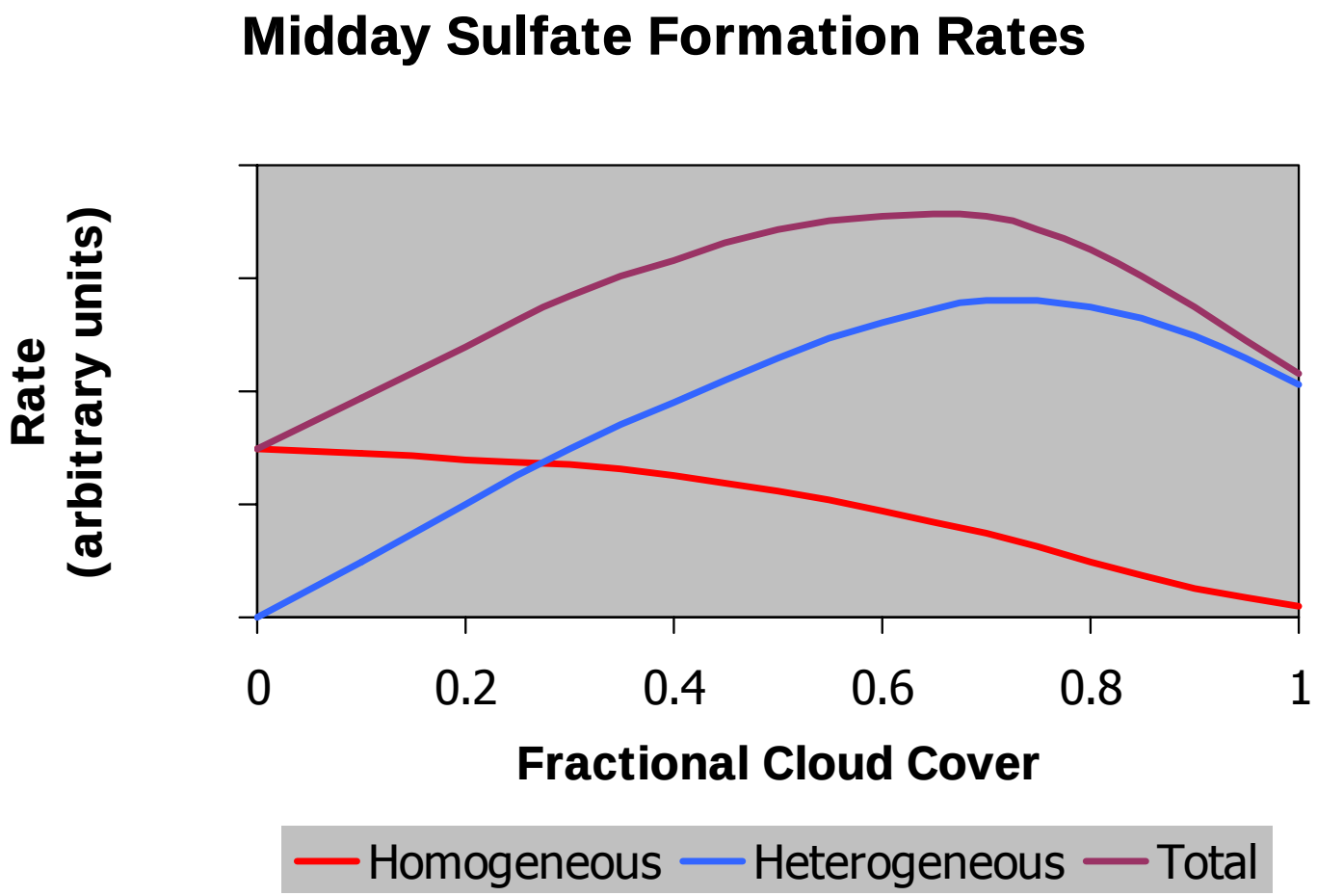
Treatment of Clouds by CMAQ & Their Role in Sulfate Formation

Stephen Mueller
Tennessee Valley Authority
Muscle Shoals, AL

The Link between Clouds & Sulfate Aerosol

- Indirect: clouds affect UV flux & photolysis rates which in turn control photochemical reactions & SO_2 oxidation.
- Direct: clouds serve as reactors that enable aqueous (heterogeneous) reactions resulting in SO_2 oxidation.

Model for Relationship between Sulfate Aerosol & Cloud Cover



Multiple Cloud Personalities in CMAQ

- Cloud fraction from meteor. model is used to calculate photolysis rates.
- Cloud & rain water content from meteor. model determines presence of “resolved” clouds (cloud chemistry step 1).
- CMAQ diagnoses presence of subgrid-scale convective clouds from temperature/moisture profiles (cloud chemistry step 2).

CMAQ Heterogeneous Chemistry

- CMAQ cloud chemistry steps 1 & 2 are done separately & without interaction (at least I think that is true).
- In summer, "resolved" clouds in lower atmosphere are far fewer than subgrid-scale convective clouds over eastern U.S.
- Conclusion: subgrid-scale clouds play dominant role in cloud sulfate formation.

How do we examine how well CMAQ simulates cloud cover?

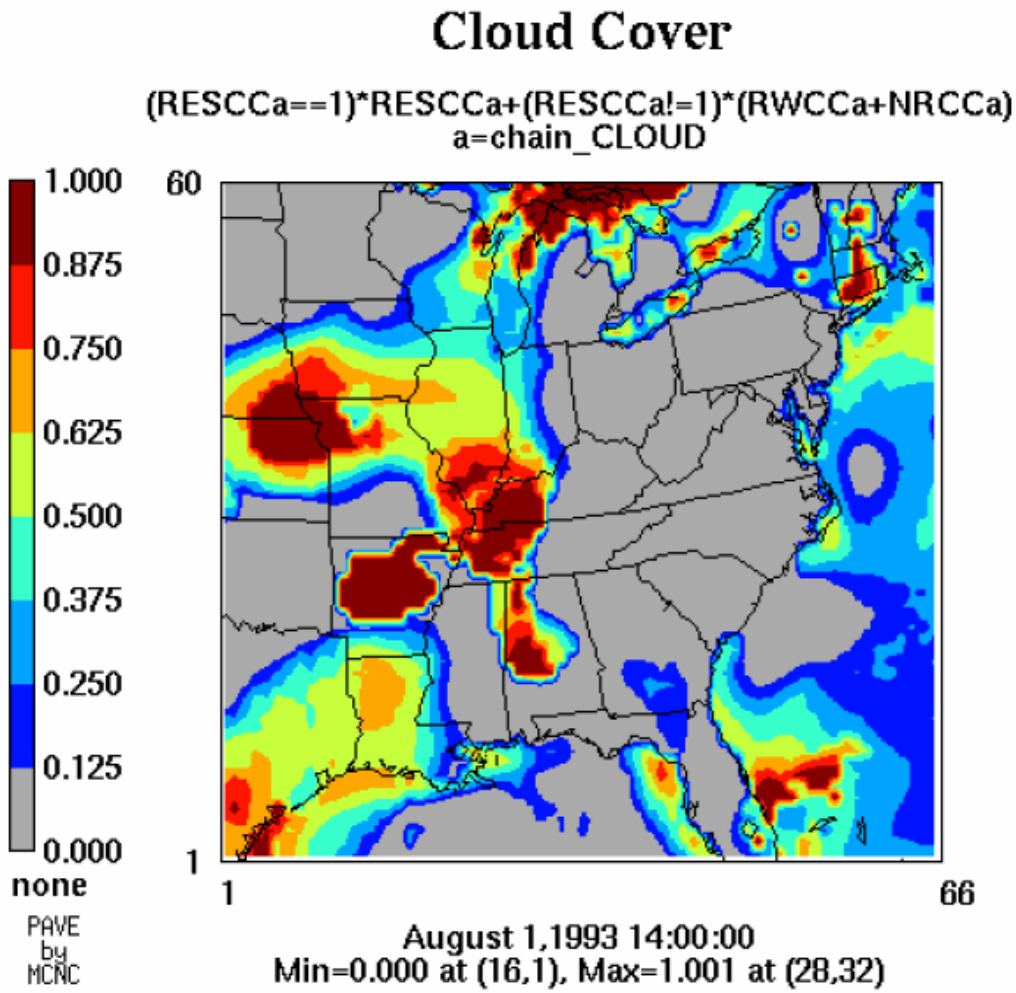
- Examining meteor. model output does not answer the question.
- CMAQ cloud outputs are needed: must include both resolved and subgrid-scale clouds.
- Modified versions of CMAQ modules ***cldproc***, ***rescld*** & ***radmcld*** now exist to produce netCDF (PAVE-compatible) files with cloud fields.

CMAQ Clouds Revealed

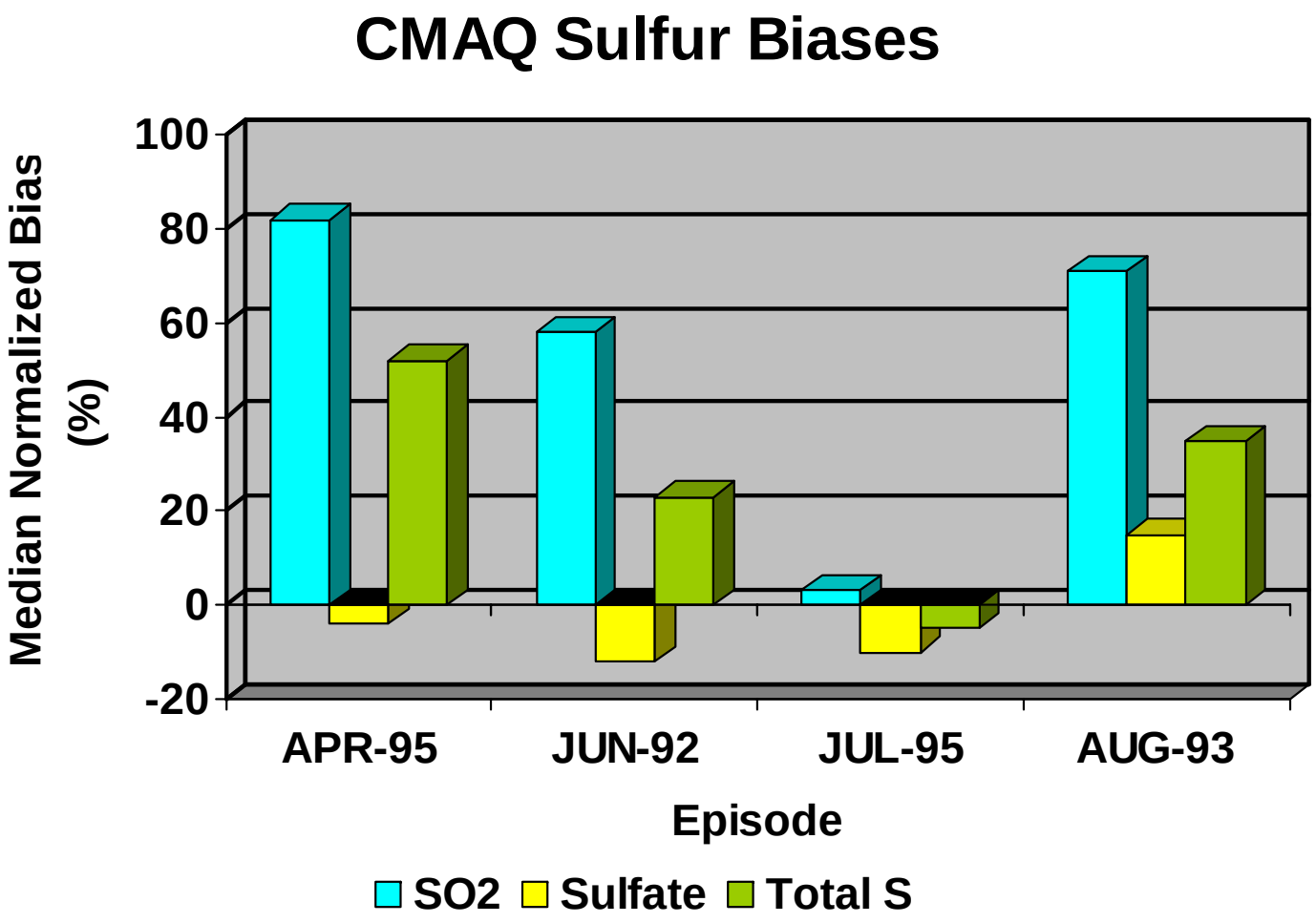
Cloud fields available:

CBASE - cloud base ht.
CTOP – cloud top ht.
RESCC – resolved clouds
RWCC – subgrid precip. cloud cover
NRCC – subgrid non-precip. cloud cover

Total cloud cover computed from RESCC, RWCC & NRCC.

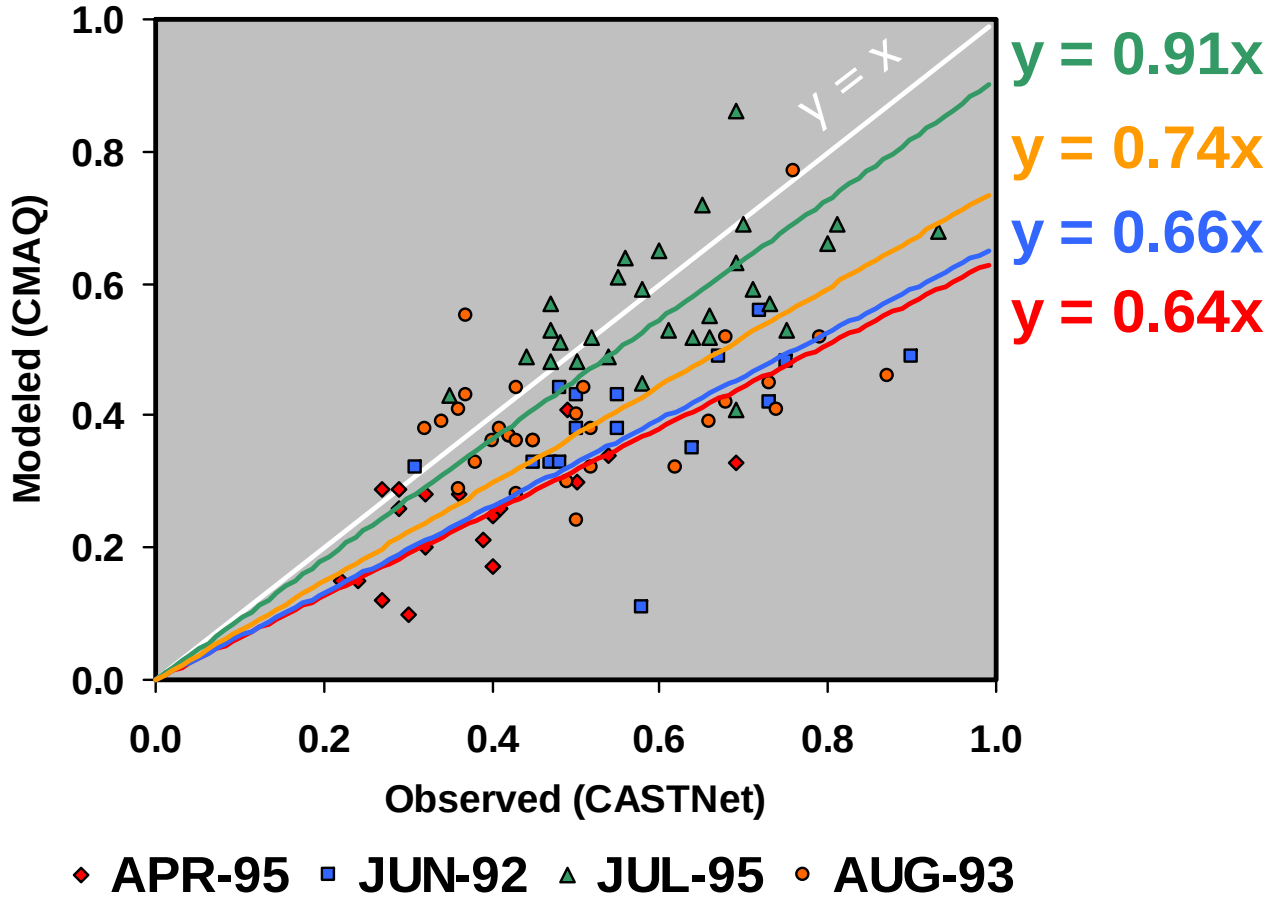


Sulfur Bias in CMAQ?

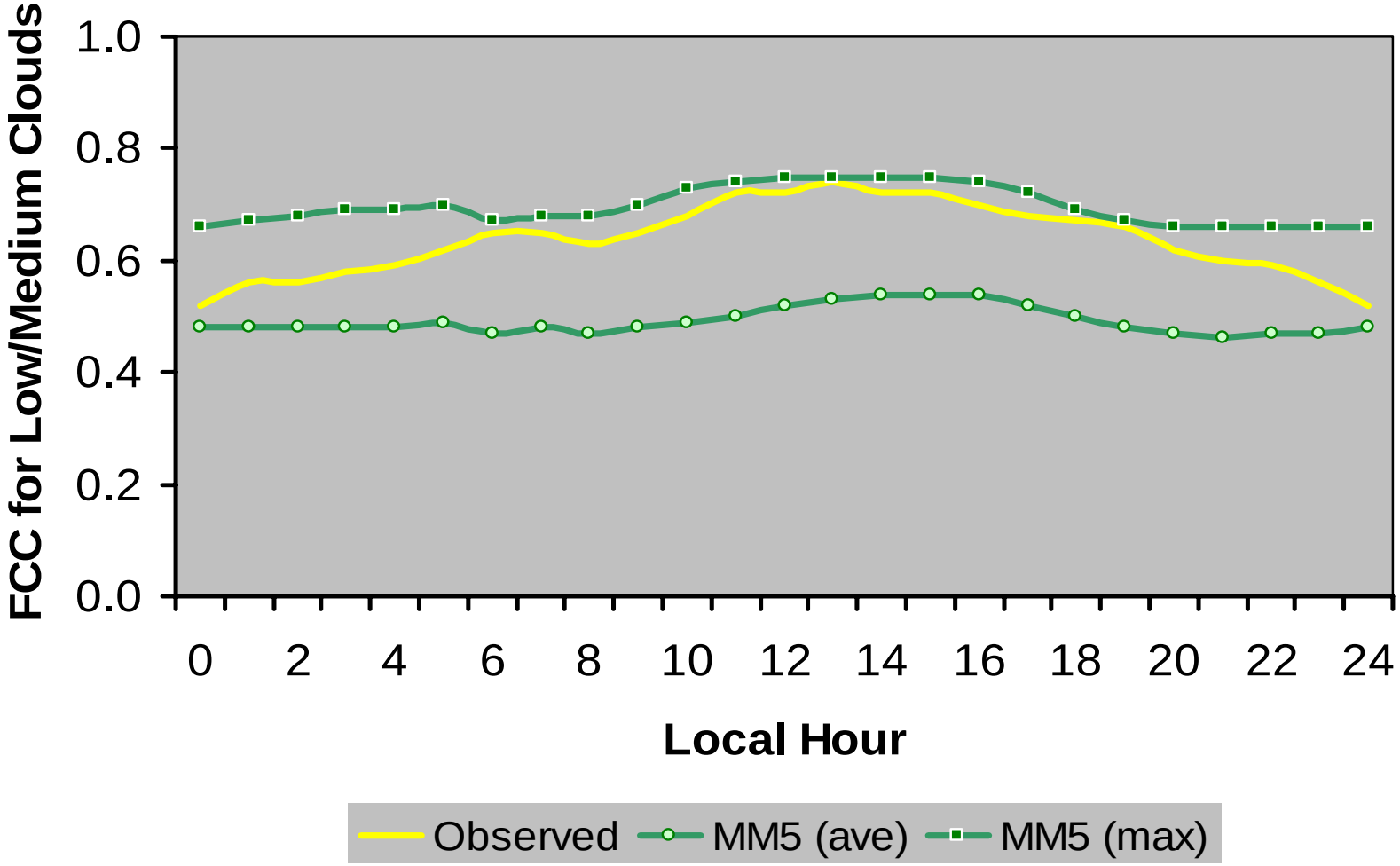


Sulfur Ratios Reveal Story

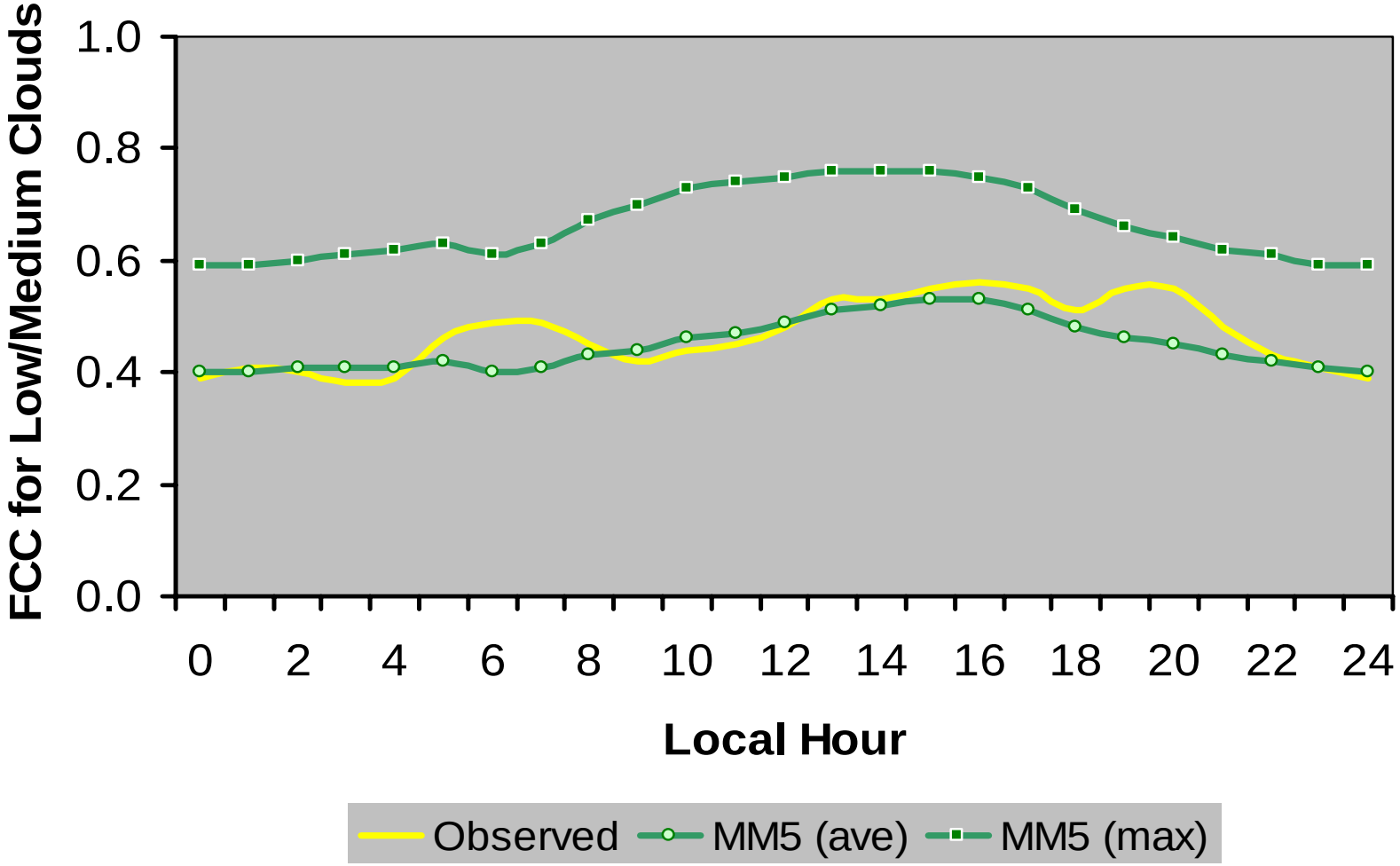
S Ratio =
(Sulfate-S) /
(Sulfate-S + SO2-S)



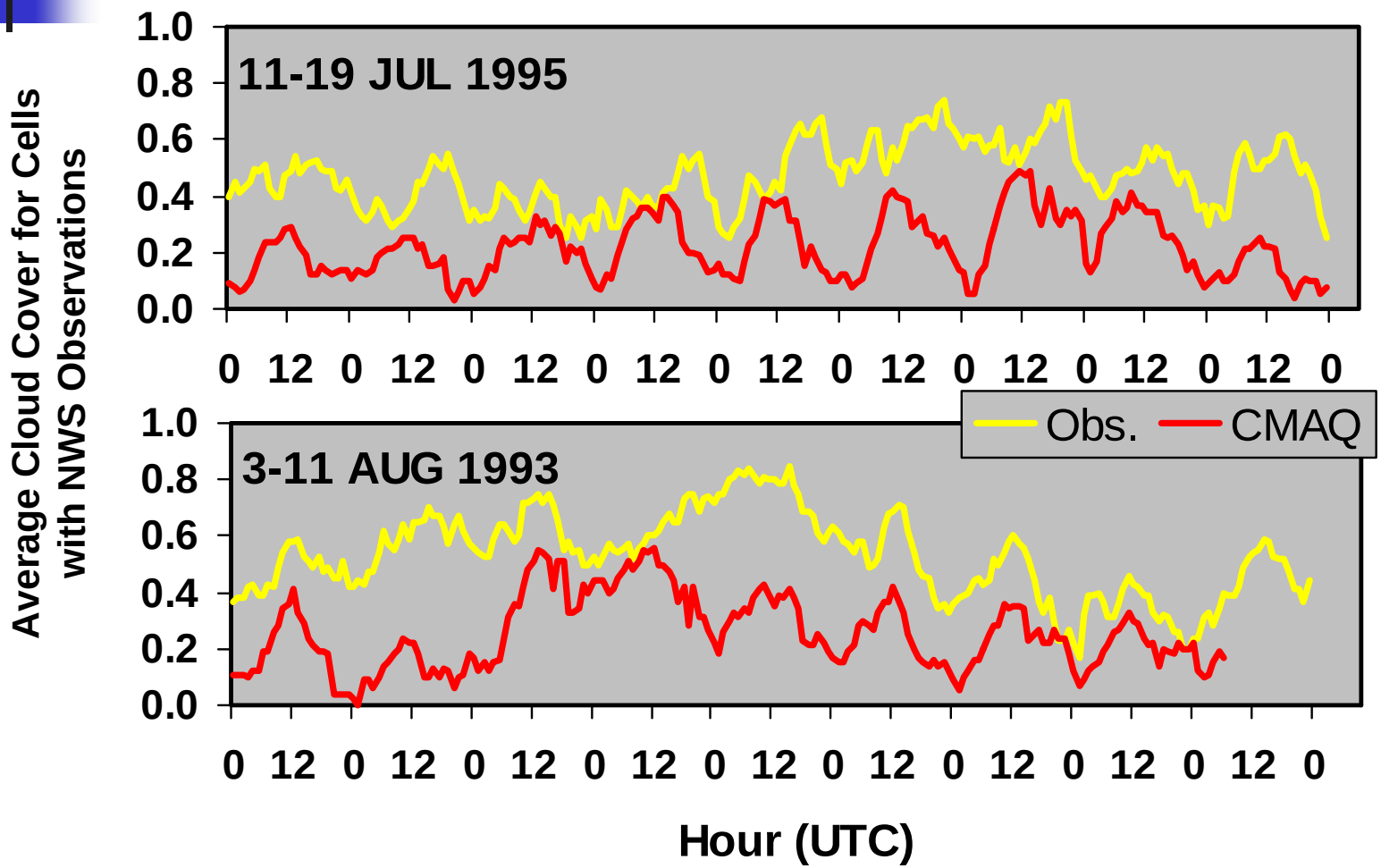
MM5 Cloud Cover – AUG-93



MM5 Cloud Cover – JUL-95

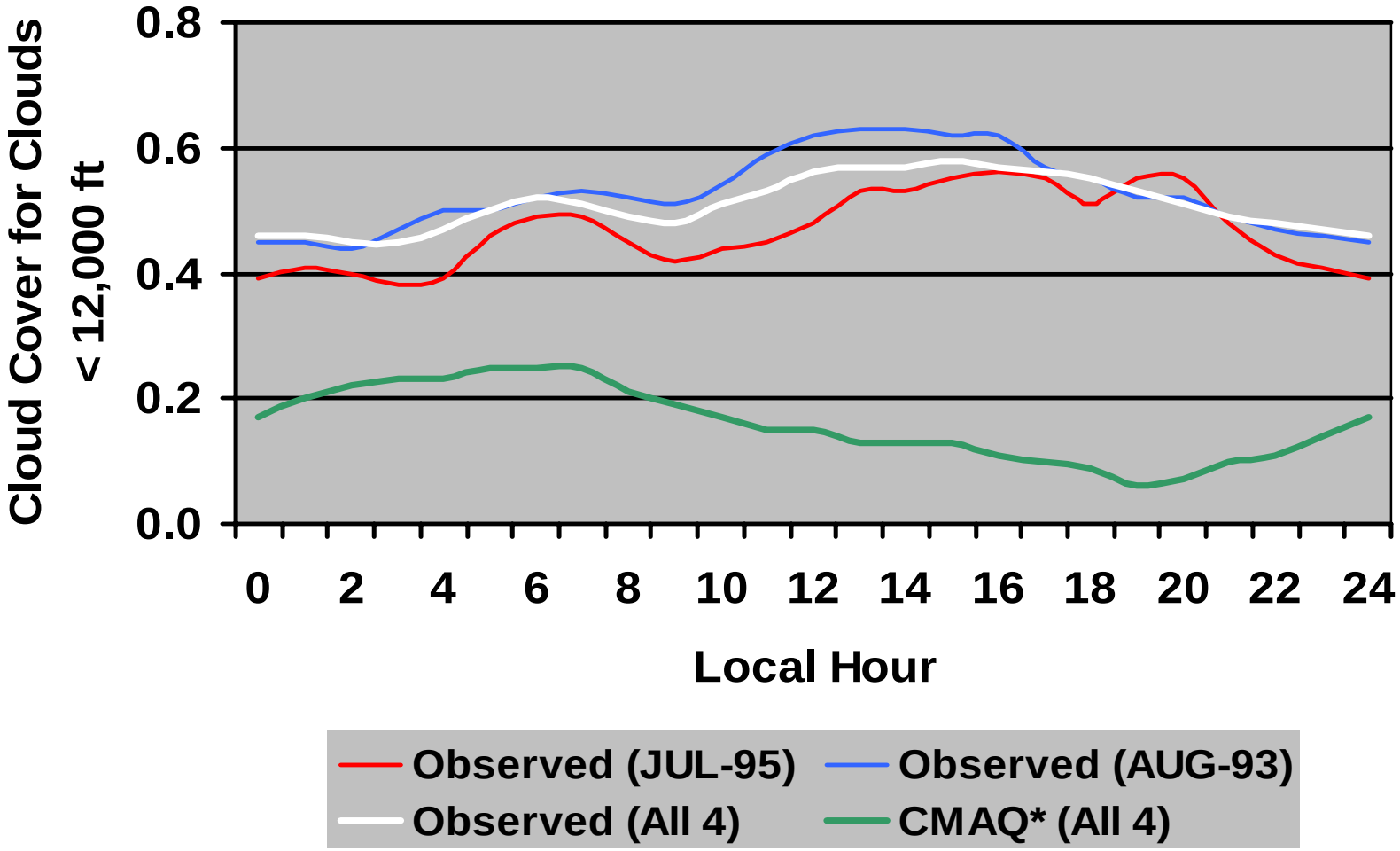


CMAQ Clouds* vs. Observations
(cloud base < 12,000 ft)



*36 km grid only, but 12 km results looked very similar.

Diurnal Cloud Cover Patterns for Four Modeled Episodes



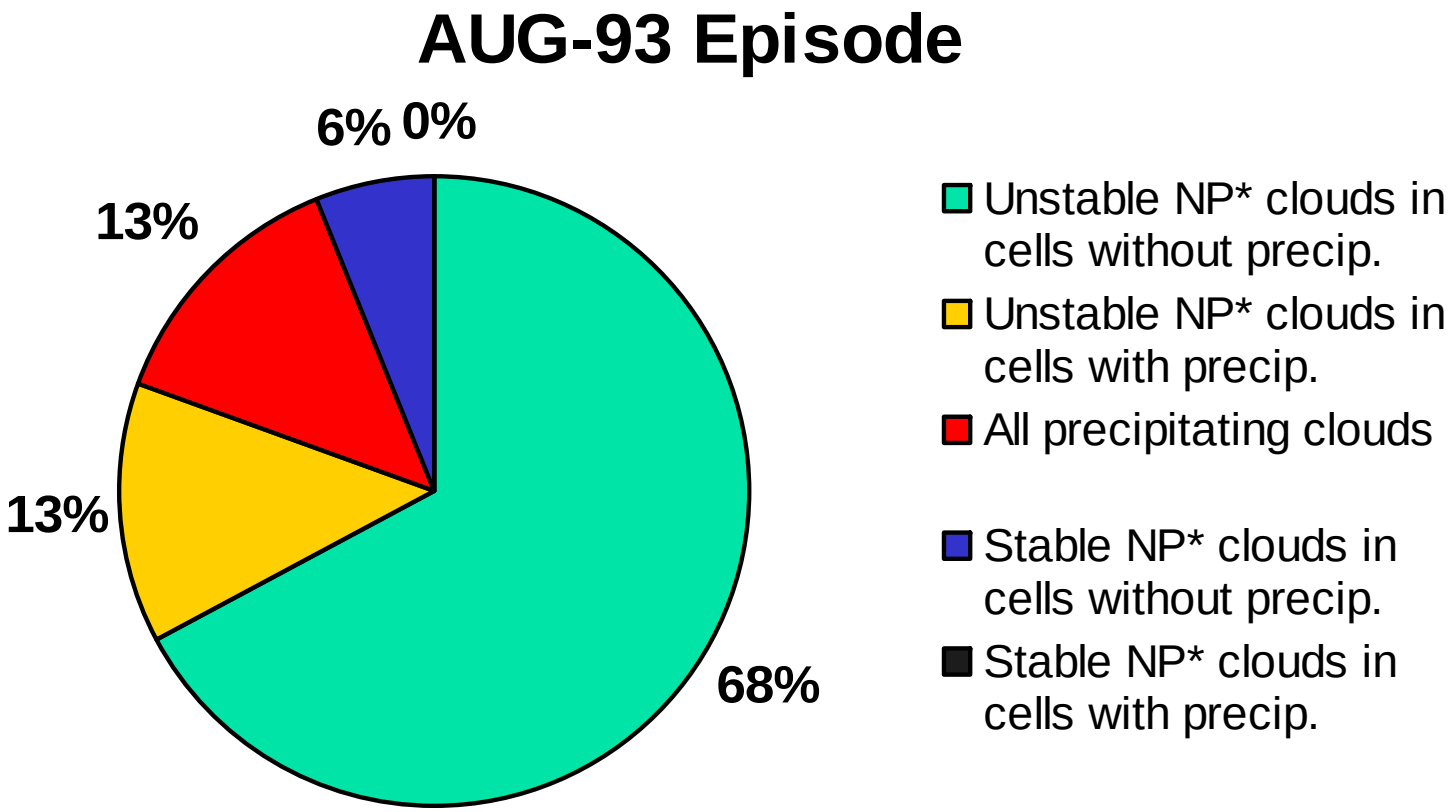
Problems with CMAQ Cloud Cover

- Fractional coverage much lower than observed for low/medium height clouds.
- CMAQ diurnal cloud pattern has afternoon minimum whereas observations indicate the opposite.
- CMAQ produces nearly continuous cloud cover over Atlantic Ocean despite warm water temperatures & little thermal contrast with airmasses.

Factors Controlling Subgrid-Scale Cloud Cover in CMAQ

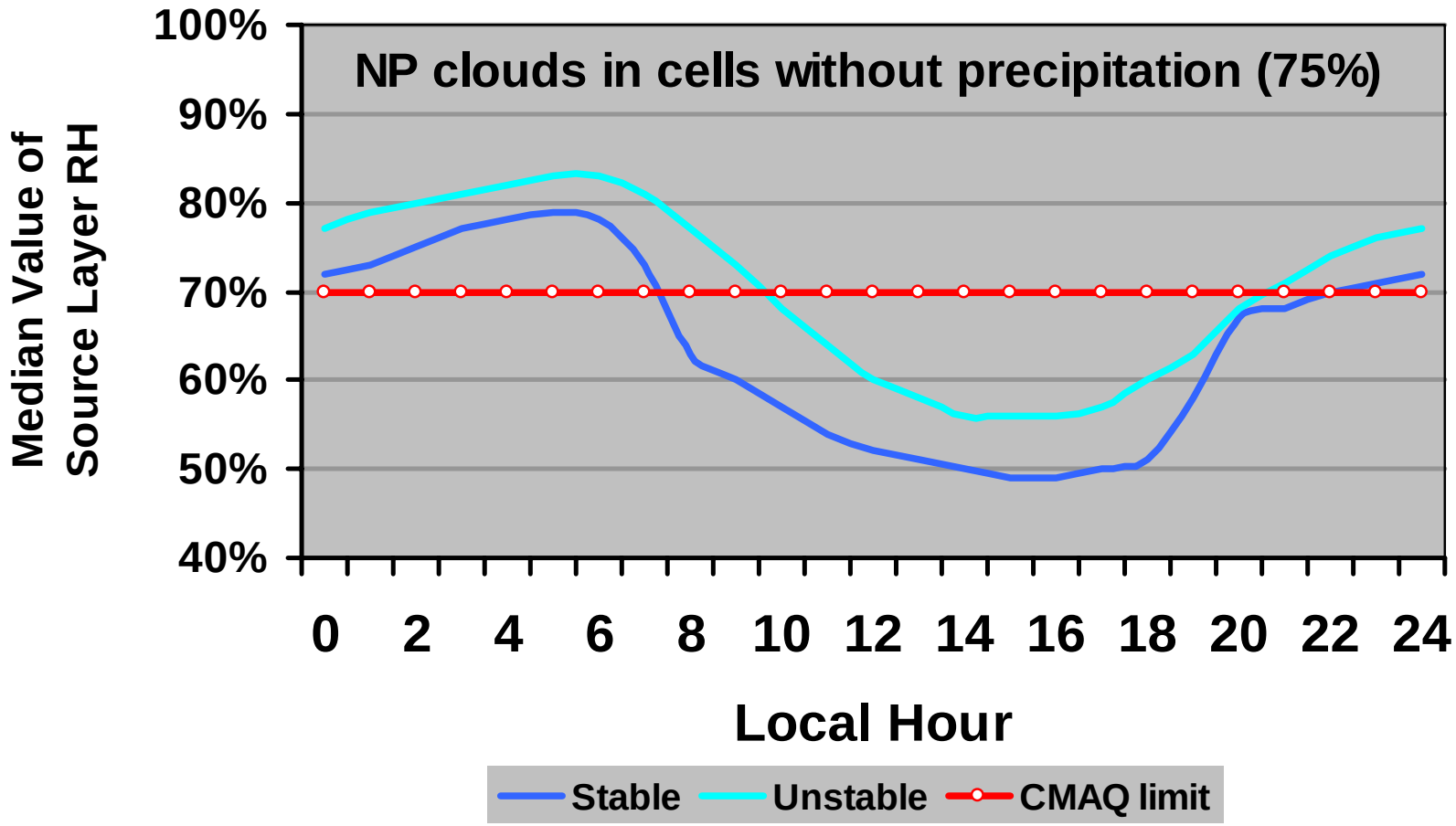
- "Source" layer relative humidity
- Number of model layers
- Cloud base & top heights
- RH limits for estimating FCC in cloud layers
- Perturbation T & Q / Vertical T & Q profiles
- Cloud entrainment ratio (untested)
- Other parameters affect RWCC & NRCC, but in small or offsetting ways.

CMAQ Subgrid-Scale Clouds: Occurrence of Conditions*

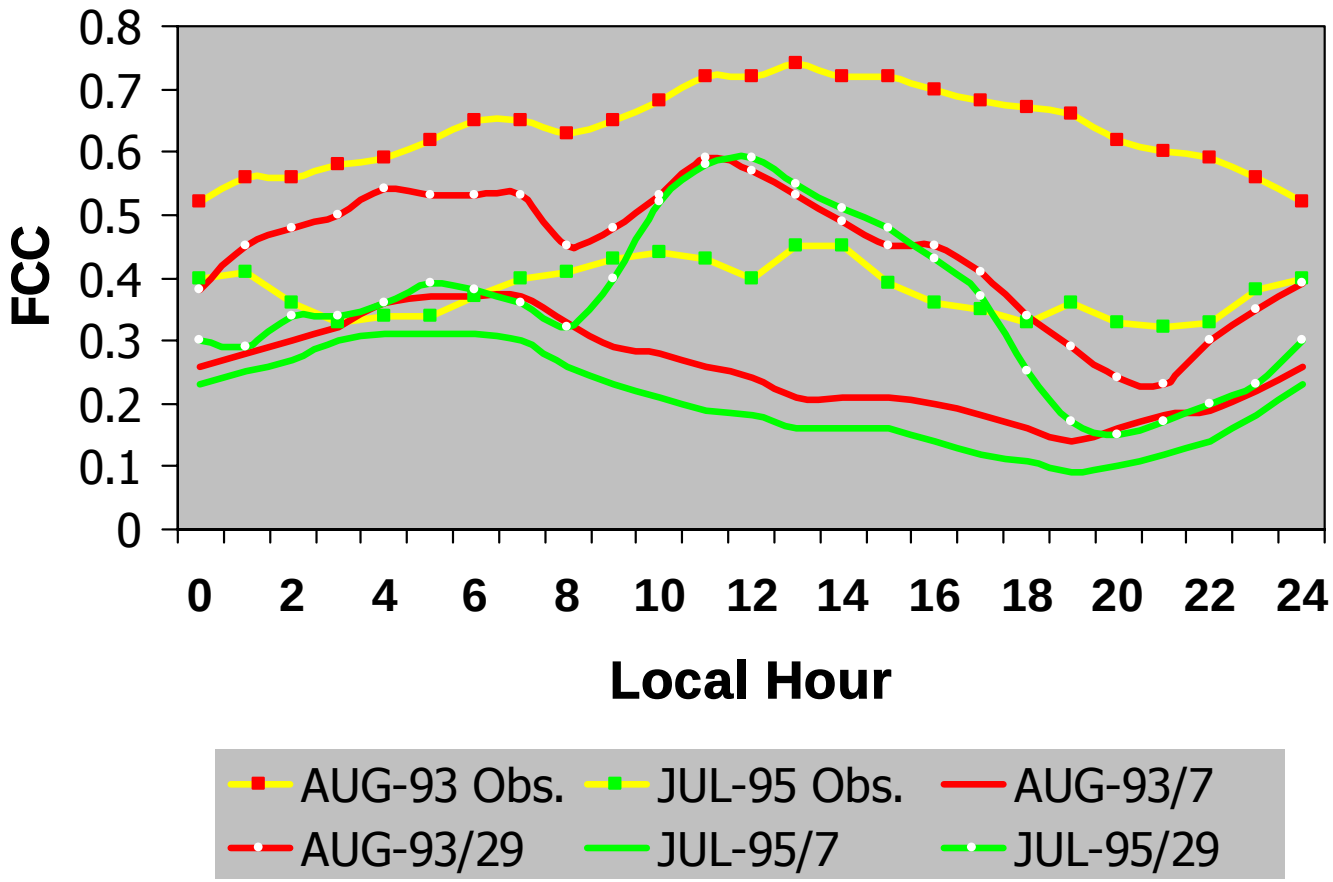


*CMAQ treats clouds differently depending on the conditions in which they form. Not all conditions lead to clouds due to limiting criteria. NP=non-precipitating

Role of "Source" Layer RH

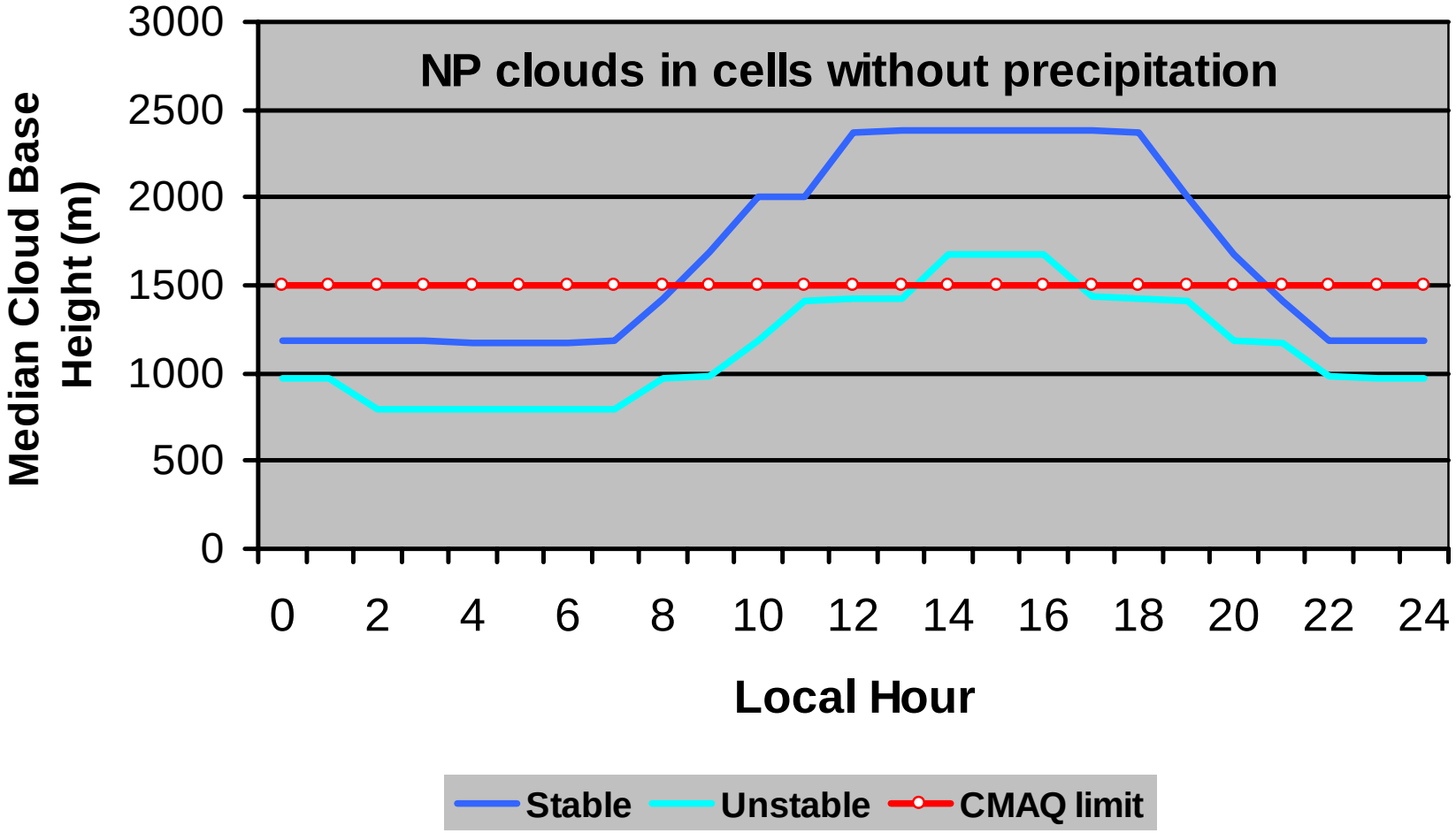


Effect of Number of Layers*

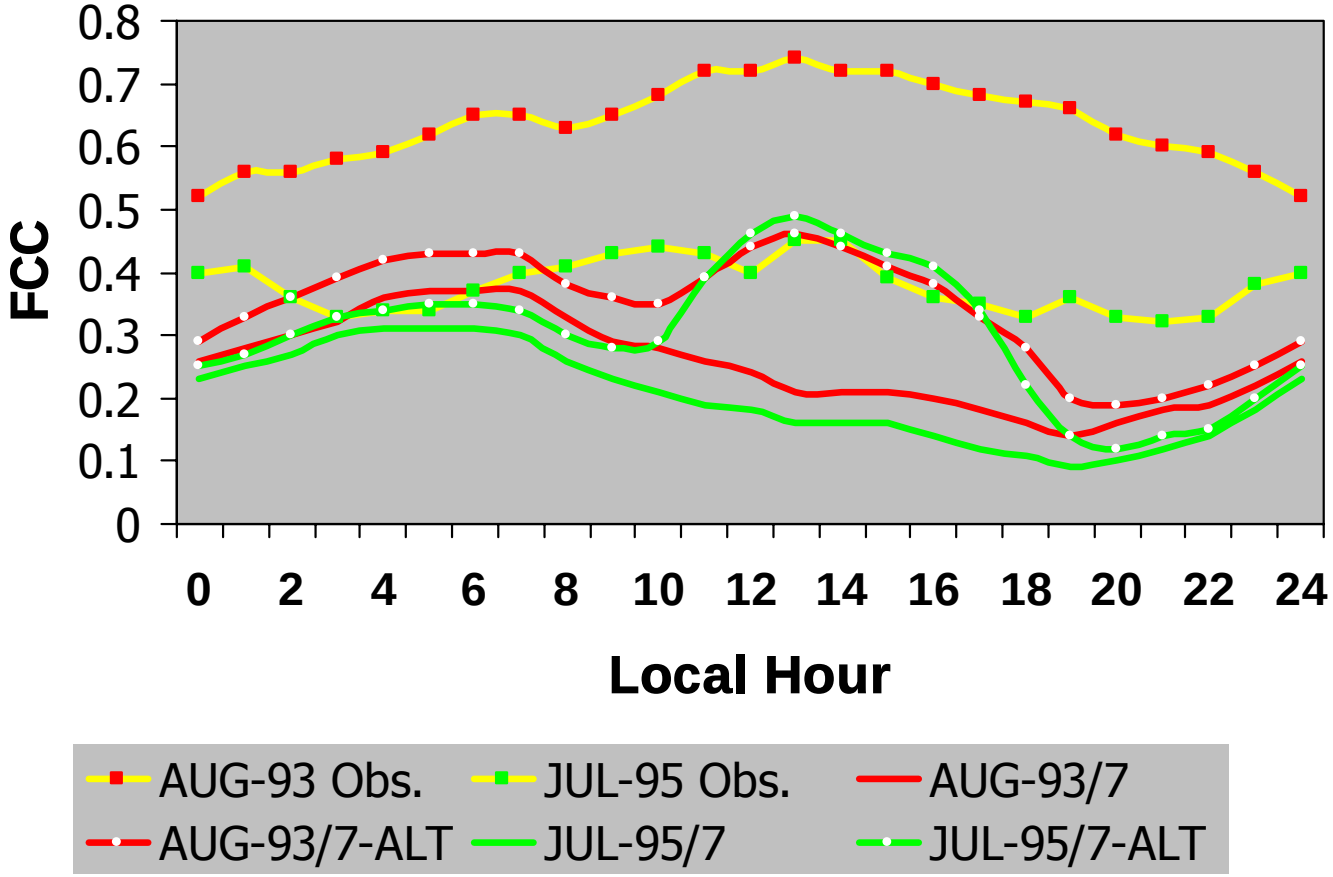


*Cloud patterns responded to a change in layers but sulfate production did not.

Role of Vertical Cloud Limits



Effect of Higher Cloud Base Limits



CMAQ Cloud Cover Responses to Other Parametric Changes

- T′ & Q′: increased values produced unrealistic diurnal cloud pattern. Making T′ & Q′ height-dependent corrected this somewhat.
- Default RH limits: FCC=1 for "source" RH>0.9; 0≤FCC≤1 for 0.7≤RH≤0.9. Setting lower RH limit to 0.6 has little effect on overall FCC.

Major Changes Needed

- None of tested modifications produced enough overall cloud cover or significant increases in S Ratio.
- Root of problem is definition of "source" RH (SRH).
- SRH is almost always surface or near surface layer. RH in these layers has diurnal cycle that is at a minimum in afternoon. Controlling RH should be in cloud layers, not surface.
- Should resolved cloud cover be increased? CMAQ resolved cloud cover is mostly absent even for episodes when large-scale cloud cover is expected (i.e., AUG-93).

Modifications to CMAQ Subgrid-Scale Cloud Diagnoses

1) Remove all limits to cloud heights (makes more sense when using larger numbers of layers).
2) Adopt new cloud diagnostic scheme, replacing SRH with RH for cloud layers.
3) Make T’ & Q’ height dependent.

Modified NCAR CAM2 Cloud Diagnostic Scheme

- Marine cloud cover in layer below 750 mb estimated based on potential temperature difference between surface and 700 mb.
- Cloud cover over land (or above 750 mb over water) estimated from RH and vertical velocity in “potential” cloud layers.

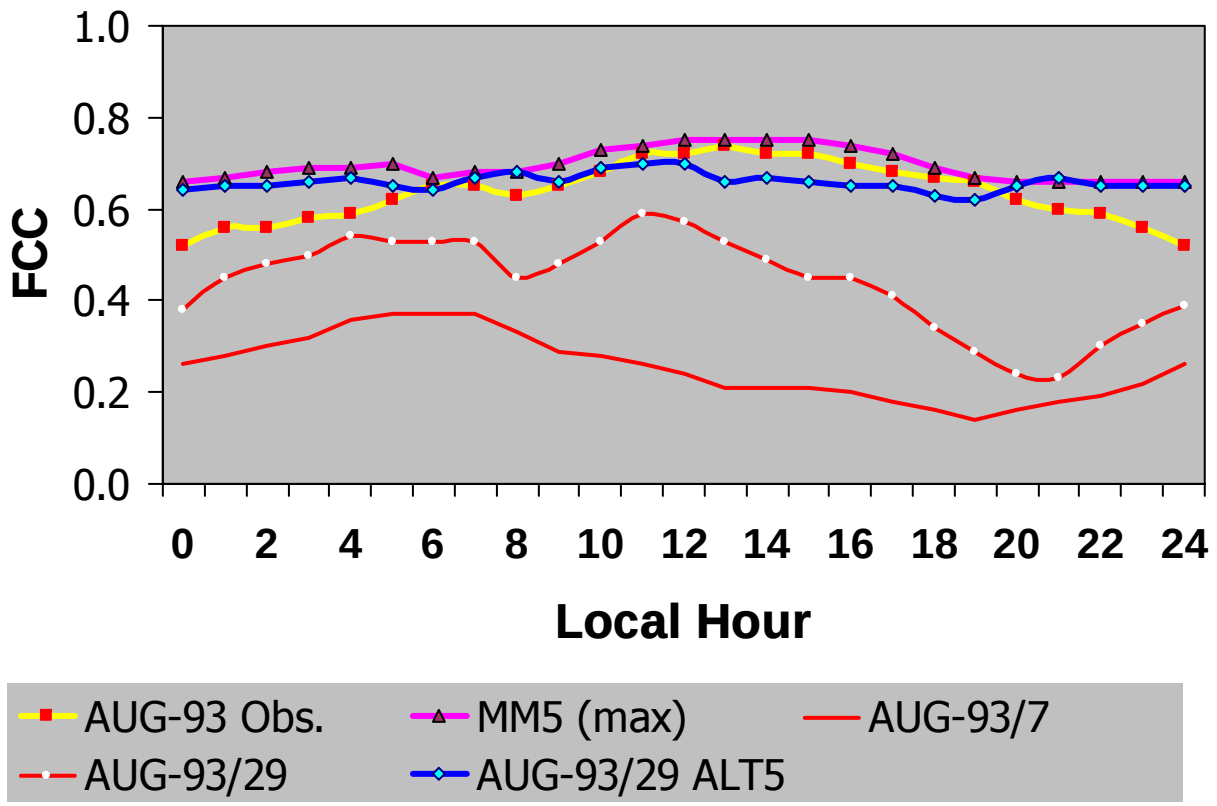
Modified Resolved Cloud Cover

- CMAQ assumes clouds present for total cloud + rain water mixing ratio ≥0.05 g/kg.
- Experimenting with lower limits in 0.01 – 0.03 g/kg range.
- Resolved cloud fraction is very sensitive to this parameter: becomes dominant over subgrid-scale clouds at 0.01 threshold.

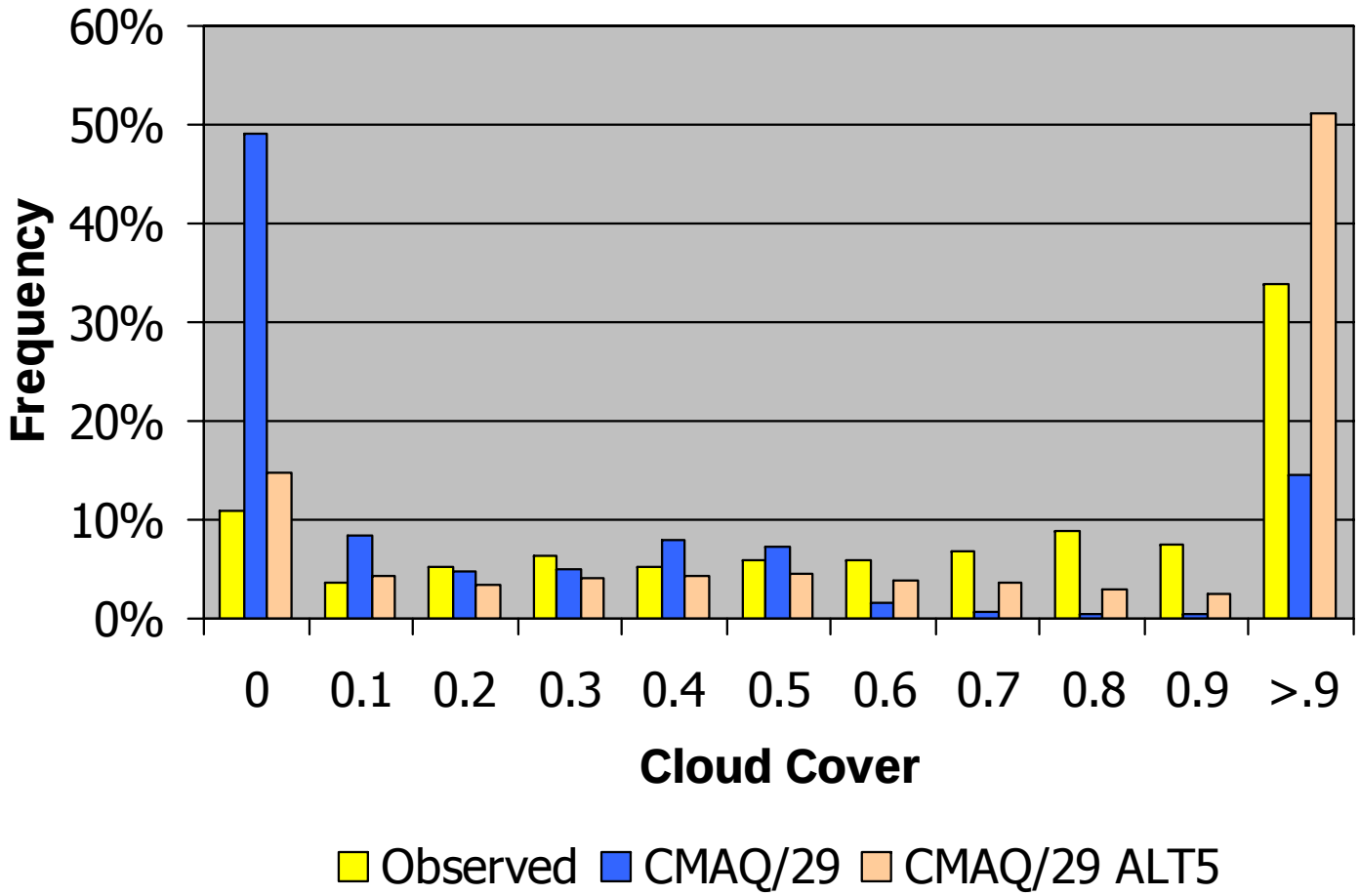
Effects of New Methodology

- Decreased marine cloud cover.
- Increased cloud cover over land, especially for afternoon hours.
- Increased S Ratio.
- Increased contribution from resolved clouds.

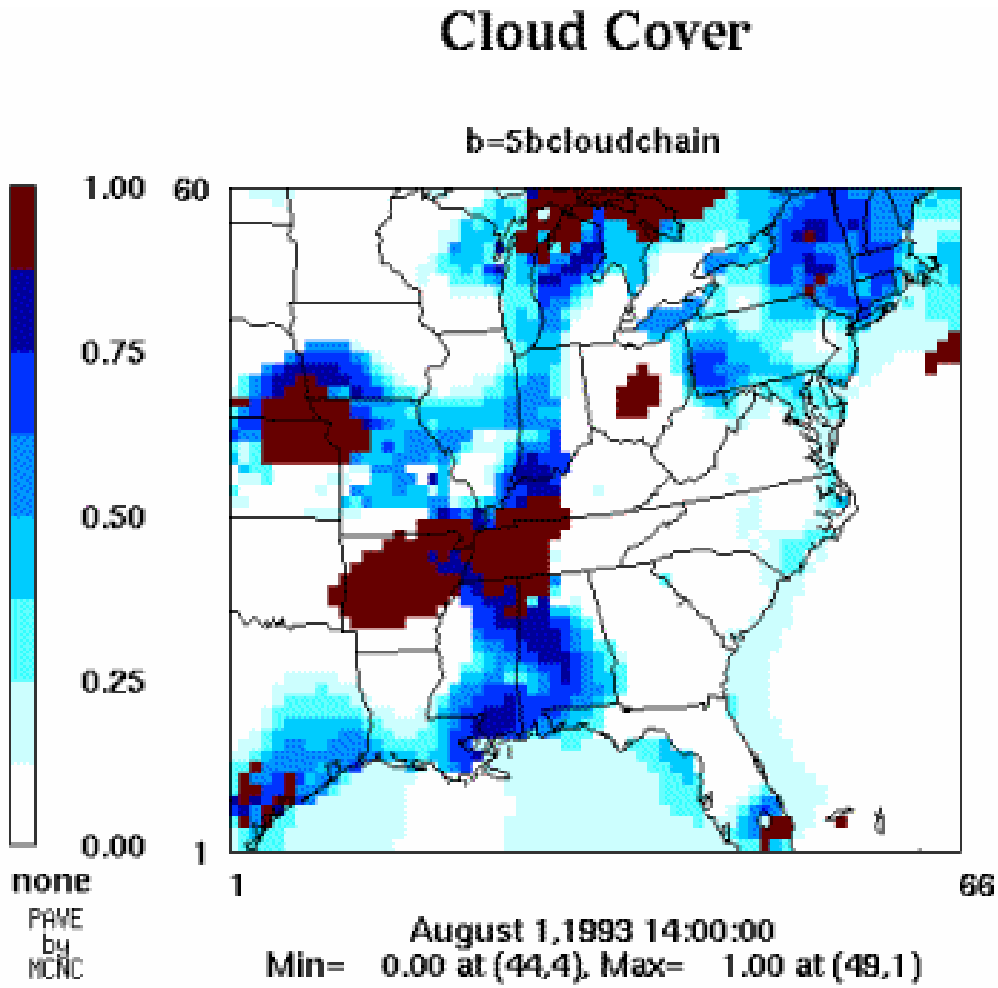
Cloud Cover in Revised CMAQ (ALT5) Compared with Original CMAQ



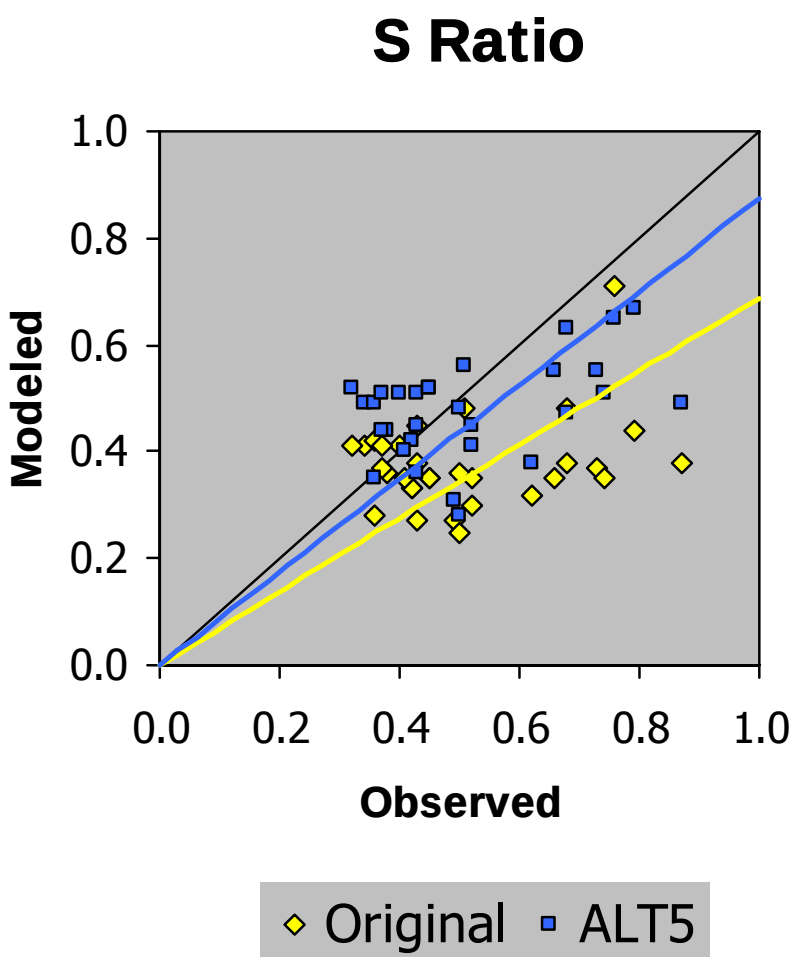
Cloud Cover Frequency Distributions

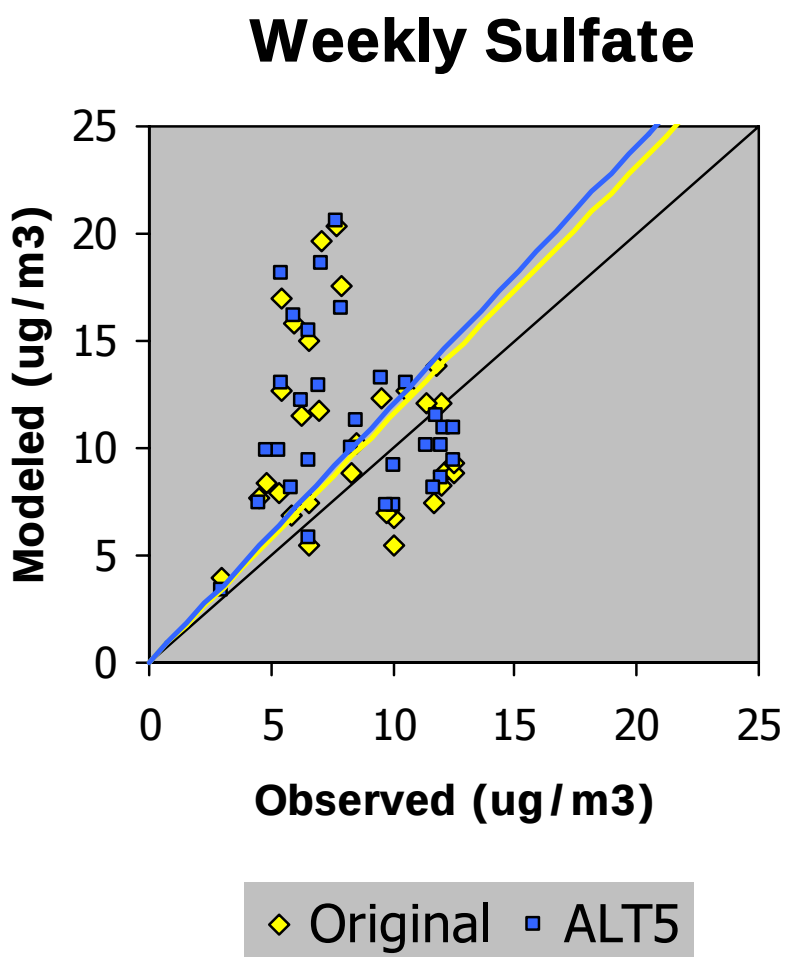


Revised CMAQ Cloud Patterns



Changes in S Performance





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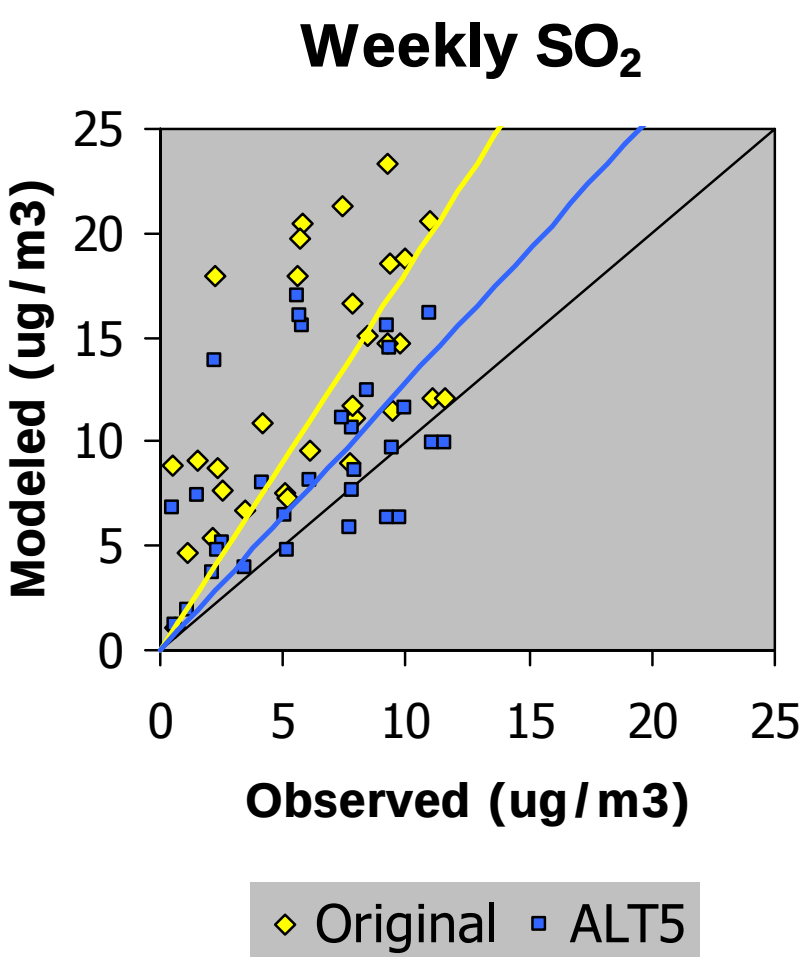
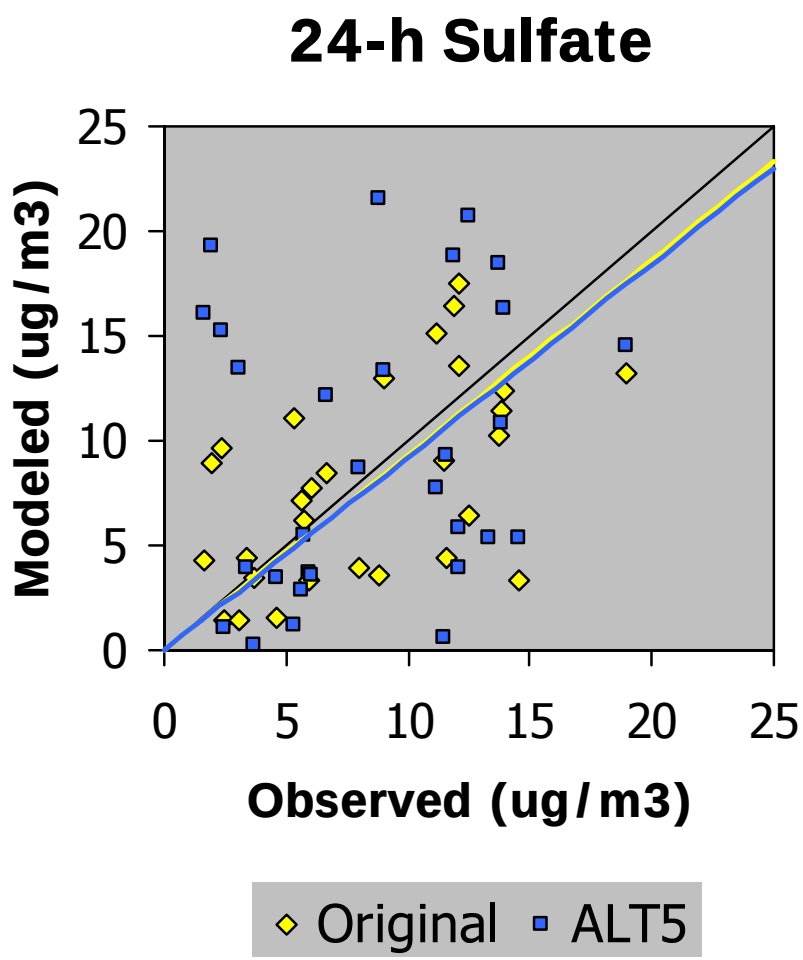
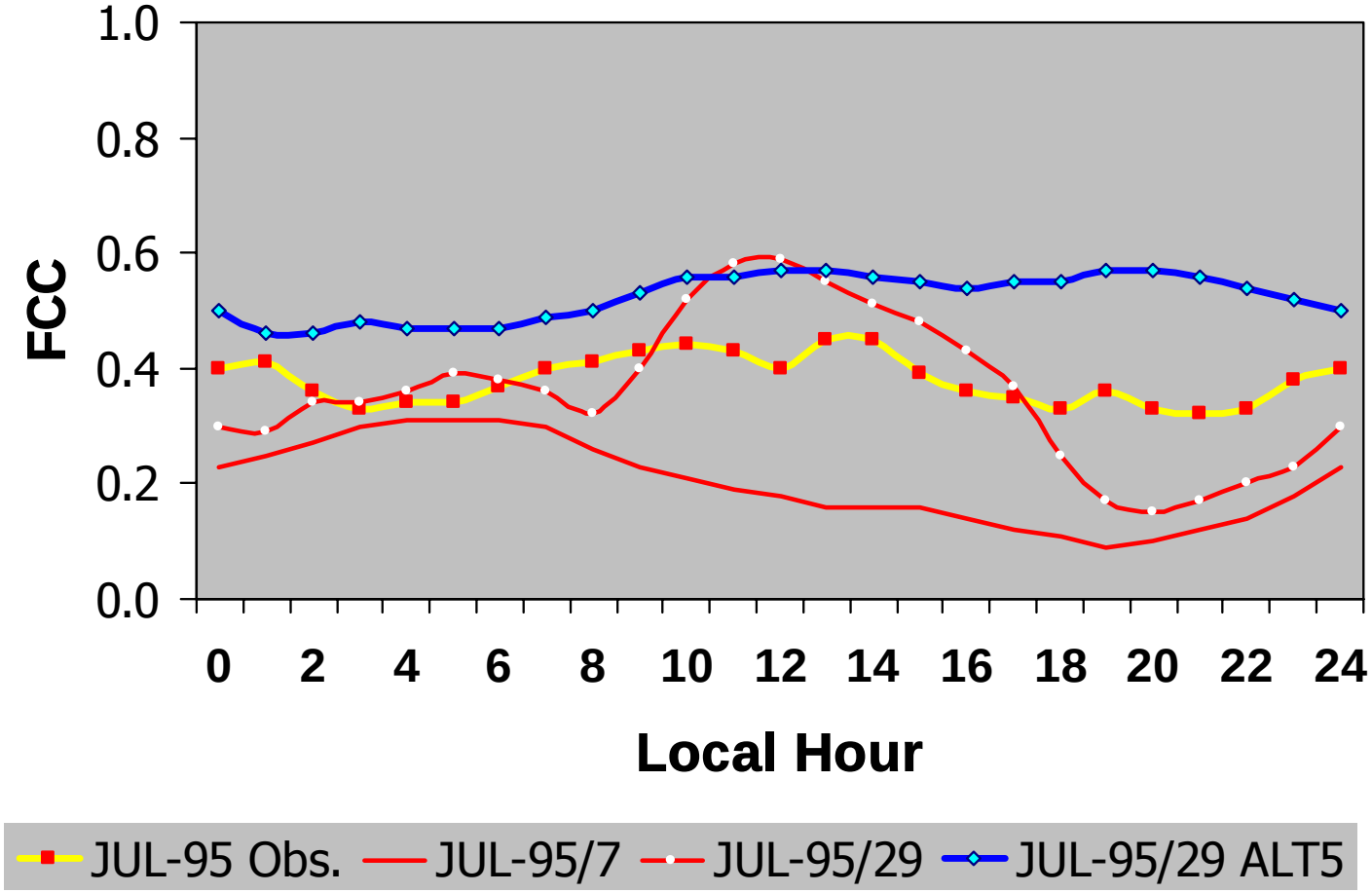
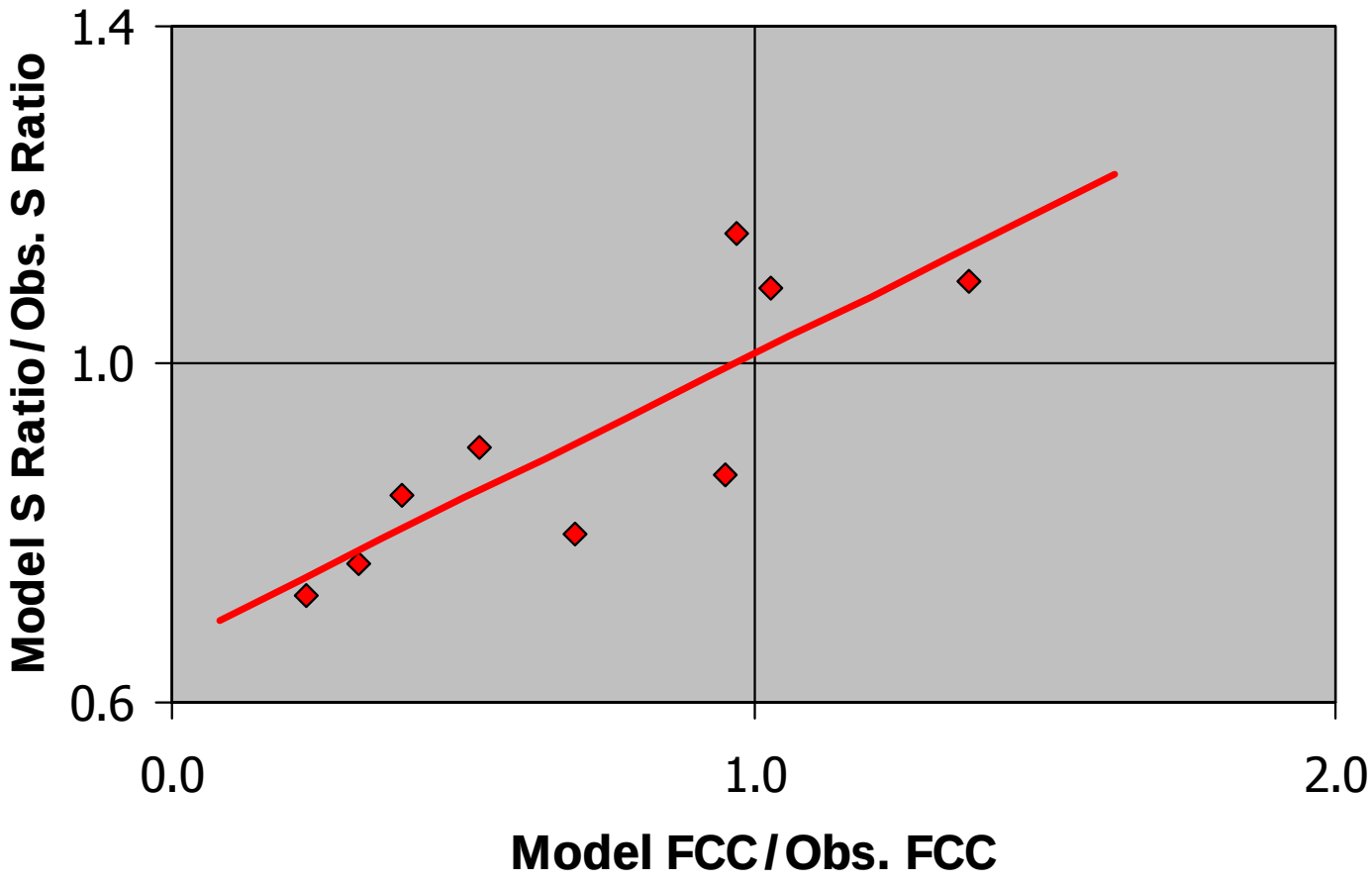




Cloud Cover for JUL-95



Sulfur vs. Cloud Performance in CMAQ



Summary

- Cloud cover appears to be represented reasonably well by MM5 but not by the current version of CMAQ.
- CMAQ underestimates cloud cover substantially; the bias is worse in afternoon.
- Old assumptions in CMAQ are probably not justified when using larger numbers of layers.
- Bias in the S species balance is clearly related to cloud cover bias.

Conclusions

- CMAQ needs a new cloud diagnostic methodology for subgrid-scale clouds.
- Implementing the CAM2 cloud cover approach in CMAQ produced more realistic cloud cover and better sulfur performance.
- Cloud cover performance needs to be evaluated for both meteorological & air quality models because the approaches used by the models may provide significantly different results for identical conditions.