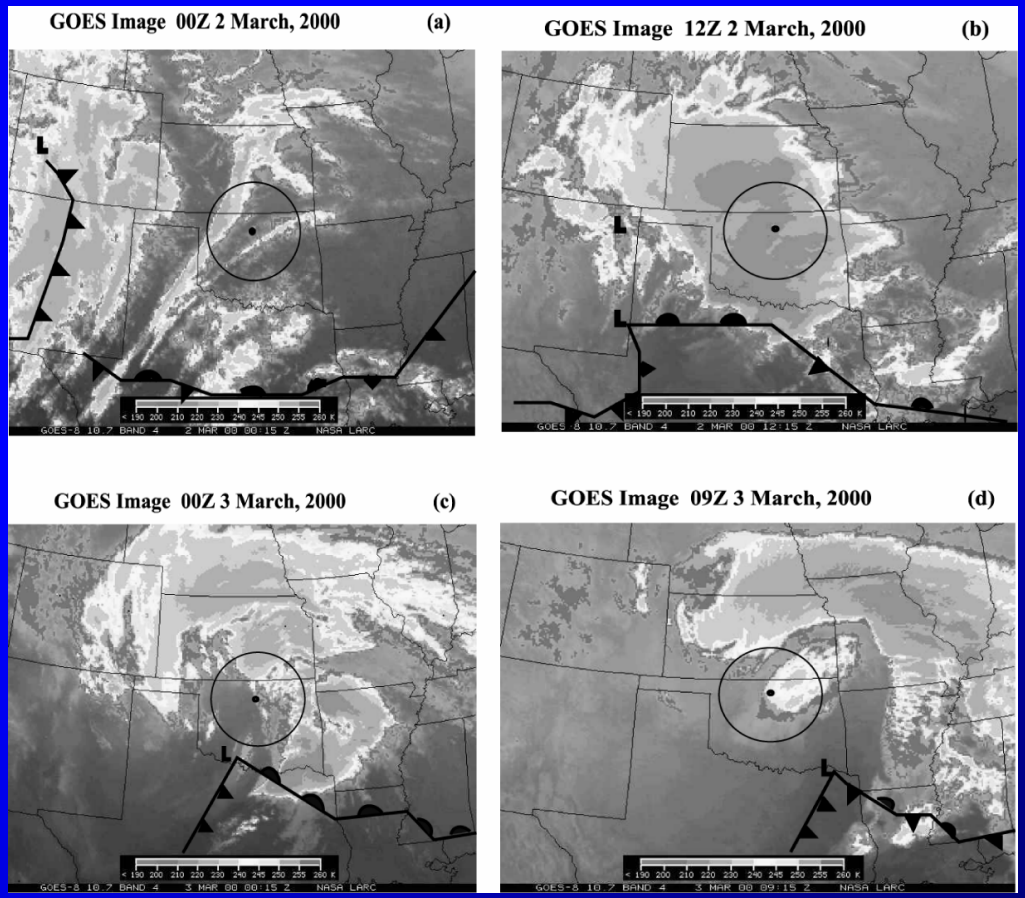
- A key point of the project is to run the model at climate model resolution (not weather prediction resolution) to assess how the climate model behaves in the way it is normally run.

- The CAPT project involves a number of people at LLNL (Jim Boyle, Mike Fiorino, Jay Hnilo, Jerry Potter, Tom Phillips, Shaocheng Xie) and at NCAR (Dave Williamson and Jerry Olson)

A Case Study

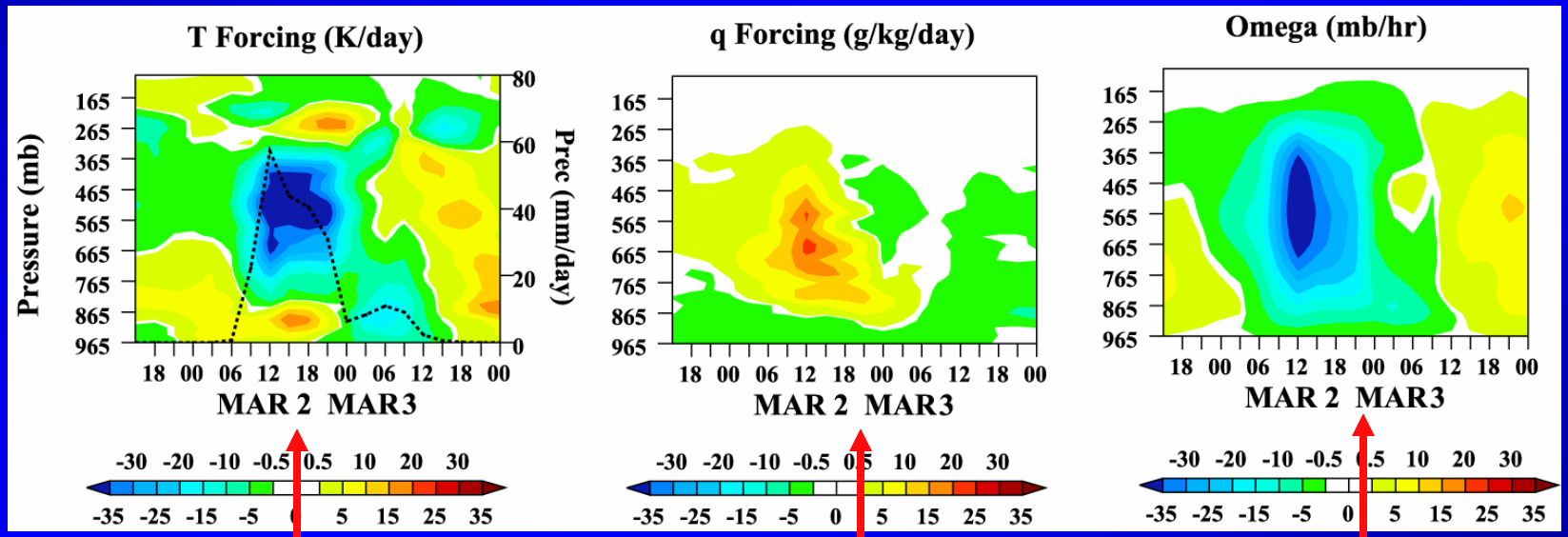
To illustrate the SCM and CAPT approaches consider the case of a strong frontal passage at the ARM Southern Great Plains site on March 2-3, 2000

GOES Infrared Satellite Images



Large-scale Forcing from LLNL Analysis

Strong Frontal Passage, March 2-3, 2000

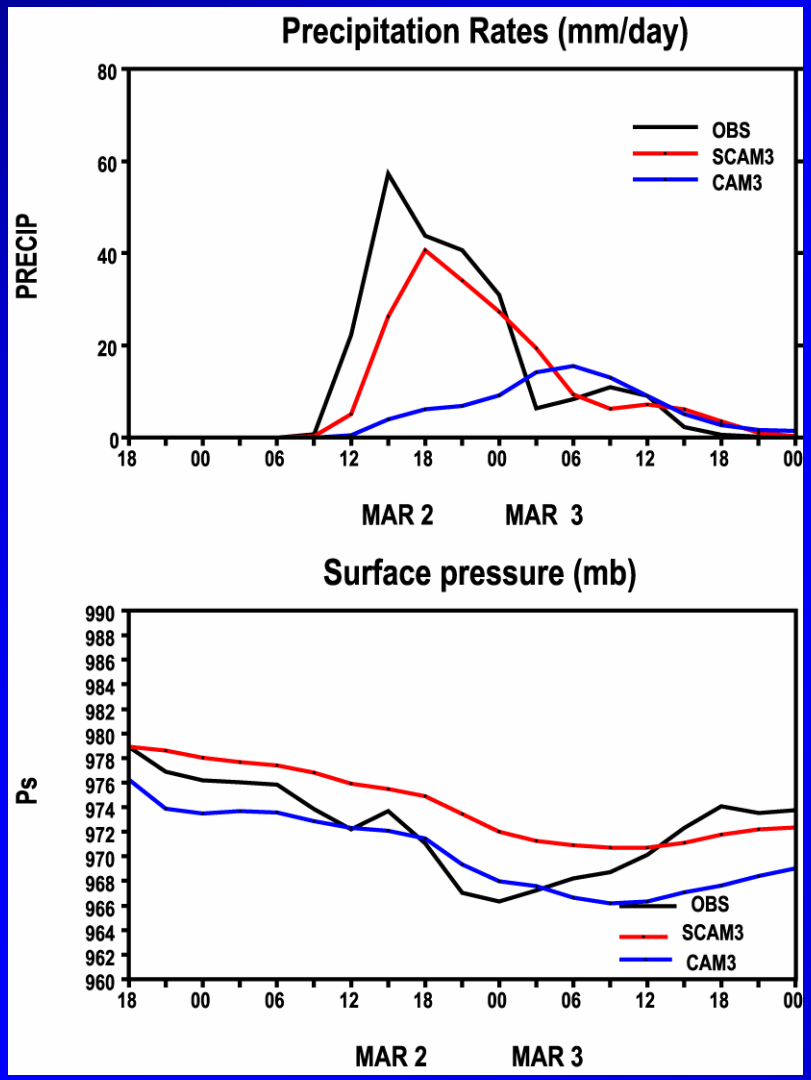


$$-V \bullet \nabla s - \omega \frac{\partial s}{\partial p}$$

$$-V \bullet \nabla q - \omega \frac{\partial q}{\partial p}$$

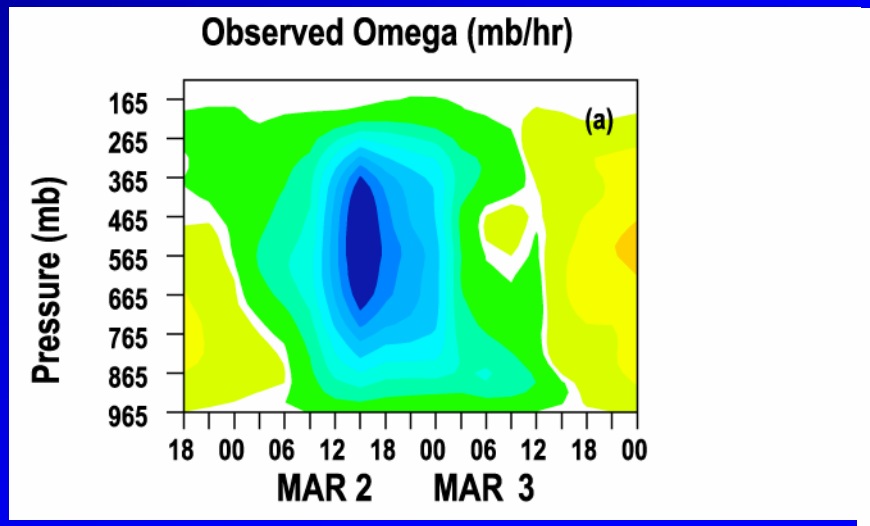
$$\omega$$

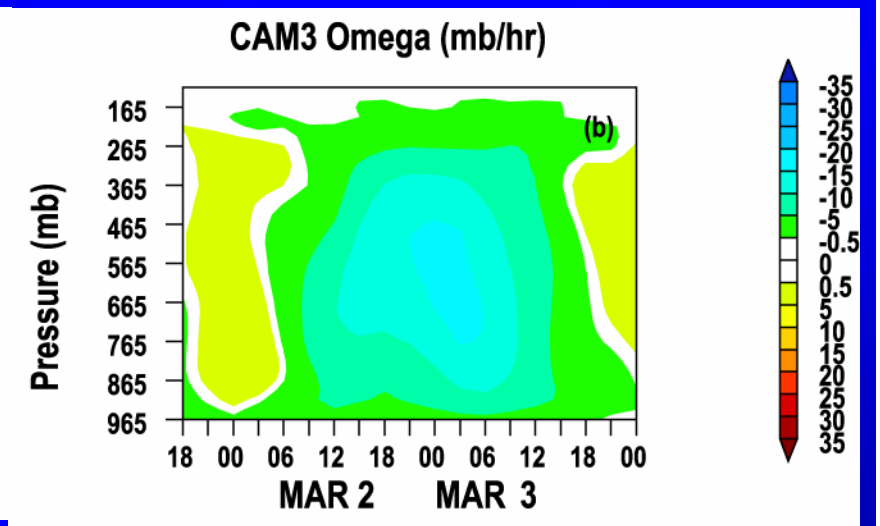
Surface Precipitation and Pressure

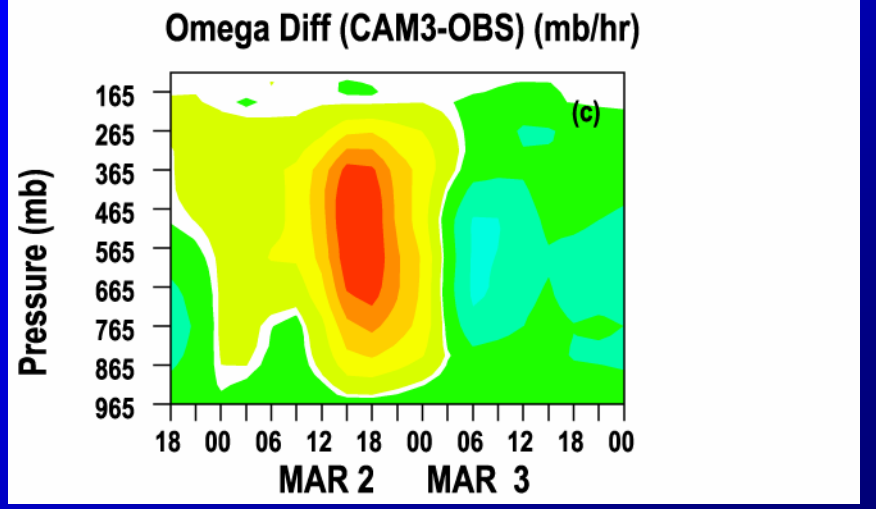


- The Single Column Model (SCAM3) does well with observed precipitation
- The CAPT forecast (CAM3) with the same model is delayed ~12 hours
- The CAPT forecast has weaker intensity to precipitation – a common problem to low resolution models

Vertical Motion



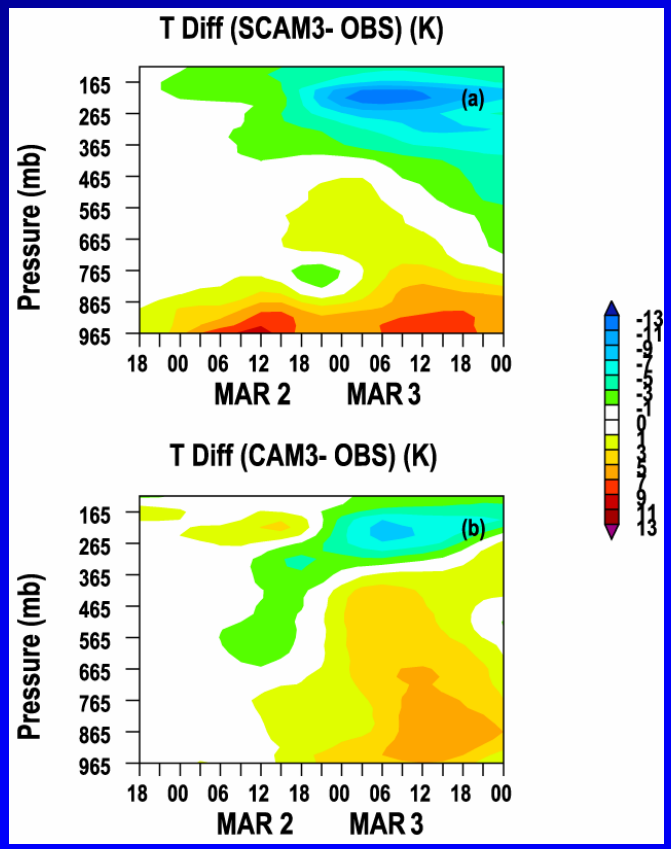




- **The CAPT forecast significantly underestimates the strength of the vertical motion field**

Temperature and Water Vapor Errors

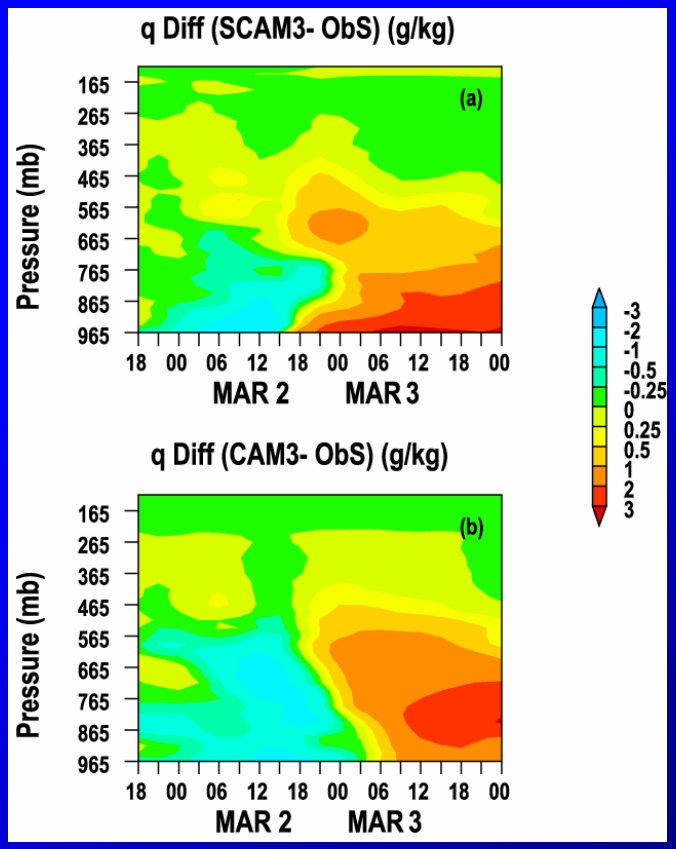
Temperature



SCM

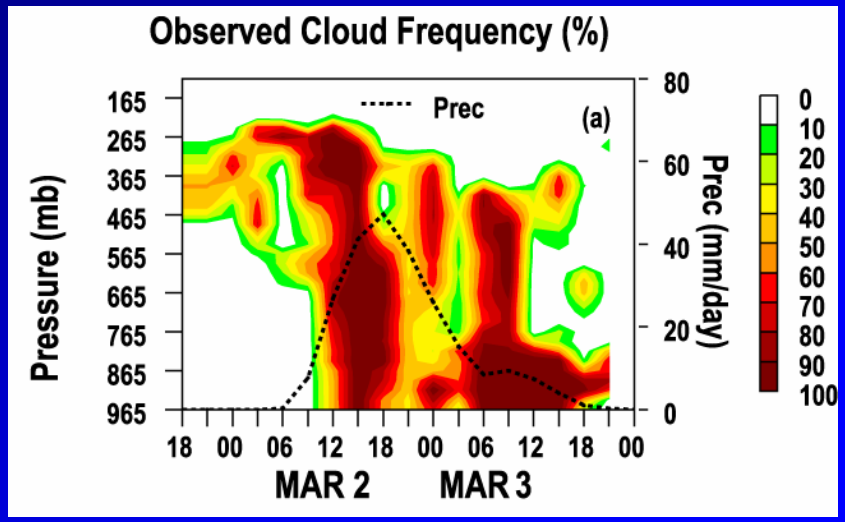
GCM

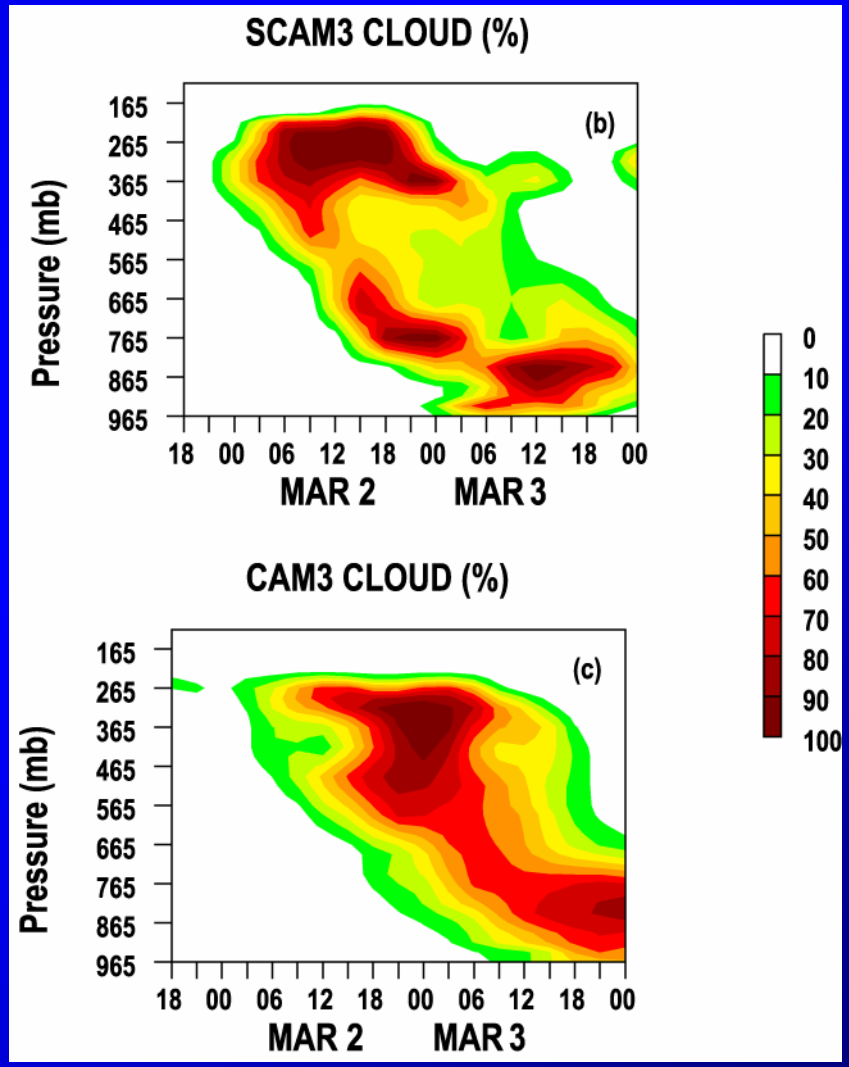
Water Vapor



Despite poor simulation of precipitation, the GCM's temperature and moisture errors are not larger!

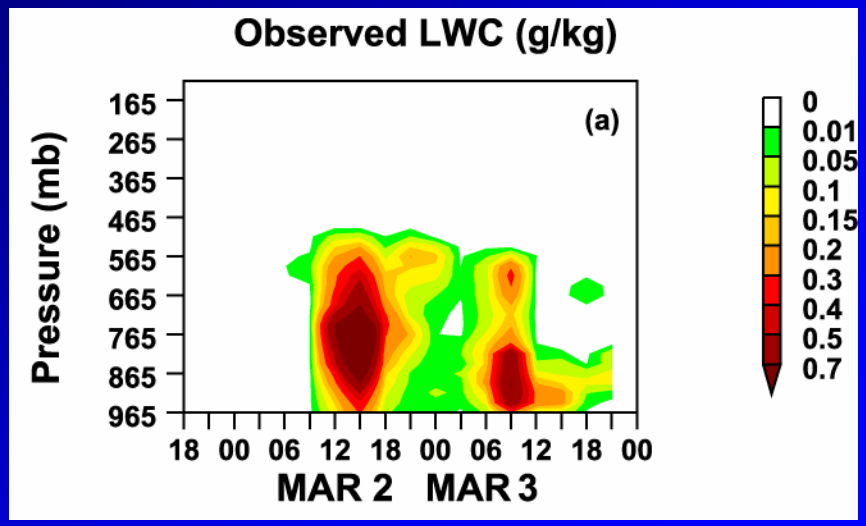
ARM Radar Observed Cloud Fraction

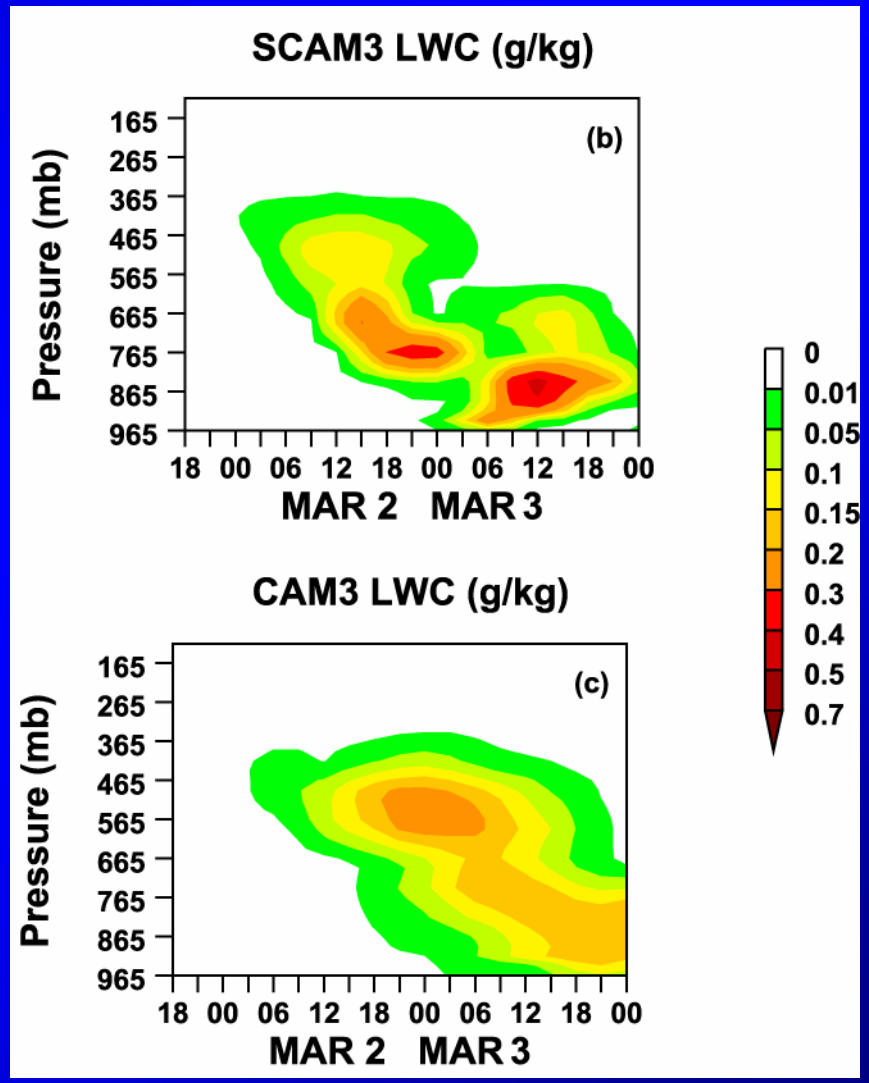




- Radar cloud fraction is from a single point – must very careful in interpreting this in terms of a grid-box averaged cloud fraction
- SCM and GCM cloud fractions are not that different – despite different storm intensities

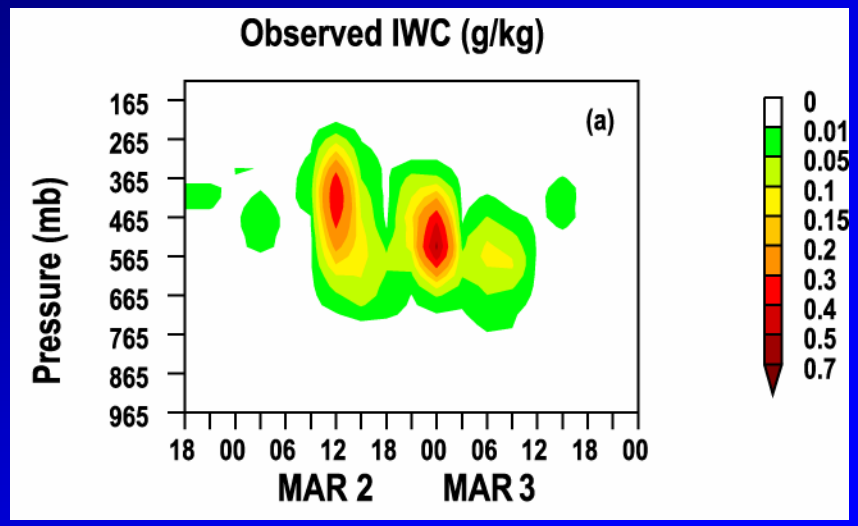
Liquid Cloud Microphysics

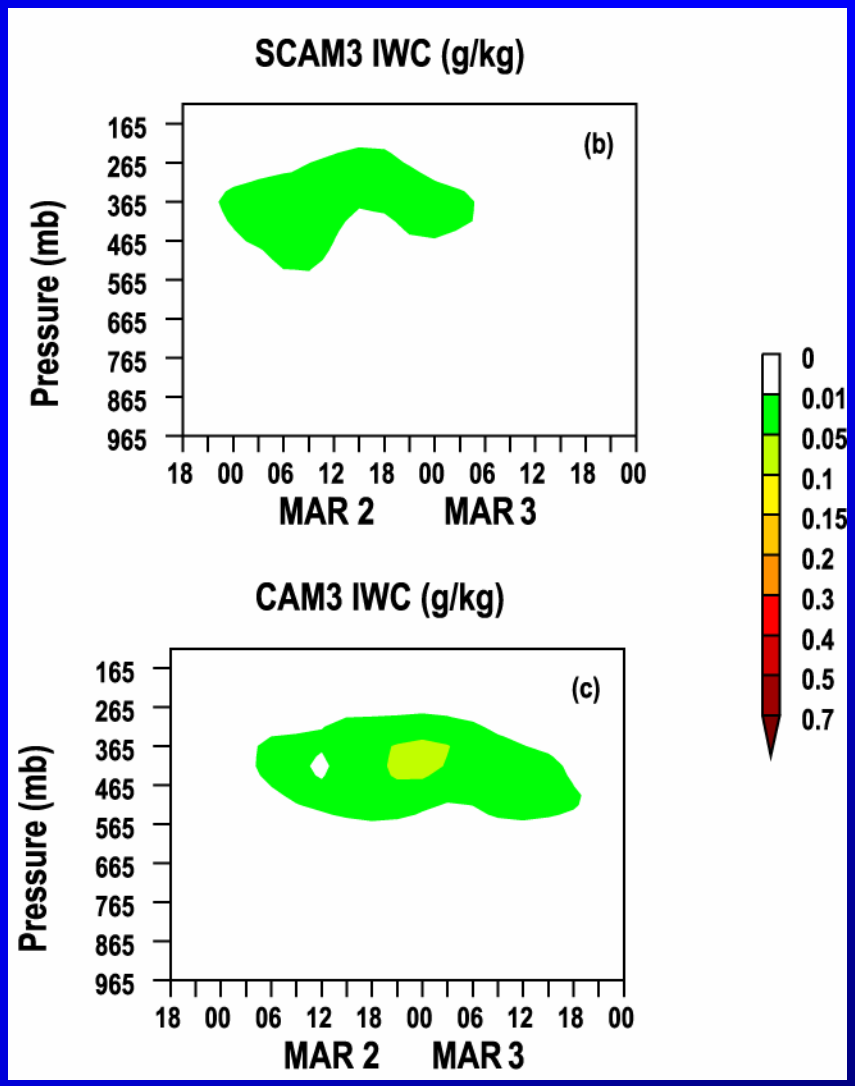




- From ARM cloud radar reflectivity one can retrieve the amount of mass of liquid in the clouds
- However the retrievals are not good in heavy precipitation
- The liquid cloud field is not too different between the SCM and the GCM

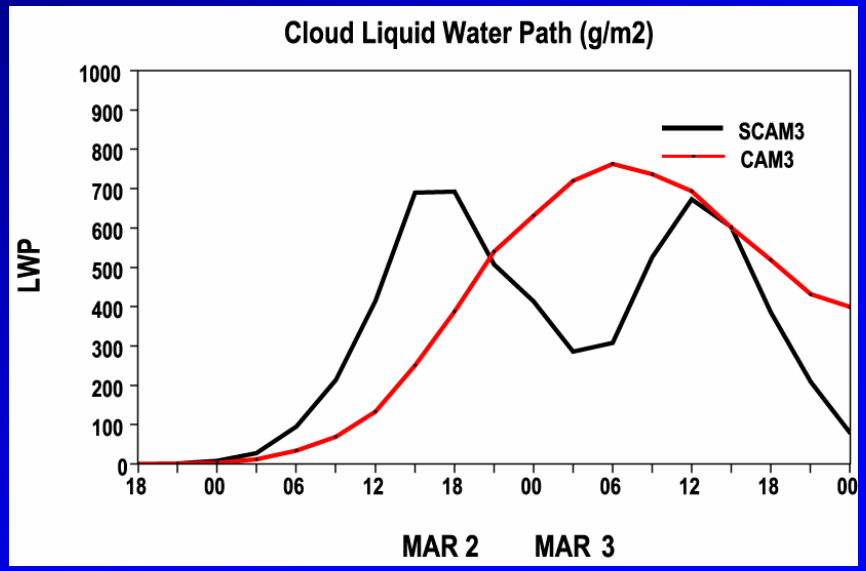
Ice Cloud Microphysics

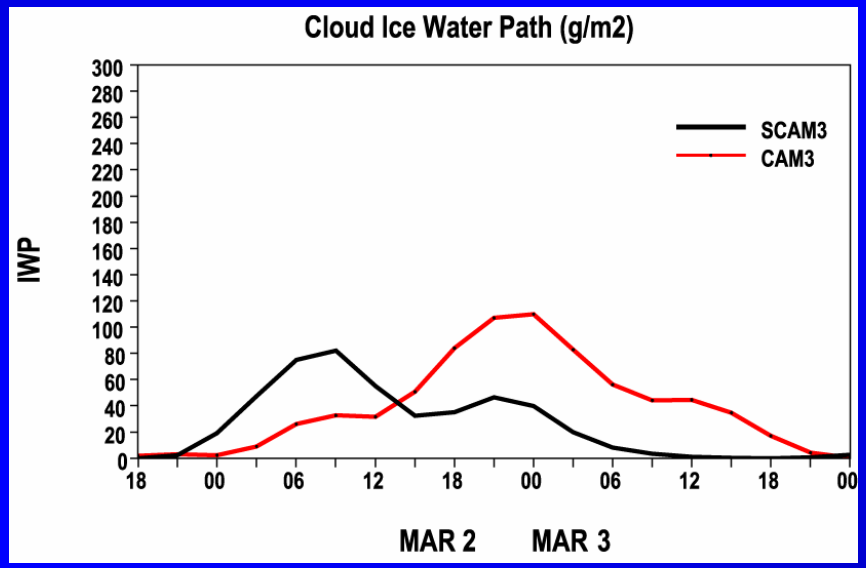




- The ice cloud field is not too different between the SCM and the GCM

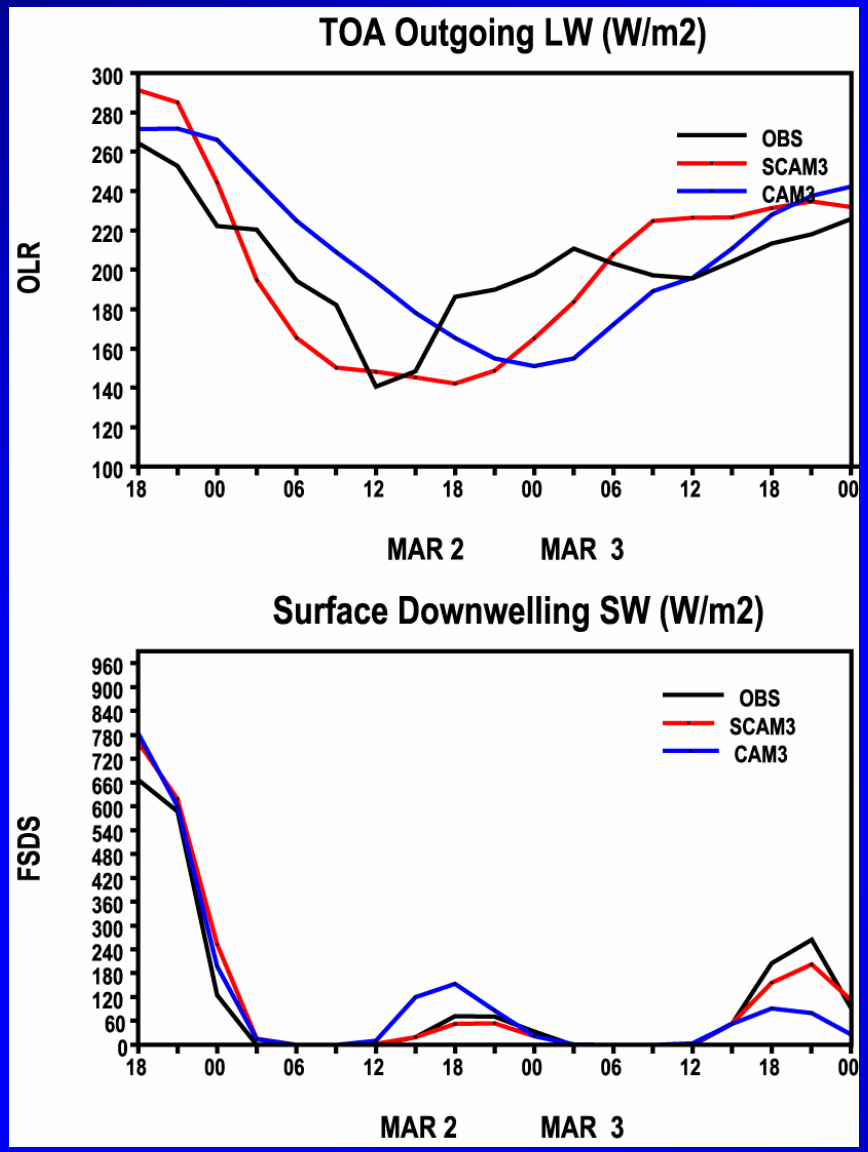
Column Integrated Liquid and Ice





- **Again it is remarkable how similar the amounts of condensed water are despite the very different vertical motion fields!**

Radiation Fields



- The longwave at the top of the atmosphere is most sensitive to the cloud-top temperature (or height of the clouds) – both simulations produce similar results
- The SCM and the GCM have about the right amount of solar radiation passing through the clouds.

Studies Using SCM - CAPT approaches

- Williamson et al. 2005: Obviously you don't want to draw too many conclusions from one case study. One should look for systematic errors. For example, Williamson et al. (2005) looked at the mean temperature and water vapor budget errors for "rainy" periods for several events at the ARM site from CAPT forecasts.

Studies Using SCM - CAPT approaches

- Xie et al. 2004: Proposed a modified convection parameterization for the NCAR CAM. Tested it for ARM summertime conditions in both SCM and CAPT integrations. The modification reduced the tendency for the convection scheme to produce overly frequent rain and yielded an improved simulation of summertime precipitation over North America.

SCM References

Xie S., R. T. Cederwall, M. Zhang (2004), Developing long-term single-column model/cloud system–resolving model forcing data using numerical weather prediction products constrained by surface and top of the atmosphere observations, *J. Geophys. Res.*, 109, D01104, doi:10.1029/2003JD004045.

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