Satellite Data Assimilation into Meteorological / Air Quality Models

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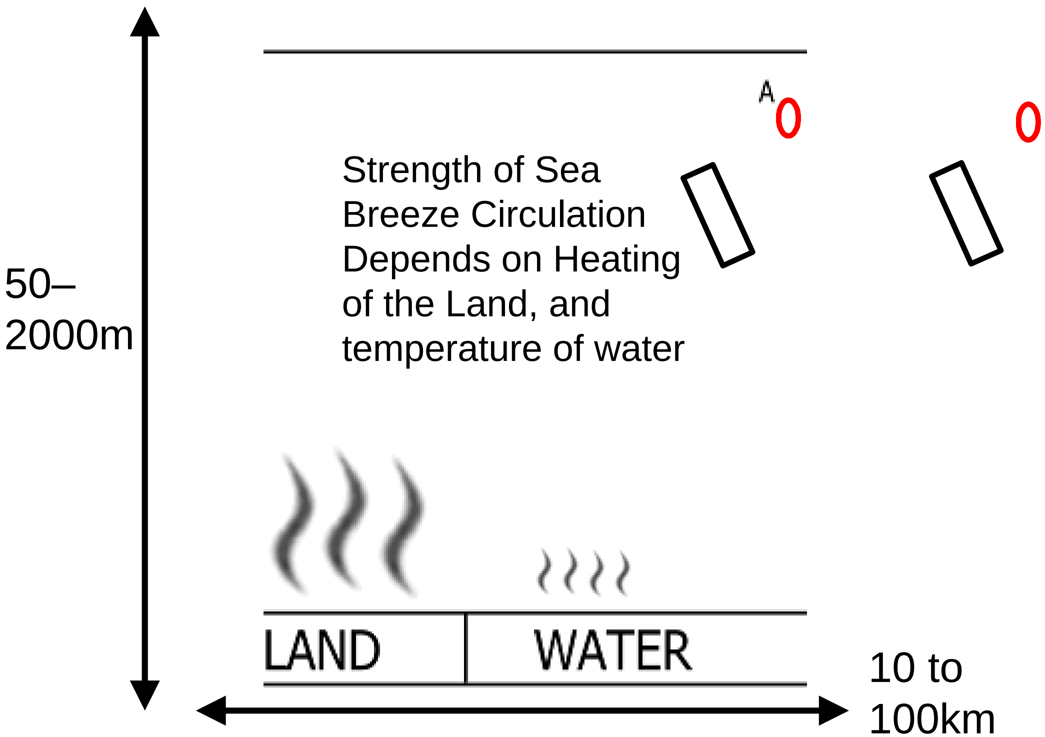
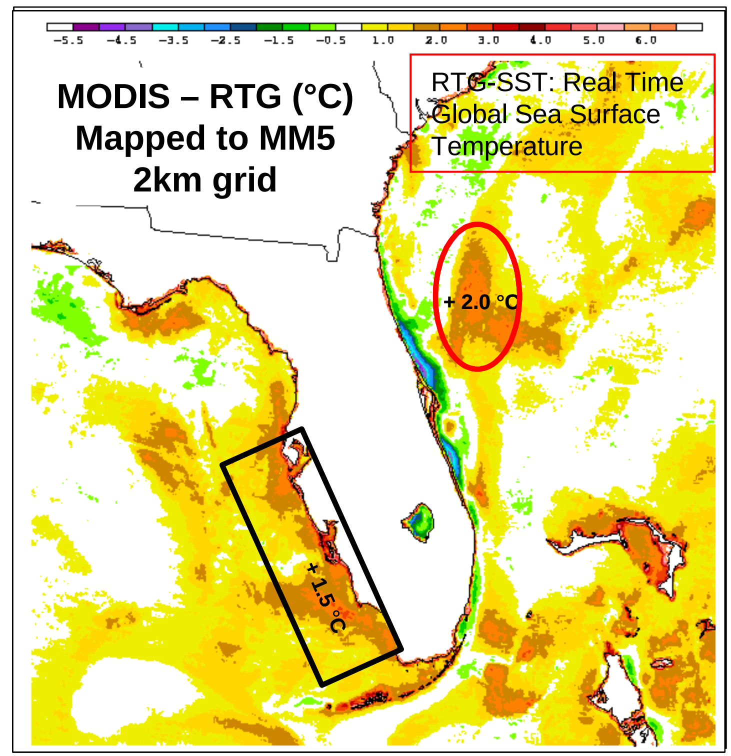
Relevance to MMS and Gulf of Mexico Environmental Issues

The sea breeze is critically important in air quality in the coastal areas. For example, in Houston, high concentrations are associated with wind reversals related to the land/sea breeze system.



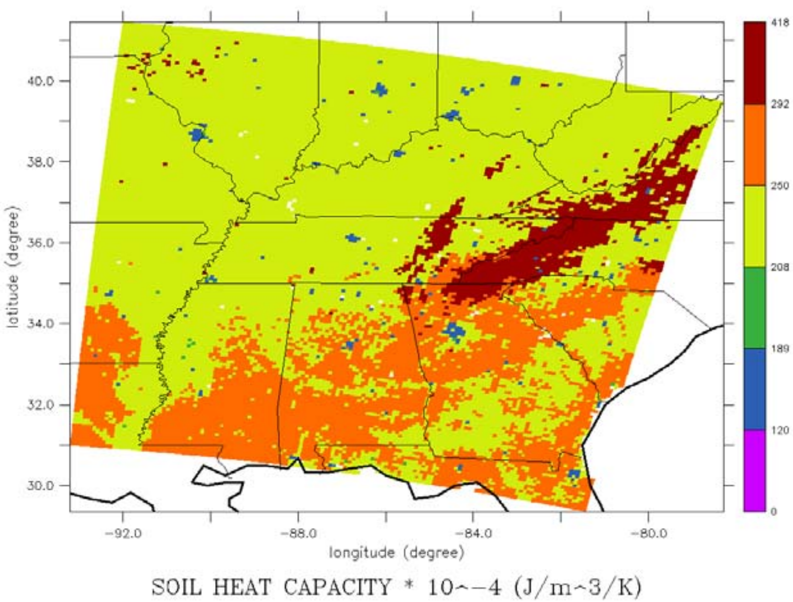


Relevance … continued …

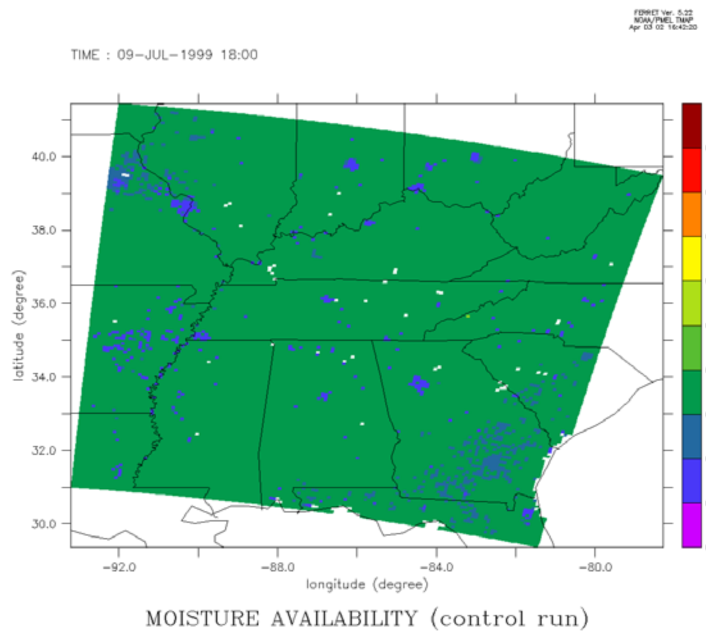
The rate at which the land surface heats up in the morning and cools down in the evening is related to surface characteristics such as **heat capacity**, **surface moisture and incoming solar radiation**.

However, these parameters are ill-defined and not directly observable on fine scales from standard networks.

MM5 Landuse Heat Capacity

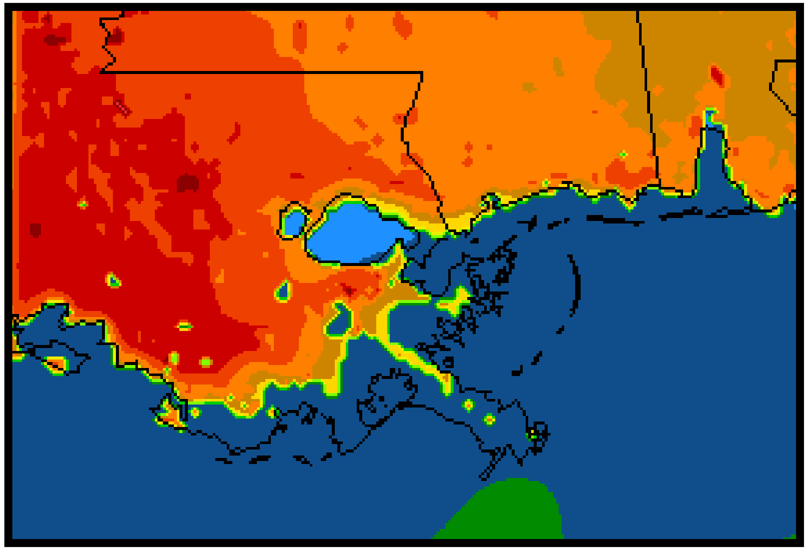


MM5 Landuse Moisture Availability

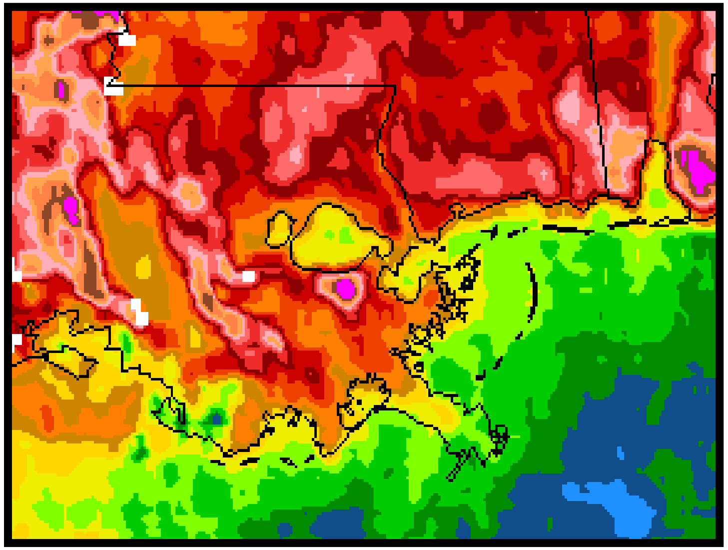


Relevance … continued …

Specification of land - water boundaries can be difficult in complex coastlines and at marshy boundaries



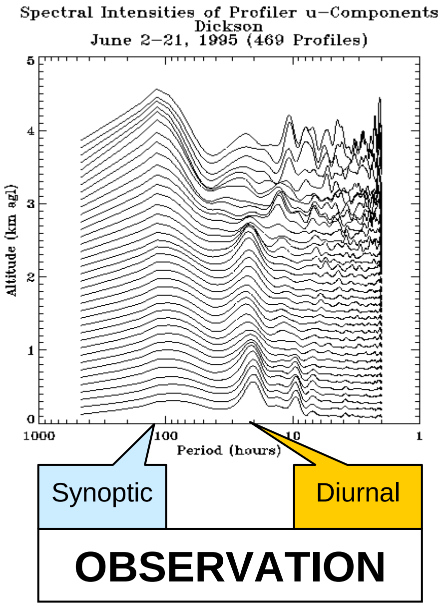
MM5 Skin Temperatures

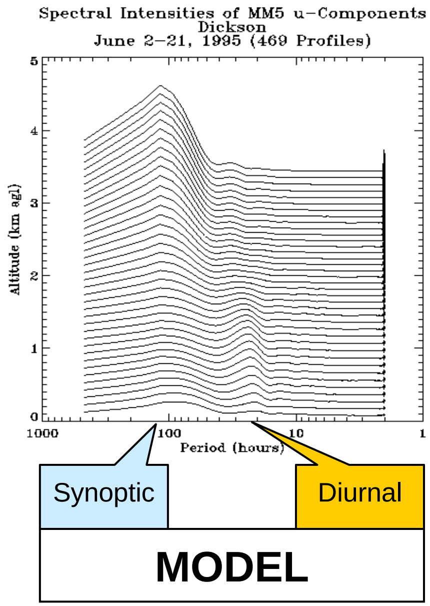


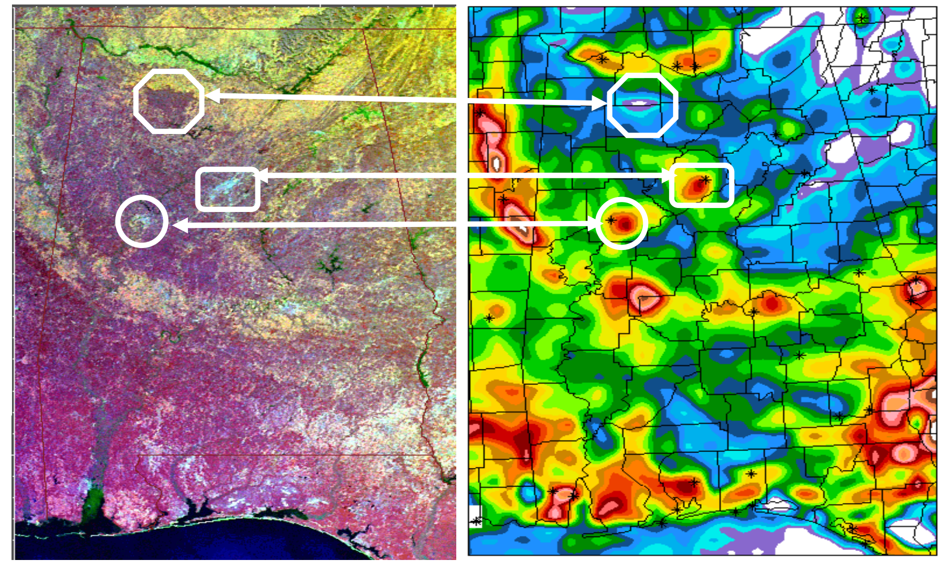
Satellite Skin Temperatures

Use satellite data to naturally determine heat capacity and moisture fraction of grids.

Problem With Existing Met. Models







AVHRR

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

Models do not maintain as much energy at higher frequencies as observations indicate. This can severely hinder short term forecasting efforts.

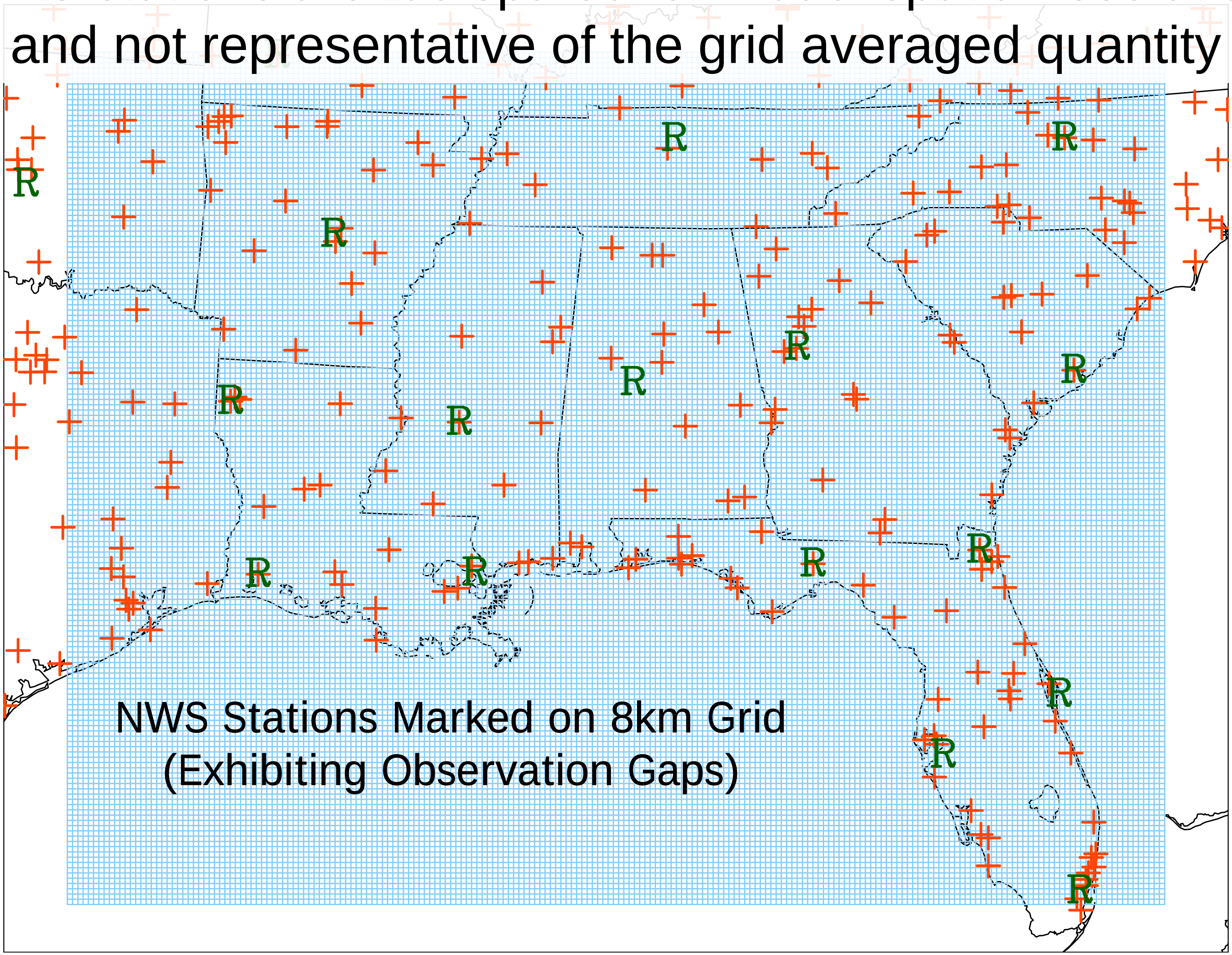
Satellite data can be utilized to fill the diurnal energy gap and to improve the model performance with respect to short term forecasts.

Appealing attributes of GOES data:

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

Problem with the Use of Surface Data

NWS stations are too sparse for model spatial resolution and not representative of the grid averaged quantity



Satellite Data Assimilation into Meteorological / Air Quality Models

Motivation:

- To improve the fidelity of the physical atmosphere in air quality modeling systems such as MM5/CMAQ.
- Models are too smooth and do not maintain as much energy at higher frequencies as observations. Surface properties and clouds are among major model uncertainties causing this problem. NWS stations are too sparse for model spatial resolution and are not representative of the grid averaged quantity. Therefore, their utilization in data assimilation is limited. On the other hand, satellite data provide pixel integral quantity compatible with model grid.

Targets for assimilation:

- Surface energy budget: Insolation, albedo, moisture availability, and bulk heat capacity.
- Vertical motion and clouds.
- Photolysis rates in CMAQ

Surface Energy Budget

Three Uncertain Parameters

Bulk Heat Capacity → $$C_b\left(\frac{dT_G}{dt}\right) = (R_N + H + G) + E$$ ← Evaporative Heat Flux

Net Short-wave radiation obtained from Satellite (→ R_N)

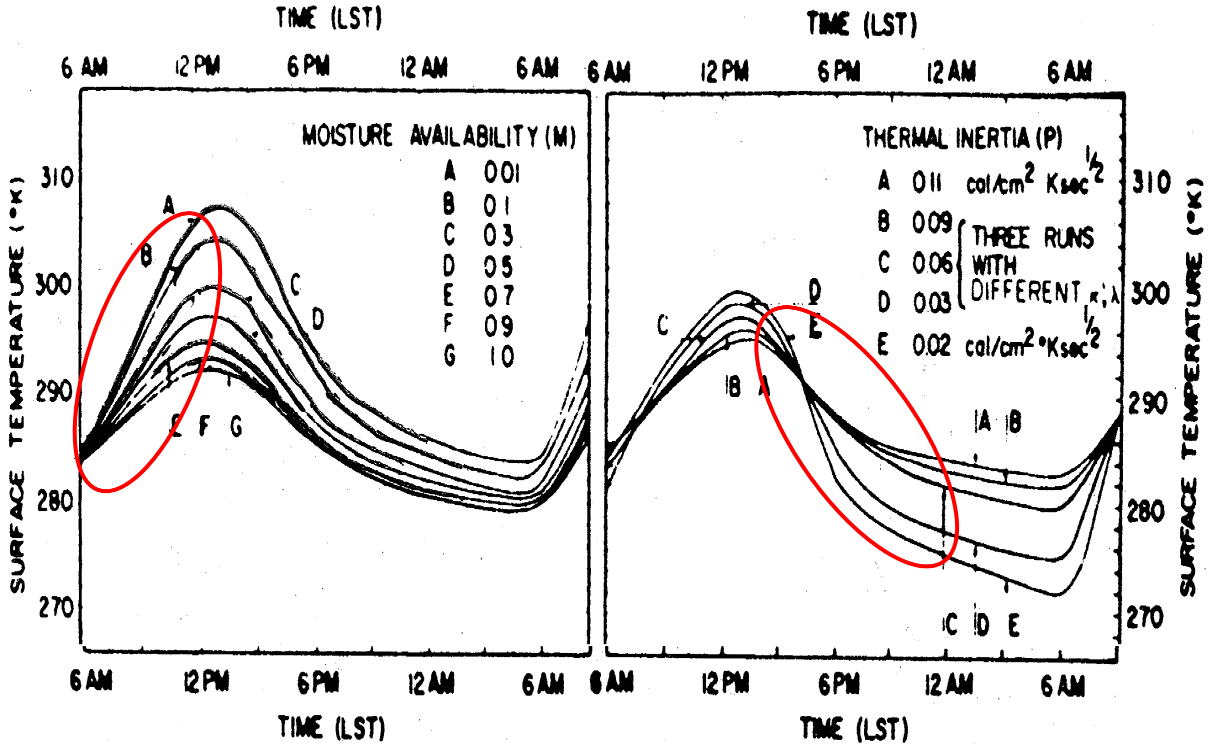
Grid scale heat capacity and moisture availability very difficult to define

Grid box made up of soil, trees, buildings, grass, water etc.

Model heat capacity not well defined fundamentally.

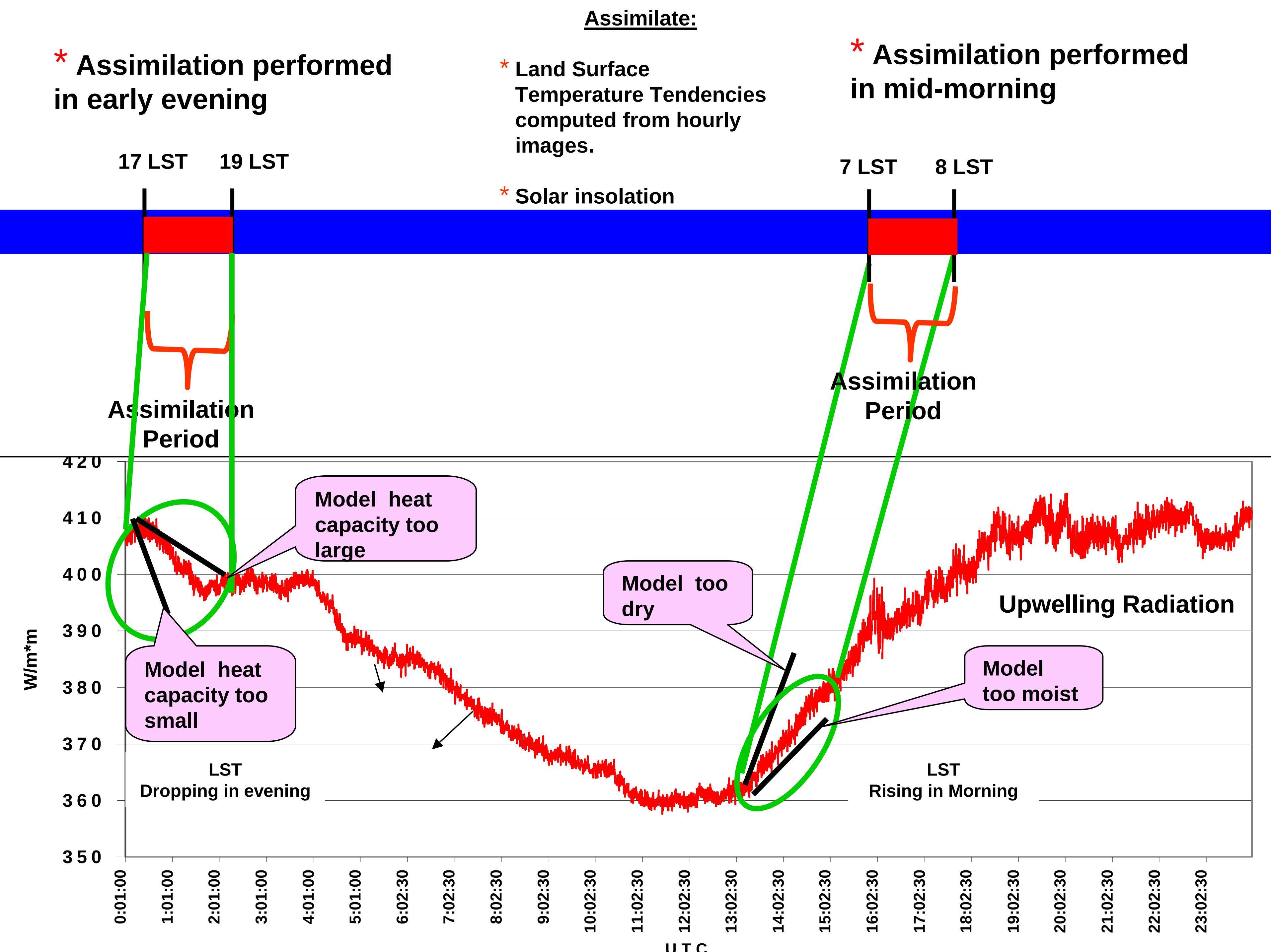
Sensitivity of Surface Energy Budget to Various Parameters

Moisture Availability



Thermal Inertia

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


Assimilate:
* Assimilation performed in early evening
* Land Surface Temperature Tendencies computed from hourly images.
* Solar insolation
* Assimilation performed in mid-morning
17 LST
19 LST
7 LST
8 LST
Assimilation Period
Assimilation Period
Model heat capacity too large
Model heat capacity too small
Model too dry
Model too moist
Upwelling Radiation
LST Dropping in evening
LST Rising in Morning
W/m*m
420
410
400
390
380
370
360
350
0:01:00
1:01:00
2:01:00
3:01:00
4:01:00
5:01:00
6:02:30
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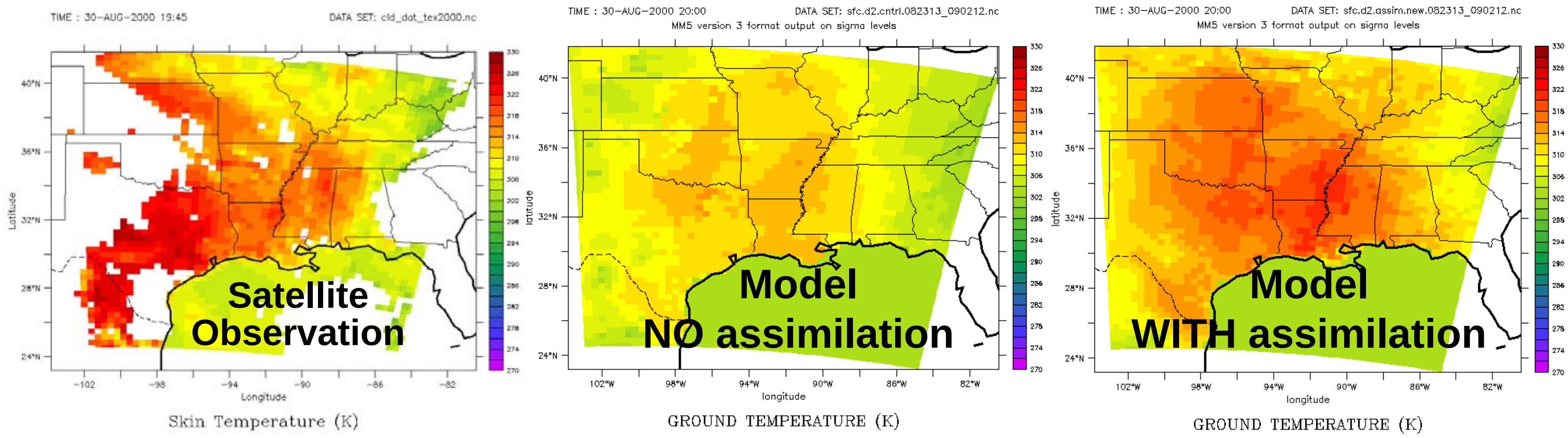
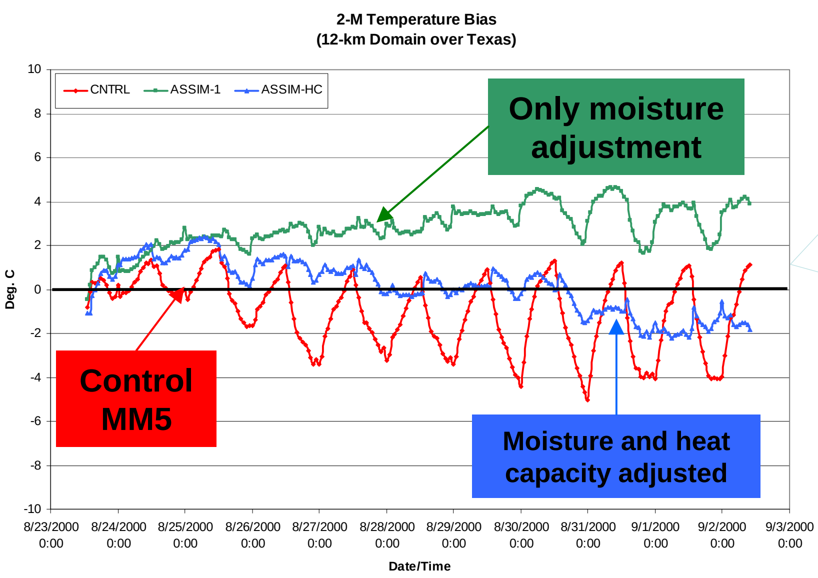
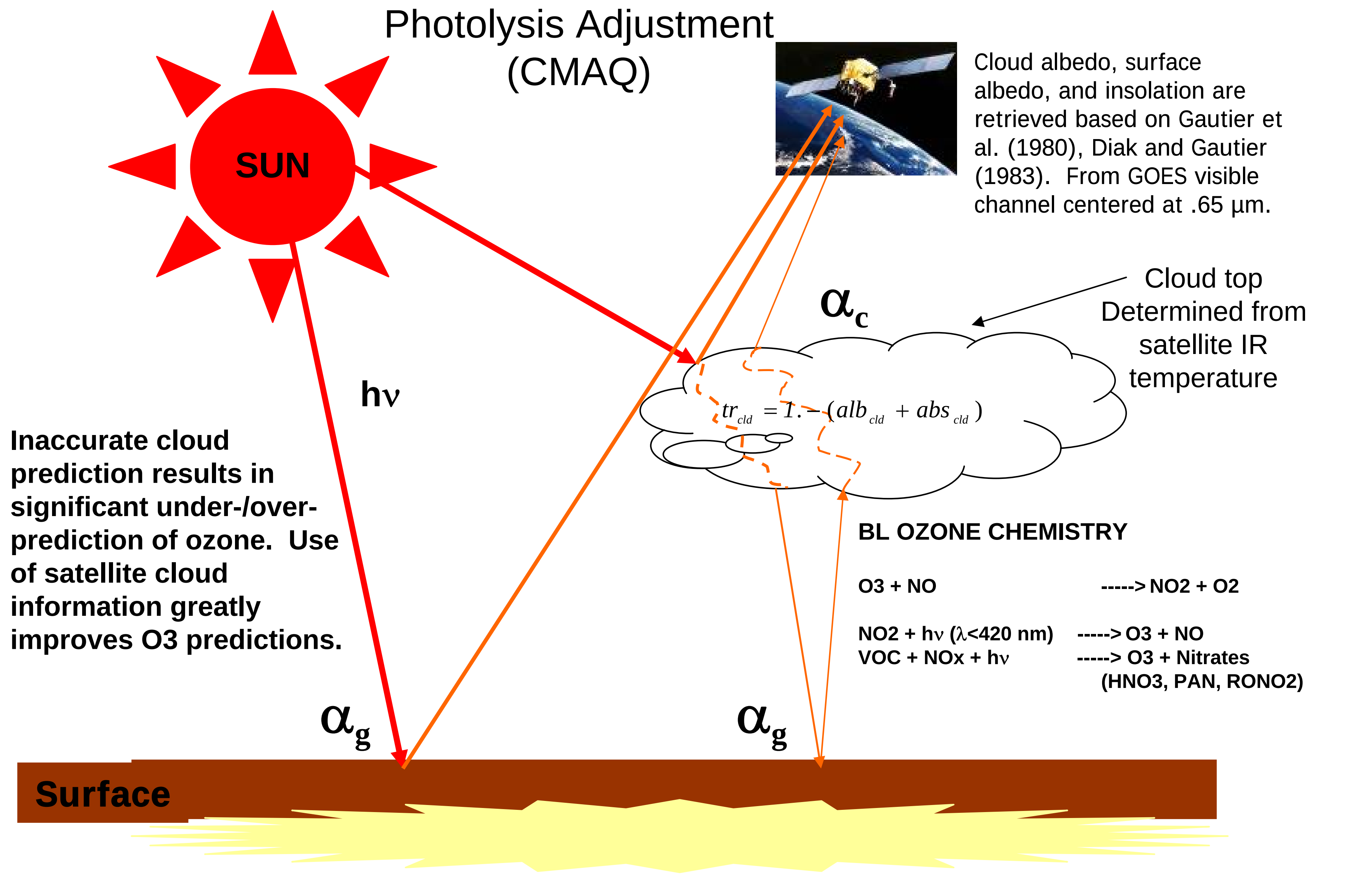


Our work during Texas Air Quality Study has shown that the satellite data assimilation technique greatly improves the surface/air temperature predictions.



Comparing model 2-M temperature predictions to the observed temperatures from National Weather Service stations shows that the satellite assimilation technique **(blue line)** reduces the forecast bias in the model (warm bias at night and cold bias during the day).

McNider et al.2005.


Photolysis Adjustment
(CMAQ)
SUN
hν
Cloud albedo, surface albedo, and insolation are retrieved based on Gautier et al. (1980), Diak and Gautier (1983). From GOES visible channel centered at .65 µm.
α_c
Cloud top Determined from satellite IR temperature
$tr_{cld} = 1. - (alb_{cld} + abs_{cld})$
Inaccurate cloud prediction results in significant under-/over-prediction of ozone. Use of satellite cloud information greatly improves O3 predictions.
BL OZONE CHEMISTRY
O3 + NO -----> NO2 + O2
NO2 + hν (λ<420 nm) -----> O3 + NO
VOC + NOx + hν -----> O3 + Nitrates (HNO3, PAN, RONO2)
α_g
α_g
Surface

MM5-Method

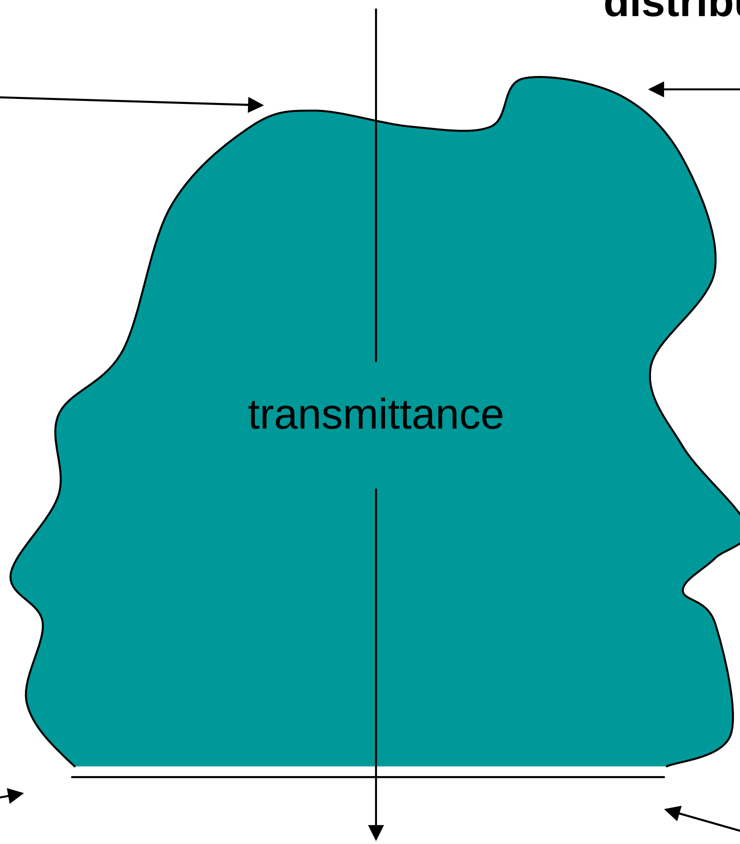
Satellite Method

Photolysis Rates

Assume MM5 derived cloud distribution is correct

Cloud top

Determined from satellite IR temperature



Cloud top

Determined from model

Transmittance =

1- reflectance - absorption

Observed by satellite

F(reflectance)

Transmittance

Determined from LWC = f(RH, T) and assumed droplet size

Cloud Base

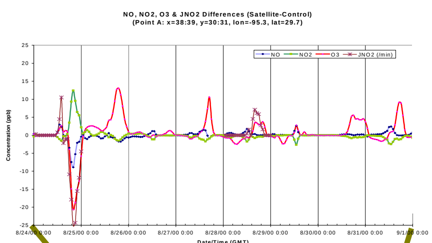
Determined from LCL

Cloud Base

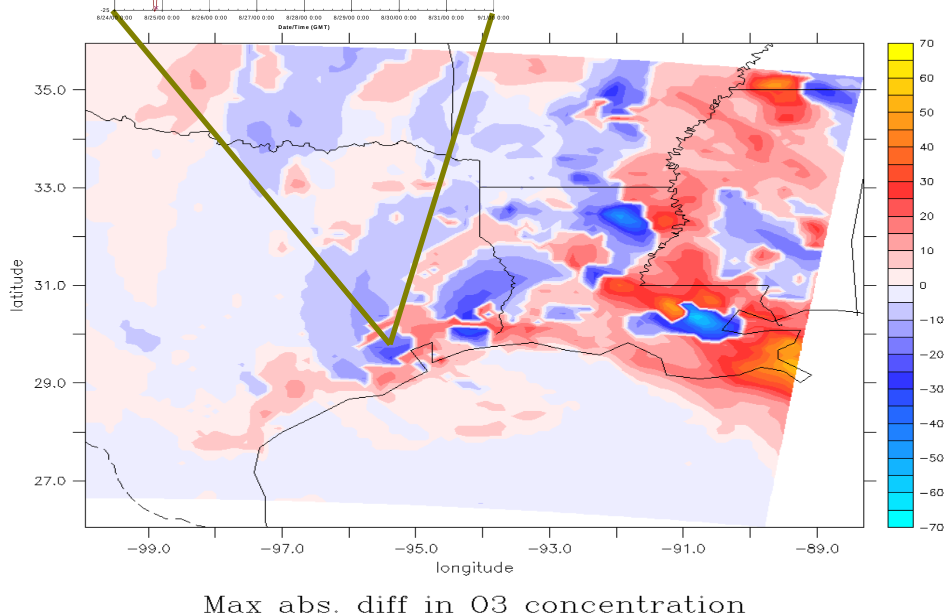
Determined from MM5

ADJUSTING PHOTOLYSIS RATES IN CMAQ BASED ON GOES OBSERVED CLOUDS

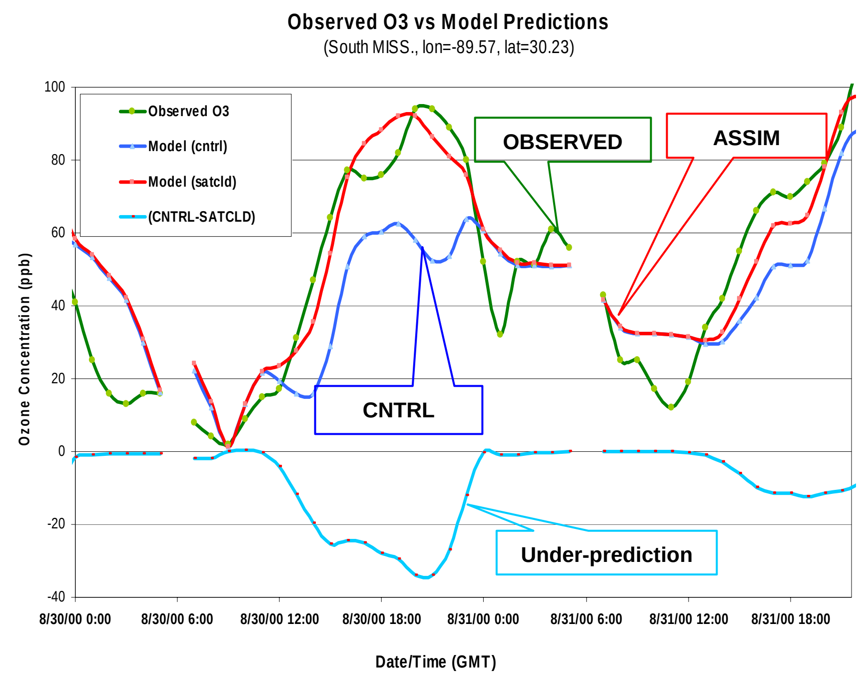
- This technique will be included in the next release of CMAQ
- Cloud albedo and cloud top temperature from GOES is used to calculate cloud transmissivity and cloud thickness
- The information is fed into MCIP/CMAQ
- CMAQ parameterization is bypassed and photolysis rates are then adjusted based on GOES cloud information



The differences between NO, NO2, O3 (ppb) and JNO2 from satellite cloud assimilation and control simulations for a selected grid cell over Houston-Galveston area.



Adapted from: Pour-Biazar et al. 2007



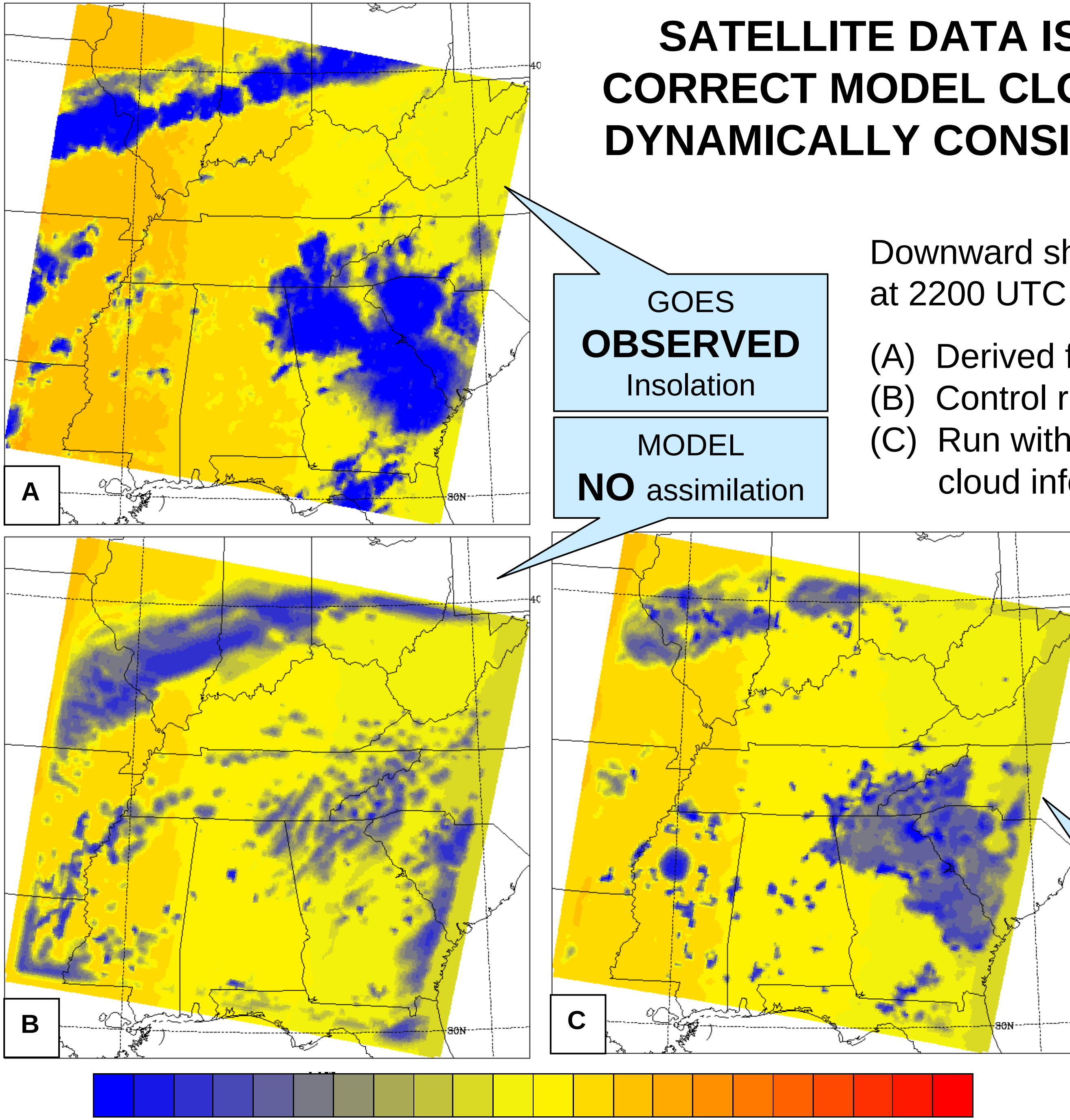
ASSIMILATION OF GOES-DERIVED CLOUD PRODUCTS IN MM5

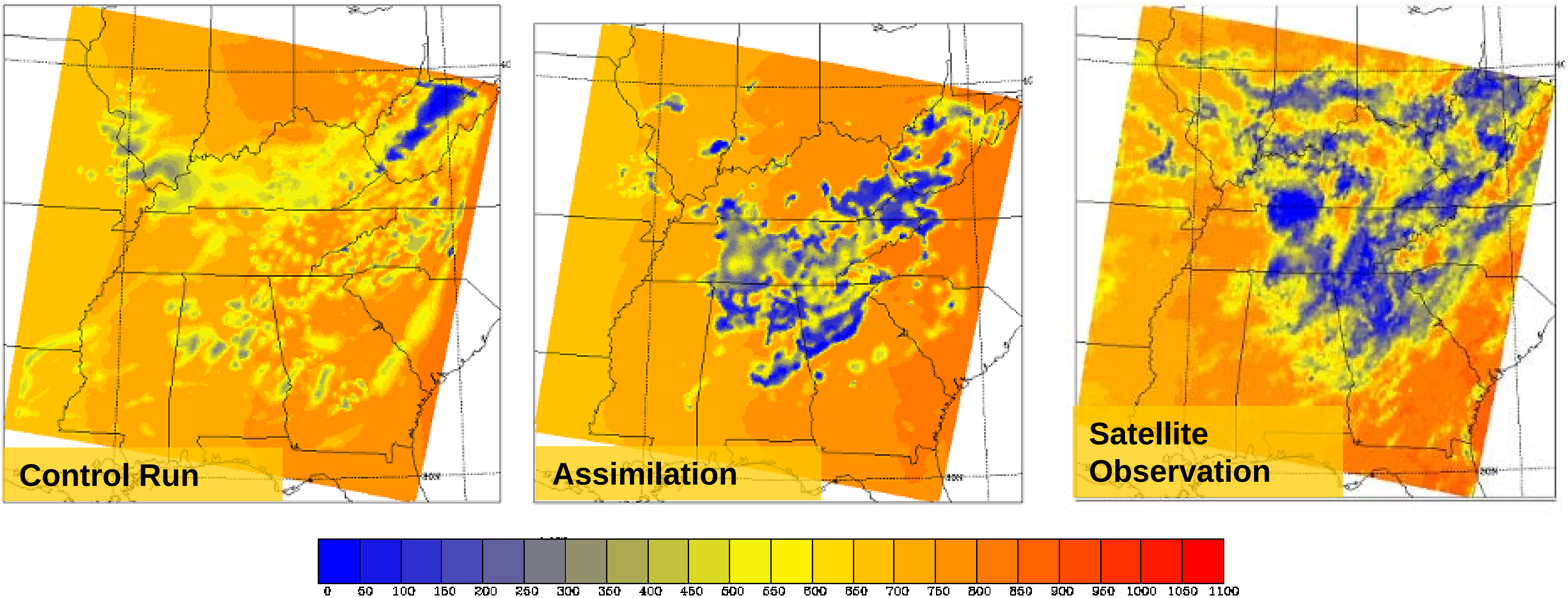
- Use GOES cloud top temperatures and/or cloud albedoes to determine a maximum vertical velocity (Wmax) in the cloud column.
- Adjust divergence to comply with Wmax in a way similar to O'Brien (1970).
- Calculate new horizontal divergent wind components.
- Nudge MM5 winds toward new horizontal wind field.
- Determine a way to remove erroneous model clouds.

SATELLITE DATA IS UTILIZED TO CORRECT MODEL CLOUD FIELDS IN A DYNAMICALLY CONSISTENT MANNER

Downward shortwave radiation in W m^{-2} at 2200 UTC 6 July 1999.

(A) Derived from GOES–8 satellite.
(B) Control run with no assimilation.
(C) Run with assimilation of satellite cloud information.

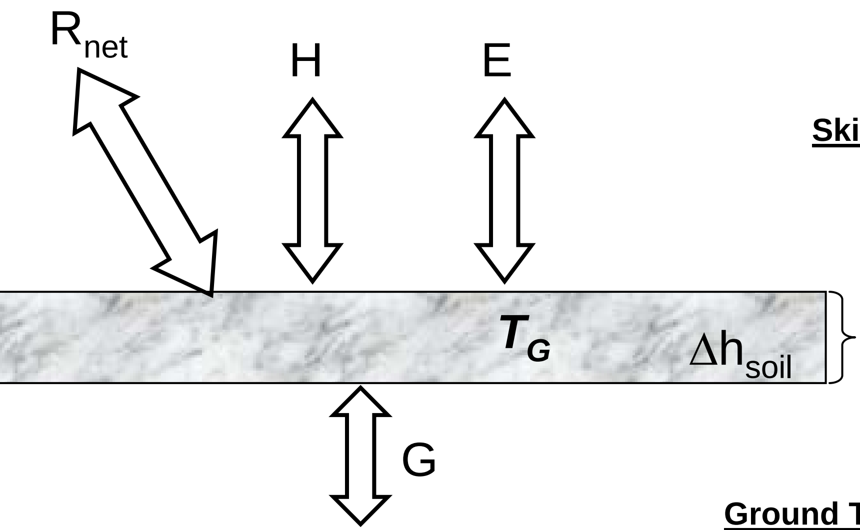


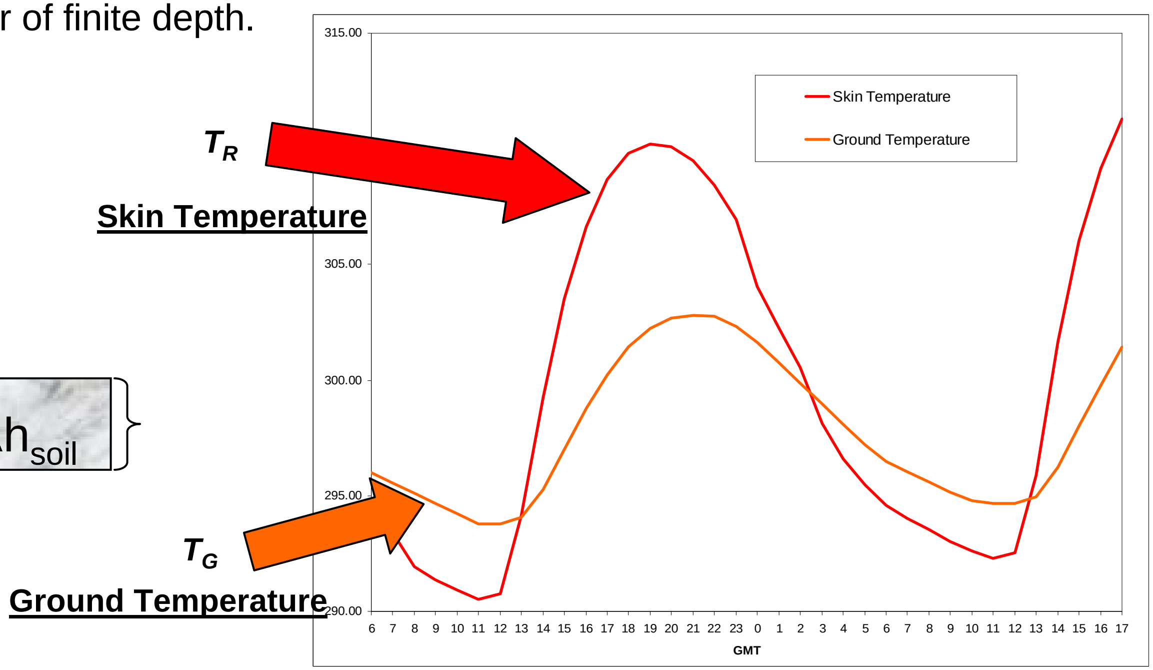


Surface incident shortwave radiation in W m^{-2} for 2 July 1999. Assimilation and satellite observation plots are @ 14:45 UTC, and the control run is @ 15:00 UTC. Control: Control run with no assimilation. Assimilation: Run with assimilation of satellite cloud information. Satellite Observation: Derived from GOES–8 satellite.

Addressing the Problem of Dry/Warm Bias in the Assimilation Technique

- Improvements we made in MM5 (e.g., better numerical solvers in the surface module, etc.) helped in identifying a main cause of dry/warm bias in the model.
- Problem:
  - The MM5 slab model utilizes one temperature to describe impact of the land in the surface to boundary layer interface. But satellite sees the surface radiating skin rather than the ground which describes some layer of finite depth.





Problem

$$E_S = c_b\left[\left(\frac{dT_G}{dt}\right)_m - \left(\frac{dT_G}{dt}\right)_S\right] + E_m$$

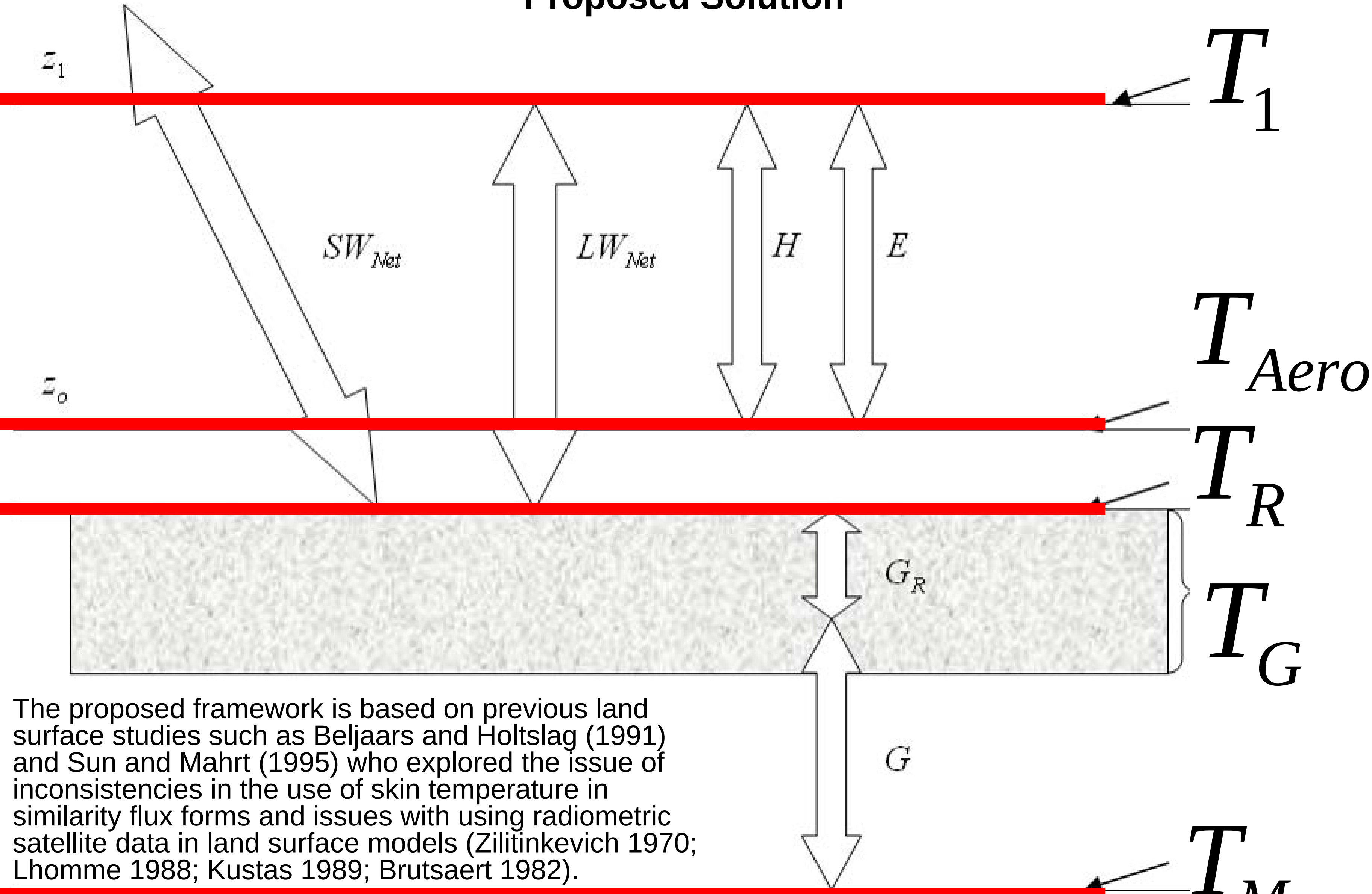
Model solves for temperature of slab

Satellite retrieves skin temperature

- Taking the difference between a mid-morning skin temperature tendency and ground temperature tendency leads to much larger than necessary adjustments to the moisture availability.

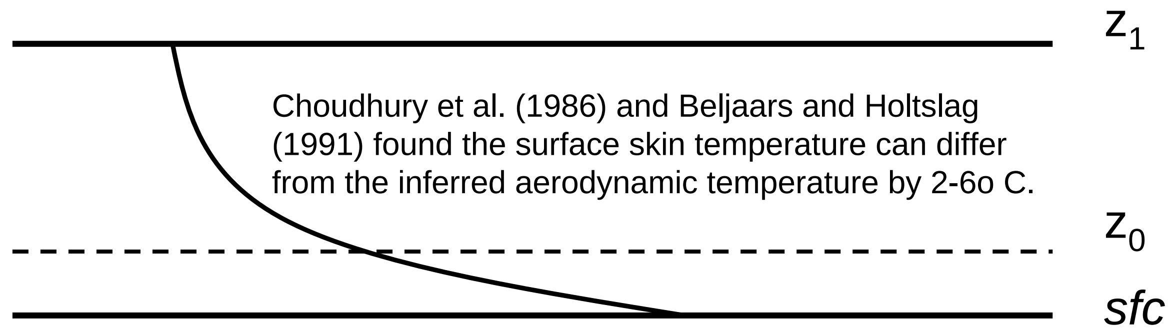
- In addition, replacing ground temperature with skin temperature leads to problems with surface similarity formulations.

Proposed Solution



The proposed framework is based on previous land surface studies such as Beljaars and Holtslag (1991) and Sun and Mahrt (1995) who explored the issue of inconsistencies in the use of skin temperature in similarity flux forms and issues with using radiometric satellite data in land surface models (Zilitinkevich 1970; Lhomme 1988; Kustas 1989; Brutsaert 1982).

Proposed Solution Background



There have been several ways presented in literature to reduce error caused by replacing the aerodynamic temperature with the skin temperature.

1. Determine new stability functions for the exchange coefficients (Brutsaert 1982).
2. Replace the roughness height for heat with a “radiometric roughness height.”
   - Makes the roughness height for heat much smaller than for momentum thus effectively increasing the surface resistance (Kustas et al. 1989; Sugita and Brutsaert 1996).
3. Introducing an extra resistance term due to the difference between the aerodynamic temperature and the skin temperature (Llhomme et al. 1988).
4. Formulate empirical formula for the relationship between the aerodynamic temperature and the skin temperature (Zilitinkevich 1970; Garrat and Francey 1978); Brutsaert 1982).

Method

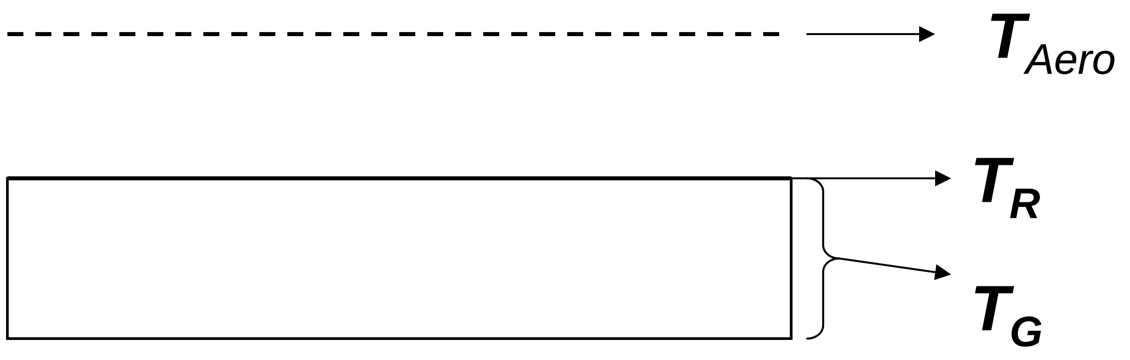
Step 1: Assuming an infinitesimally thin skin, we can solve for Skin temperature from diagnostic Surface Energy balance equation using root finding technique

Step 2: Apply Zilitinkevich adjustment to arrive at Aerodynamic temperature

$$T_{Aero} = T_{Zo} = T_R + 0.0962(\theta_* / k)(u_* z_o / \nu)^{0.45}$$

Step 3: Calculate Ground temperature using prognostic Surface Energy balance Equation

Step 4: Arrive at a physically consistent 3-temperature system



Application of McN94

- Recall $$E_S = c_b\left[\left(\frac{dT_G}{dt}\right)_m - \left(\frac{dT_G}{dt}\right)_S\right] + E_m$$

- If the ground temperature tendency was available from satellite, this would work. We only have skin temperature tendency.

- To invoke the McN94 technique within this new system we develop a relationship between the model skin and ground temperatures.

$$\frac{dT_G}{dt} = \alpha\frac{dT_R}{dt}$$

- We can then arrive at a version of the McN94 adjustment for which we have all the components in a physically consistent manner

$$E_S = c_b\left[\left(\frac{dT_G}{dt}\right)_m - \left(\alpha\frac{dT_R}{dt}\right)_S\right] + E_m$$

Results: 4 July 2003

- Initialize model using vertical profiles and land use parameters as given by an MM5 forecast.

- Initial conditions valid 06UTC 4 July 2003

- Assimilation implemented from 13UTC to 15UTC (Forecast hour 8 through 10). (3 adjustments)

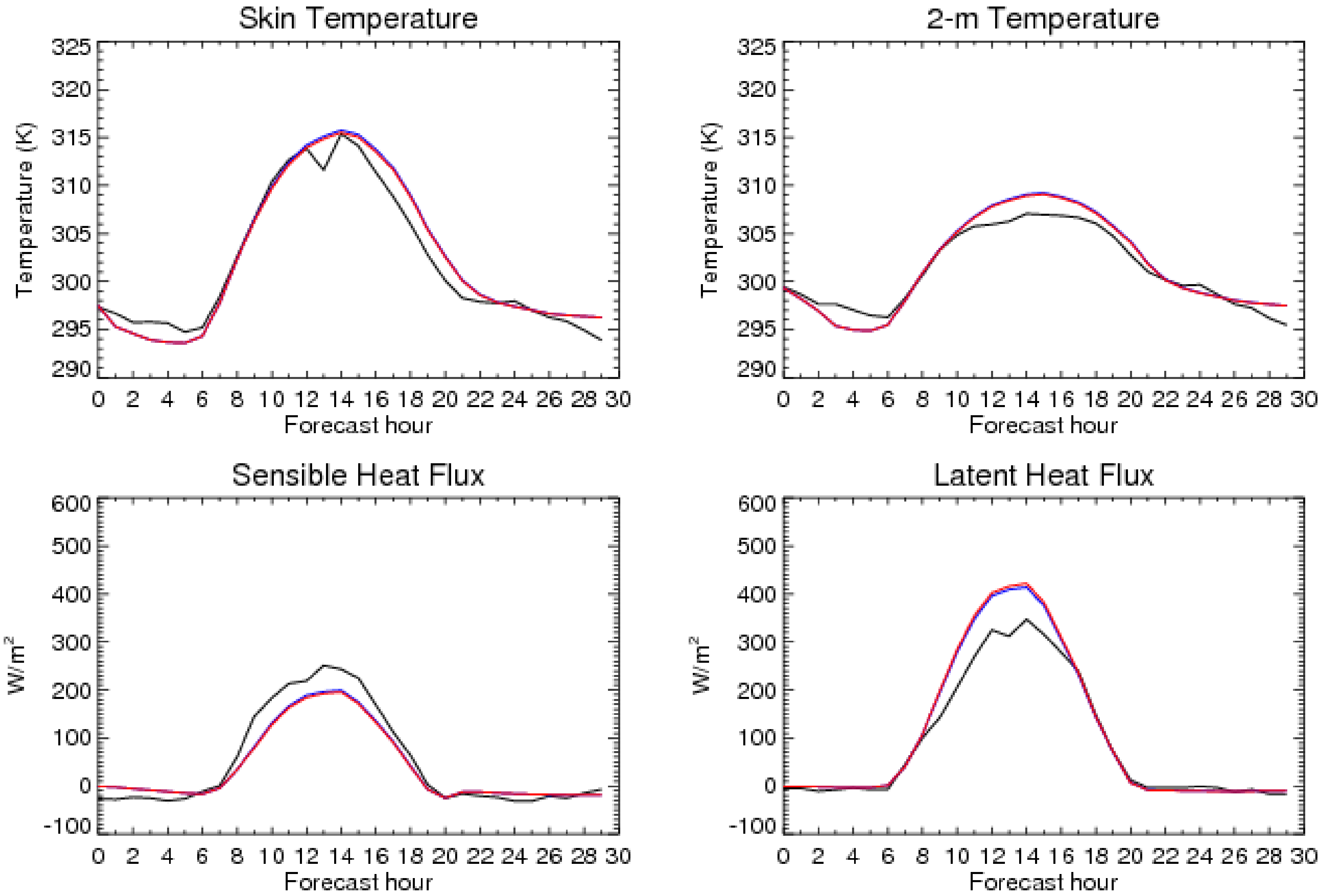
- Model results compared with ground-based measurements from the Oklahoma Mesonet.

- Infrared Thermometer (IRT) used for observed skin temperature.
  - Emissivity of 1.0

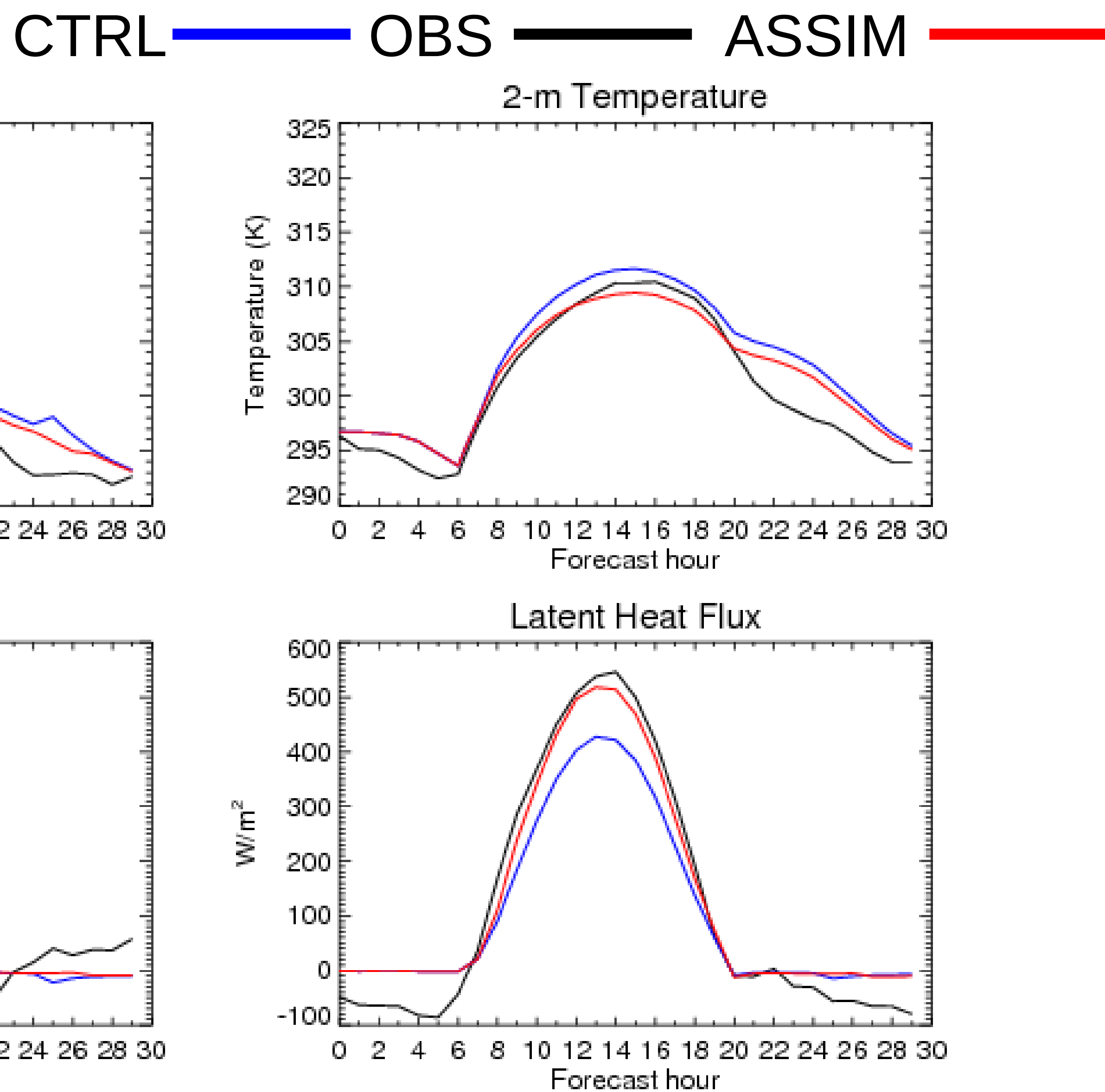
- Incoming shortwave radiation from tower measurements used as model input.

Results NRMN

CTRL OBS ASSIM



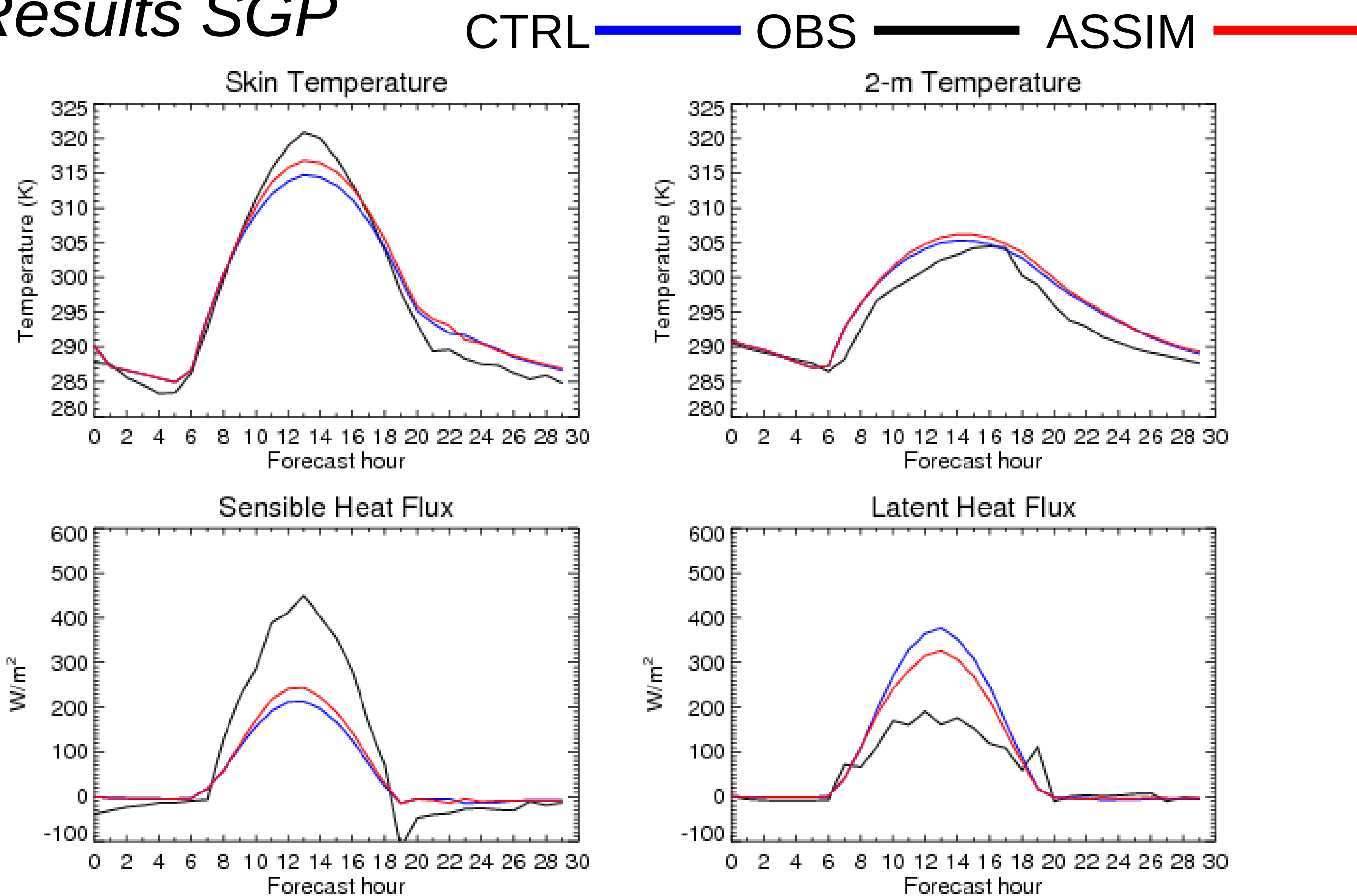
Results Foraker

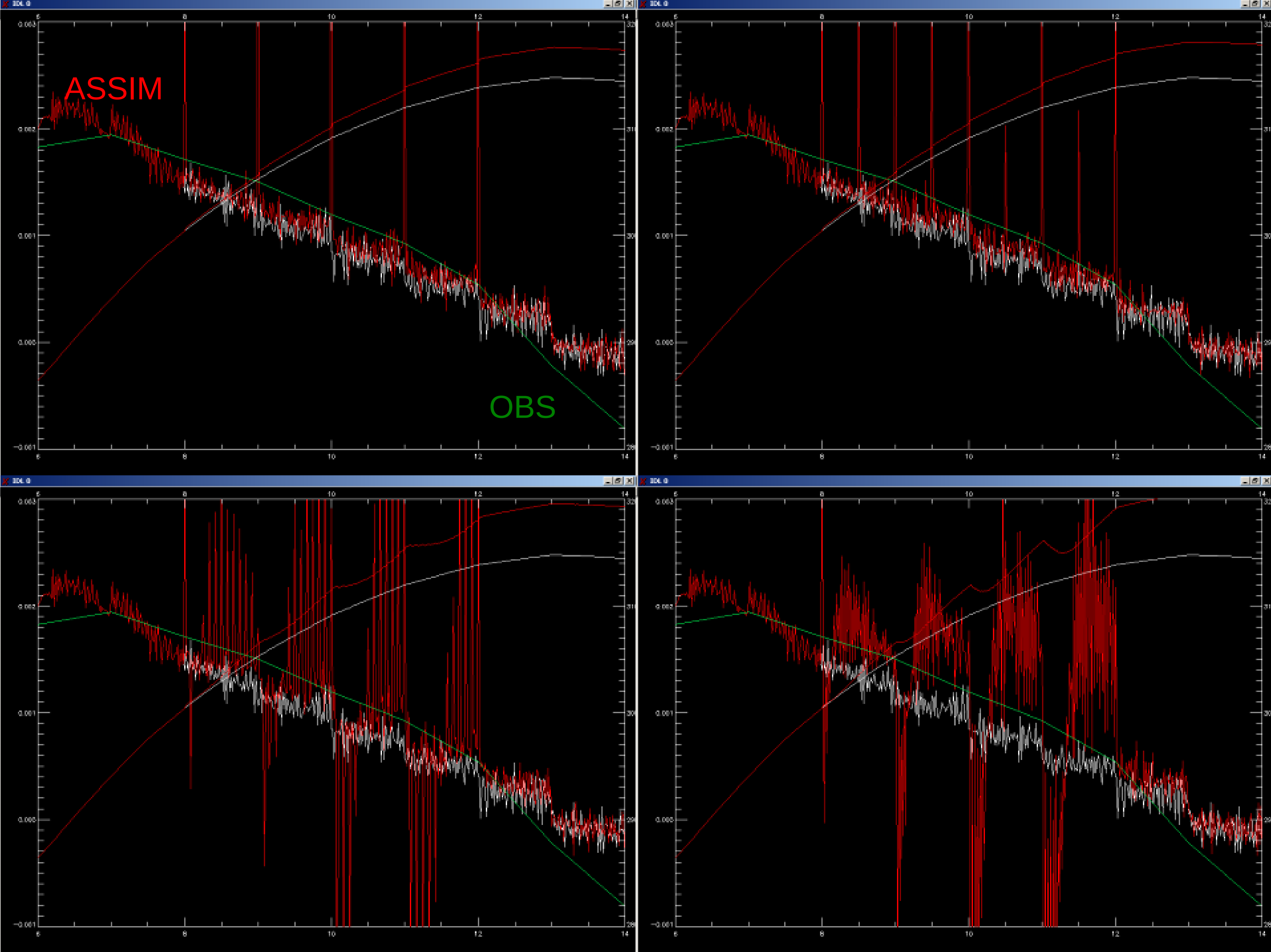


Results: 28 July 2005

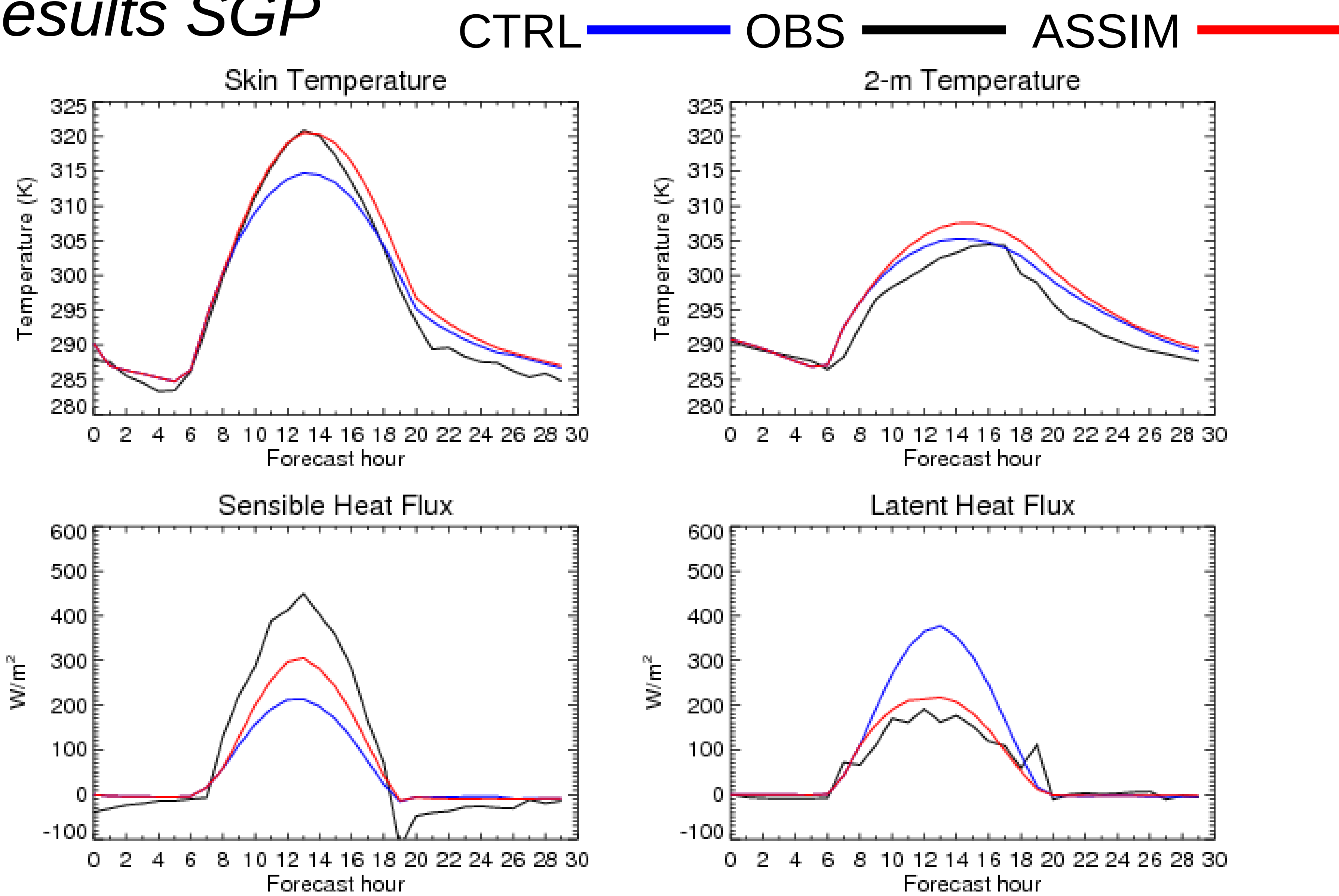
- Initialize model using vertical profiles and land use parameters as given by an MM5 forecast.
- Initial conditions valid 06UTC 28 July 2005
- Model results compared with ground-based measurements from the ARM-CART Southern Great Plains (SGP) Central Facility (CF).
- Infrared Thermometer (IRT) used for observed skin temperature.
  - Emissivity of 1.0
- Incoming shortwave radiation from tower measurements used as model input.

Results SGP


CTRL
OBS
ASSIM
Skin Temperature
2-m Temperature
Temperature (K)
Forecast hour
Sensible Heat Flux
Latent Heat Flux
W/m²
325
320
315
310
305
300
295
290
285
280
600
500
400
300
200
100
0
-100
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30


ASSIM
OBS

Results SGP



CTRL
OBS
ASSIM
Skin Temperature
2-m Temperature
Temperature (K)
Forecast hour
Sensible Heat Flux
Latent Heat Flux
W/m2

Concluding Remarks

- Photolysis adjustment work has been included in the official CMAQ release by EPA.
- MMS has been acknowledged for its contribution to the air quality community.
- The next step for GOES assimilation work is to refine and implement the three temperature system into a full three-dimensional system (e.g. WRF).
- We would like to thank MMS for supporting this research.

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