Experience in Real-time Forecasting and Role of Data Assimilation

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Outline of Talk

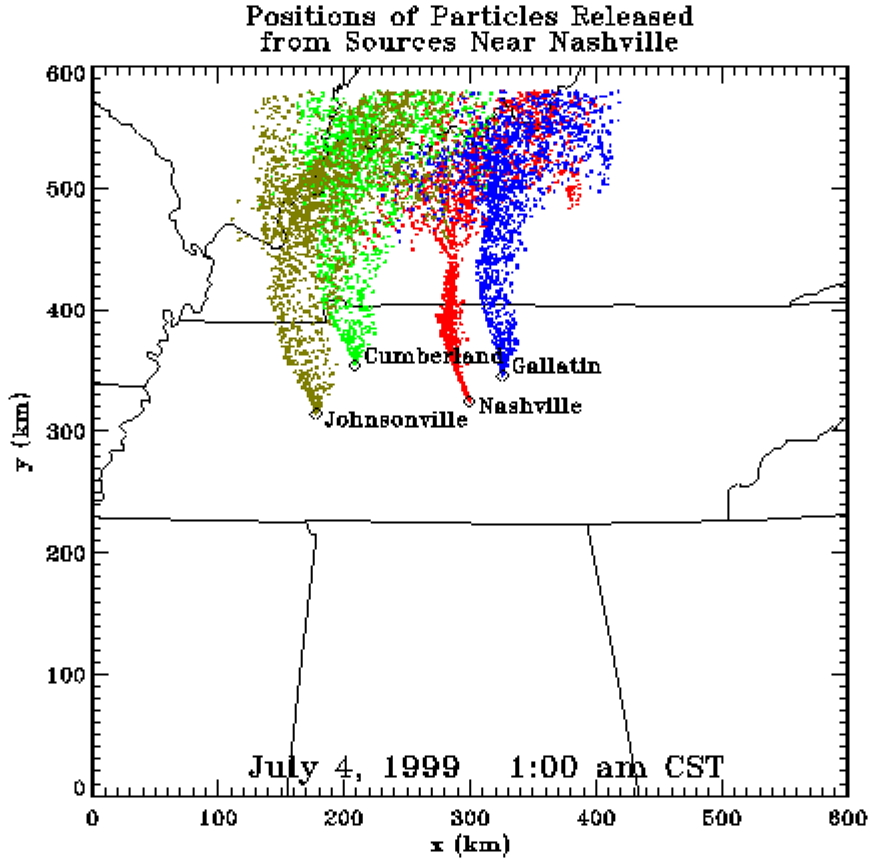
I. Overview of Experiences with Real-time Forecasting During Field Program Intensives During the Southern Oxidant Study (Atlanta, Nashville and Houston)

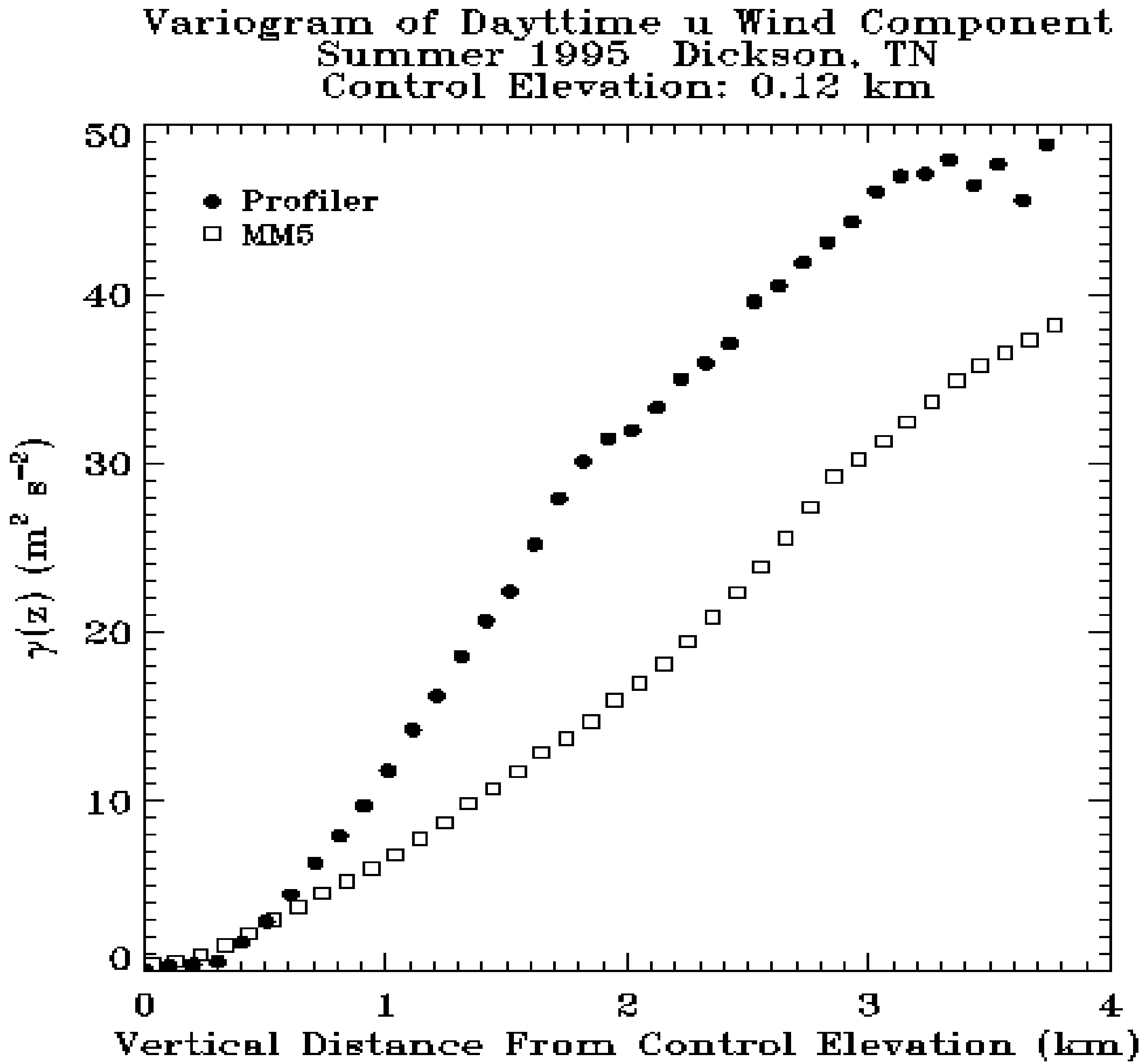
II. Overview of Experience with Real-time Coupled MM5 and MAQSIP Photochemical Modelin in Birmingam, AL.

III. Role of Data Assimilation

Boundary Layer Models Coupled to Lagrangian Particle Models -1994-2000

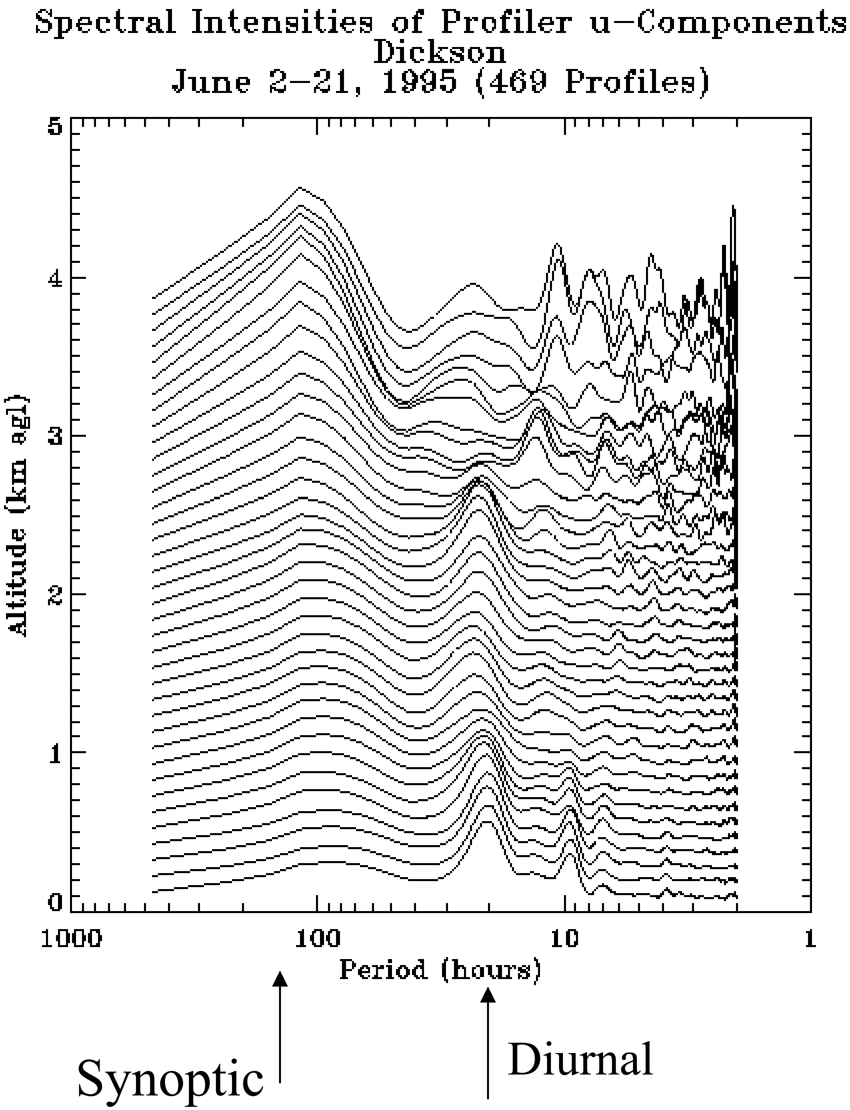
- Used for Aircraft Planning
- Radar Profiler Data Assimilated

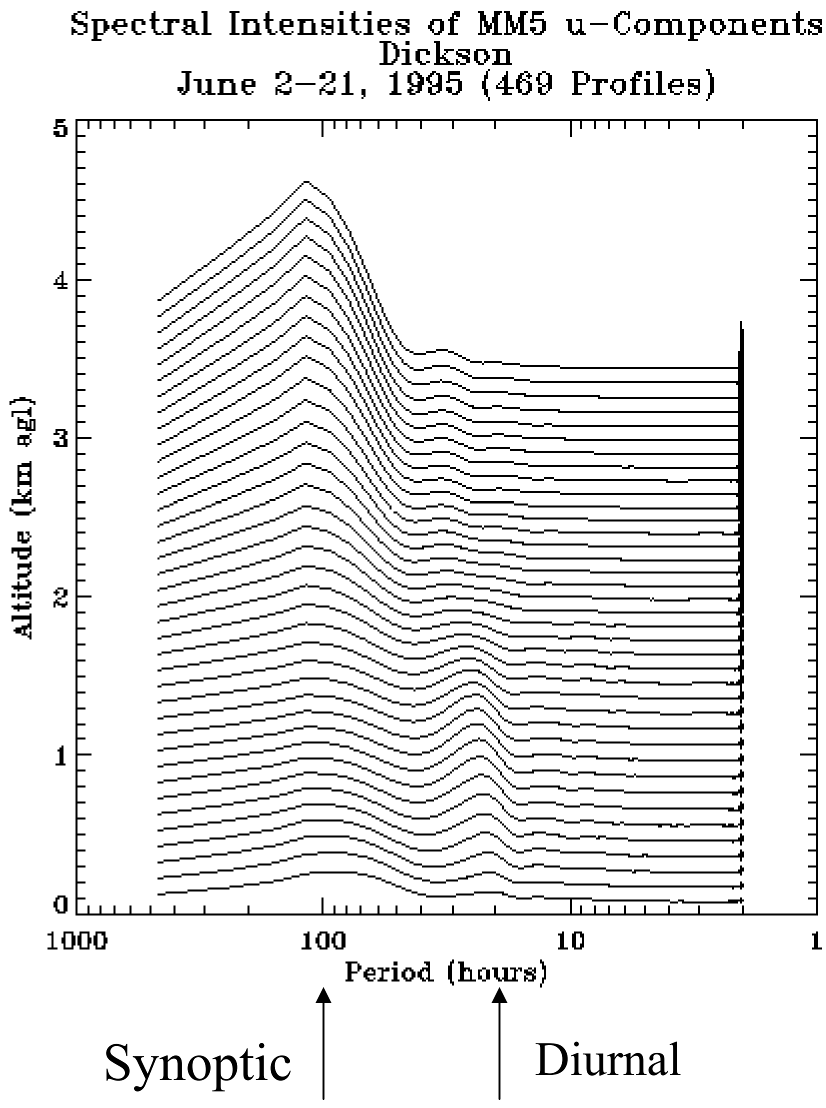


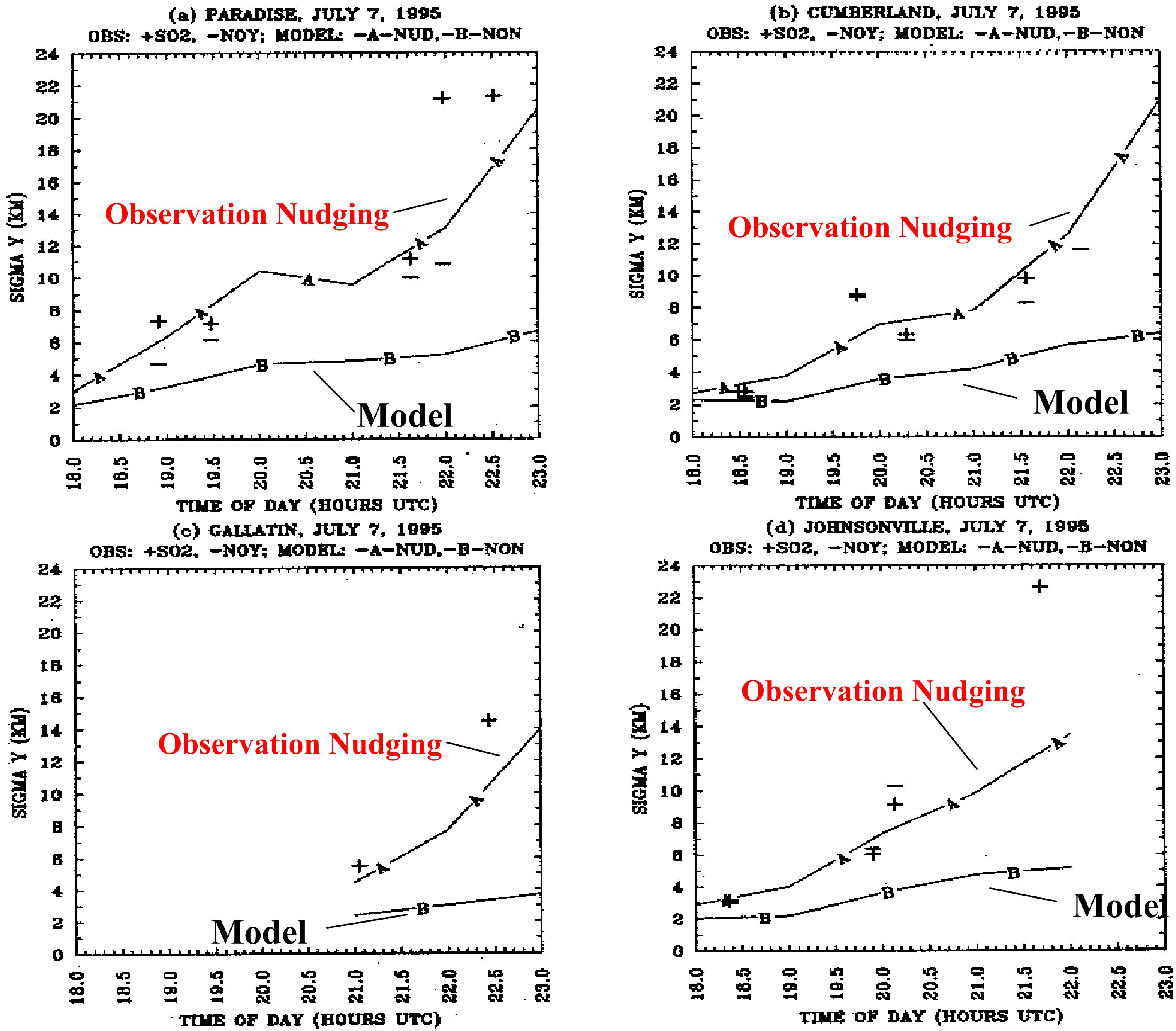


Variogram of Dayttime u Wind Component
Summer 1995 Dickson, TN
Control Elevation: 0.12 km
Profiler
MM5
γ(z) (m2 s−2)
0
10
20
30
40
50
0
1
2
3
4
Vertical Distance From Control Elevation (km)

Models Do Not Maintain as Much Energy at Higher Frequencies as Observations



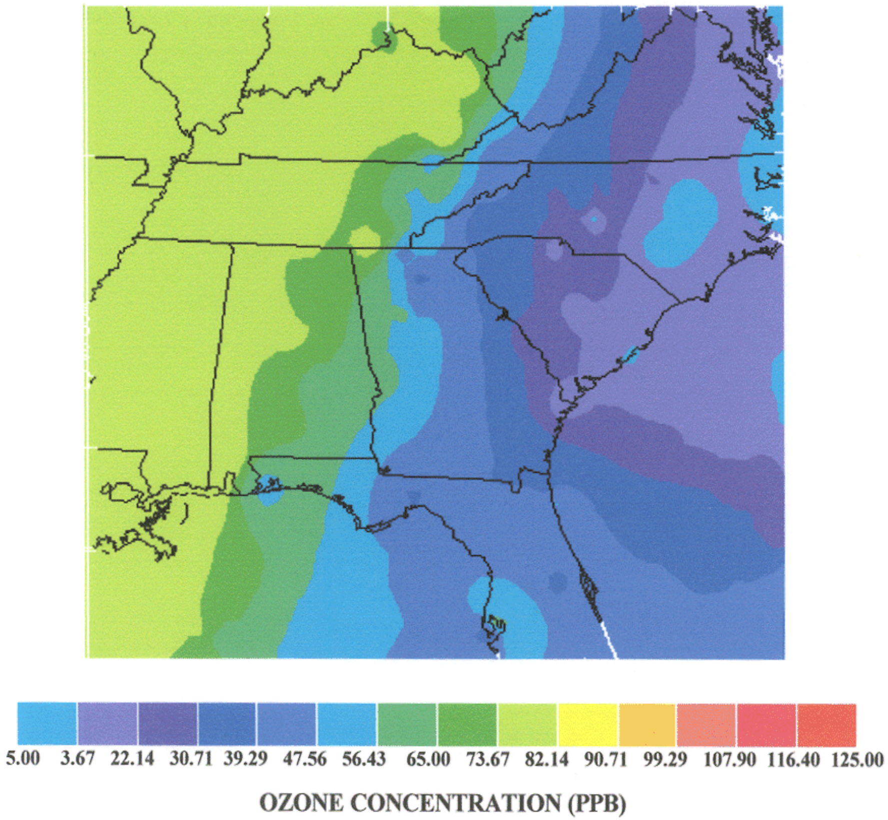



(a) PARADISE, JULY 7, 1995
OBS: +SO2, -NOY; MODEL: -A-NUD,-B-NON
SIGMA Y (KM)
TIME OF DAY (HOURS UTC)
Observation Nudging
Model
(b) CUMBERLAND, JULY 7, 1995
OBS: +SO2, -NOY; MODEL: -A-NUD,-B-NON
SIGMA Y (KM)
TIME OF DAY (HOURS UTC)
Observation Nudging
Model
(c) GALLATIN, JULY 7, 1995
OBS: +SO2, -NOY; MODEL: -A-NUD,-B-NON
SIGMA Y (KM)
TIME OF DAY (HOURS UTC)
Observation Nudging
Model
(d) JOHNSONVILLE, JULY 7, 1995
OBS: +SO2, -NOY; MODEL: -A-NUD,-B-NON
SIGMA Y (KM)
TIME OF DAY (HOURS UTC)
Observation Nudging
Model

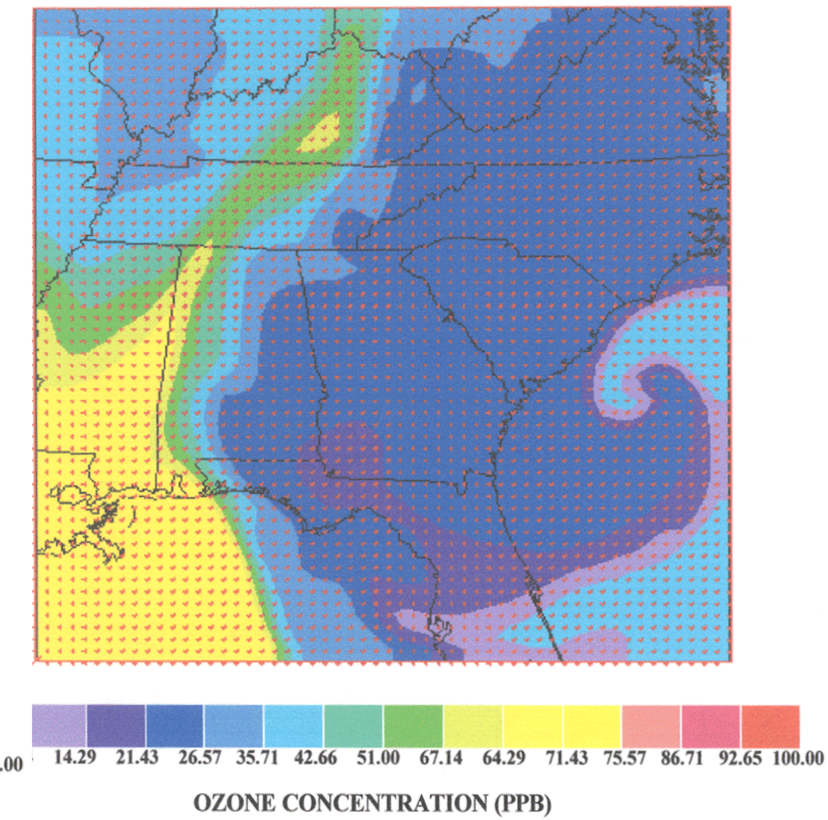
Role of Transport in Statistical Forecast Models Used in SOS in 1995 Nashville Field Program

Ms. Toree Myers - M.S. Student

- Most statistical models used for air quality modeling use only local variables - e.g. previous day ozone, local winds.
- This investigation made a first attempt at quantifying the role of ozone transport to local ozone levels using observed ozone in a mesoscale model.
- Surface ozone observed at noon over the Eastern US was objectively analyzed on a horizontal grid during a two month period.
- Values were distributed uniformly vertically through the mixed layer.
- Ozone was transported as a conservative tracer in the RAMS model
- Data was statistically analyzed.



Initial Objective Analysis of Noon Time Observed Ozone Data



RAMS Forecast of Advected Field of Ozone as a Conservative Tracer

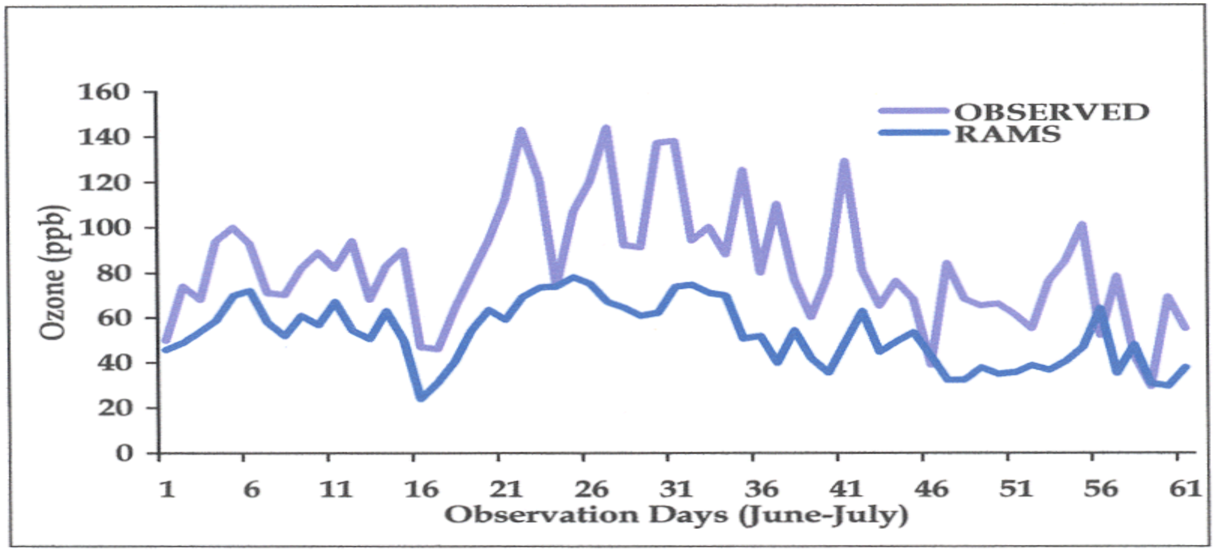


Figure 9.1. RAMS Forecasted Noon Ozone Versus Observed Maximum Ozone Concentration Using 1995-1996 Atlanta Ozone Data.

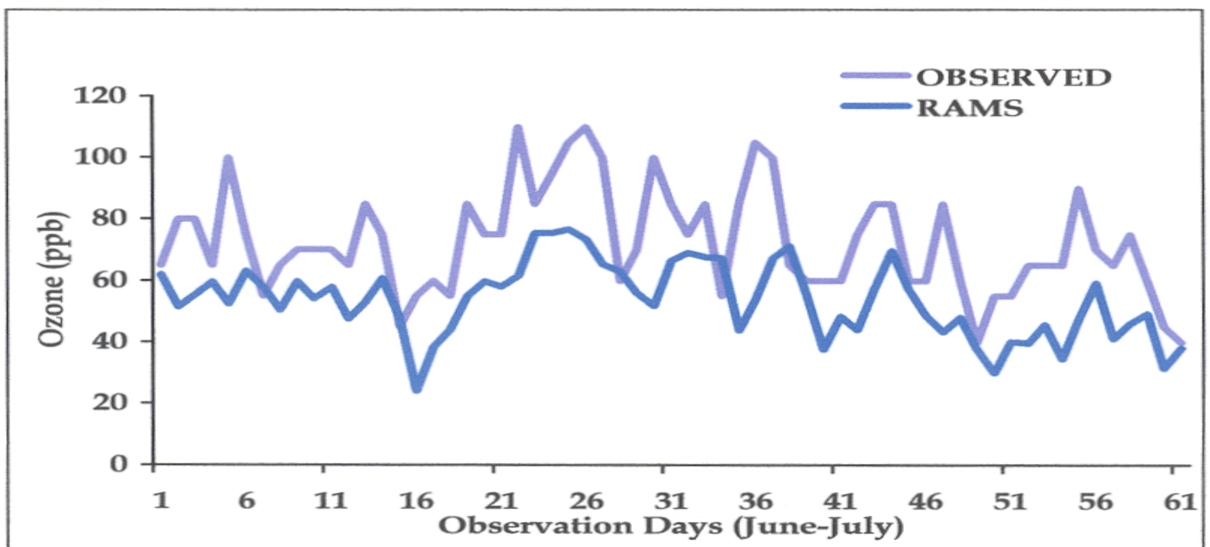


Figure 9.2. RAMS Forecasted Noon Ozone Versus Observed Maximum Ozone Concentration Using 1995-1996 Percy Priest (Nashville) Ozone Data.

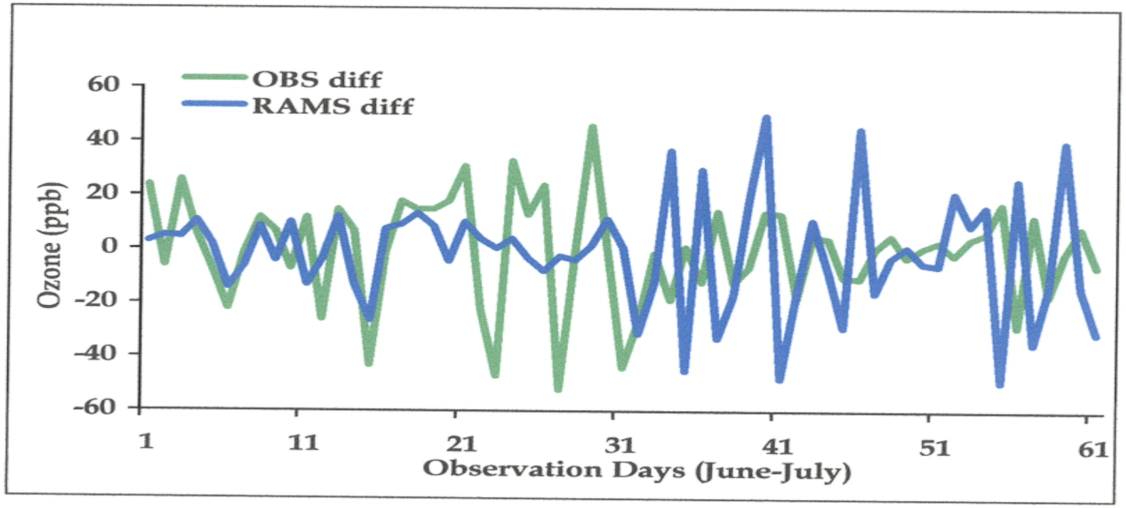


Figure 9.5. Transport (RAMS Tomorrow - RAMS Today) Versus Daily Changes in Observed Ozone for Atlanta 1995-1996 Ozone Data.

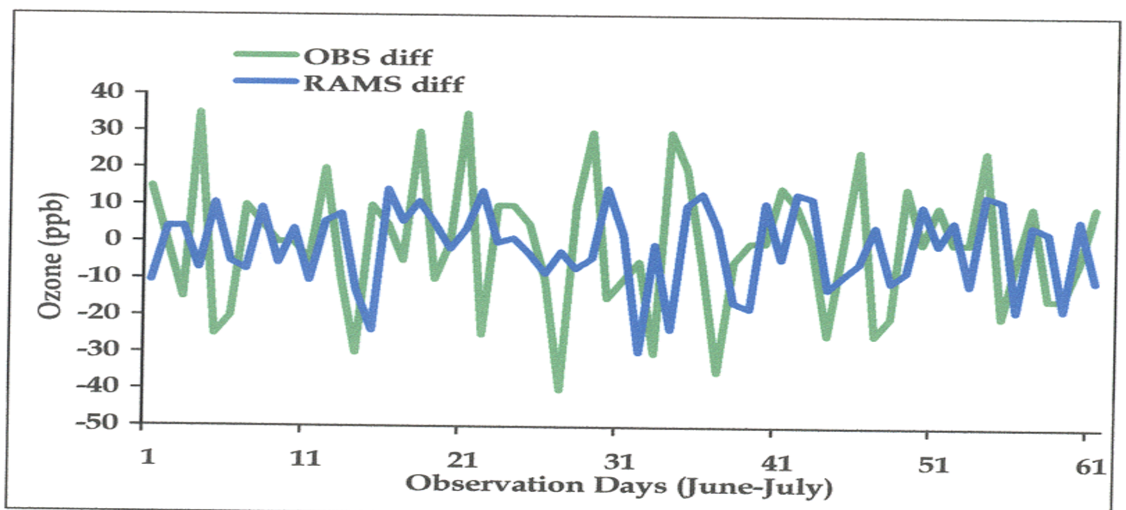


Figure 9.6. Transport (RAMS Tomorrow - RAMS Today) Versus Daily Changes in Observed Ozone for Percy Priest (Nashville) 1995-1996 Ozone Data.

Table 9.1. Coefficient of Determination for Transport Analyses. Transport = RAMS Forecasted Ozone Tomorrow - RAMS Forecasted Today.

MODEL DEVELOPED	Atlanta R^2	Fairfield R^2	Edmond R^2	Percy R^2
1995 RAMS vs. OBSERVED	0.497	0.0602	0.157	0.317
1995 TRANSPORT vs. DIFFERENCE IN OBSERVED	0.153	0.0171	0.00200	0.00539
1996 RAMS vs. OBSERVED	0.467	0.215	0.158	0.00854
1996 TRANSPORT vs. DIFFERENCE IN OBSERVED	0.121	0.00863	0.00198	0.00487
1995-1996 RAMS vs. OBSERVED	0.359	0.0487	0.315	0.313
1995-1996 TRANSPORT vs. DIFFERENCE IN OBSERVED	6.337E-05	0.00766	0.0172	0.00223

Real-time Air Quality Forecasting Using MM5 and MAQSIP for the Birmingham, Alabama Area

Joint Program Between

University of Alabama in Huntsville

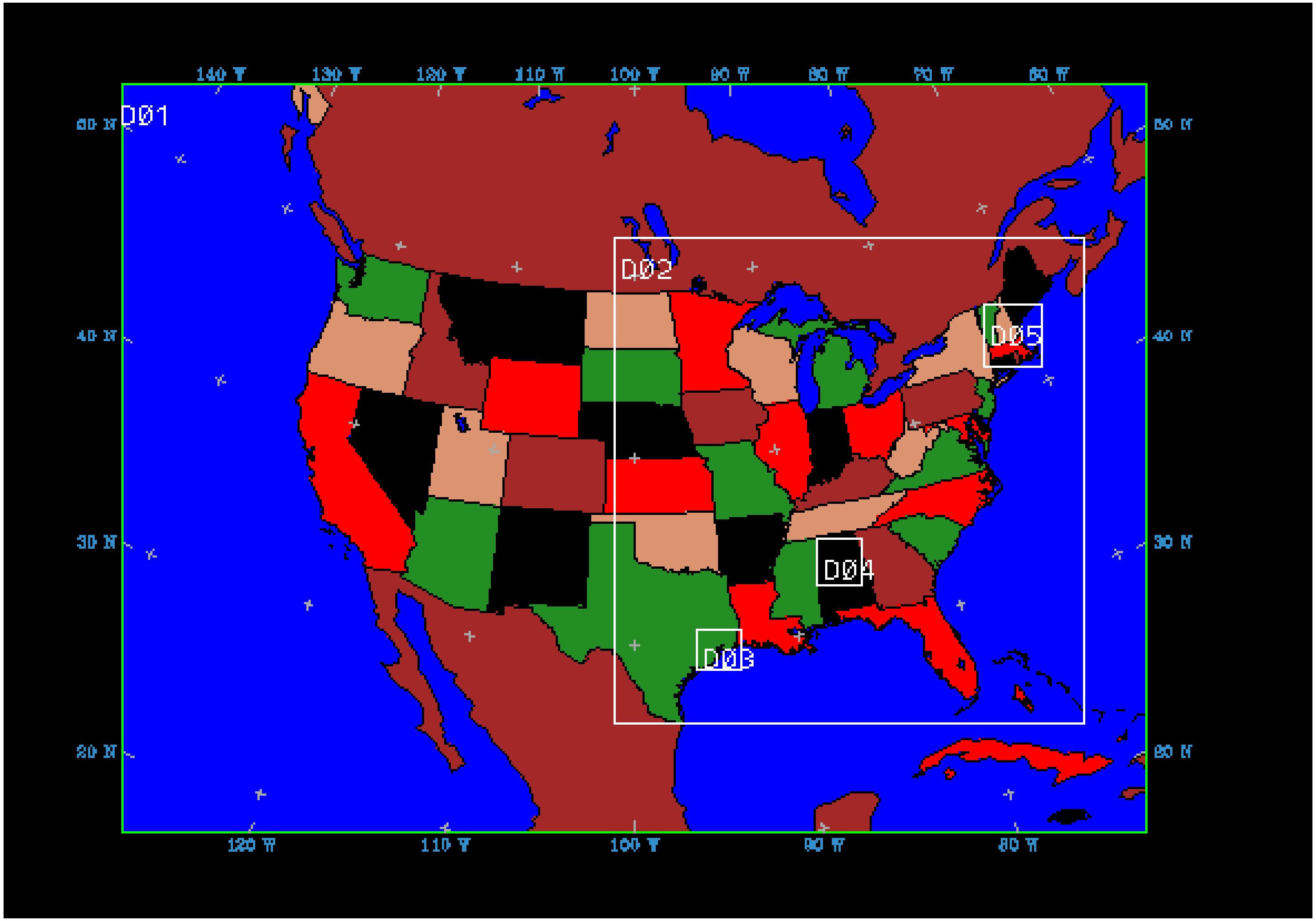
MCNC Environmental Modeling Center

State of Alabama

U.S. EPA

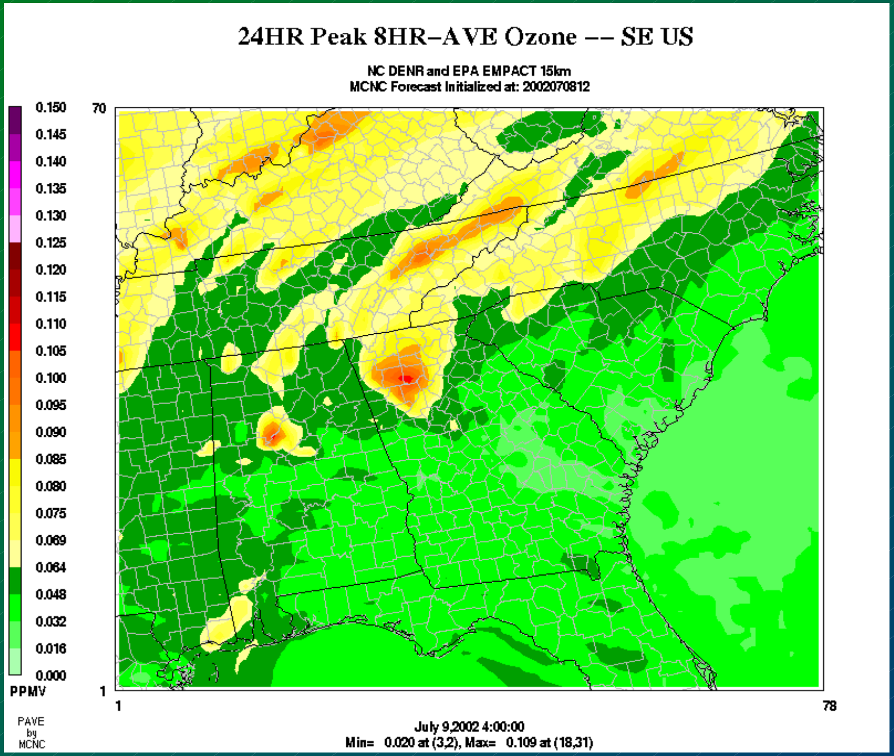
- Models used:
  - *MAQSIP-RT Photochemical Model*
    - Improved treatment of cloud attenuation effects.
    - New: Activated AIRNOW ozone monitor data assimilation system to initialize MAQSIP-RT
  - *Sparse-Matrix Operator Kernel Emissions (SMOKE)*
    - BEIS-3,NET-99 Point/Area, Mobile-5
    - All emissions *online* including point-source specific plume rise
  - *PSU/NCAR MM5V3.4 initialized with NCEP/Eta Analysis*

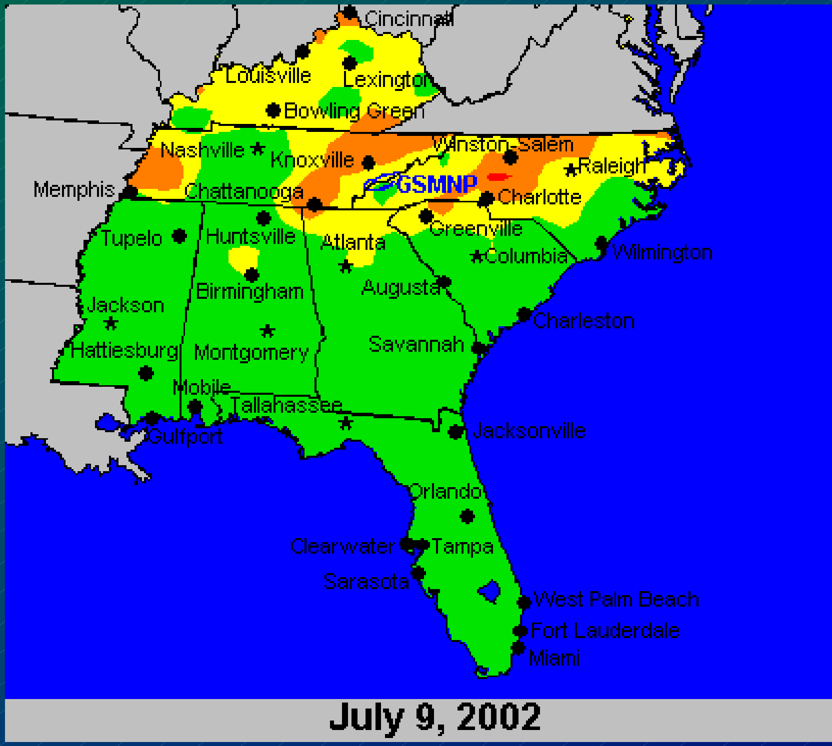
- MM5 Domains: 45/15/5 km



MAQSIP-RT Forecasts, 2002: SE and Alabama—July 5-13 SE US

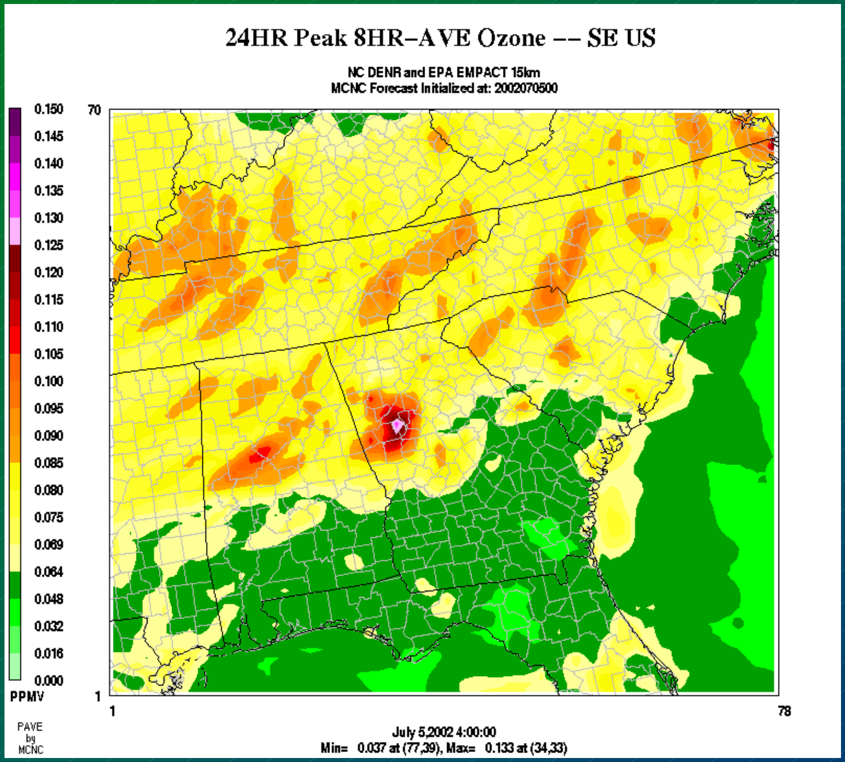
- 15km SE Day 1 Fcst vs Obs: July 9

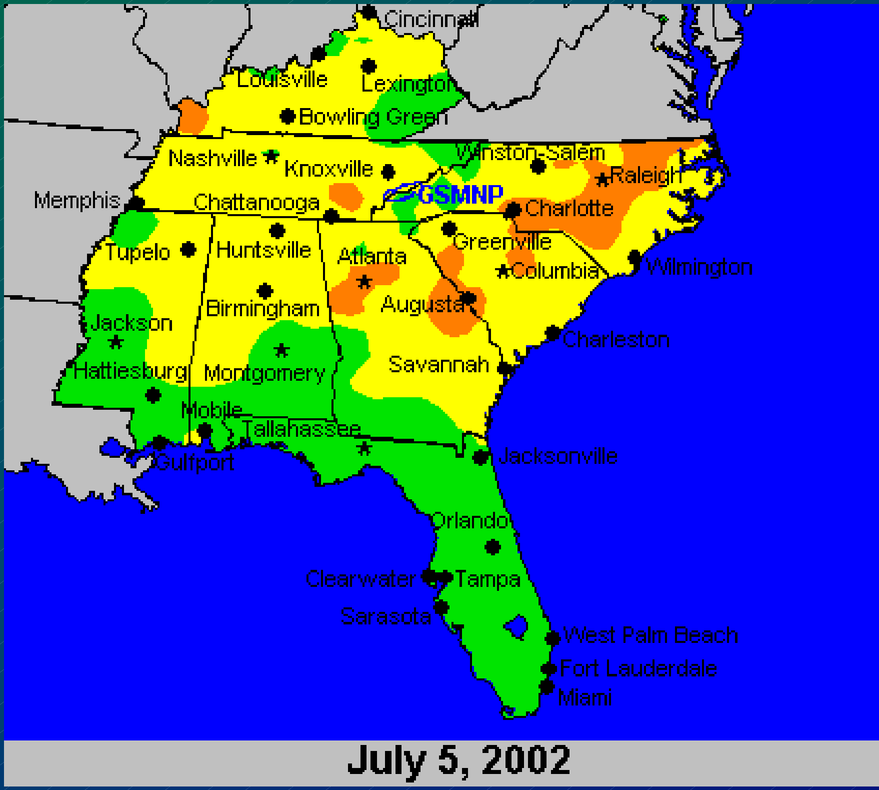




MAQSIP-RT Forecasts, 2002: SE and Alabama—July 5-13 SE US

- 15km SE Day 1 Fcst vs Obs: July 5





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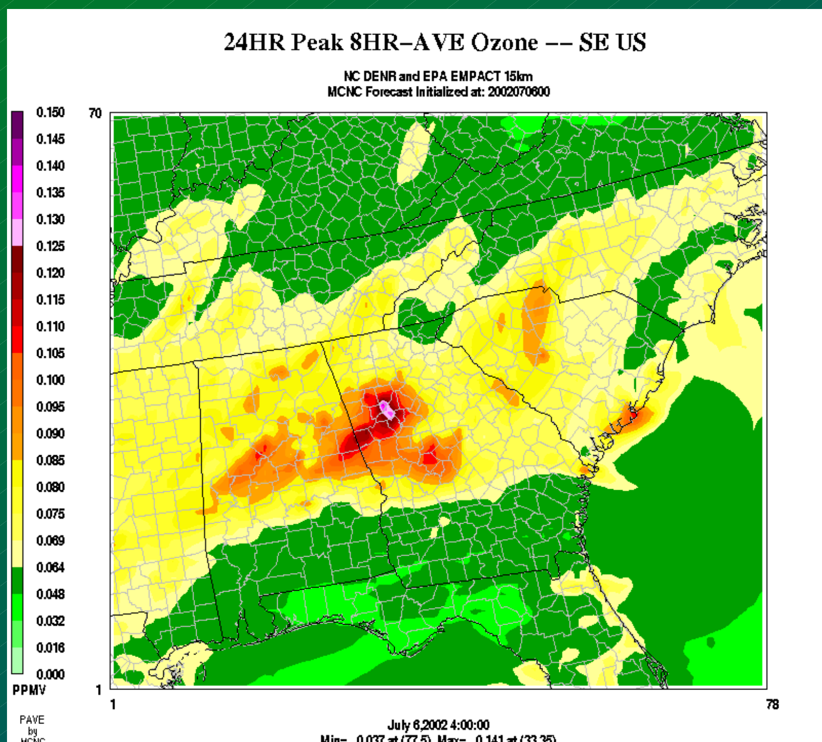
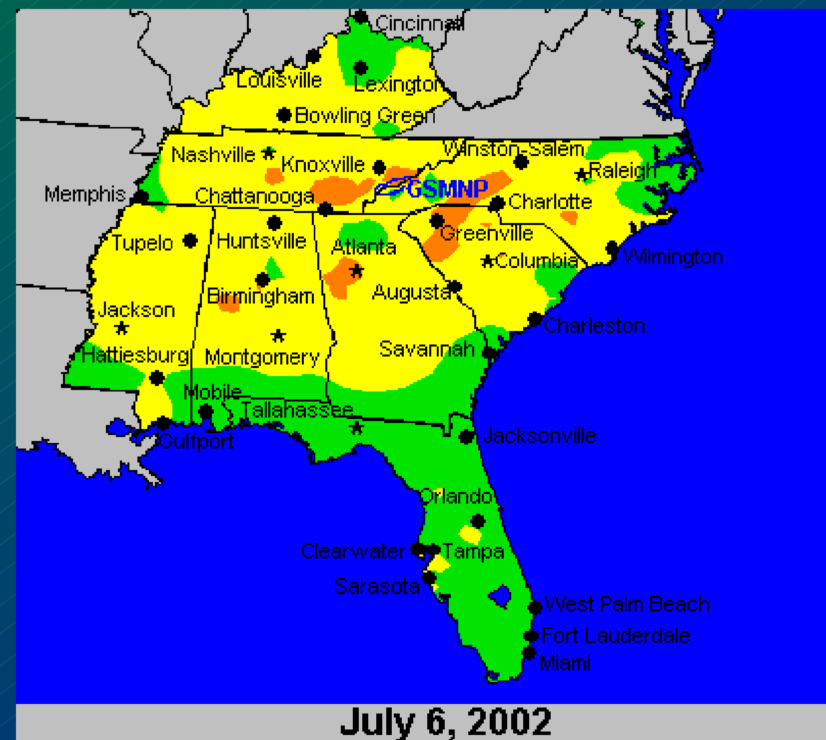
MAQSIP-RT Forecasts, 2002: SE and Alabama—July 5-13 SE US

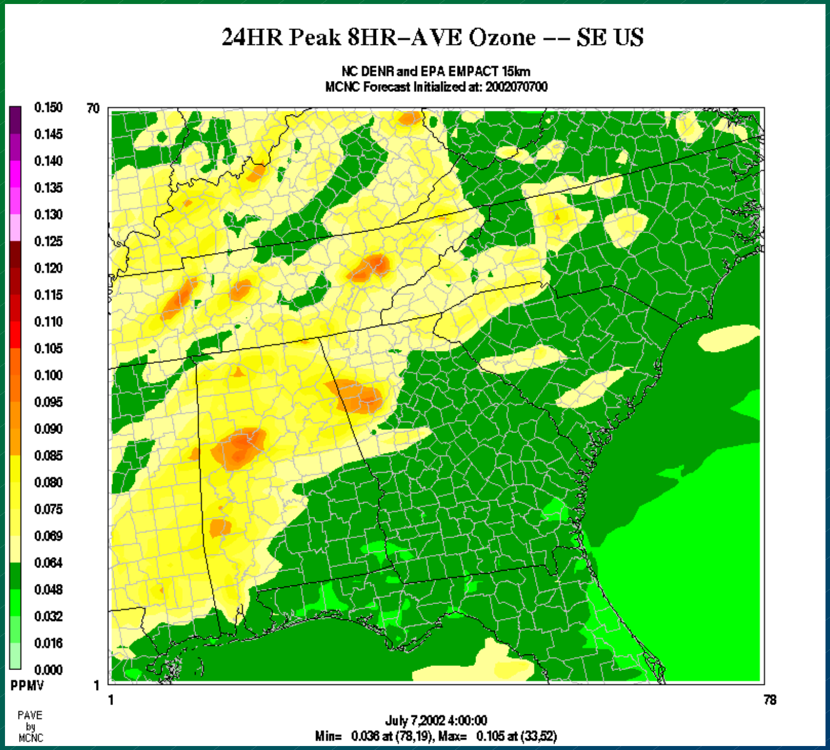
- **15km SE Day 1 Fcst vs Obs: July 6**

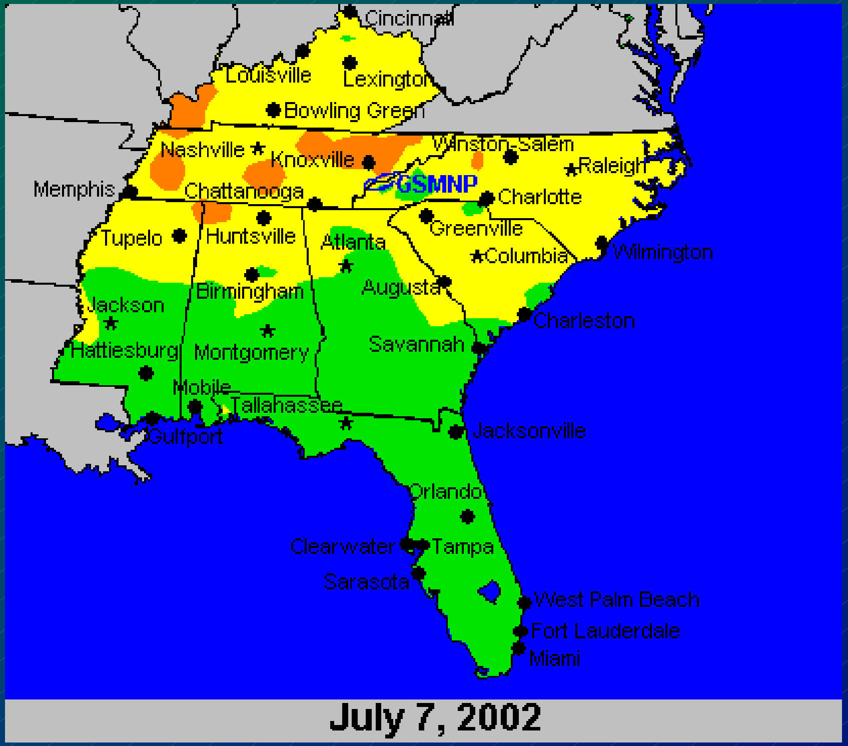




MAQSIP-RT Forecasts, 2002: SE and Alabama—July 5-13 SE US

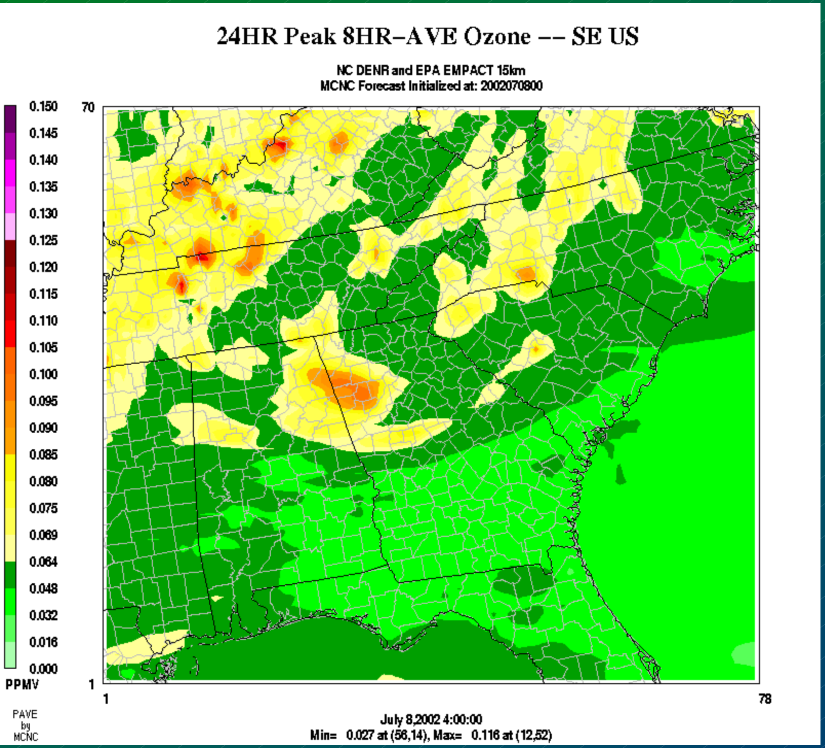
- 15km SE Day 1 Fcst vs Obs: July 7

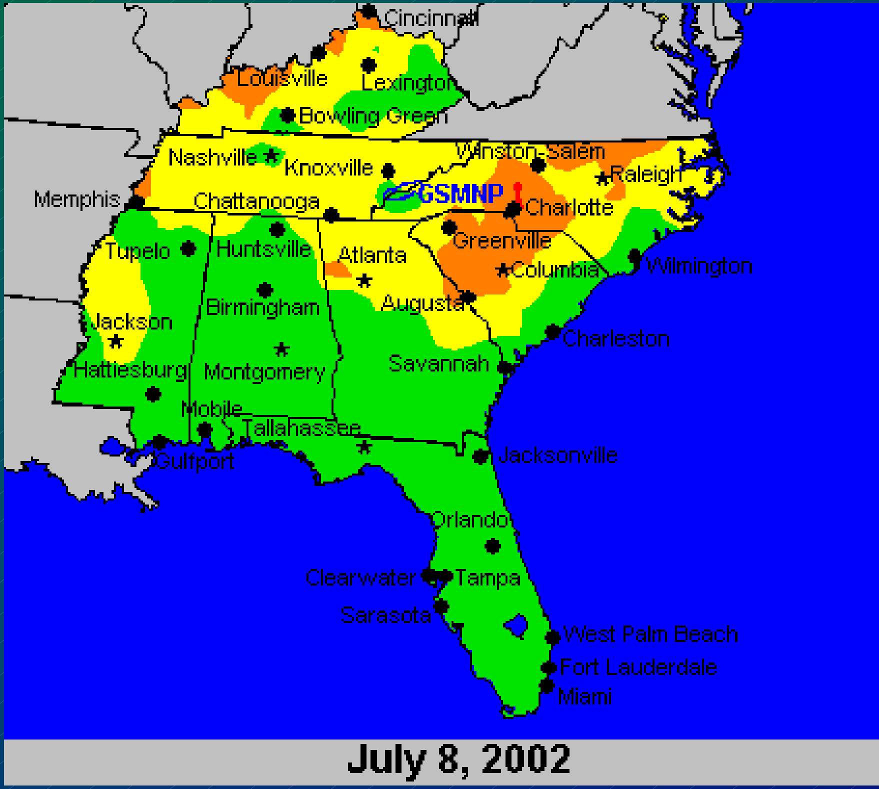




MAQSIP-RT Forecasts, 2002: SE and Alabama—July 5-13 SE US

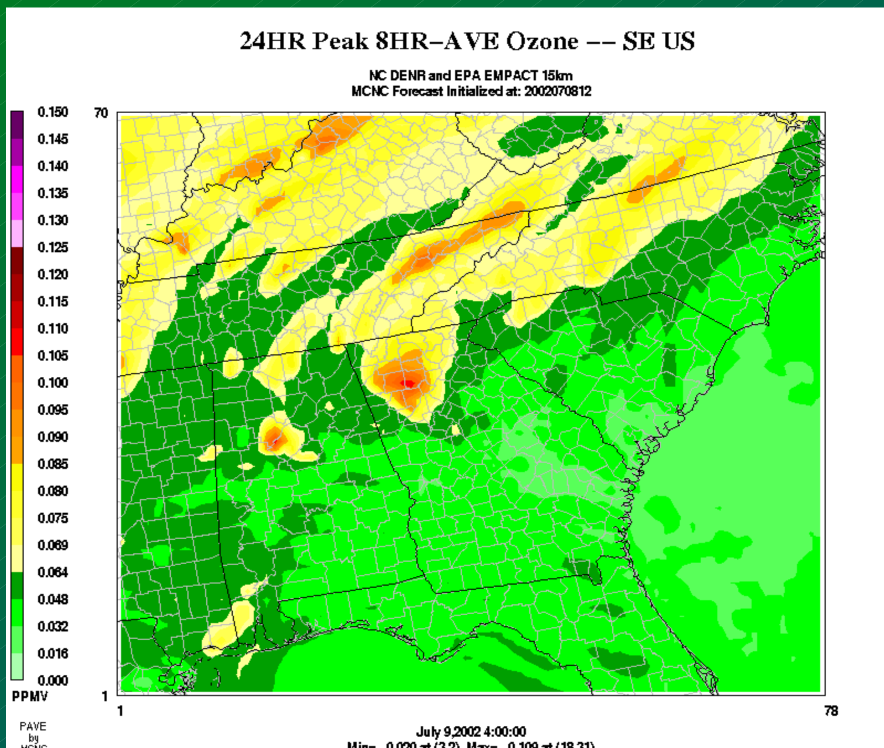
- 15km SE Day 1 Fcst vs Obs: July 8

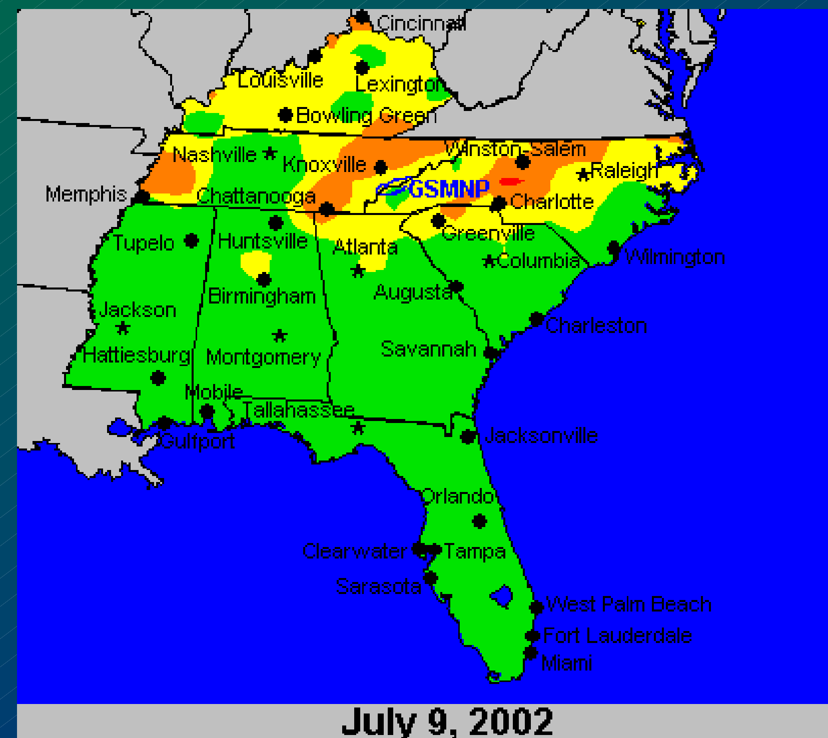




MAQSIP-RT Forecasts, 2002: SE and Alabama—July 5-13 SE US

- **15km SE Day 1 Fcst vs Obs: July 9**





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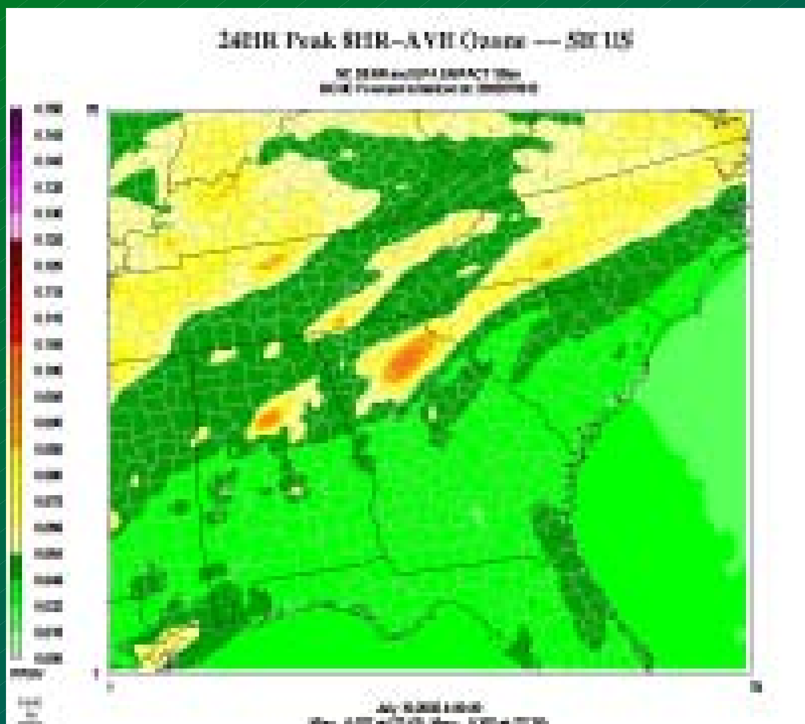
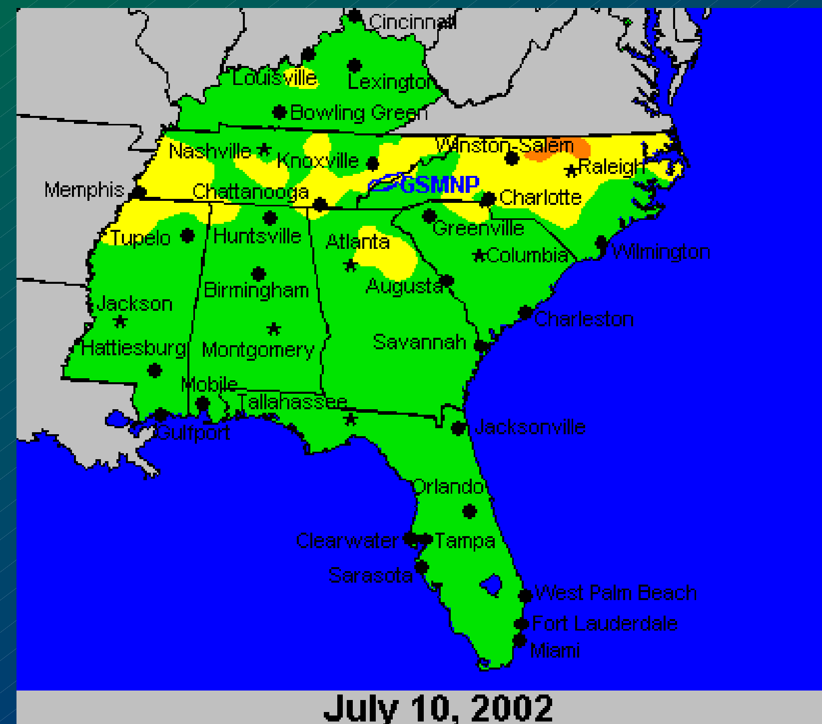
MAQSIP-RT Forecasts, 2002: SE and Alabama—July 5-13 SE US

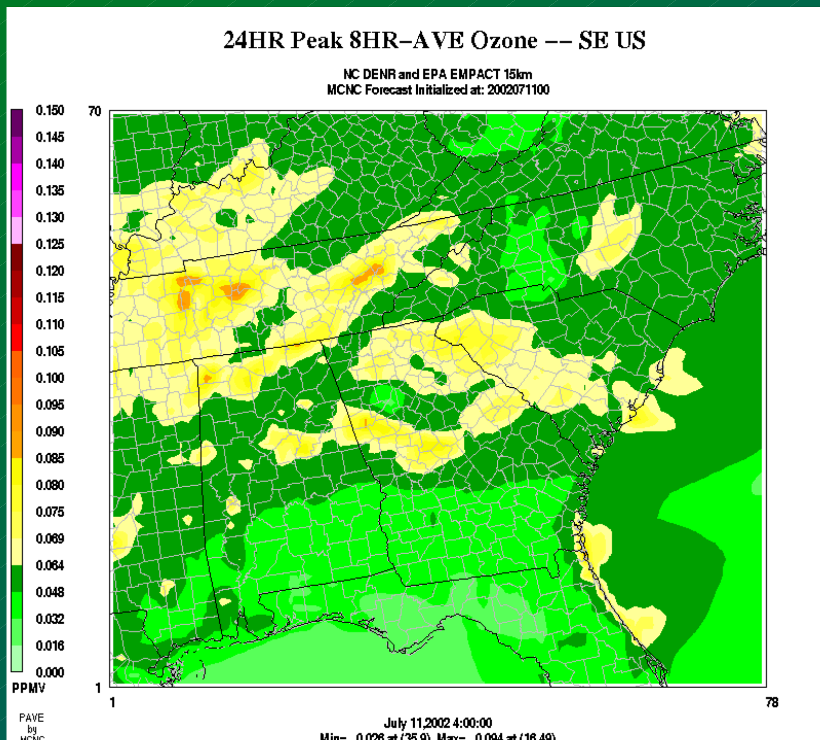
- 15km SE Day 1 Fcst vs Obs: July 10

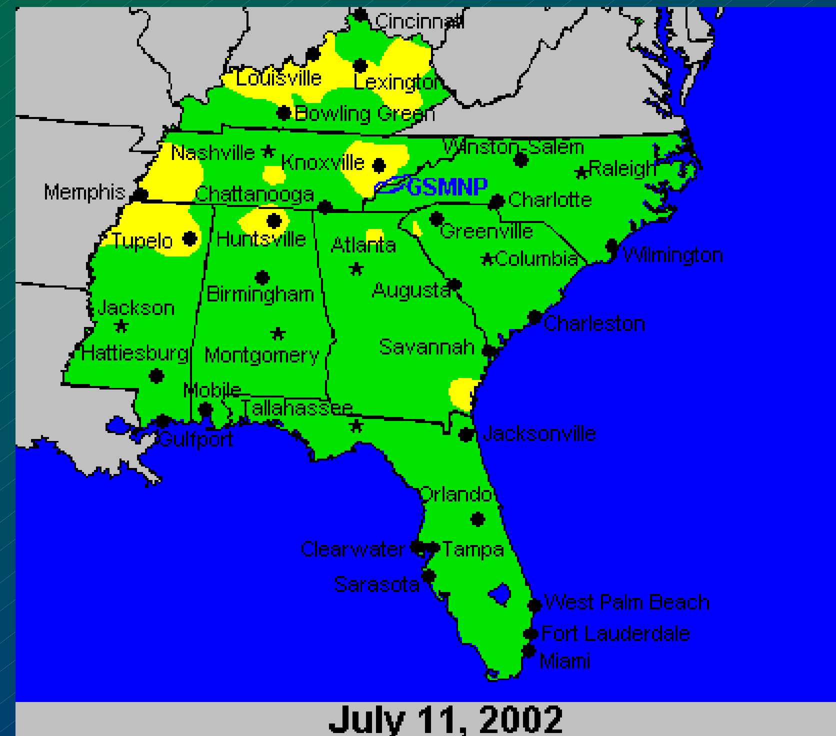




MAQSIP-RT Forecasts, 2002: SE and Alabama—July 5-13 SE US

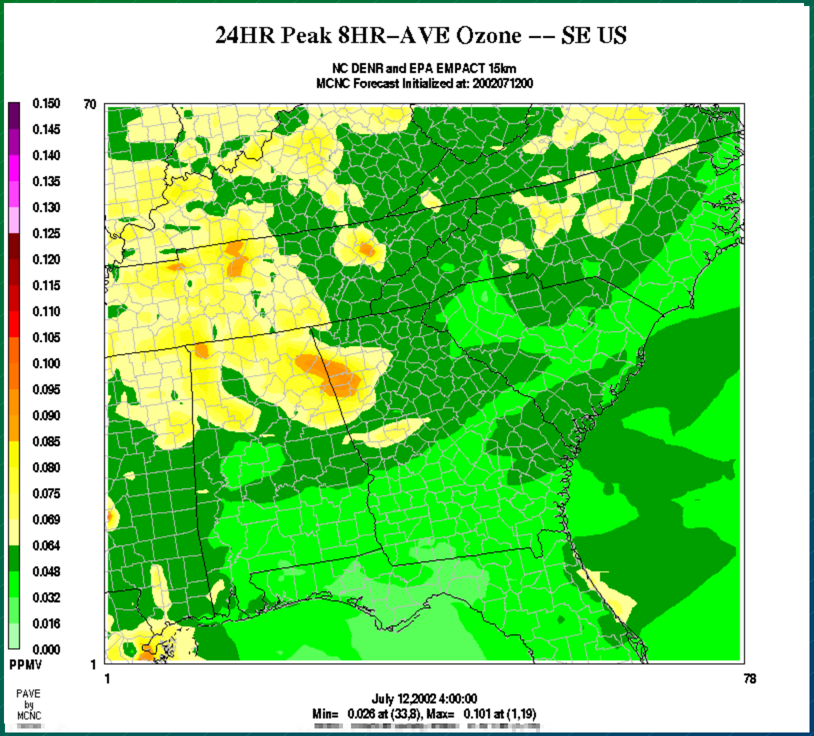
- **15km SE Day 1 Fcst vs Obs: July 11**

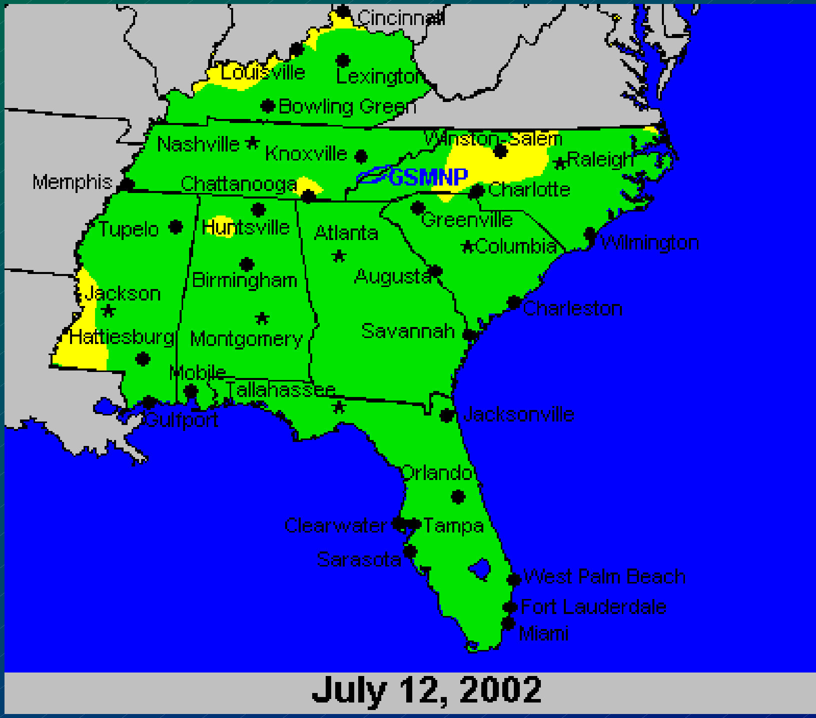




MAQSIP-RT Forecasts, 2002: SE and Alabama—July 5-13 SE US

- **15km SE Day 1 Fcst vs Obs: July 12**





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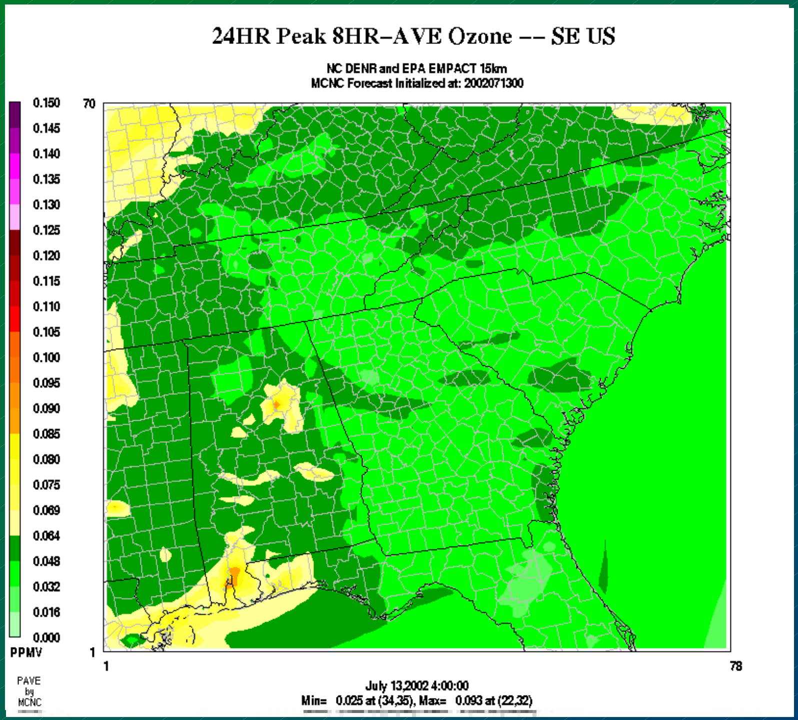
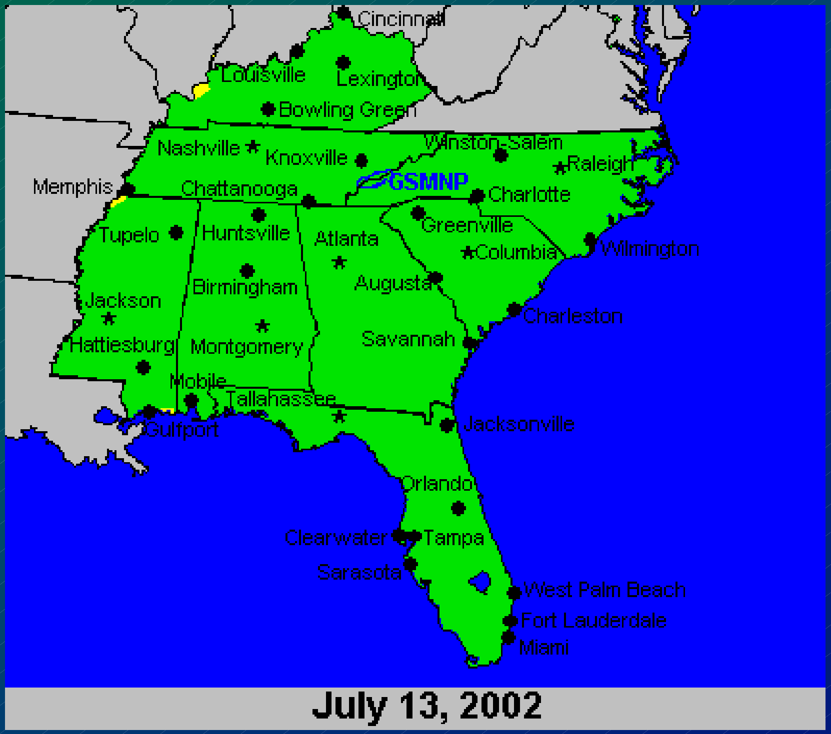
MAQSIP-RT Forecasts, 2002: SE and Alabama—July 5-13 SE US

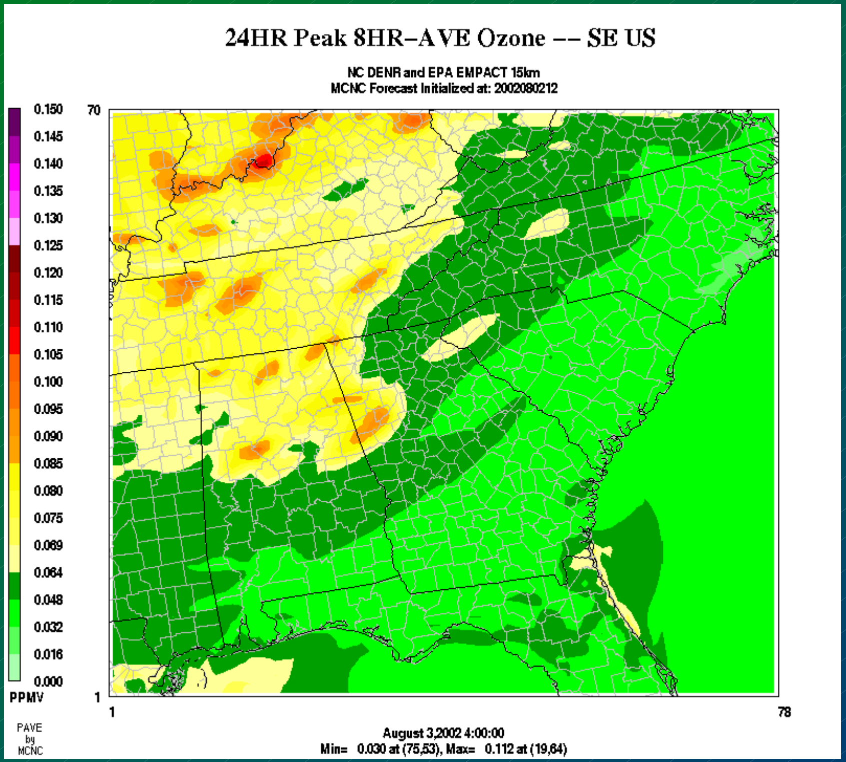
- **15km SE Day 1 Fcst vs Obs: July 13**

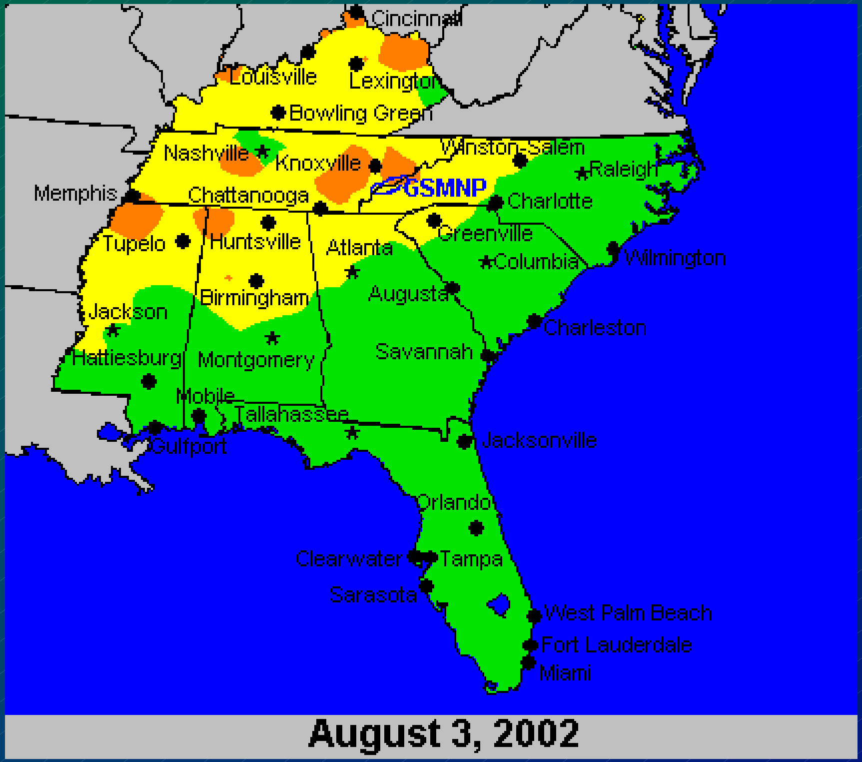




MAQSIP-RT Forecasts, 2002: SE and Alabama—Aug 2-10 SE US

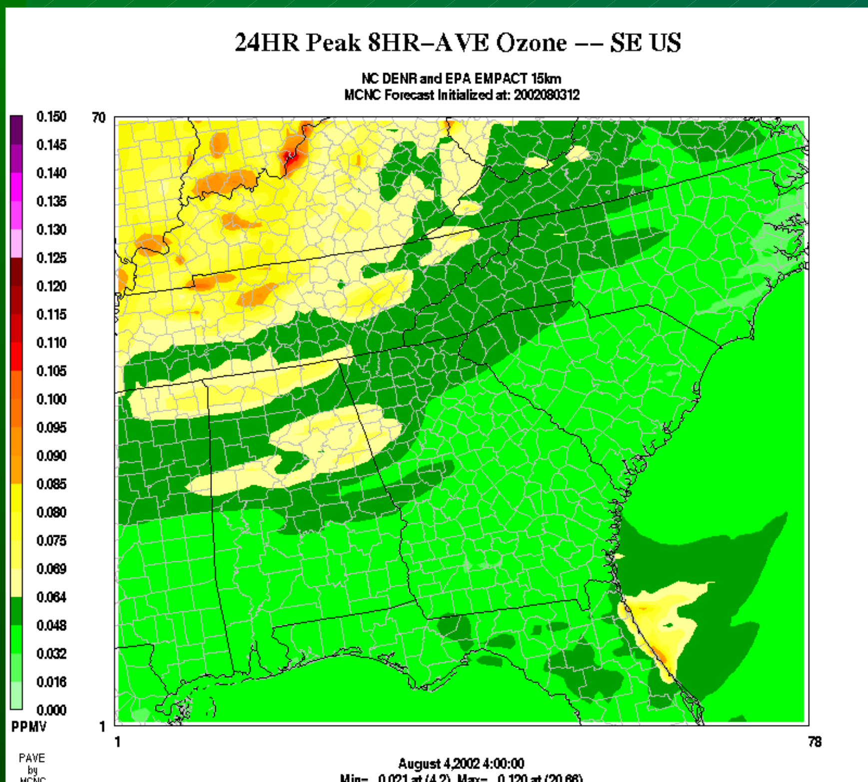
- **15km SE Day 2 Fcst vs Obs: Aug 3**

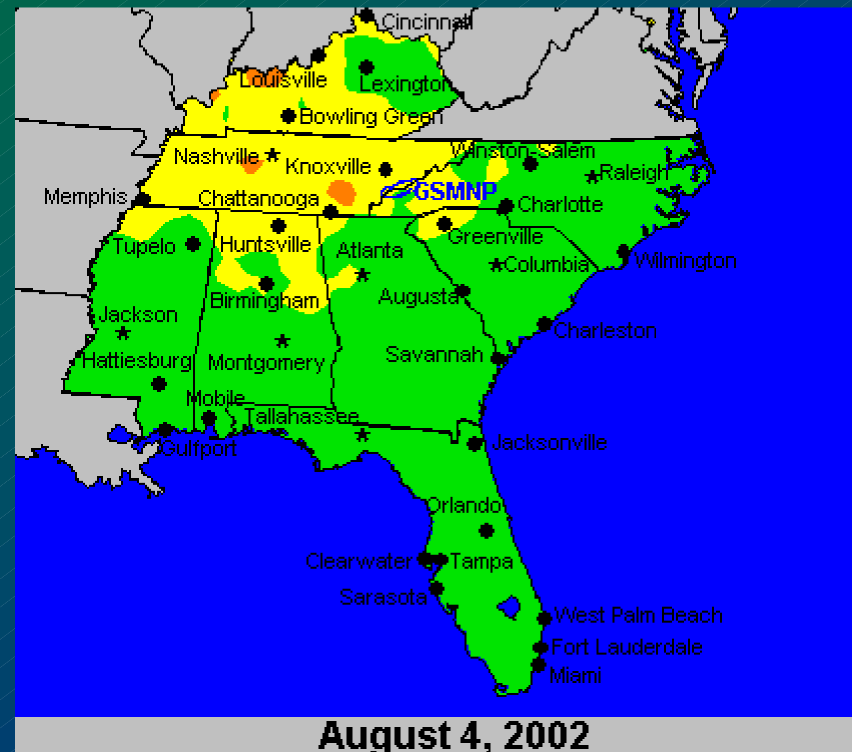




MAQSIP-RT Forecasts, 2002: SE and Alabama—Aug 2-10 SE US

- 15km SE Day 2 Fcst vs Obs: Aug 4





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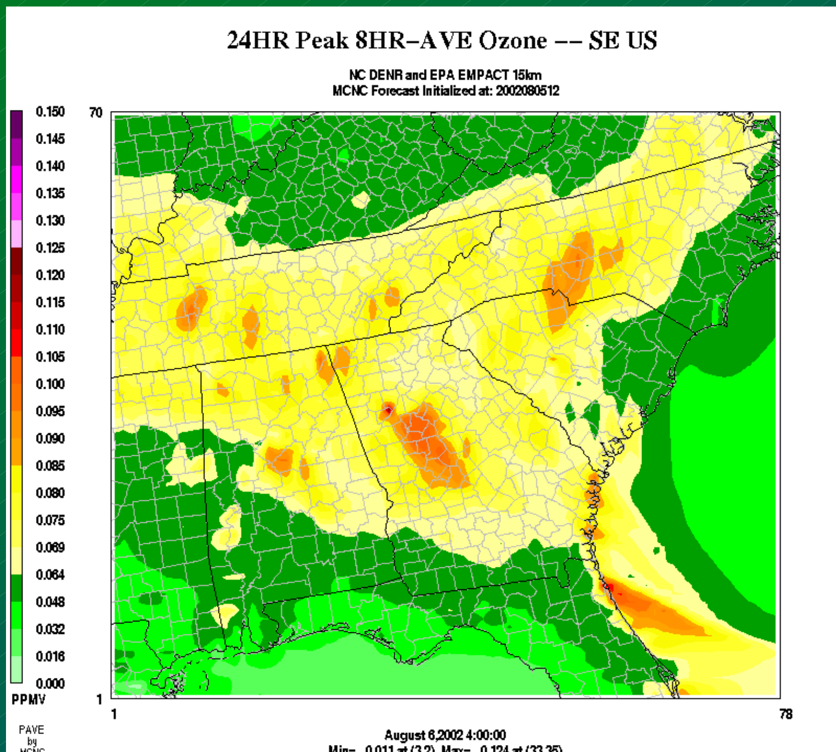
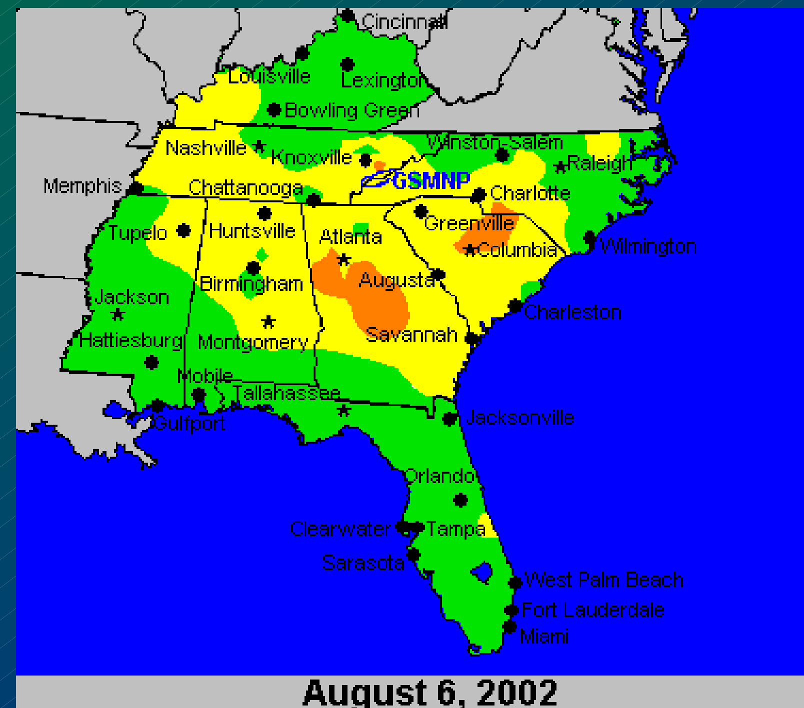
MAQSIP-RT Forecasts, 2002: SE and Alabama—Aug 2-10 SE US

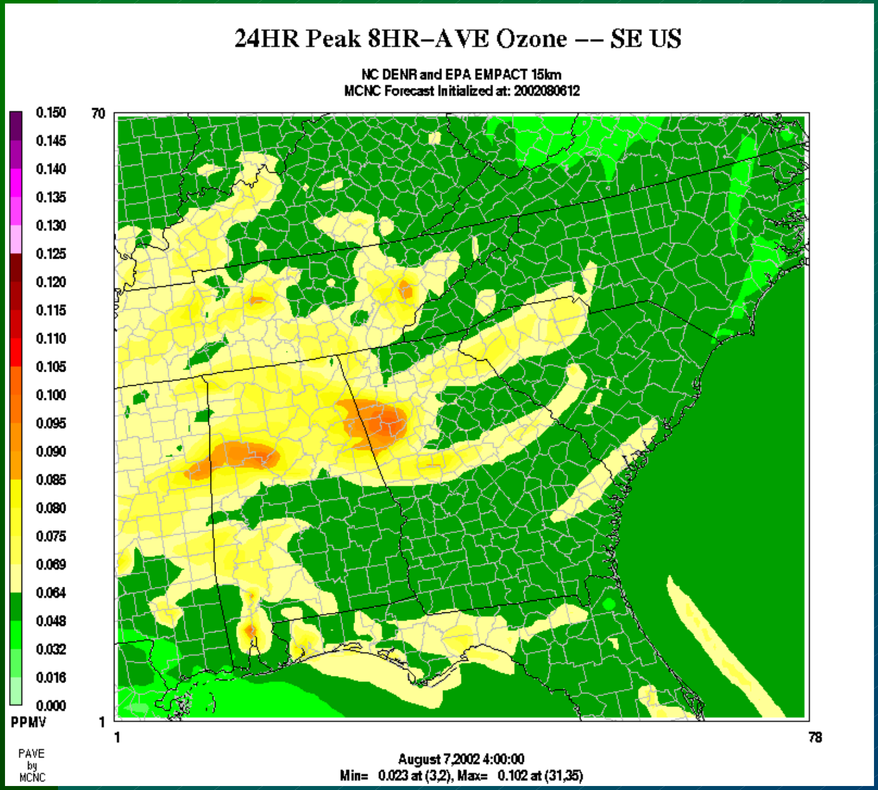
- **15km SE Day 2 Fcst vs Obs: Aug 6**

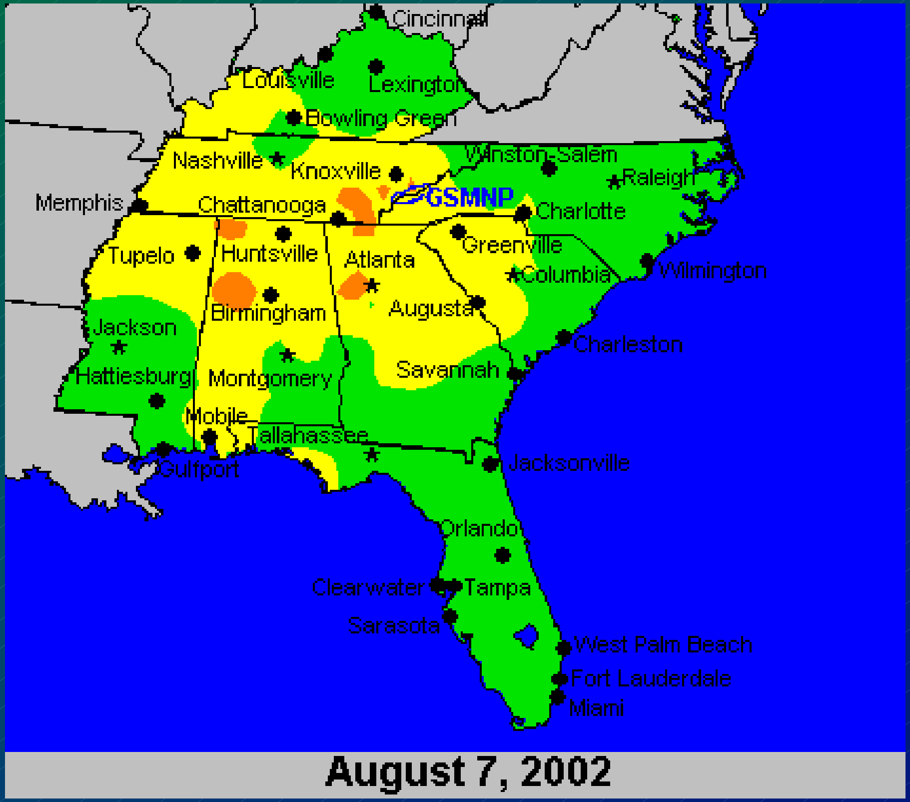




MAQSIP-RT Forecasts, 2002: SE and Alabama—Aug 2-10 SE US

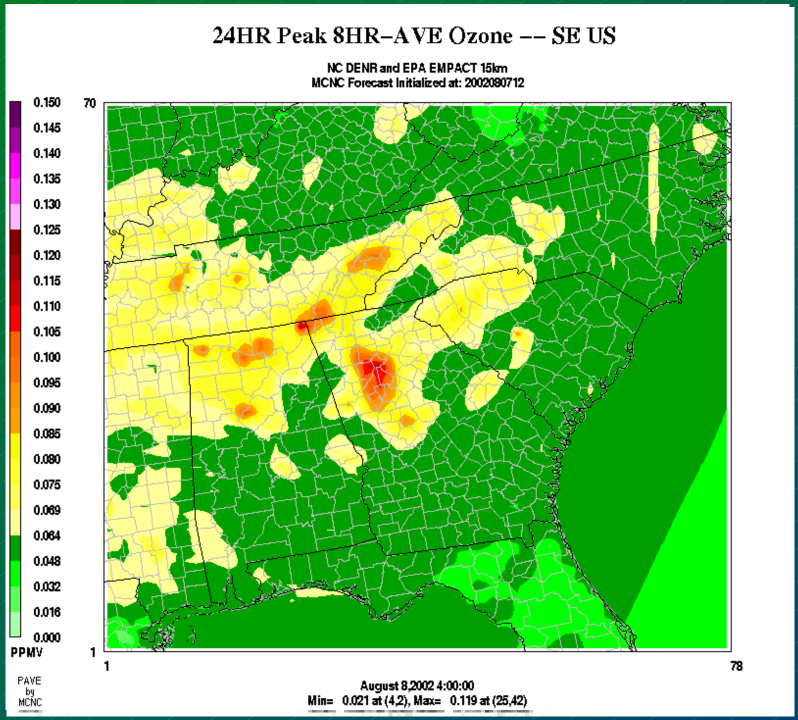
- **15km SE Day 2 Fcst vs Obs: Aug 7**

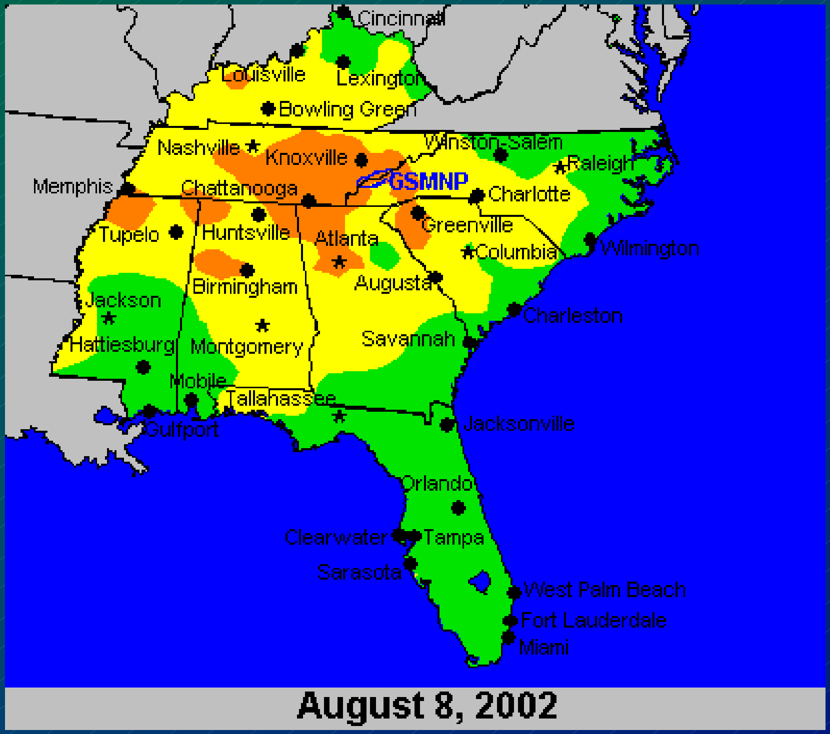




MAQSIP-RT Forecasts, 2002: SE and Alabama—Aug 2-10 SE US

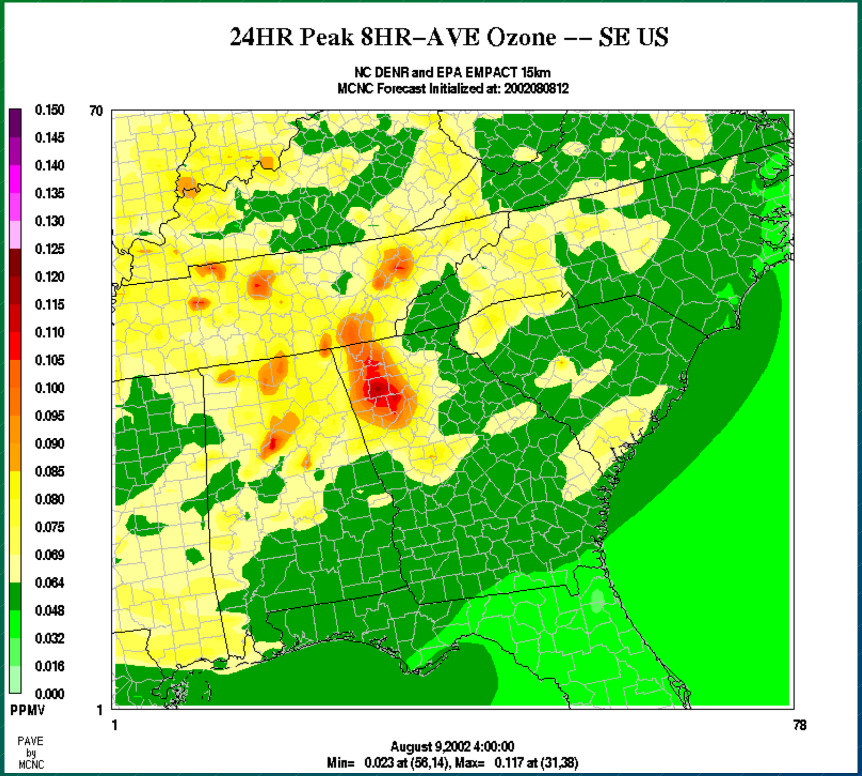
- **15km SE Day 2 Fcst vs Obs: Aug 8**

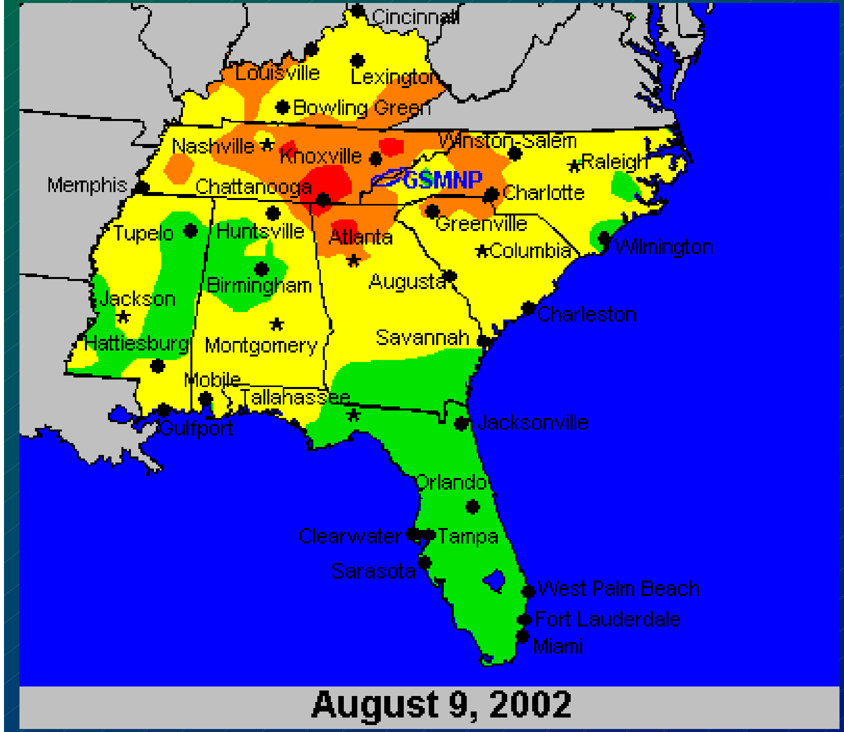




MAQSIP-RT Forecasts, 2002: SE and Alabama—Aug 2-10 SE US

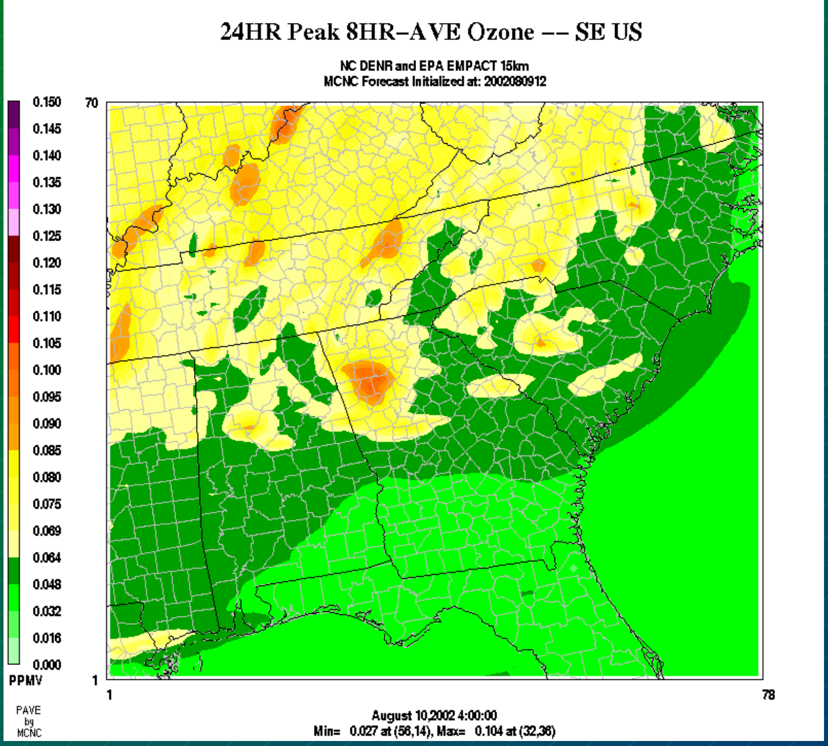
- 15km SE Day 2 Fcst vs Obs: Aug 9

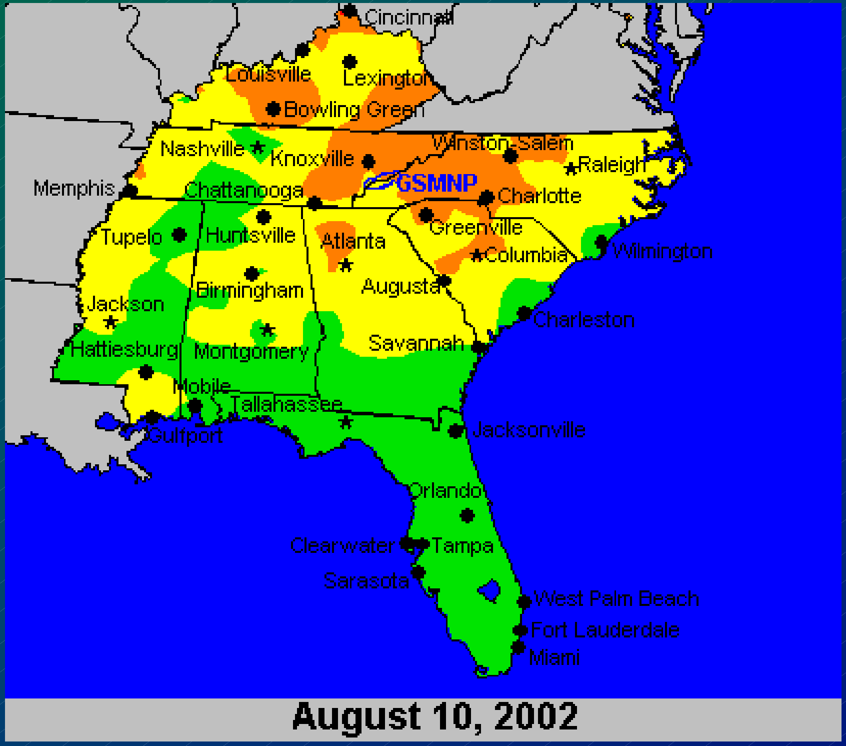




MAQSIP-RT Forecasts, 2002: SE and Alabama—Aug 2-10 SE US

- **15km SE Day 2 Fcst vs Obs: Aug 10**





		MAQSIP-RT Predictions			Regression	CART	ADEM	Observed
		1 Day	1 Day(00z)	2 Day(12z)	Equation	Tool	Published	Bham
		5km	15km	45km	Forecast	Forecast	Forecast	Peak O3
Date	Day	8hr Cat	8hr Cat	8hr Cat	8hr Cat	8hr Cat	8hr Cat	8hr Cat
6/26/2002	Wed		1		1	1	1	1
6/27/2002	Thu		1	1	1	1	1	1
6/28/2002	Fri		1	1	1	1	1	1
6/29/2002	Sat		2	2	1	1	1	1
6/30/2002	Sun		3	3	1	1	1	1
7/1/2002	Mon		4	4	2	2	2	3
7/2/2002	Tue		3	3	2	2	2	1
7/3/2002	Wed		3	3	2	2	2	2
7/4/2002	Thu	2	3	3	2	2	2	2
7/5/2002	Fri	3	4	3	2	2	3	2
7/6/2002	Sat	3	2	4	2	2	3	3
7/7/2002	Sun	2	2	2	2	2	2	2
7/8/2002	Mon	2	2	2	2	1	3	1
7/9/2002	Tue	2	2	2	2	2	2	2
7/10/2002	Wed		3	3	2	2	2	1
7/11/2002	Thu	2	2	3	2	1	2	1
7/12/2002	Fri			2	1	1	1	1
7/13/2002	Sat				1	1	1	1
7/14/2002	Sun	2	2		1	1	1	1
7/15/2002	Mon	2	3	2	1	1	1	1
7/16/2002	Tue			3	2	1	2	1
7/17/2002	Wed				1	1	2	1
7/18/2002	Thu				2	1	2	1

Green

0-64ppb

Yellow

65-88ppb

Orange

85-104ppb

Red

105-124ppb

		MAQSIP-RT Predictions			Regression	CART	ADEM	Observed
		1 Day	1 Day(00z)	2 Day(12z)	Equation	Tool	Published	Bham
		5km	15km	45km	Forecast	Forecast	Forecast	Peak O3
Date	Day	8hr Cat	8hr Cat	8hr Cat	8hr Cat	8hr Cat	8hr Cat	8hr Cat
7/19/2002	Fri				1	2	1	1
7/20/2002	Sat				1	1	1	1
7/21/2002	Sun				1	2	1	2
7/22/2002	Mon	3	3		2	2	2	2
7/23/2002	Tue	3	3	3	2	2	2	2
7/24/2002	Wed	2	3	3	2	1	2	1
7/25/2002	Thu		2	2	1	1	1	1
7/26/2002	Fri	1	2	1	1	1	1	2
7/27/2002	Sat			1	1	1	1	1
7/28/2002	Sun	1	2		1	1	2	1
7/29/2002	Mon	1	2	2	1	1	1	1
7/30/2002	Tue	2	2	2	1	1	1	1
7/31/2002	Wed	1	1	2	1	1	1	1
8/1/2002	Thu	1	2	2	1	2	1	1
8/2/2002	Fri		3	2	2	2	2	2
8/3/2002	Sat			2	2	2	3	3
8/4/2002	Sun				2	2	2	2
8/5/2002	Mon	2	2		2	3	2	1
8/6/2002	Tue			3	2	2	2	3
8/7/2002	Wed	2	2	2	2	2	3	3
8/8/2002	Thu				2	2	3	3
8/9/2002	Fri				2	2	3	2

		MAQSIP-RT Predictions			Regression	CART	ADEM	Observed
		1 Day	1 Day(00z)	2 Day(12z)	Equation	Tool	Published	Bham
		5km	15km	45km	Forecast	Forecast	Forecast	Peak O3
Date	Day	8hr Cat	8hr Cat	8hr Cat	8hr Cat	8hr Cat	8hr Cat	8hr Cat
8/10/2002	Sat			2	2	2	2	2
8/11/2002	Sun	2	2		2	2	2	2
8/12/2002	Mon			2	2	3	2	2
8/13/2002	Tue				2	2	2	2
8/14/2002	Wed				1	1	1	1
8/15/2002	Thu				1	1	1	1
8/16/2002	Fri				1	1	1	1
8/17/2002	Sat				1	1	1	1
8/18/2002	Sun				1	1	1	1
8/19/2002	Mon	1	2		1	1	1	1
8/20/2002	Tue	2	2	2	1	2	1	1
8/21/2002	Wed	2	3	3	1	2	2	3
8/22/2002	Thu	2	2	2	2	2	2	1
8/23/2002	Fri	1	2	1	1	1	1	2
8/24/2002	Sat			2	1	1	2	2
8/25/2002	Sun	2	2		1	1	2	1
8/26/2002	Mon	2	2	2	1	2	2	2
8/27/2002	Tue	2	2	3	2	2	2	2
8/28/2002	Wed	2	2	3	2	2	2	2
8/29/2002	Thu	2	2	2	2	2	2	1
8/30/2002	Fri	1	1	1	1	1	1	1
8/31/2002	Sat			1	1	1	1	1

Performance of Tools Used to Predict Maximum One-Hour-Average Ozone Concentrations in the Greater Birmingham Area

June 26 - August 31, 2002

Forecast Tool	Bias*	Std. Error*	Absolute Error*	Valid Values (%)	Missing Values (%)
MAQSIP-RT (5 km)	0.31	0.12	0.56	48	52
MAQSIP-RT (15 km)	0.72	0.12	0.81	64	36
MAQSIP-RT (45 km)	0.64	0.20	0.82	66	34
Regression	-0.04	0.08	0.34	100	0
CART	0.00	0.07	0.30	100	0
ADEM Published	0.15	0.07	0.33	100	0

*Number of AQI categories (positive values indicate overprediction)

Need for Data Assimilation

•Fundamental problem in air quality forecasting is the lack of complete three-dimensional chemical data to initialize model.

•Even if some data are available (such as surface ozone) it is not clear how to balance the chemical system with this data.

•Most current methods simply re-initialize meteorology but keep chemistry on the grid from previous forecasts.

•Unless ozone is totally dominated by short term production cannot afford to continue to forecast without some connection to reality or forecast errors (in the chemistry) will continue to grow.

•One partial solution to this dilemma is to try to minimize forecast errors in the chemistry through a physical data assimilation pre-forecast period

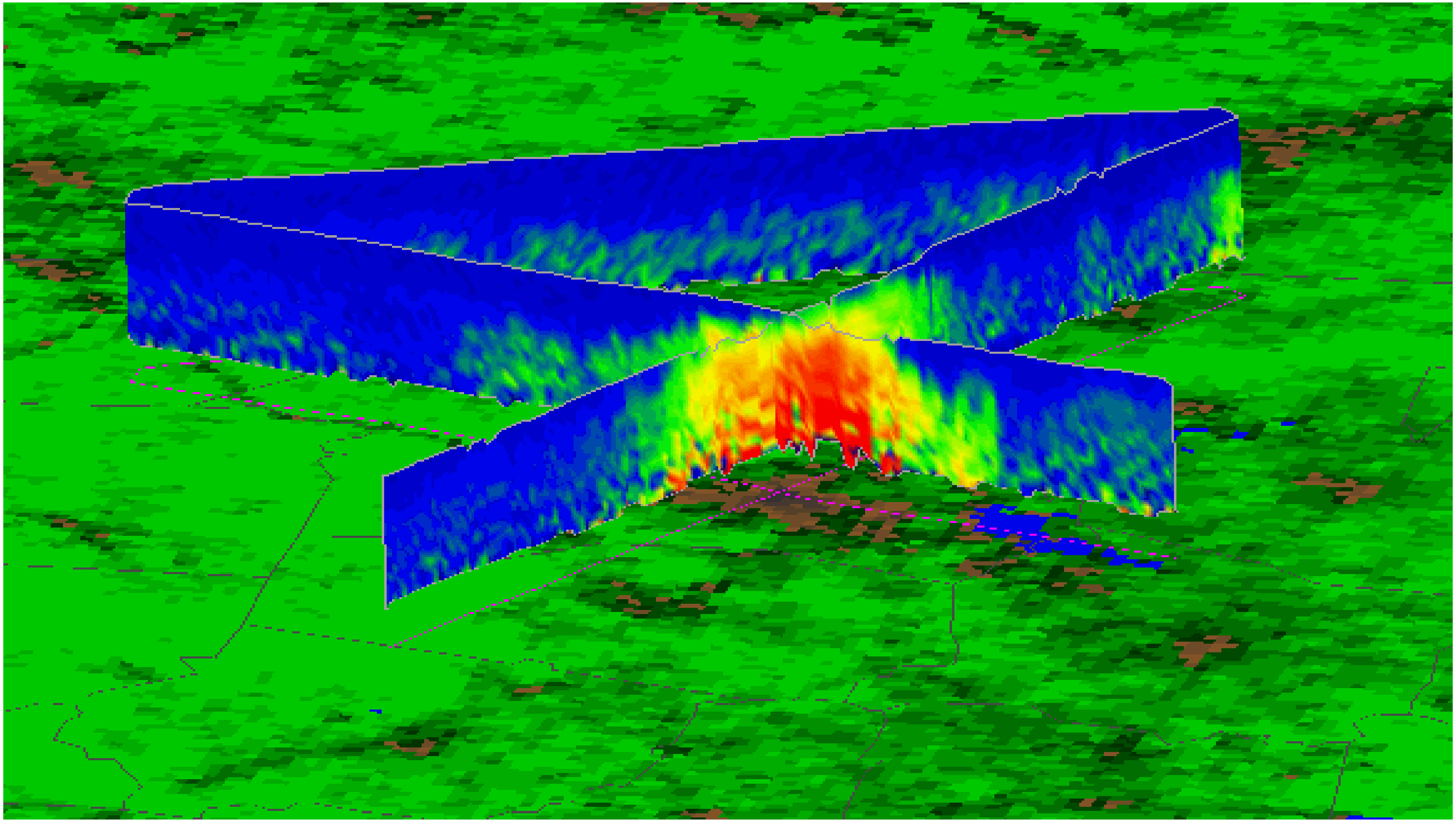
•The strategy would be to use all available physical observations from the previous day to constrain the physical atmosphere to be as close as possible to reality.

•The chemical forecast would be redone with this new physical atmosphere. This new chemical state would be used as the chemical initial conditions for the next forecast period.

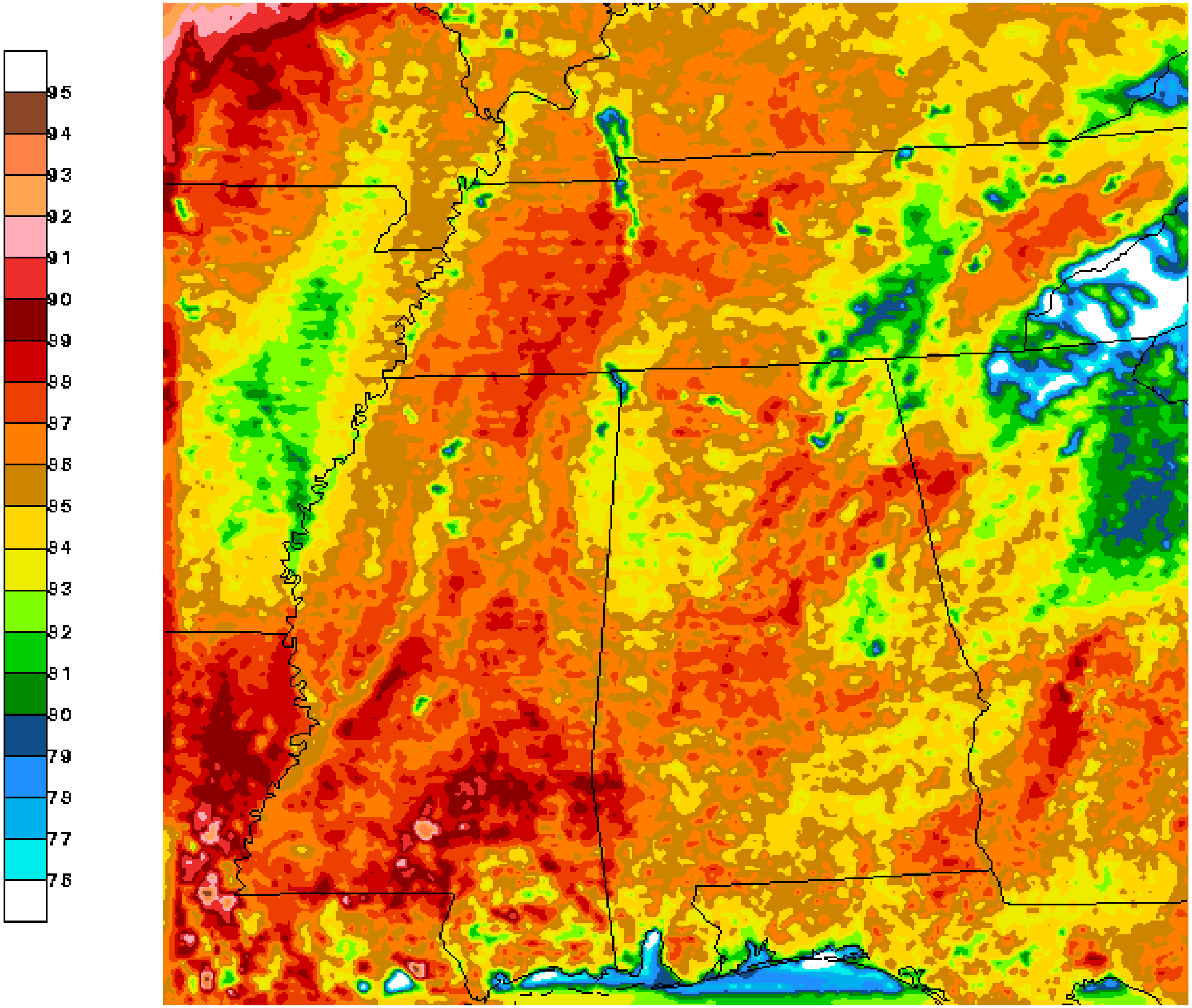
•Hopefully, this will minimize the chemical errors

The following describes a series of satellite data assimilation steps that we have developed to improve the physical atmosphere in a posteriori mode which we believe can be used in the forecast problem.

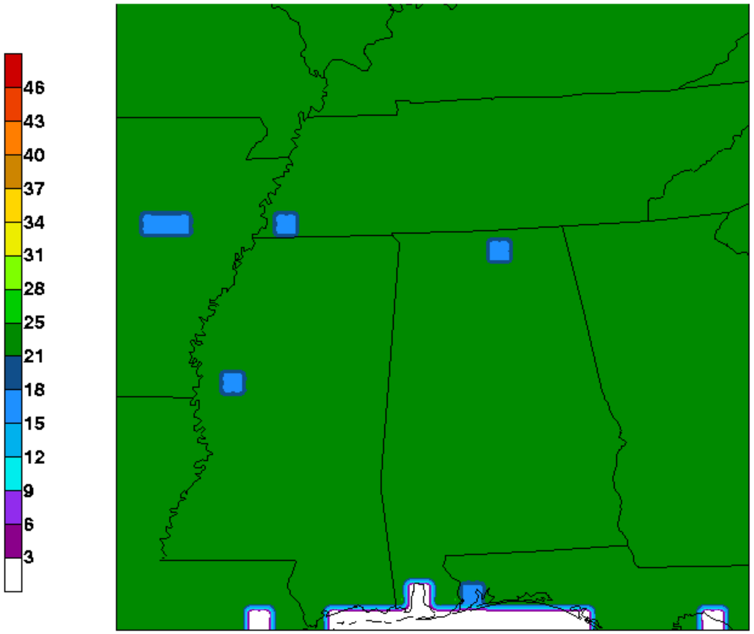
Physical models too smooth. May be due lack of forcing on small scales. Traditional meteorological data sources cannot provide mesoscale information. Satellites have potential to provide this data.



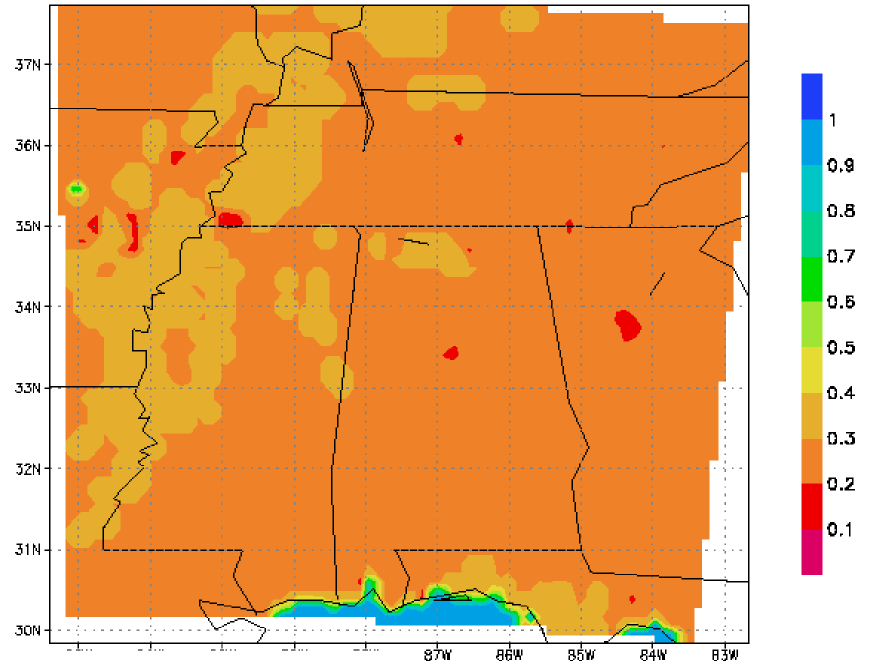
Surface Skin Temperature - September 12, 2002

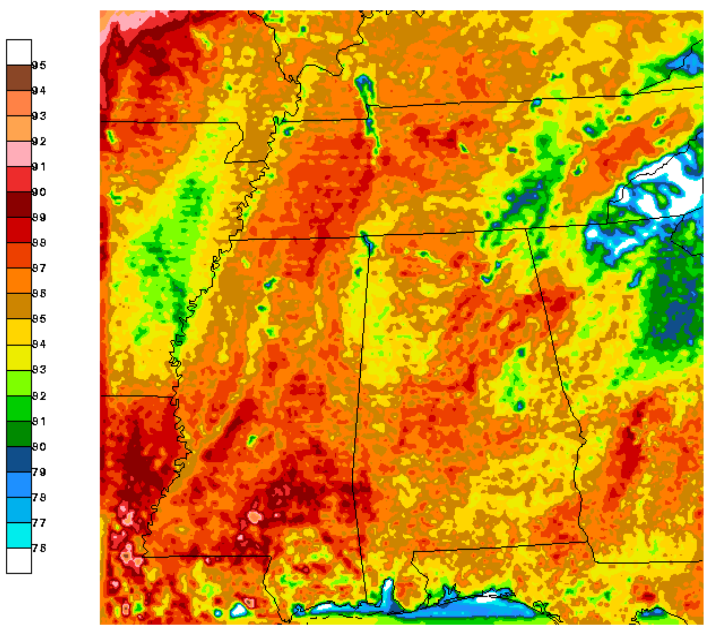


MM5 Landuse Heat Capacity

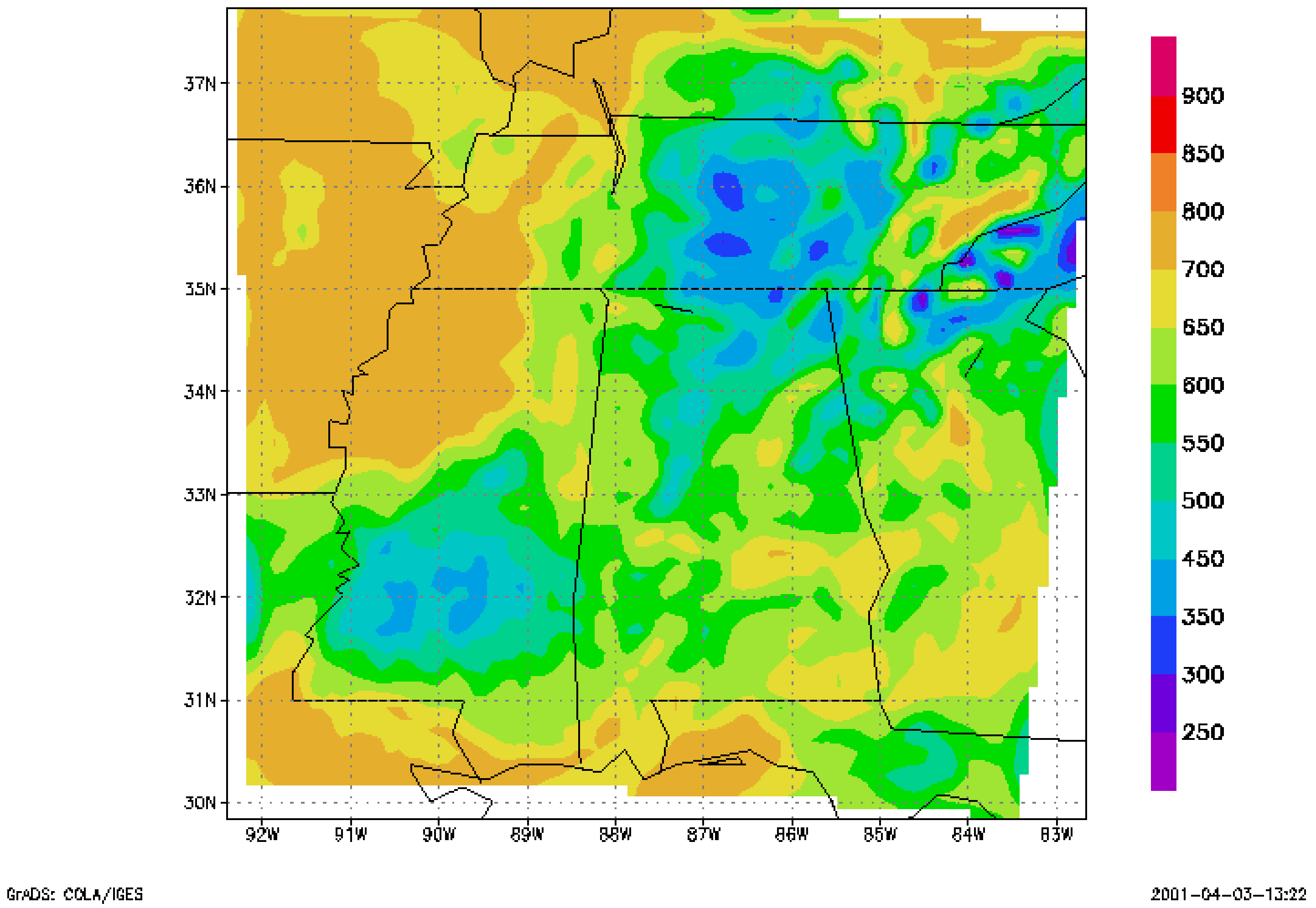


MM5 Landuse Moisture Availability

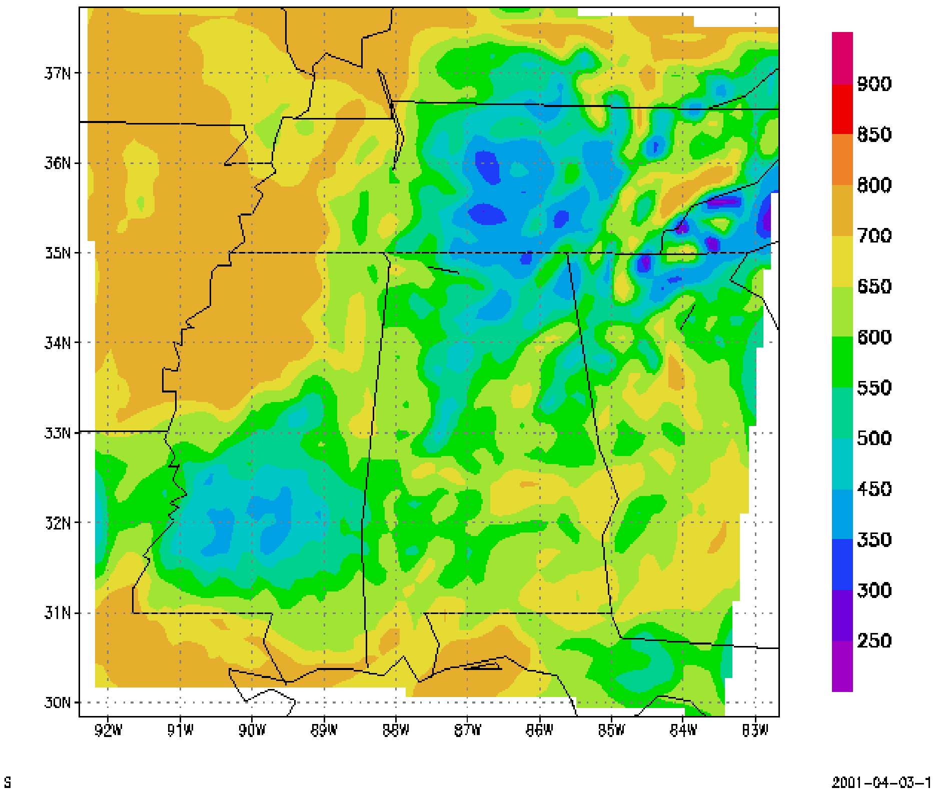




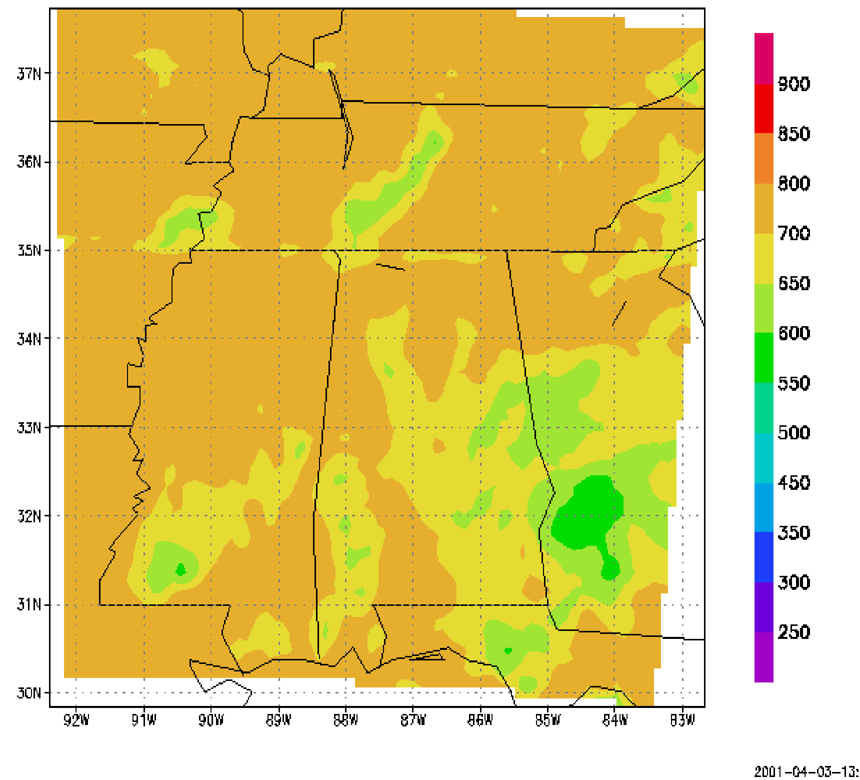
Short-wave Model Control –July 15 18Z



Short-wave Model July 15 18Z

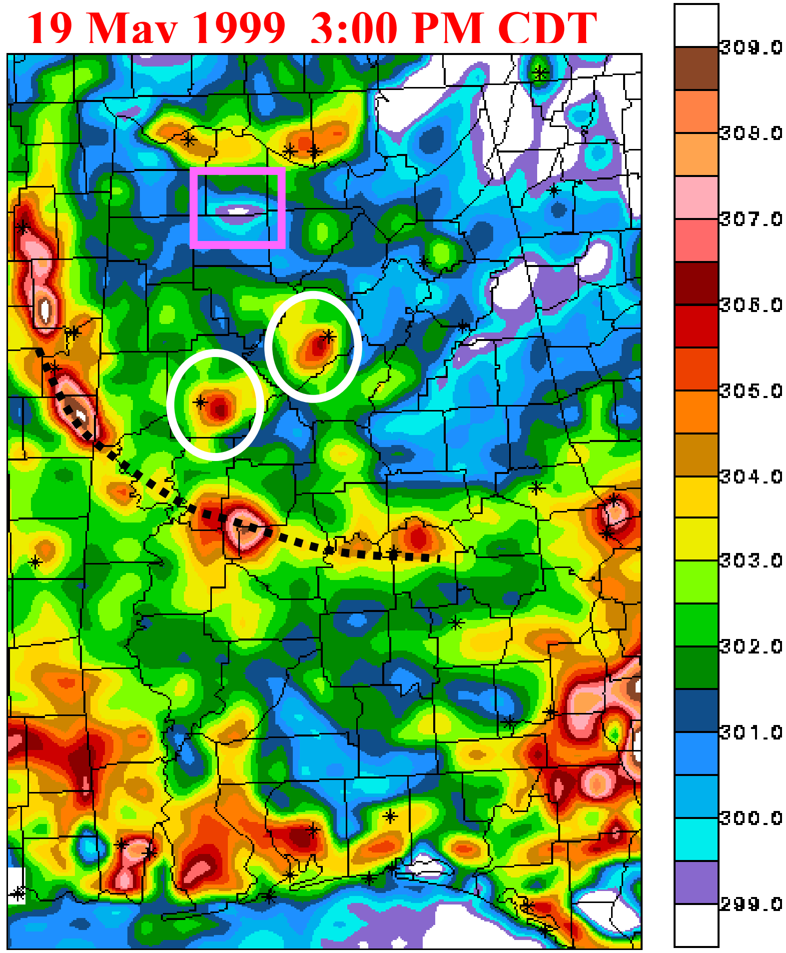


Short-Wave Satellite July 15 18Z



AVHRR

GOES-8 Skin Temperature
19 Mav 1999 3:00 PM CDT



Appealing attributes of GOES data:

* High sampling frequency
* High spatial resolution
* Pixels provide an integral quantity

Surface Energy Budget

Two Uncertain Parameters

$$C_b\left(\frac{dT_G}{dt}\right) = \left(R_N + H + G\right) + E$$

Bulk Heat Capacity

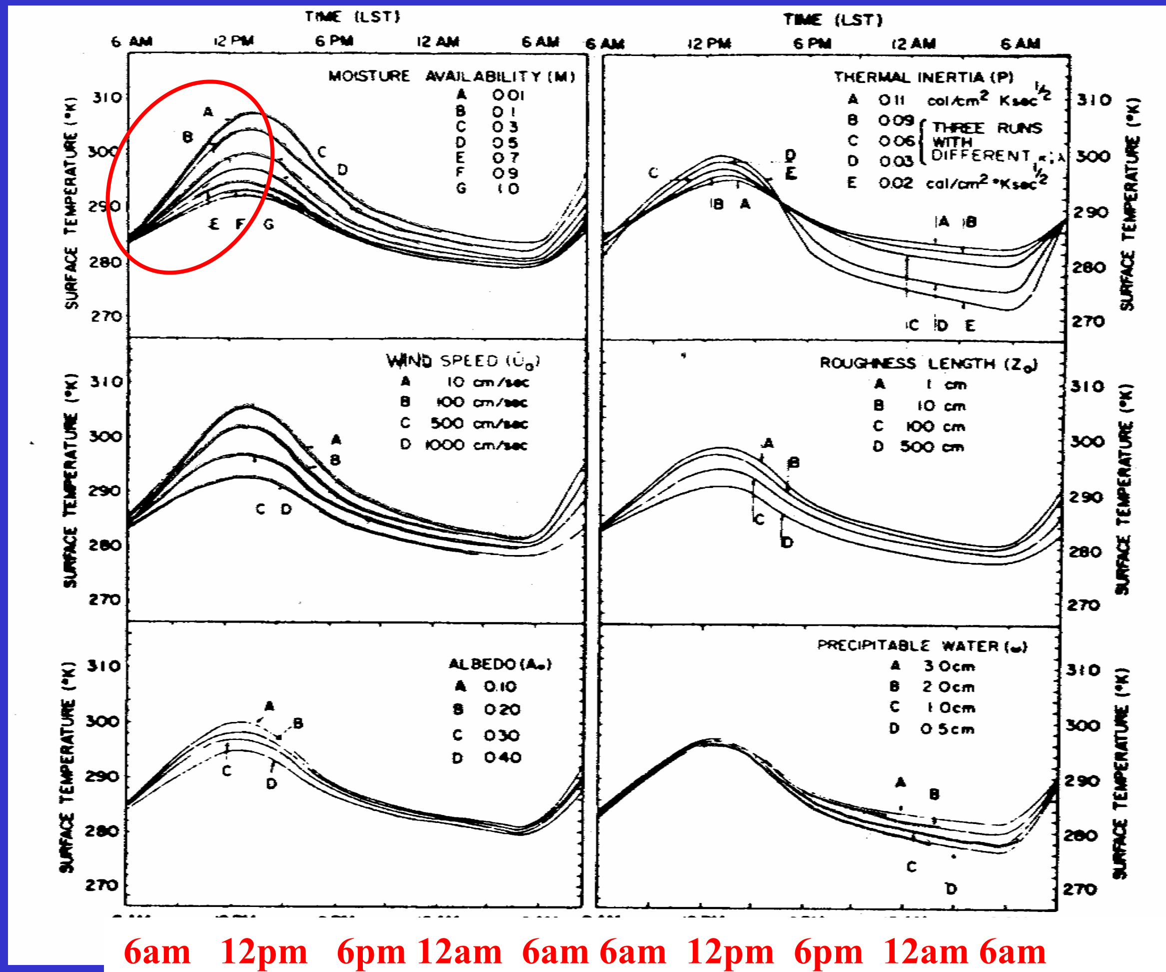
Evaporative Heat Flux

Sensitivity of Surface Energy Budget to Various Parameters

Moisture Availability

Wind Speed

Albedo



Thermal Inertia

Roughness Length

Precipitable Water

Fig. 1. Taken from Carlson (1986) to demonstrate the sensitivity of the surface energy budget model. Each panel represents the sensitivity of the simulated LST to uncertainty in a given parameter

Determining Moisture Availability from Satellite Skin Temperature Tendencies

McNider et al. 1995 *Mon.Wea.Rev applied to MM5 by Lapenta*

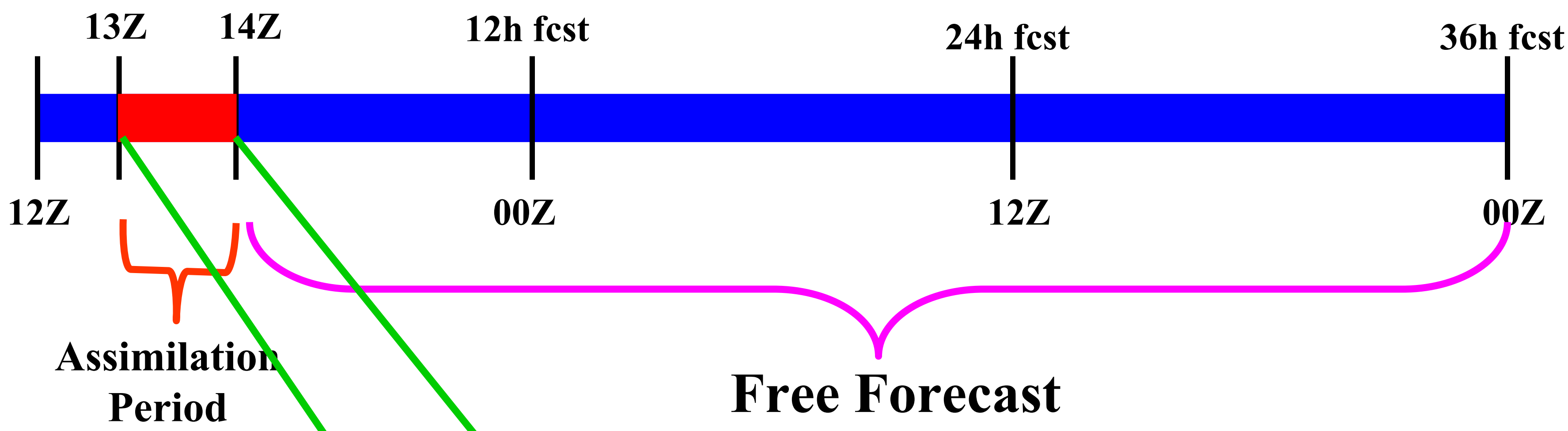
Model Energy Budget $\longrightarrow$ $$C_{b_m}\left(\frac{dT_G}{dt}\right)_m = \left(R_N + H + G\right)_m + E_m$$

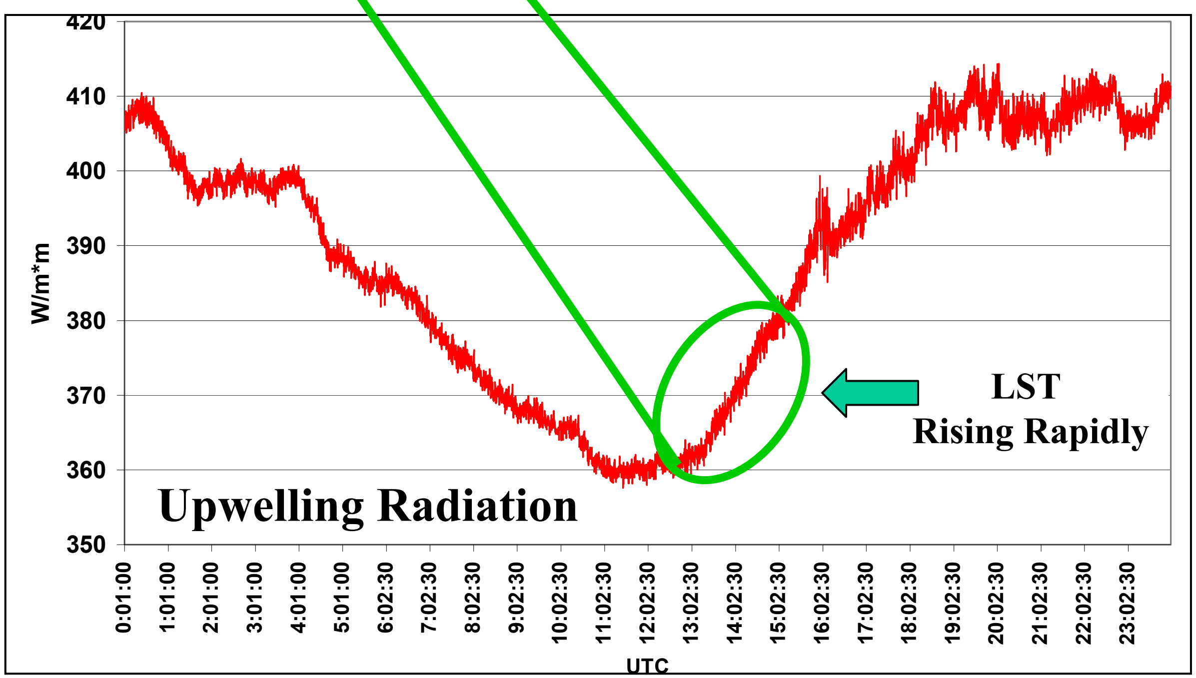
Satellite Energy Budget $\longrightarrow$ $$C_{b_s}\left(\frac{dT_G}{dt}\right)_s = \left(R_N + H + G\right)_s + E_s$$

$$E_s = C_b\left[\left(\frac{dT_G}{dt}\right)_s - \left(\frac{dT_G}{dt}\right)_m\right] + E_m$$

Derived Moisture Availability $\longrightarrow$ $$M_s = E_s \frac{\ln\left(\frac{ku_* z_a}{k_a} + \frac{z_a}{z_l}\right) - \varphi_h}{\rho k u_* \left(q_{sfc}\left(T_g\right) - q_a\right)}$$

*Assimilation performed between 1300-1400 UTC



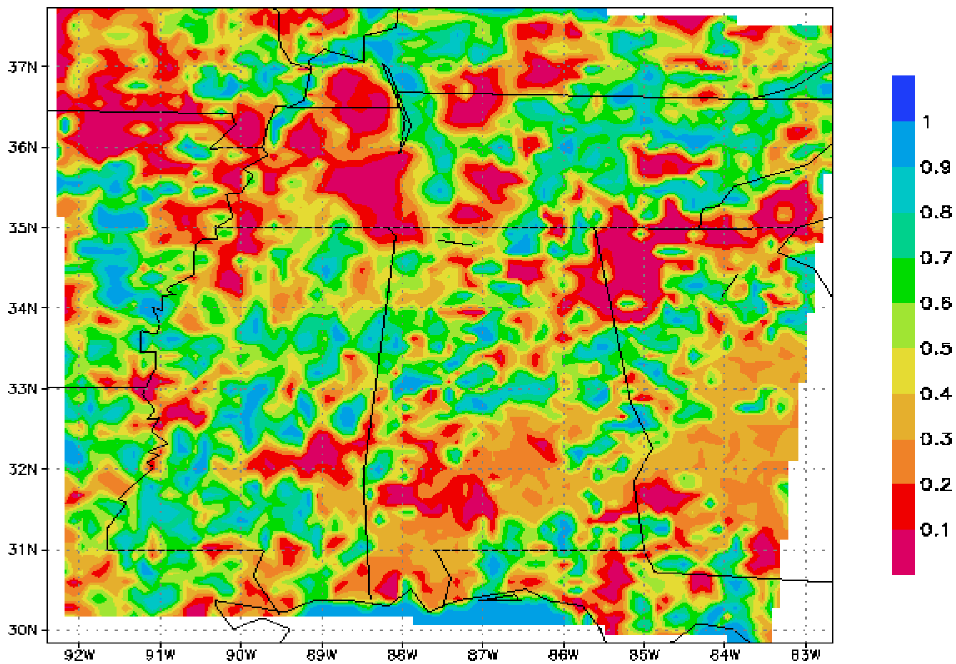


Assimilate:

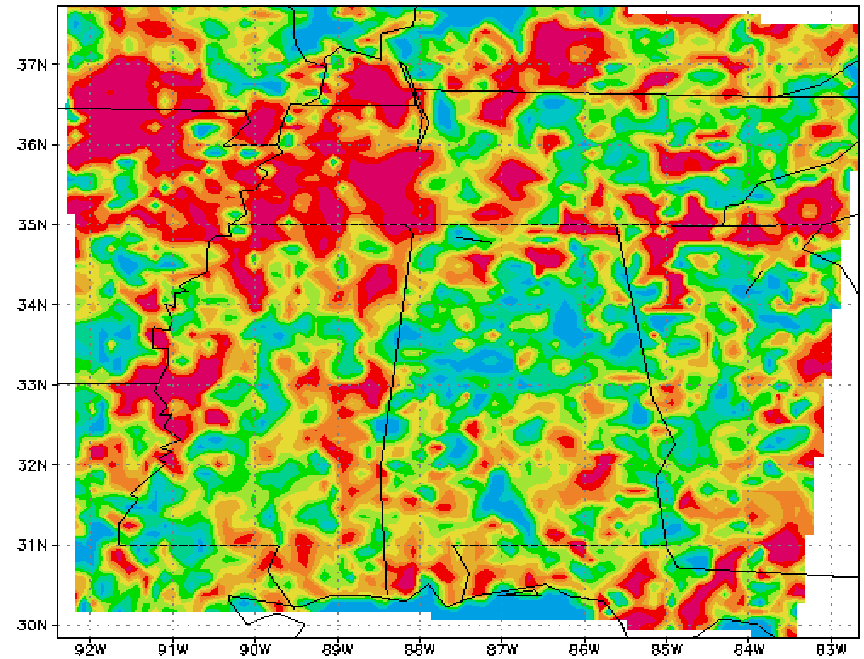
*Land Surface Temperature Tendencies computed from hourly images.

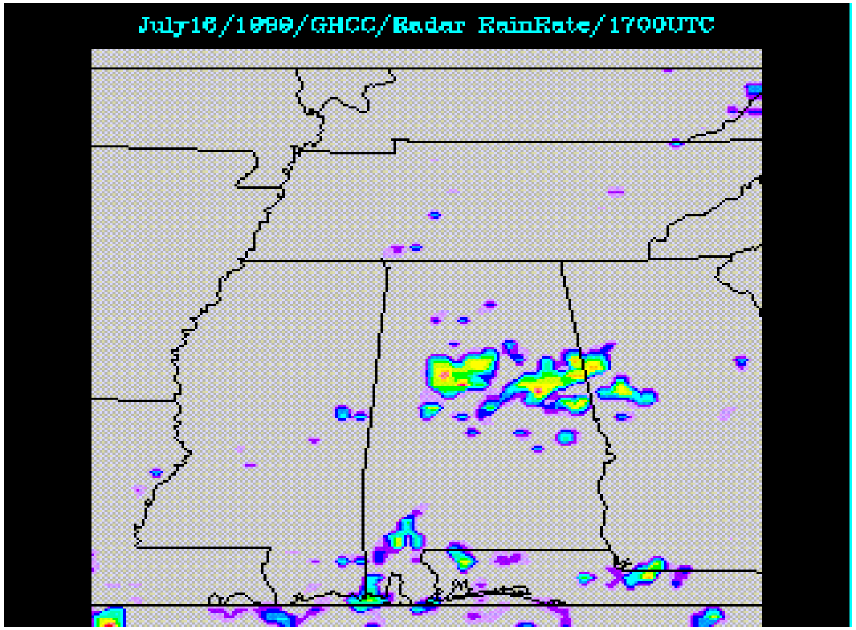
*Solar insolation

July 16



July 17



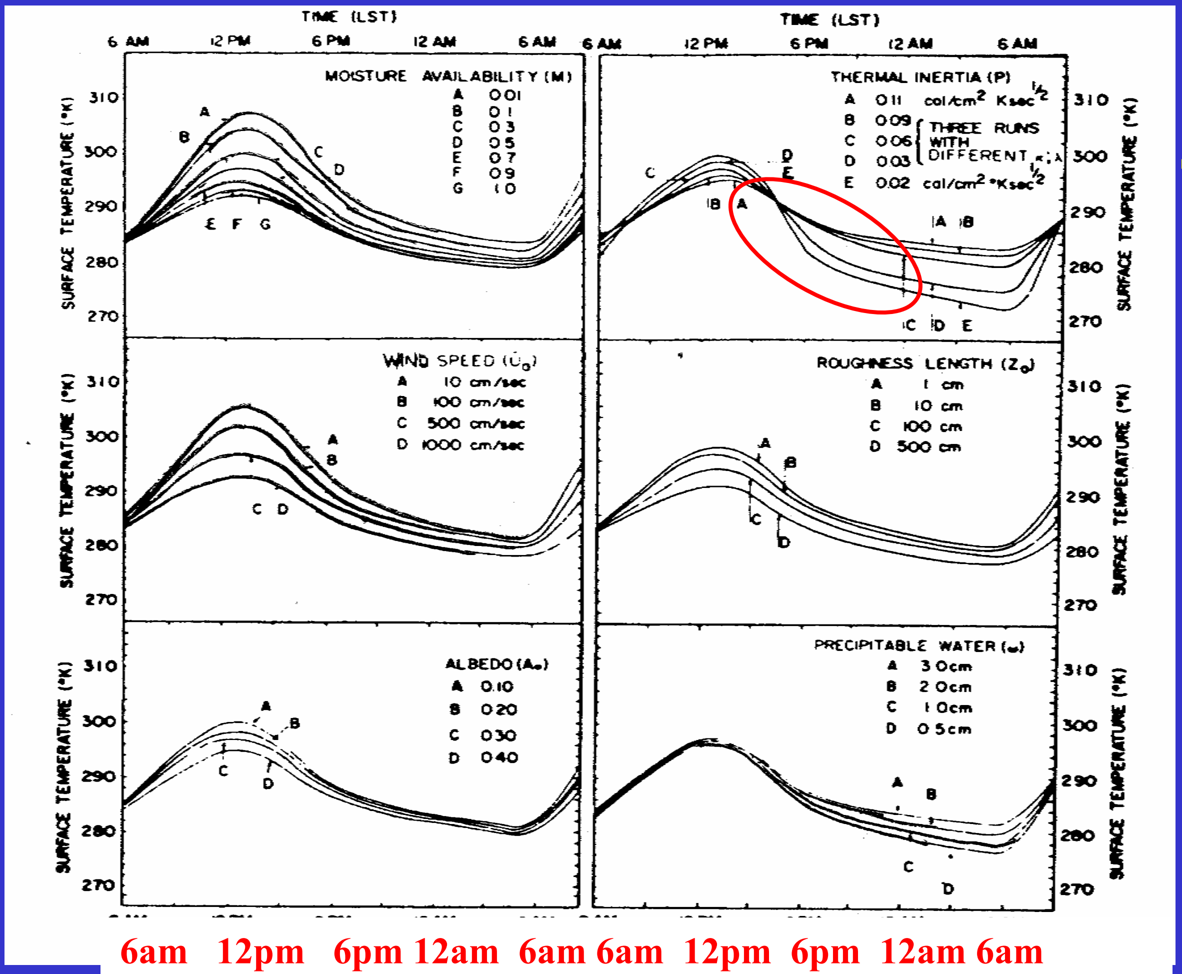


Sensitivity of Surface Energy Budget to Various Parameters

Moisture Availability

Wind Speed

Albedo



Thermal Inertia

Roughness Length

Precipitable Water

Fig. 1. Taken from Carlson (1986) to demonstrate the sensitivity of the surface energy budget model. Each panel represents the sensitivity of the simulated LST to uncertainty in a given parameter

Determining Bulk Heat Capacity

Model Energy Budget → $C_{b_m}\left(\frac{dT_G}{dt}\right)_m = \left(R_N + H + G\right)_m + E_m$

Satellite Energy Budget → $C_{b_s}\left(\frac{dT_G}{dt}\right)_s = \left(R_N + H + G\right)_s + E_s$

Derived Heat Capacity → $C_{bs} = C_{bm}\left(\frac{dT_G}{dt}\right)_m / \left(\frac{dT_G}{dt}\right)_s$

Evening Skin Tendencies

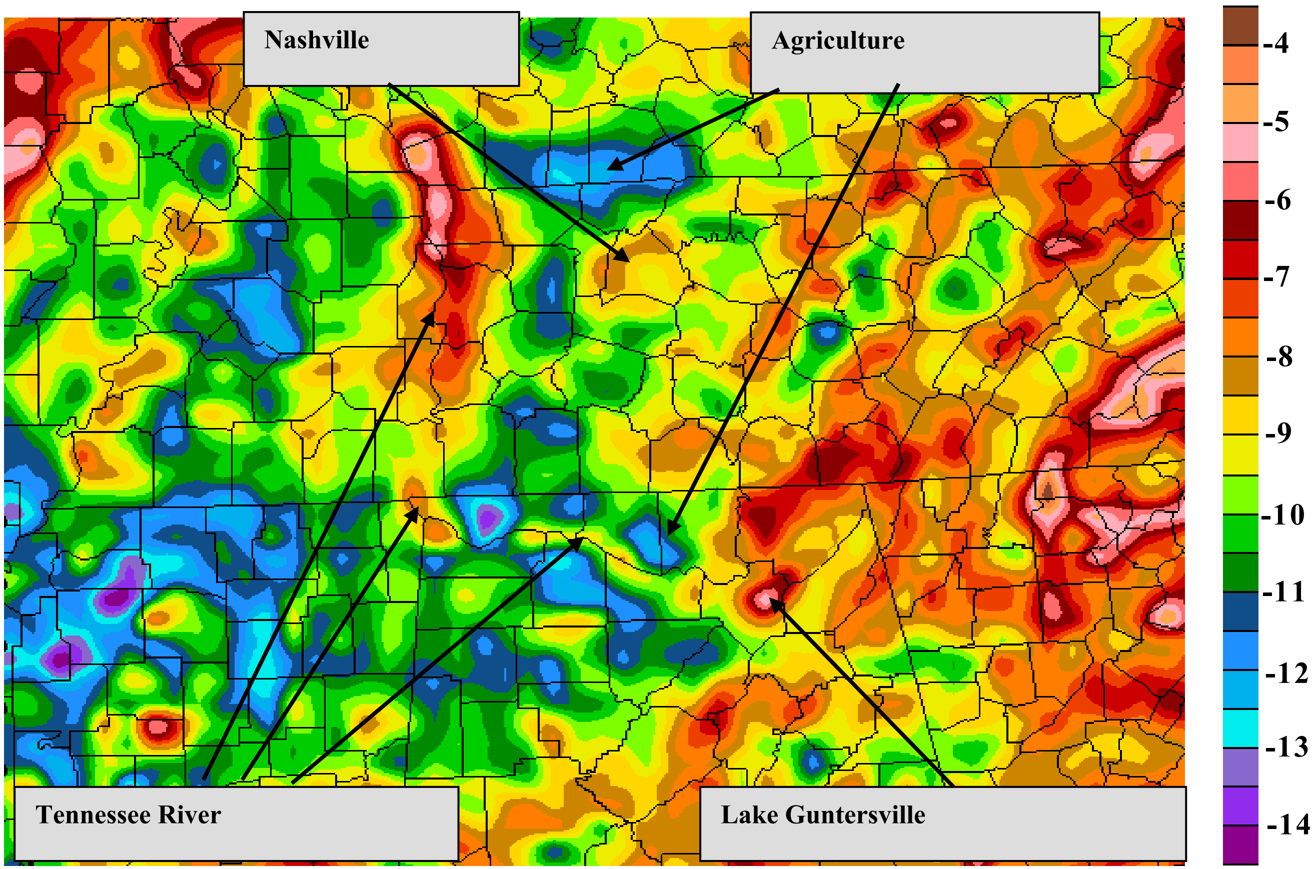
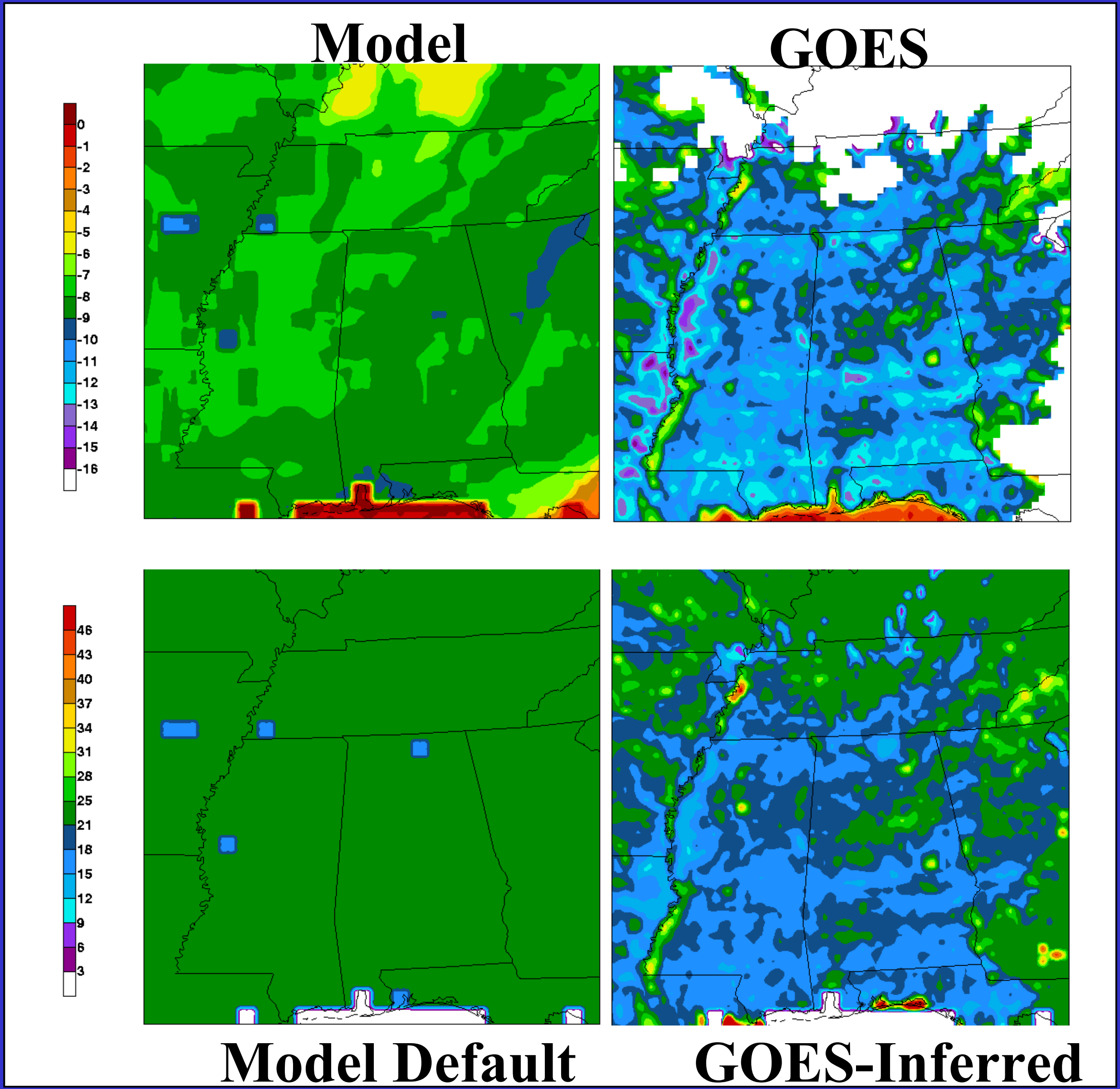


Fig. 4. ***Evening GOES imager derived LST tendency for the three-our period ending 0045 UTC 20 Sept. 2000 (K 3h^{-1}). The 4-km pixel data have been spatially averaged to ı [illegible]-km model grid.***

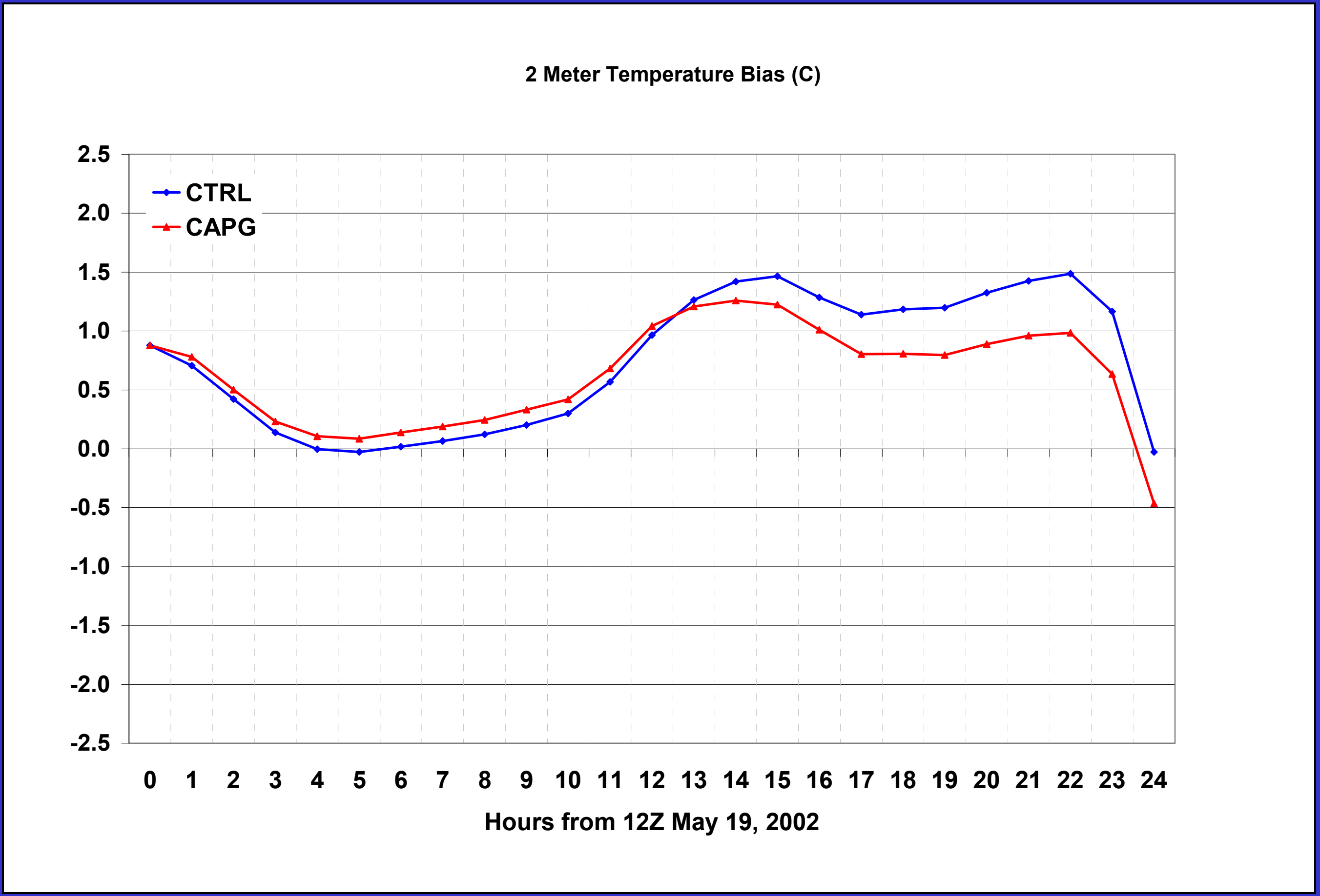
GOES-Inferred Heat Capacity

Temperature Tendency
May 19,2002
22 UTC to 02 UTC
(4-hours)

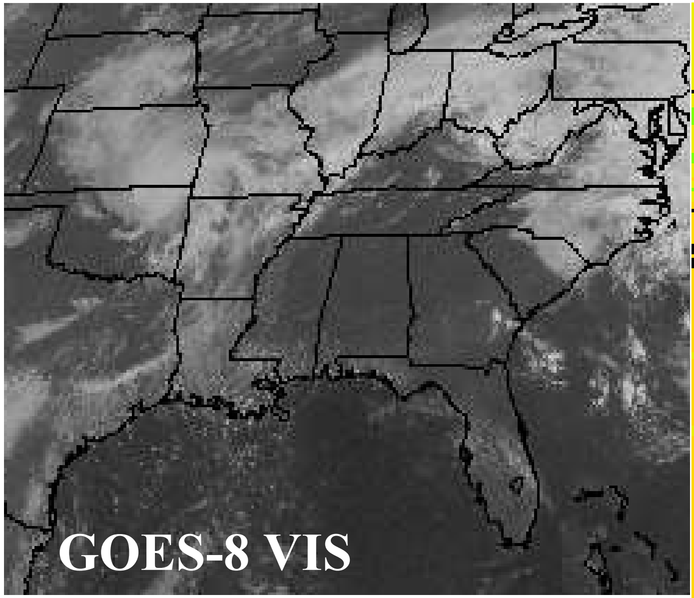
Heat Capacity

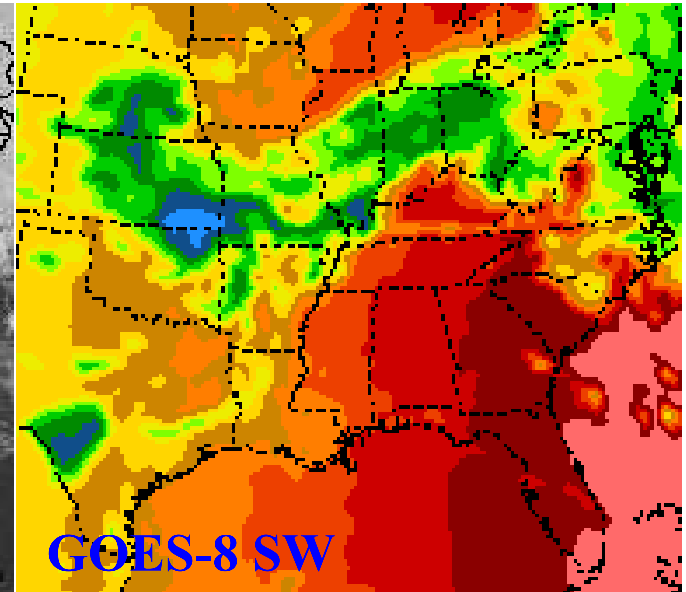


Results from 1'st Attempt



Insolation/Cloud Treatment





Clear Sky

GOES SW↓ used in R_N

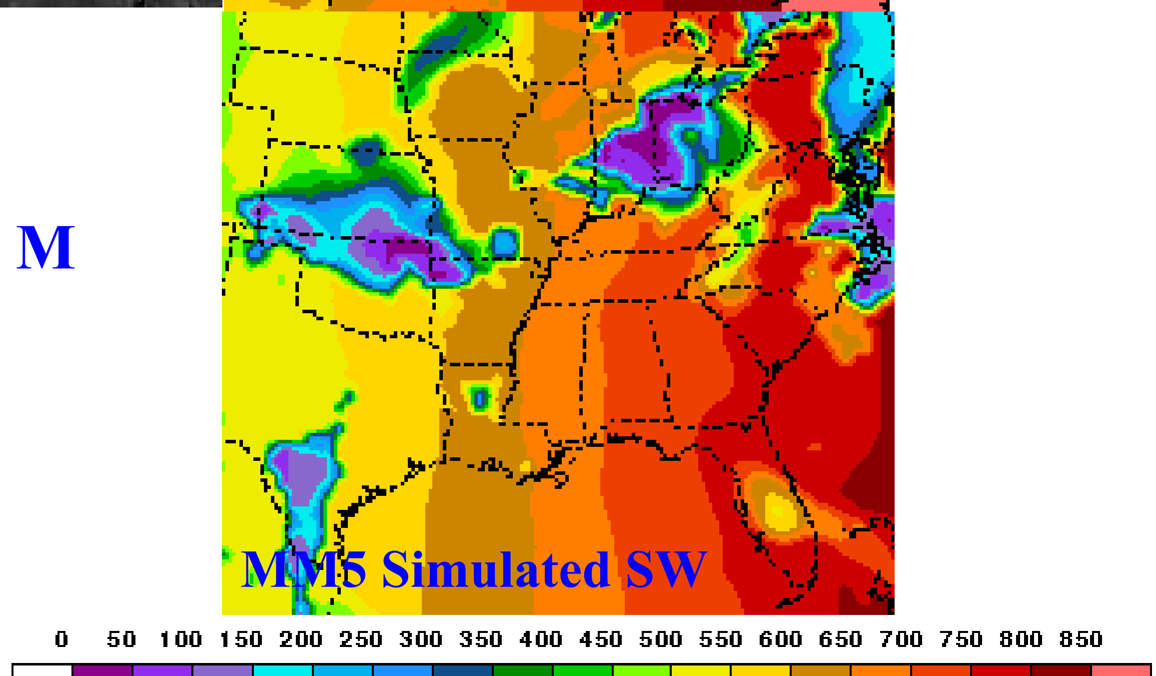
GOES $\frac{\partial T_g}{\partial t}$ used to adjust M

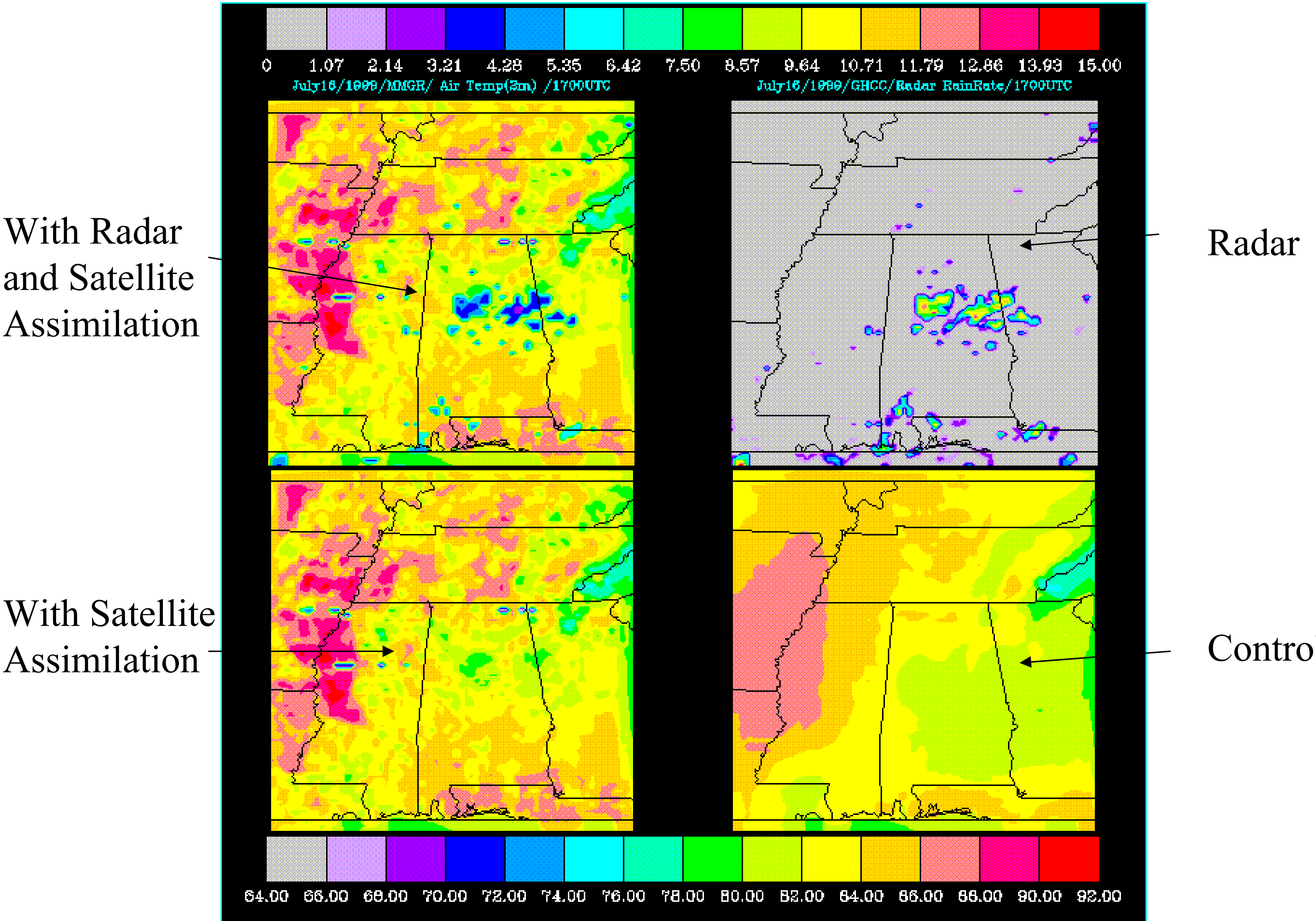
Cloudy Sky

Model SW↓ used in R_N

Model $\frac{\partial T_g}{\partial t}$ used

no adjustment in M





0 1.07 2.14 3.21 4.28 5.35 6.42 7.50 8.57 9.64 10.71 11.79 12.86 13.93 15.00
July16/1999/MMGR/ Air Temp(2m) /1700UTC
July16/1999/GHCC/Radar RainRate/1700UTC
With Radar and Satellite Assimilation
Radar
With Satellite Assimilation
Control
64.00 66.00 68.00 70.00 72.00 74.00 76.00 78.00 80.00 82.00 84.00 86.00 88.00 90.00 92.00

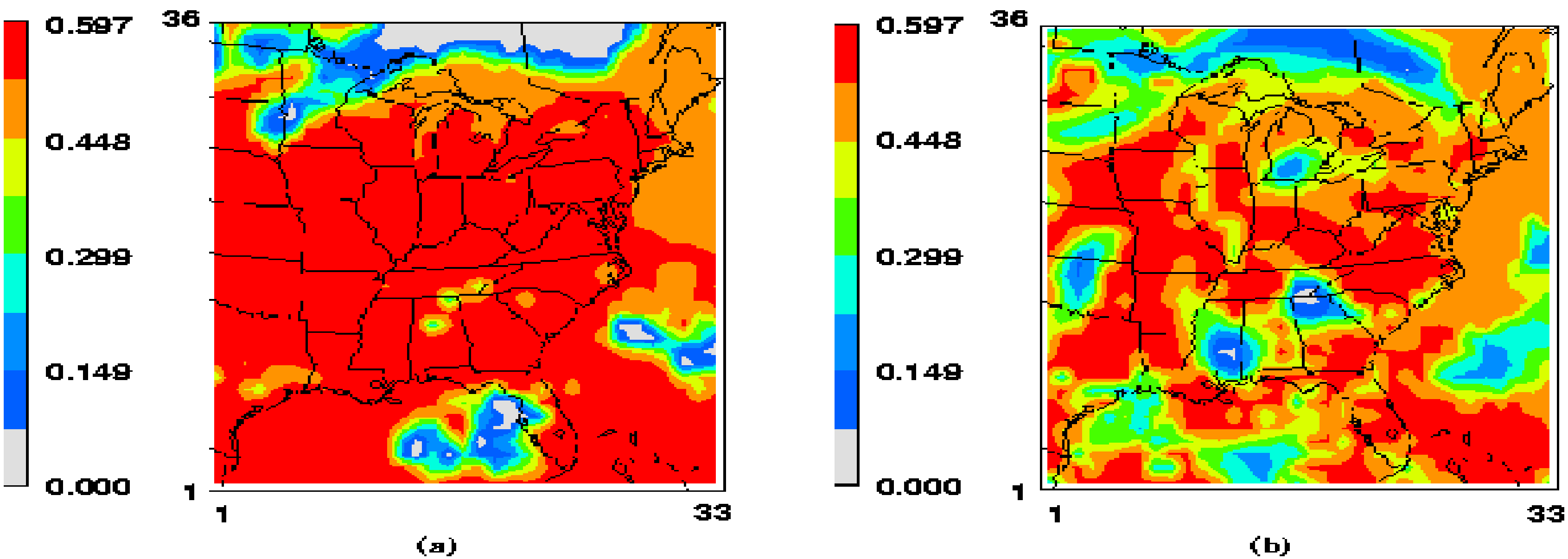
SOUTHERN OXIDANTS STUDY

Atmospheric Physics/Dynamics

Satellite Assimilation of Clouds → **Photolysis Rates First Order Effect**

JNO_2

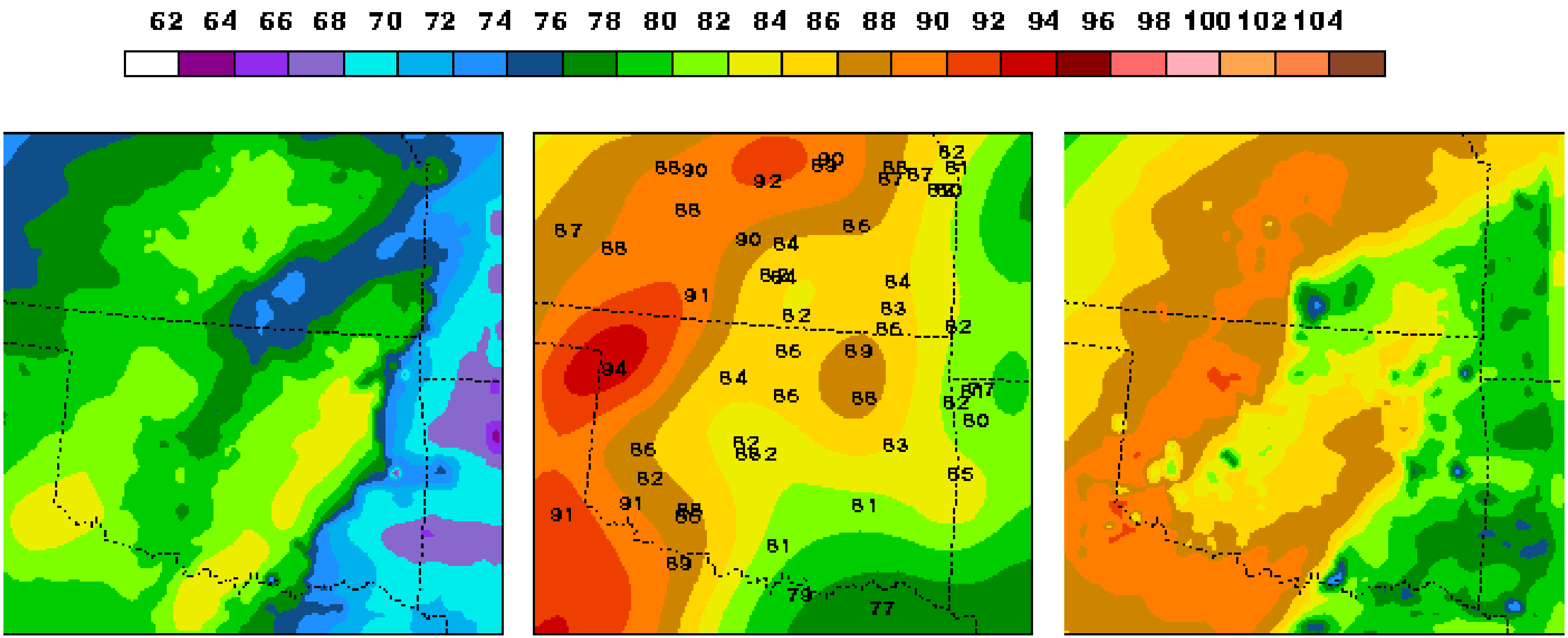
Satellite **Model**



Numerical Simulation of 2 Meter Air Temperature (°F)

5 April 2000

9 hour Forecast Valid 2100 UTC



Control
No Assimilation

Analysis of Observations

Assimilation

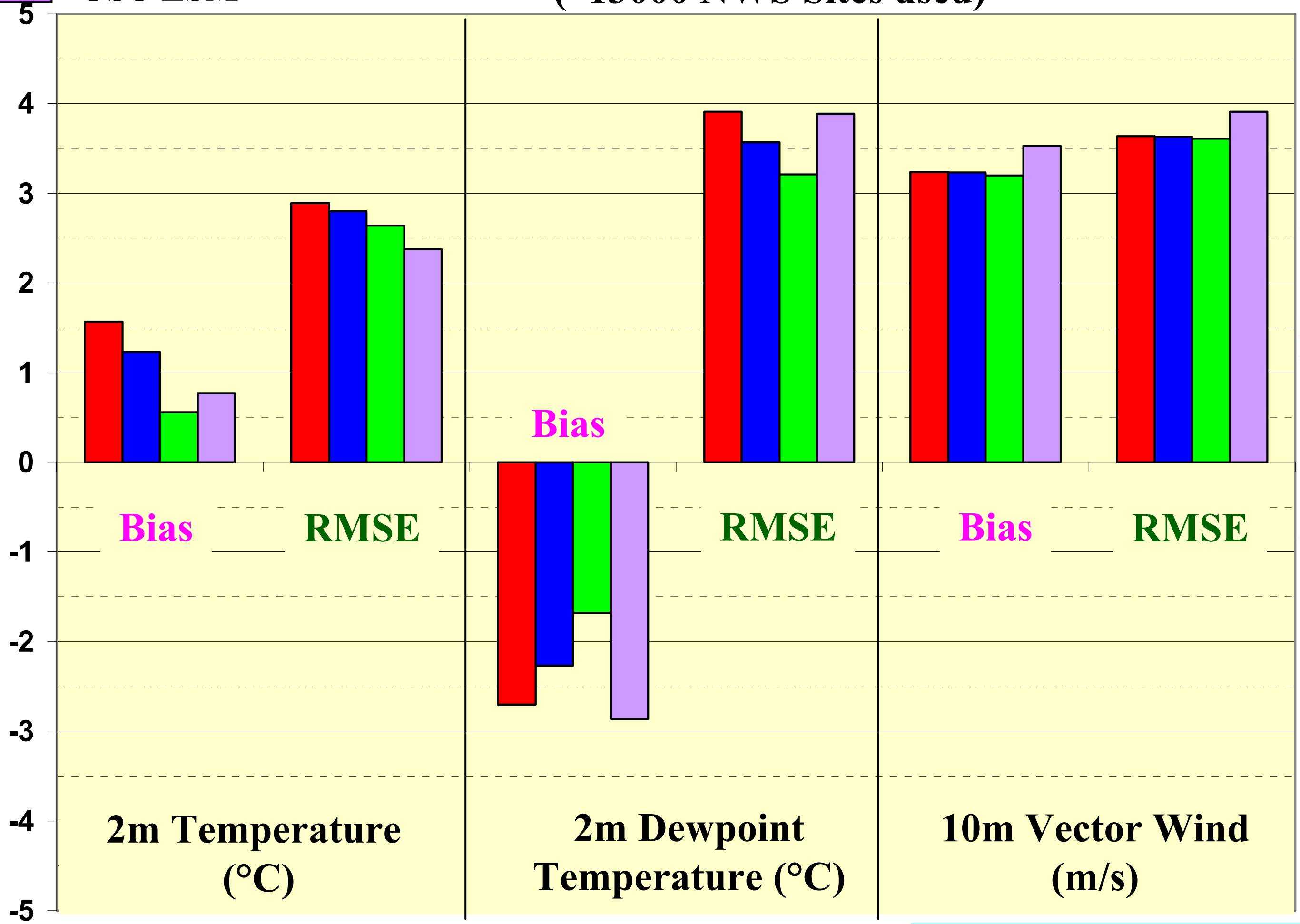
Bulk Verification Statistics

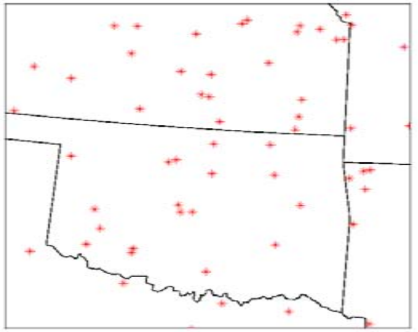
04 to 12h Forecasts

Accumulated for 26 Days

(~13000 NWS Sites used)

Control
1 HourAssim
Recycle Assim
OSU LSM





Typical NWS Site Distribution

% of Days With Improved Results

Model Configuration	T	Td
1 Hour Assimilation	54 %	54 %
Recycle Assimilation	73 %	100 %

Summary and Conclusions

- **Real-time photochemical models have promise but in Southeast need improvement to perform better than existing operational methods**
- **A data reanalysis period with data assimilation may improve initial chemical condition and quality of forecast**
- **Satellite data may provide needed information**

GOES Assimilation Procedure in MM5

McNider et al.1994 Mon.Wea. Rev

Surface Energy Budgets:

Model $$c_b\left(\frac{dT_g}{dt}\right)_M = \left(R_N + H + G\right)_M + E_M$$

Satellite $$c_b\left(\frac{dT_g}{dt}\right)_S = \left(R_N + H + G\right)_S + E_S$$

T_g=skin temperature
R_N=net radiation
H=sensible flux
E=latent flux
G=soil flux

Critical Assumptions:

- *Mid-morning energy budget over land is very sensitive to moisture availability (Wetzel 84, Carlson 86)
- *E is the most complex term in the energy budget
- *All other terms are assumed to be equal

Solve for Satellite Inferred Variables

Moisture Flux

$$E_S = C_b\left[\left(\frac{dT_g}{dt}\right)_S - \left(\frac{dT_g}{dt}\right)_M\right] + E_M$$

Moisture Availability

$$M_S = E_S \frac{\ln\left(\frac{ku_* z_a}{k_a} + \frac{z_a}{z_1}\right) - \varphi_h}{\rho k u_* \left(q_{sfc}\left(T_g\right) - q_a\right)}$$