IMPROVED METEOROLOGICAL SIMULATIONS IN SUPPORT OF AIR QUALITY STUDIES

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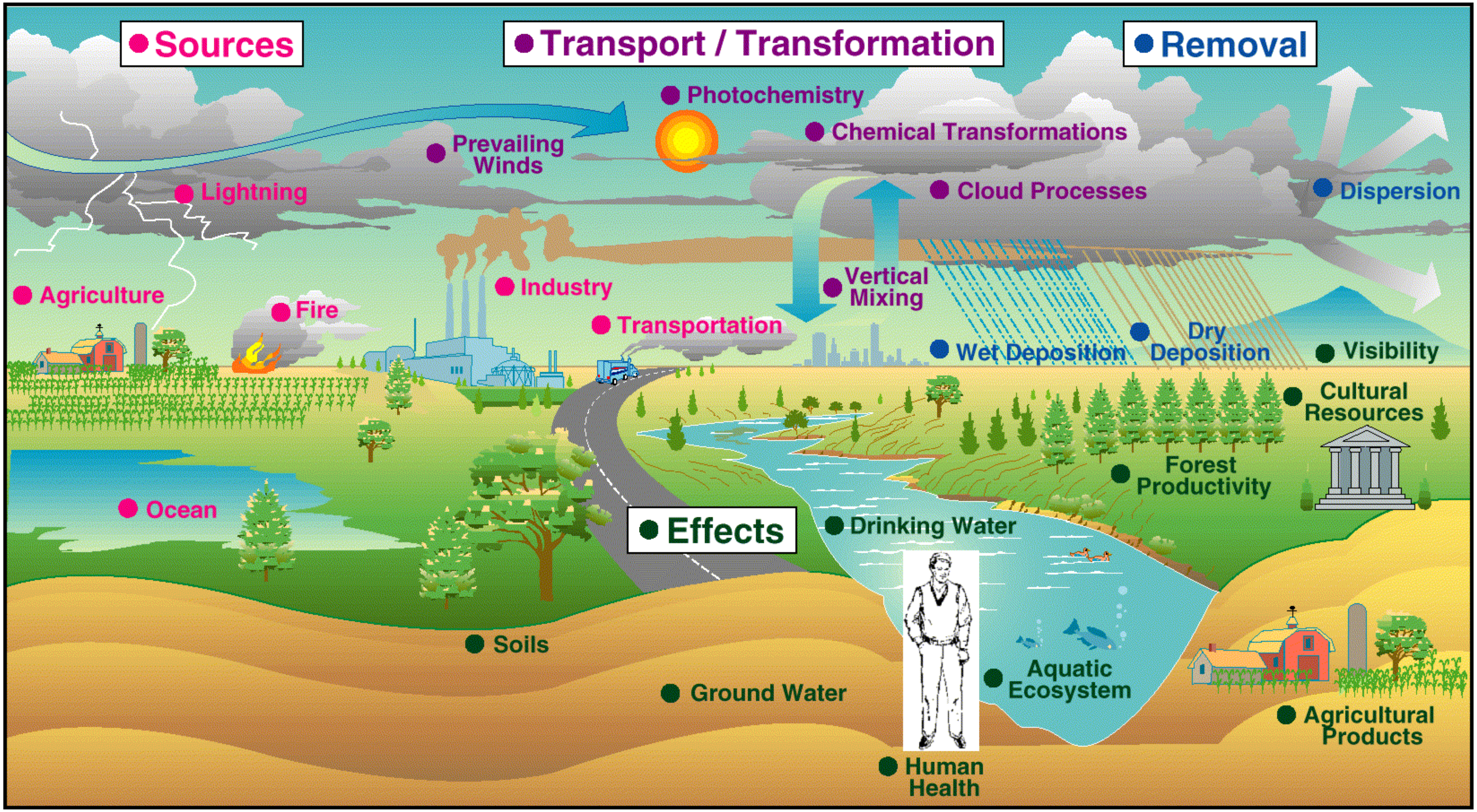
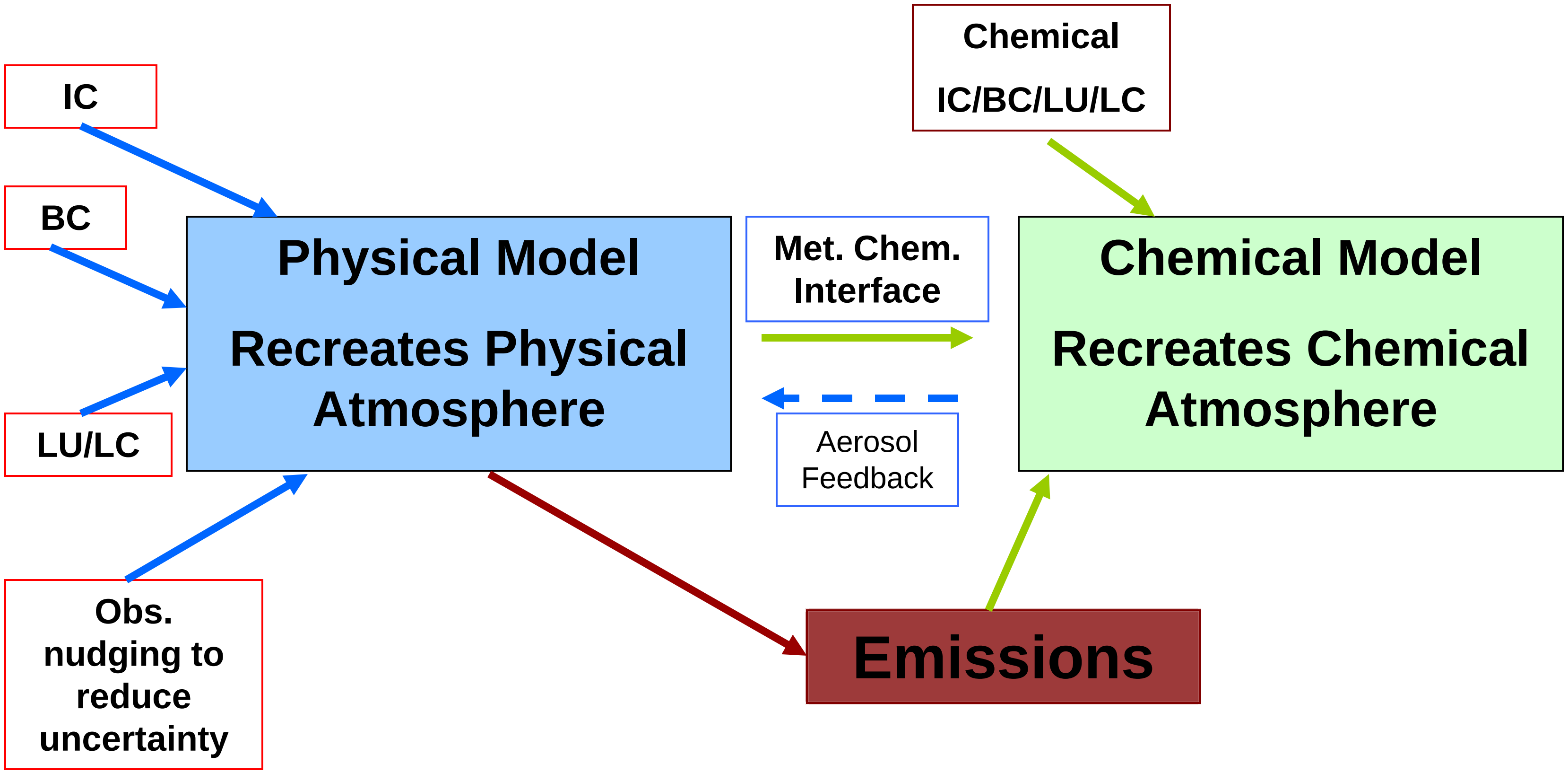
Our Environmental System Consists of Complex Interactions on Different Spatial and Temporal Scales



Air Pollution: Sources, Transport, Transformations, Removal, and Effects

AIR QUALITY MODELING SYSTEMS



The modeling system we have been using:

WRF (MM5)/Smoke/CMAQ

THE ROLE OF PHYSICAL ATMOSPHERE IN AIR QUALITY CHEMISTRY

Temperature:

- impacts biogenic emissions (soil NO, isoprene) as well as anthropogenic evaporative losses.
- Affects chemical reaction rates and thermal decomposition of nitrates.

Moisture:

- Impacts gas/aerosol chemistry, as well as aerosol formation and growth.

BL Heights:

  - Affects dilution and pollutant concentrations.

Winds:

- Impacts transport/transformation

Clouds:

- Impact photolysis rates (impacting photochemical reactions for ozone and fine particle formation).
- Impact transport/vertical mixing, LNOx, aqueous chemistry, wet removal, aerosol growth/recycling and indirect effects.

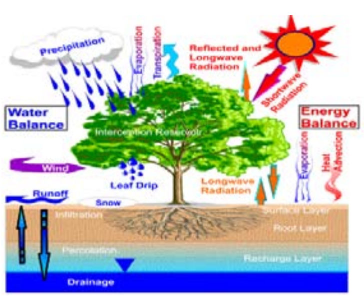
Air Quality Modeling Systems Recreate the Complex Interactions of the Environment But the Uncertainties Are Still High

Physical Atmosphere

Clouds and microphysical processes

Atmospheric dynamics

Boundary layer development



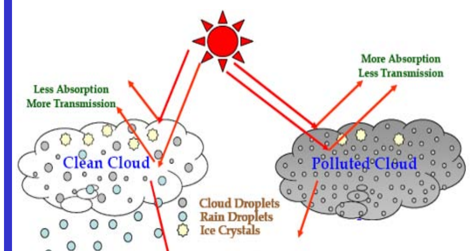
Fluxes of heat and moisture

LSM describing land-atmosphere interactions

Aerosol Cloud interaction

Winds, temperature, moisture, surface properties and fluxes

Chemical Atmosphere

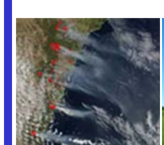


Heterogeneous chemistry, aerosol

Transport and transformation of pollutants

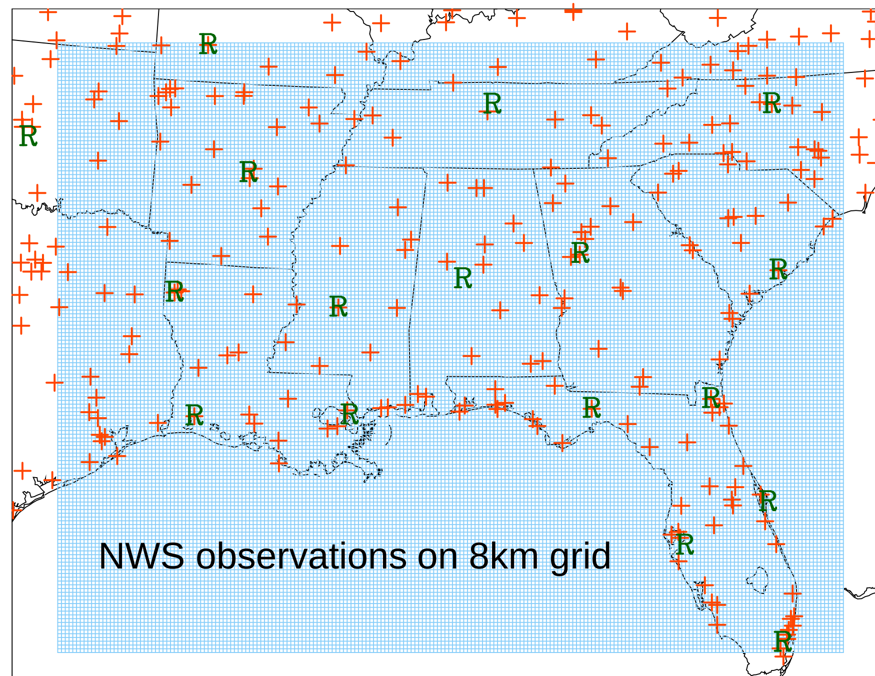
Photochemistry and oxidant formation

Natural and antropogenic emissions
Surface removal



Data Assimilation Can Improve Model Performance

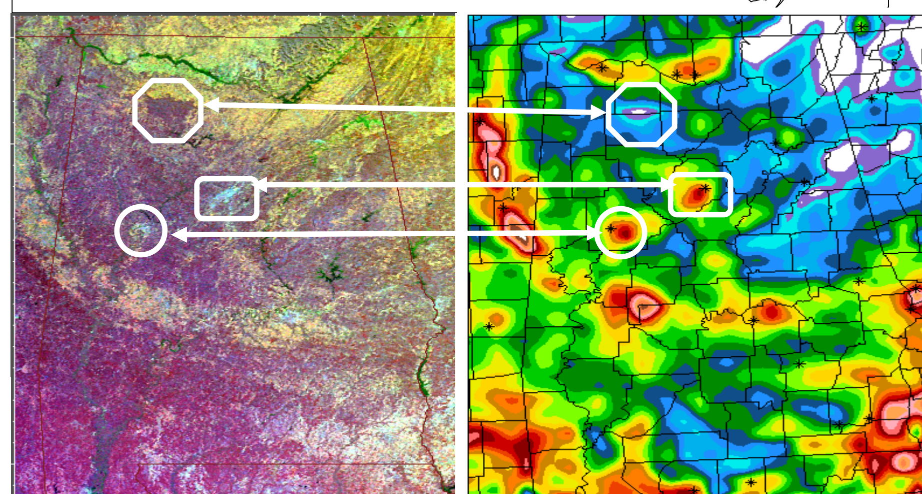
* Surface observations while valuable, are not adequate. They are sparse point measurements, while model grid cell represents average quantity for an inhomogeneous environment.



* Satellite observations offer an integral quantity comparable to model grid average quantity

* Geostationary satellite provides high sampling frequency

* Polar orbiting satellites provide higher spatial resolution at the expense of temporal resolution



AVHRR

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

Satellite Data Assimilation into Meteorological / Air Quality Models

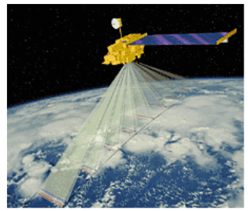
Motivation:

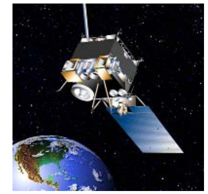
- To improve the fidelity of the physical atmosphere in air quality modeling systems such as WRF/MM5/CMAQ.
- Models are too smooth and do not maintain as much energy at higher frequencies as observations. Surface properties and clouds are among major model uncertainties causing this problem. NWS stations 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.

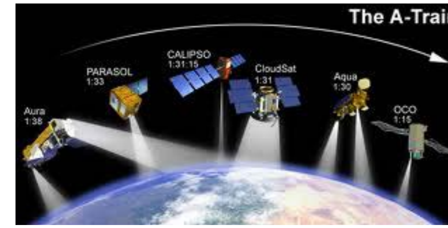
Targets for assimilation:

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

Remotely Sensed Observations Can Improve the Scientific Understanding of the Environment as Well as Improving the Model Performance







Geostationary Satellite
- Insolation
- Skin temperatures
- Cloud Properties

MODIS
- Surface emissivity
- Surface albedo
- Skin temperatures

Satellite derived Cloud properties for photolysis rates

Satellite trace gas and aerosol observations

ASSIMILATION

Physical Model

Recreates Physical Atmosphere

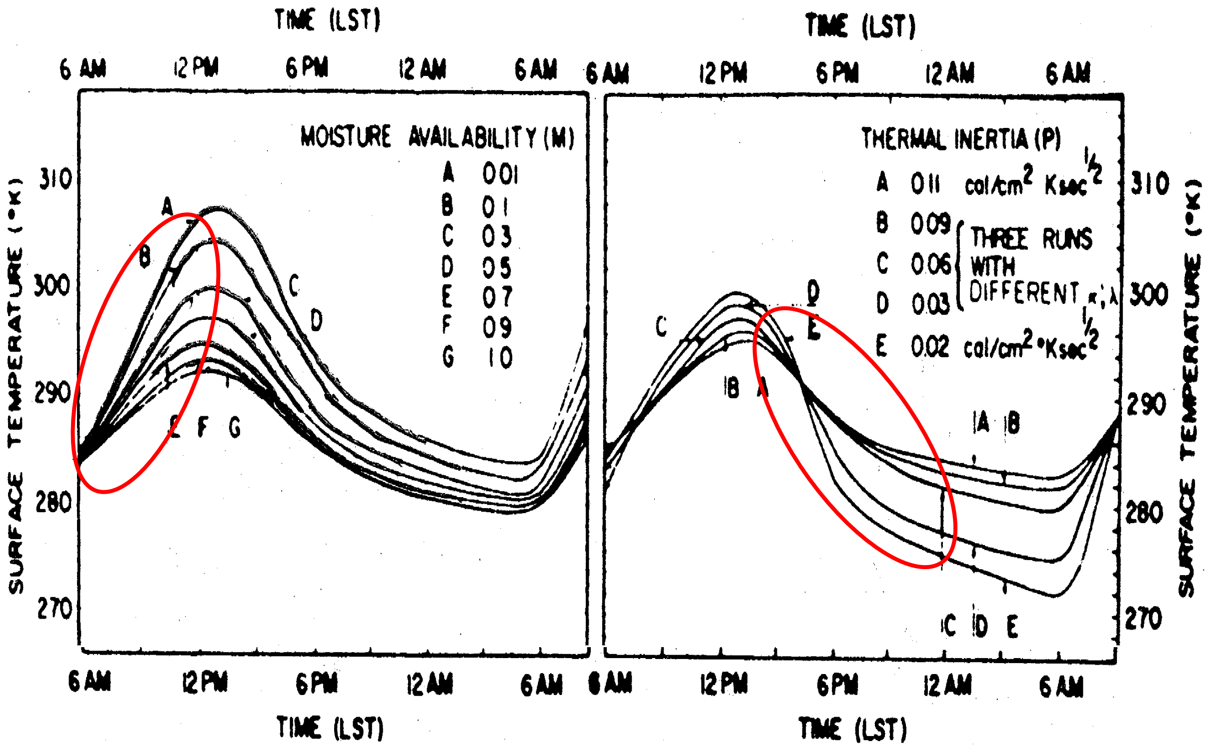
Chemical Model

Recreates Chemical Atmosphere

Geostationary and Polar Orbiting Observations for Evaluation

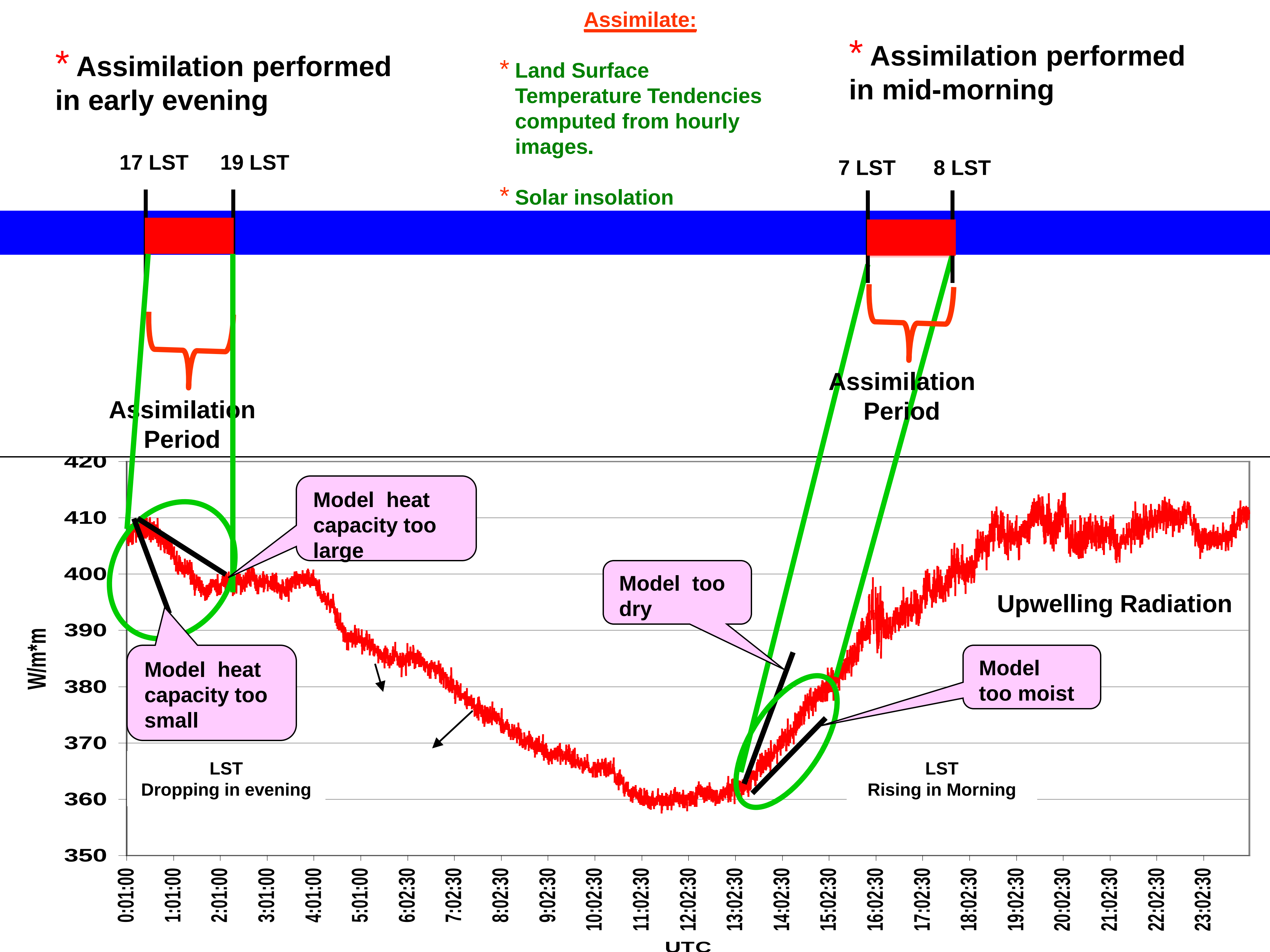
Sensitivity of Surface Energy Budget to Various Parameters

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
UTC
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
7:02:30
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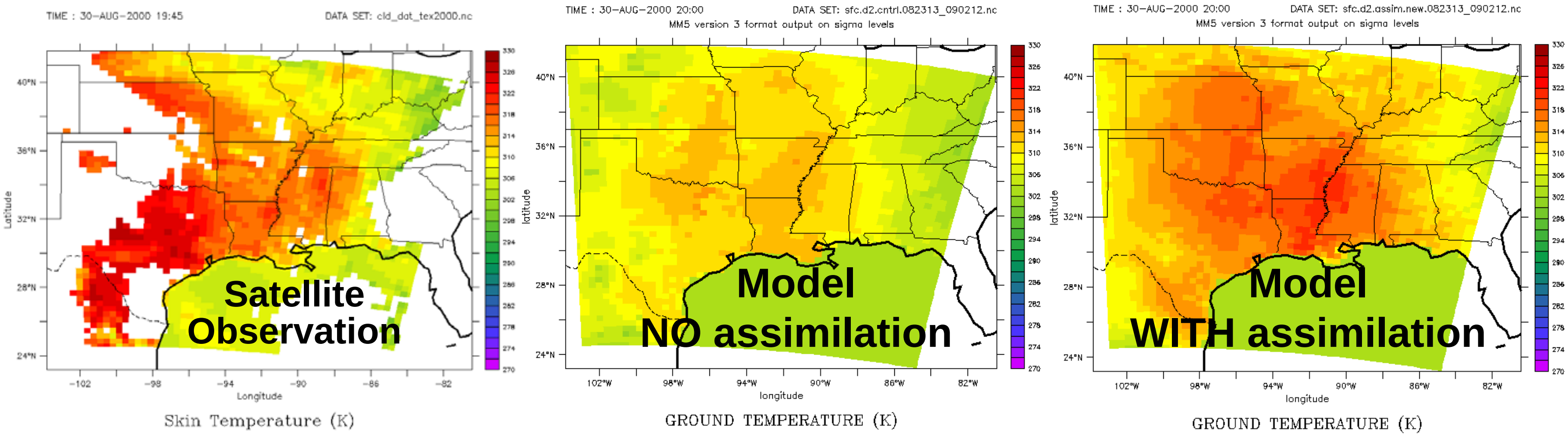
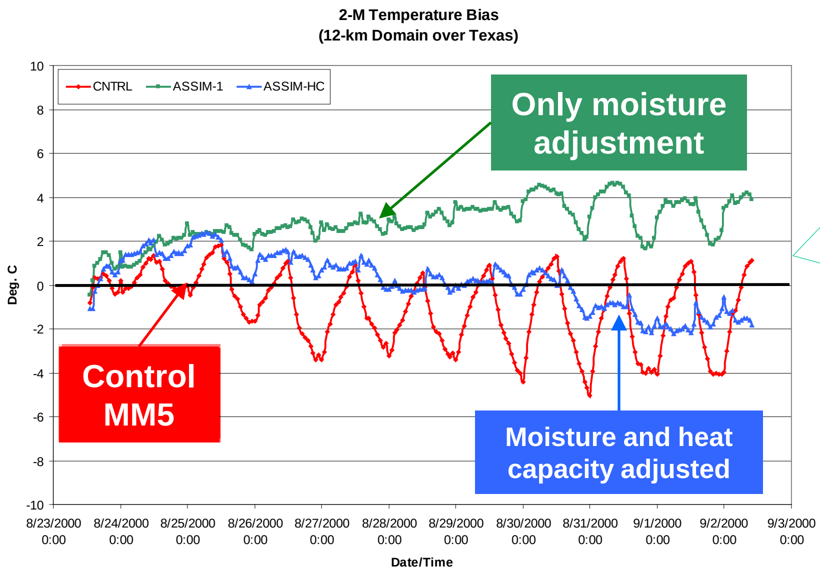


Our work during Texas Air Quality Study has shown that the satellite data assimilation technique greatly improves the surface/air temperature predictions.



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).

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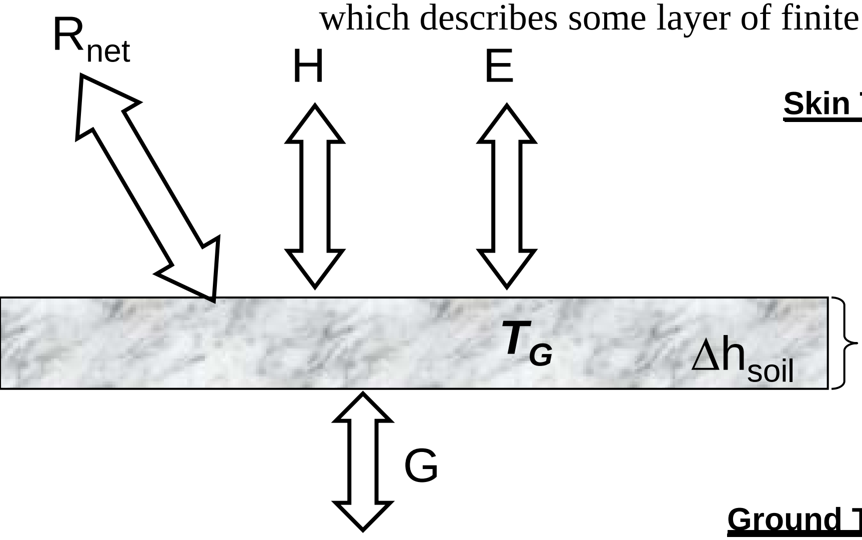
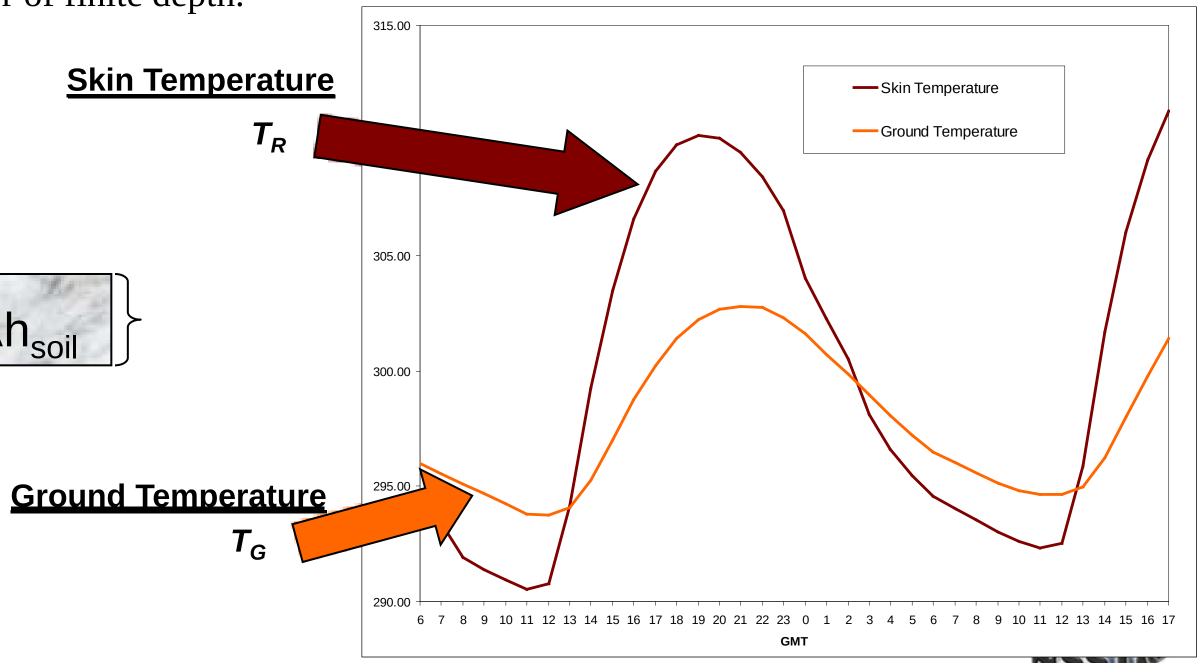
Addressing the Problem of Dry/Warm Bias in the Assimilation Technique

- 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.





Method

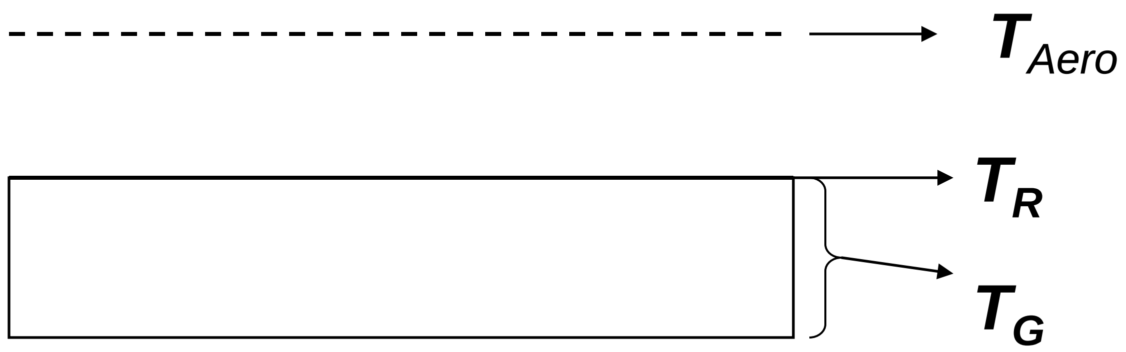
Step 1: Assuming an infinitesimally thin skin, we can solve for Skin temperature from diagnostic Surface Energy balance equation using root finding technique

Step 2: Apply Zilitinkevich (1970) adjustment to arrive at Aerodynamic temperature

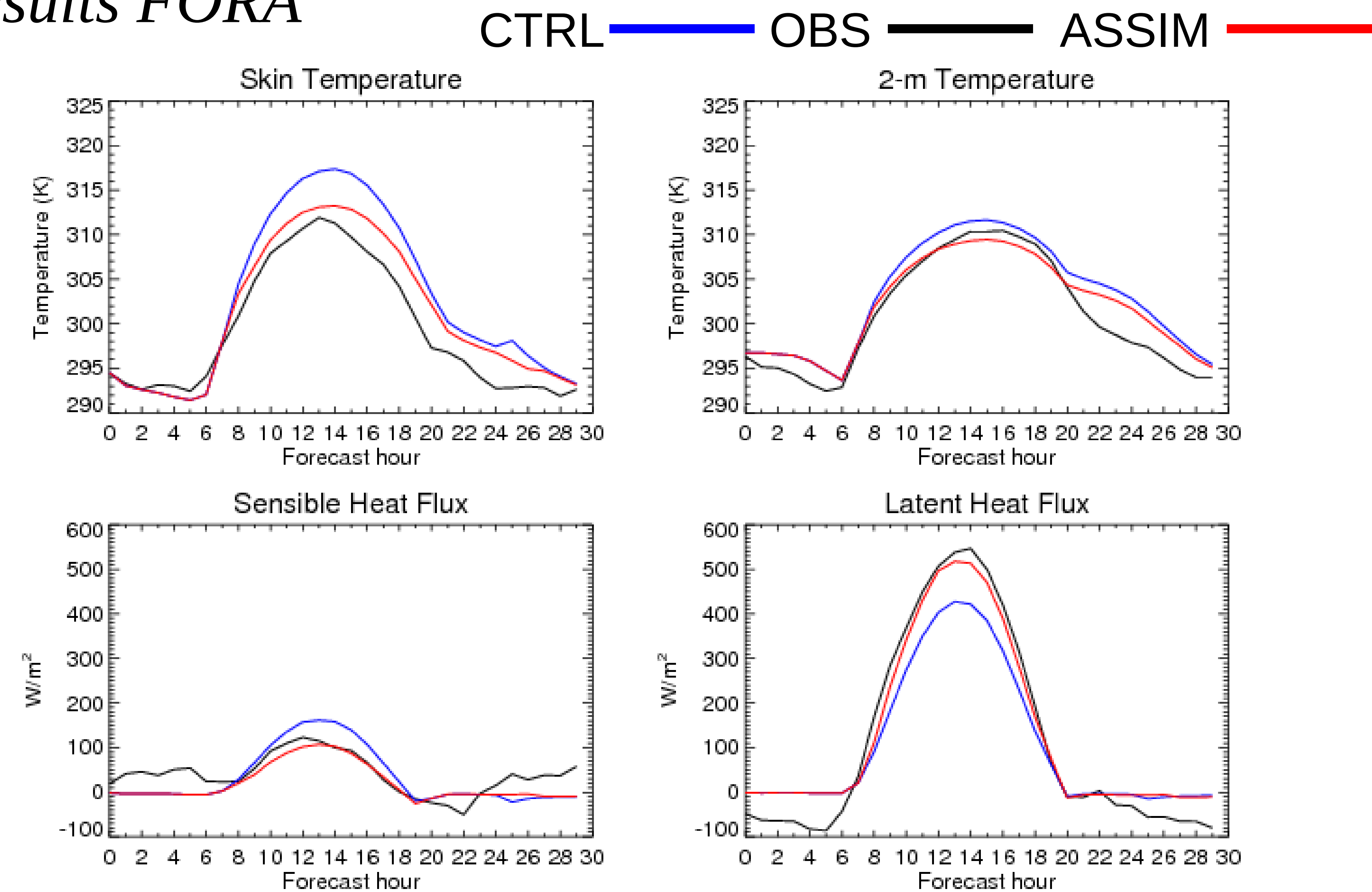
$$T_{Aero} = T_{Zo} = T_R + 0.0962\left(\theta_* / k\right)\left(u_* z_o / v\right)^{0.45}$$

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

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



Results FORA



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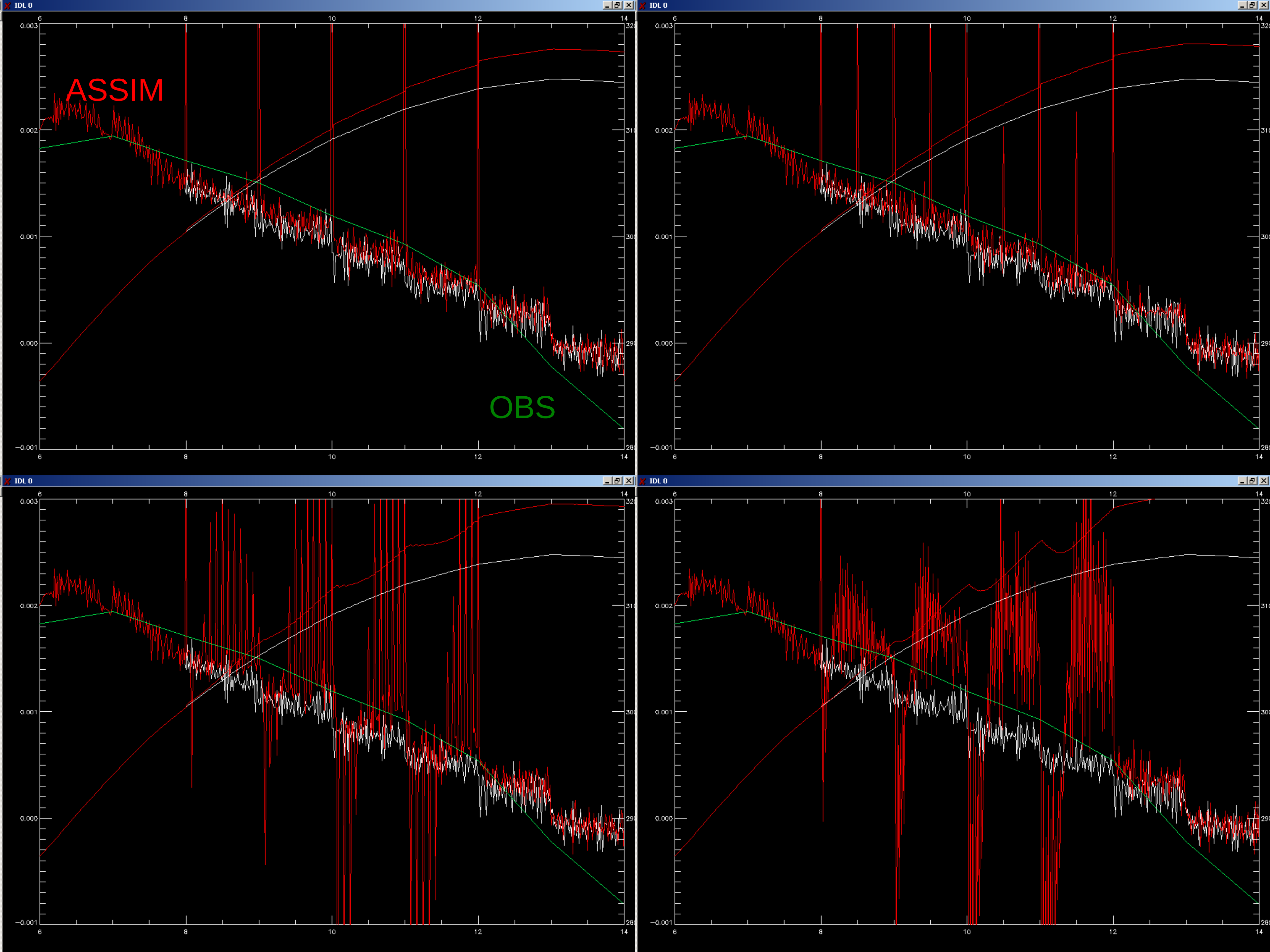

IDL 0
ASSIM
OBS
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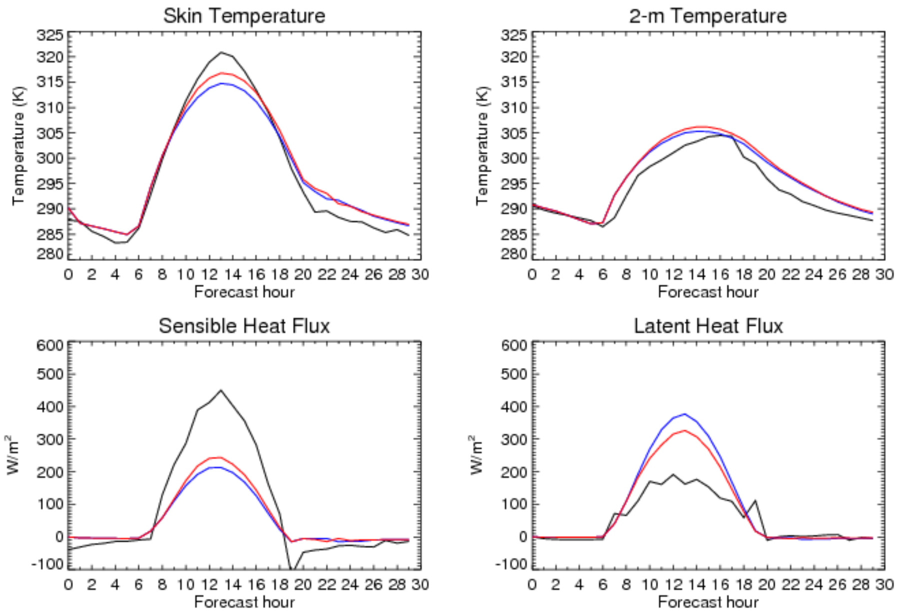
0.002
0.001
0.000
−0.001
6
8
10
12
14

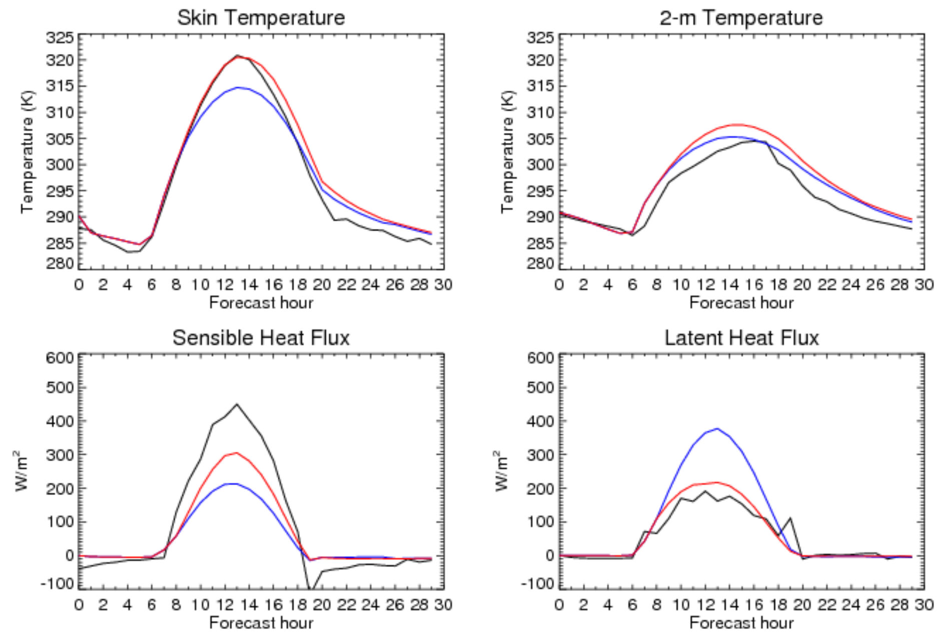
Results SGP

CTRL OBS ASSIM



Hourly adjustment

5 min. adjustment



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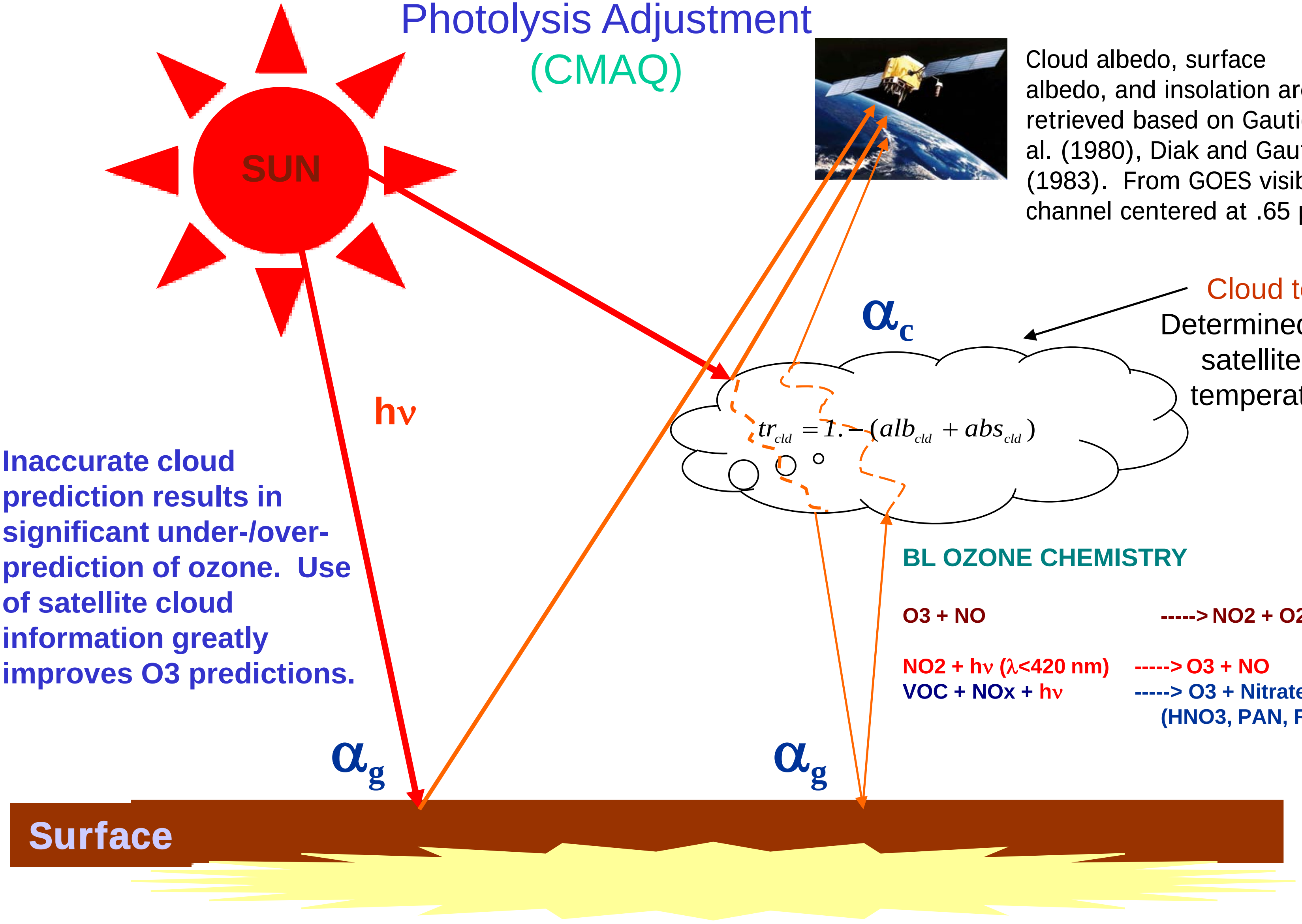
Photolysis Adjustment
(CMAQ)

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.

Cloud top
Determined from satellite IR temperature

Inaccurate cloud prediction results in significant under-/over-prediction of ozone. Use of satellite cloud information greatly improves O3 predictions.



Photolysis Rates

Satellite Method

Cloud top

Determined from satellite IR temperature

Transmittance =

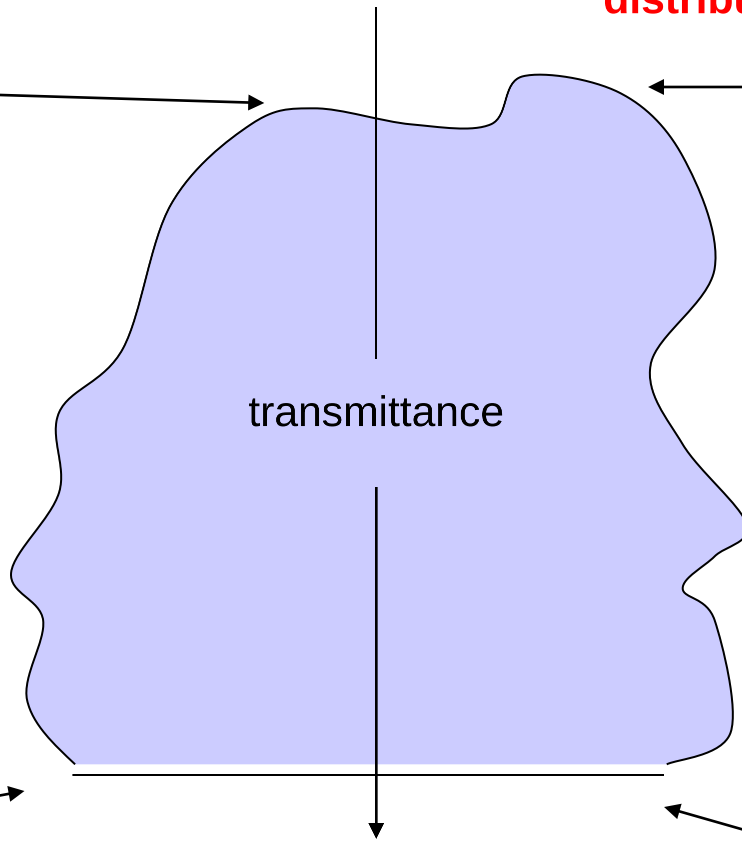
1- reflectance - absorption

Observed by satellite

F(reflectance)

Cloud Base

Determined from LCL



MM5 Method

Assume MM5 derived cloud distribution is correct

Cloud top

Determined from model

Transmittance

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

$$tr_{cld} = \frac{5 - e^{-\tau_{cld}}}{4 + 3\tau_{cld}(1 - f)}$$

Cloud Base

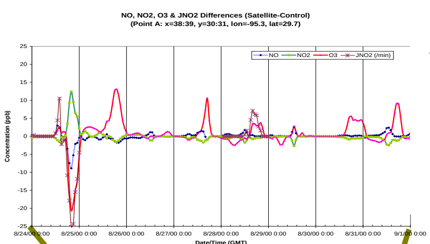
Determined from MM5

$$J_{below} = J_{clear}\left[1 + cfrac(1.6 tr_{cld} \cos(\theta) - 1)\right]$$

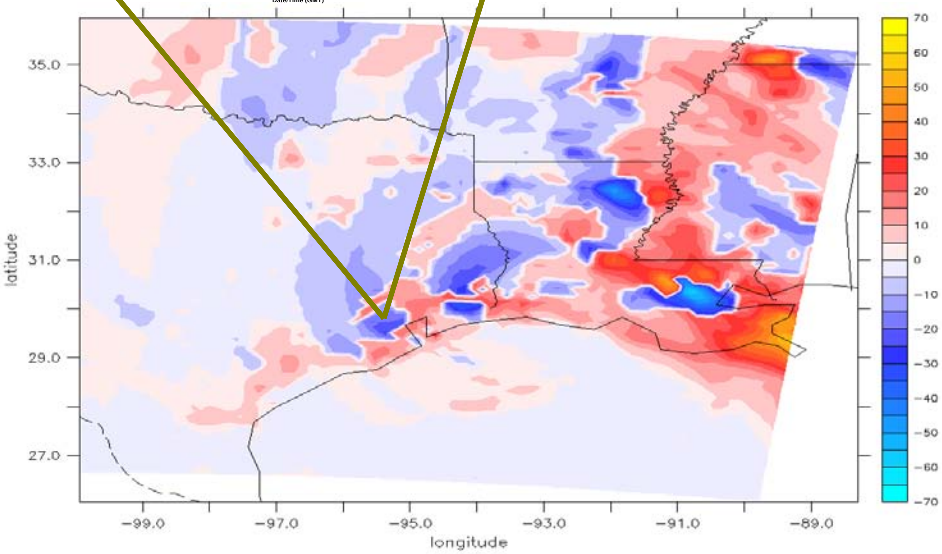
$$J_{above} = J_{clear}\left[1 + cfrac(\alpha_i (1 - tr_{cld}) \cos(\theta))\right]$$

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

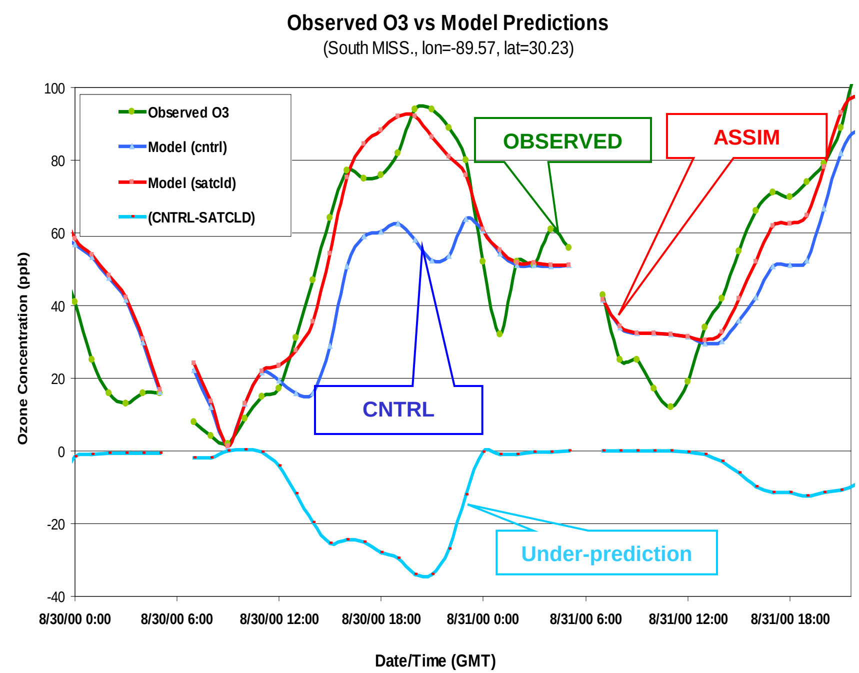


The differences between NO, NO2, O3 (ppb) and JNO2 from satellite cloud assimilation and control simulations for a selected grid cell over Houston-Galveston area.



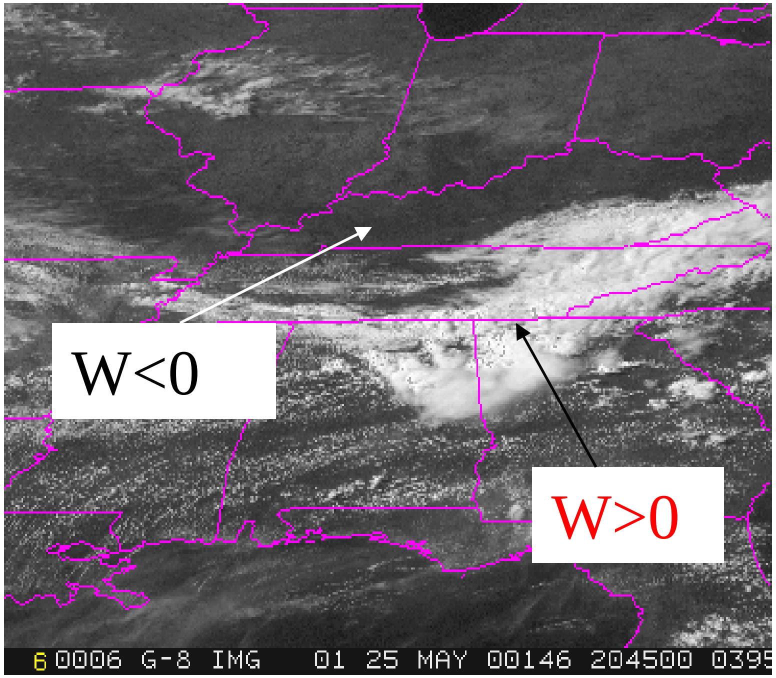
Max abs. diff in O3 concentration

Adapted from: Pour-Biazar et al., 2007



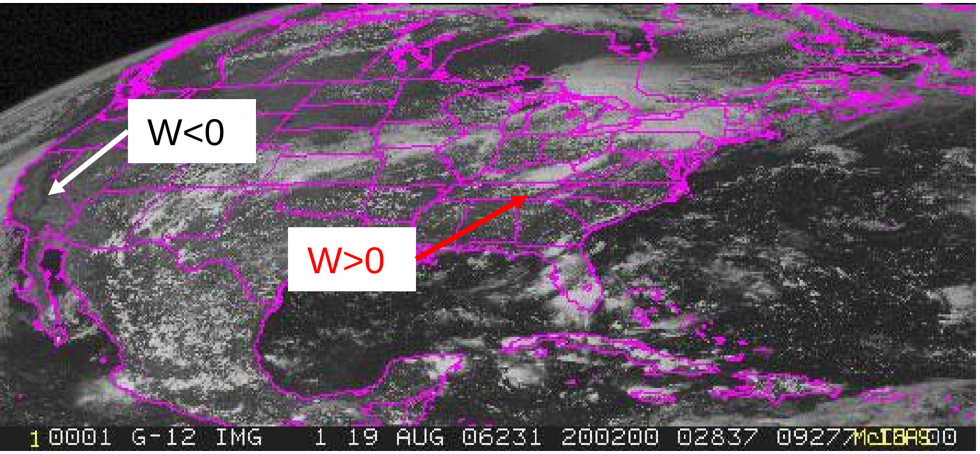
Clouds at the Right Place and Time

- Current Method for insolation and photolysis while improving physical atmosphere is inconsistent with model dynamics and cloud fields
- What if we can specify a vertical velocity supporting the clouds



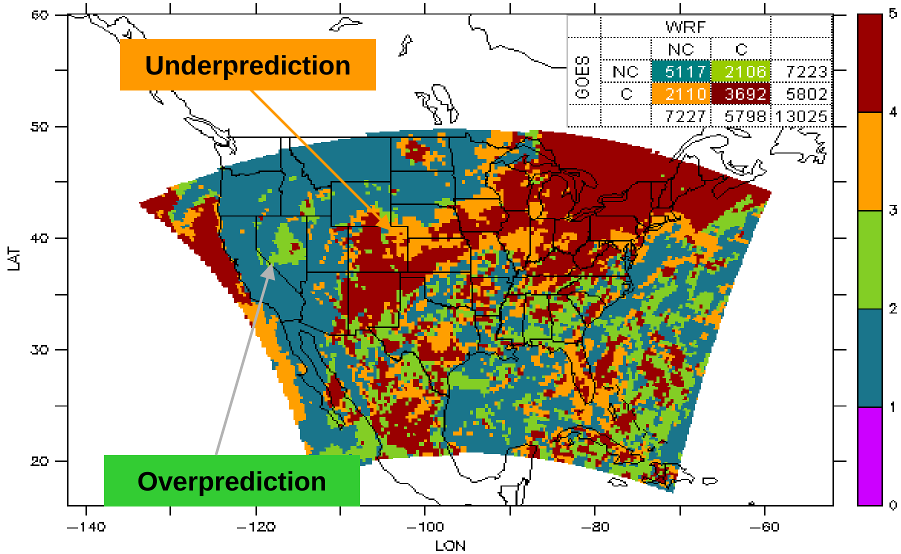
FUNDAMENTAL APPROACH FOR CORRECTING SIMULATED CLOUD FIELDS

Satellite



0.65um VIS surface, cloud features

Model/Satellite comparison



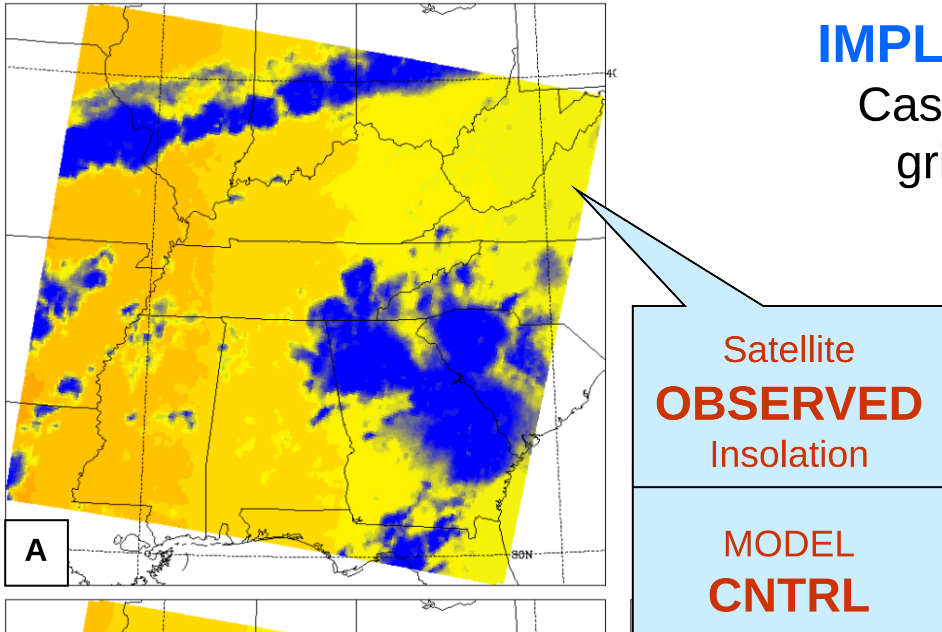
- Use satellite cloud top temperatures and cloud albedoes to determine a maximum vertical velocity (Wmax) in the cloud column (Multiple Linear Regression).
- Adjust divergence to comply with Wmax in a way similar to O’Brien (1970).
- Nudge MM5 winds toward new horizontal wind field to sustain the vertical motion.
- Remove erroneous model clouds by imposing subsidence and suppressing convective initiation.

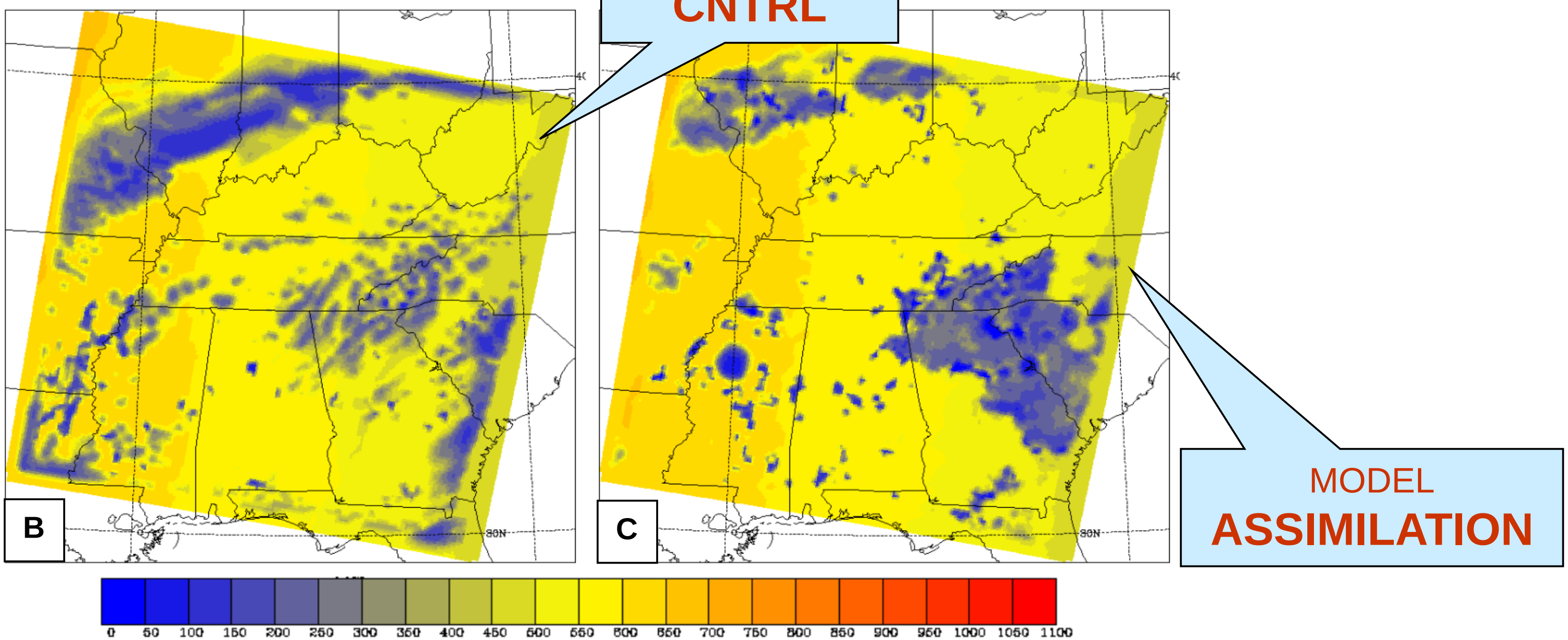
IMPLEMENTATION IN MM5

Case study: SOS 1999, 8-km grid, Kain-Fritsch scheme

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.





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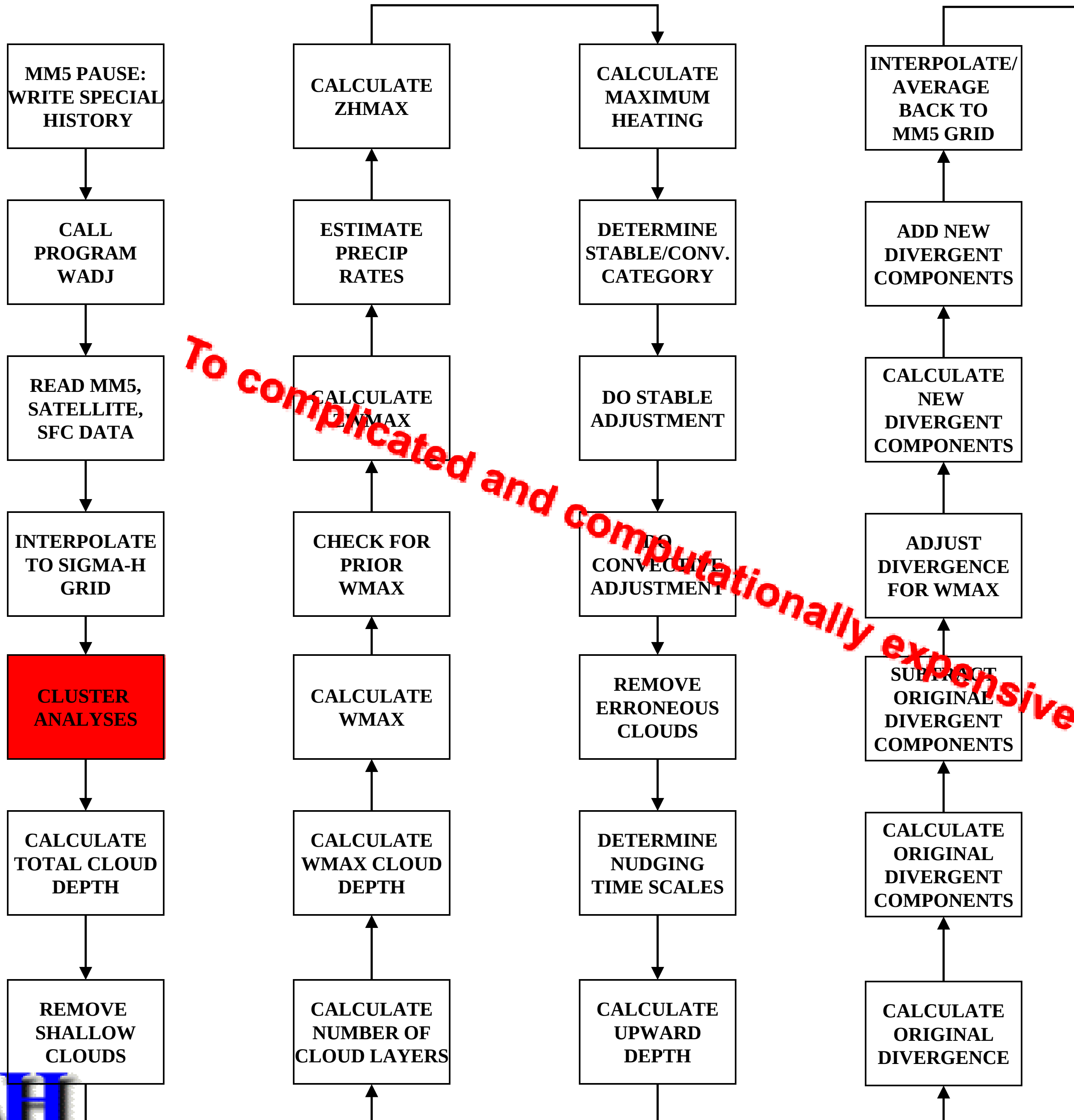


Flowchart showing the flow of the processes needed for cloud adjustment at each hour

CURRENT EFFORTS

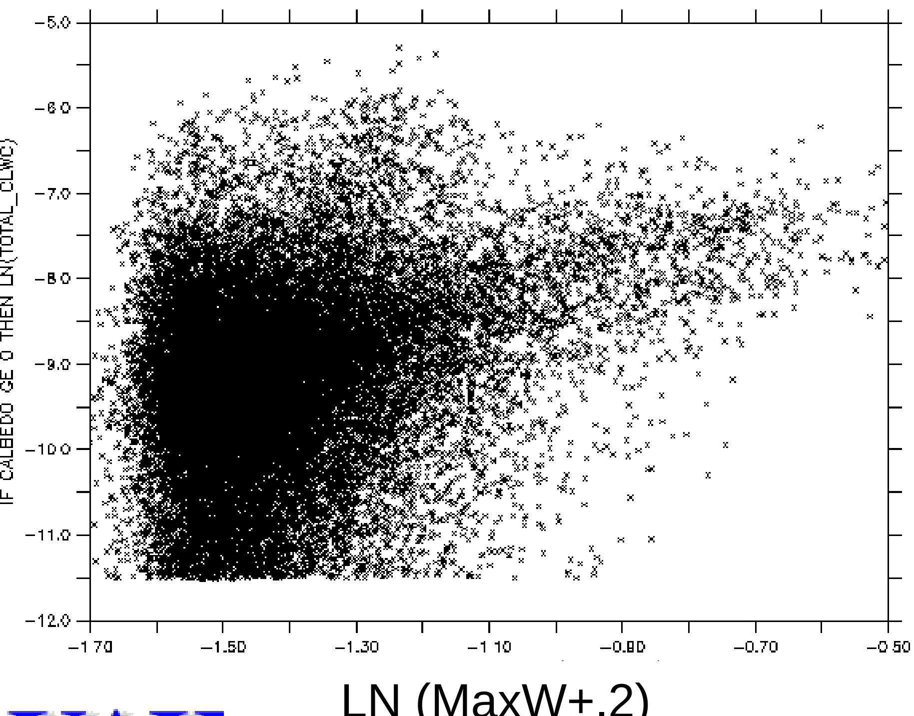
- **Two different tracks are followed:**
  - **Streamline the current technique and implement it in WRF.**
    - **Clearing erroneous clouds are more difficult in WRF. WRF's response to suppressing the convective parameterization is different from MM5 (WRF compensate by creating grid resolved clouds).**
  - **Revisit the problem and develop a simpler approach.**
    - **Focusing on daytime clouds, revisit the relationship between internal model cloud variables and relate them to what satellite can observe.**

RESULTS FROM SECOND TRACK ARE PRESENTED HERE

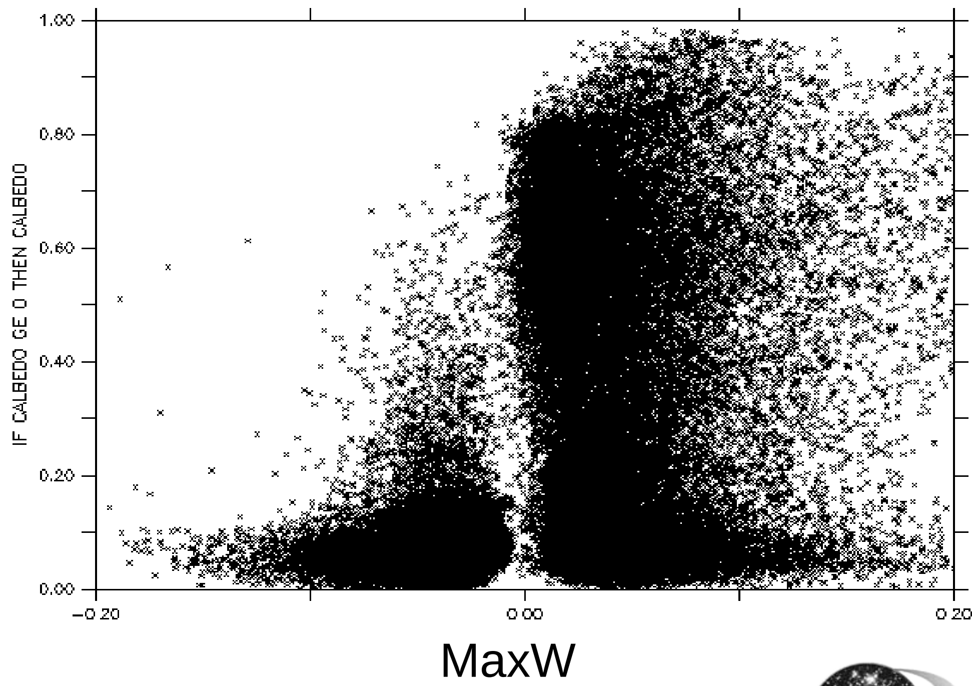
- **Case study: summer of 2006; WRF configuration: 36-km grid spacing, CONUS with 42 vertical layers; SW radiation: Dudhia; LW radiation: RRTM; Monin_Obukhov similarity with NOAH LSM; PBL scheme: YSU; Microphysics: Lin; Cumulus parameterization: Kain-Fritsch, New Grell, Grell-Devenyi; IC/BC/nudging: EDAS.**

NO CLEAR FUNCTIONAL RELATIONSHIPS BETWEEN CLOUD WATER AND/OR CLOUD ALBEDO WITH MODEL VERTICAL MOTION

Scatter plot of total cloud water and maximum vertical velocity in the model column

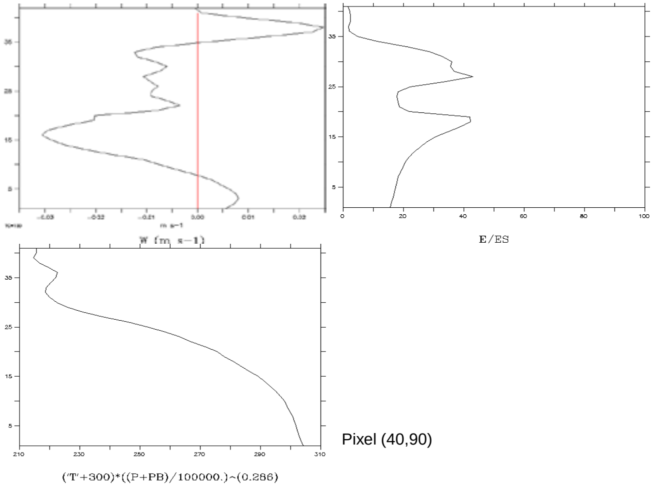


Scatter plot of cloud albedo versus maximum vertical velocity in the column



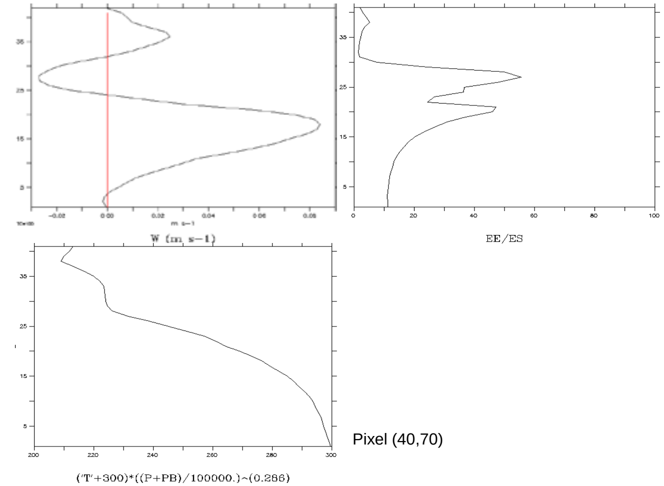
Individual profiles indicate that the appropriate vertical velocity is tied to vertical position in the column and most importantly the vertical velocity must be occurring in area of reasonable moisture for clouds to develop. Thus it appears that clouds have a very sharp threshold of when clouds form.

Subsidence, and dry atmosphere



Pixel (40,90)

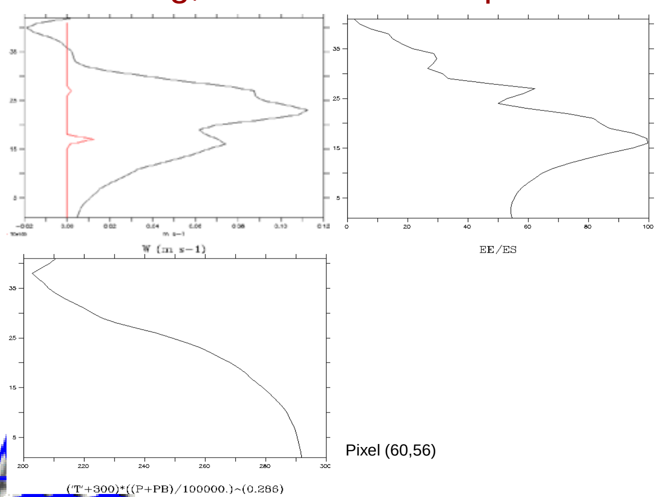
Lifting, but dry atmosphere



Pixel (40,70)

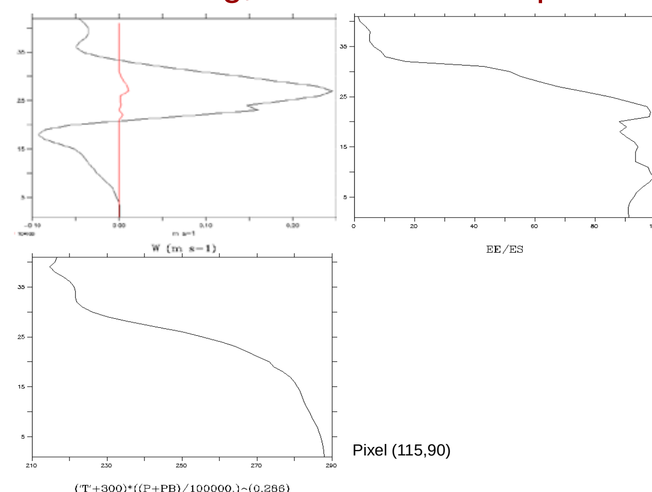
Clear grids

Lifting, and moist atmosphere



Pixel (60,56)

Small lifting, and moist atmosphere

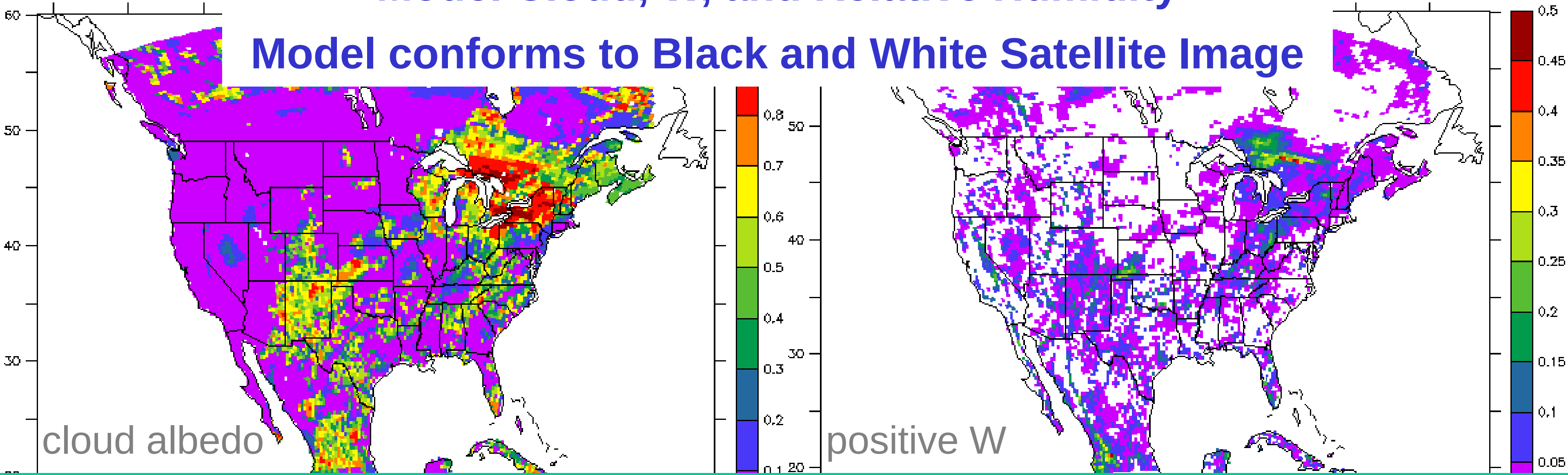


Pixel (115,90)

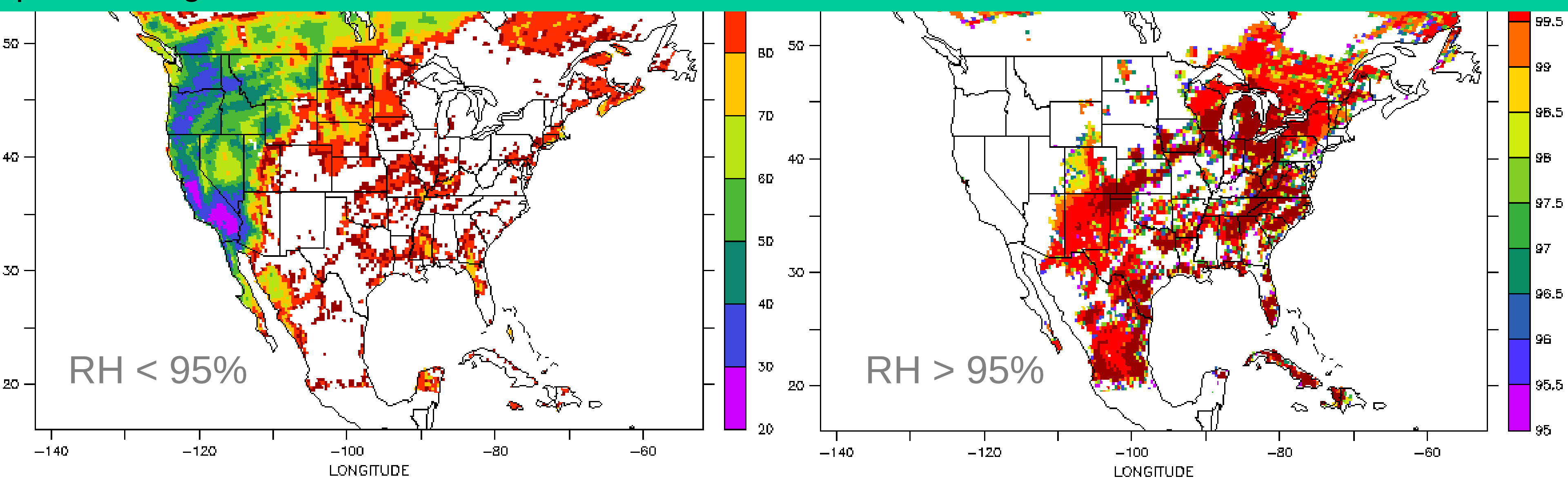
Cloudy grids

Model Cloud, W, and Relative Humidity

Model conforms to Black and White Satellite Image



Functional relationships between cloud water and/or cloud albedo with model vertical motion was not clear. Thus, threshold relationships with vertical motion and relative humidity were examined. A contingency probability approach, where the coincidence of clouds/clear occurring with positive/negative vertical motion were examined.



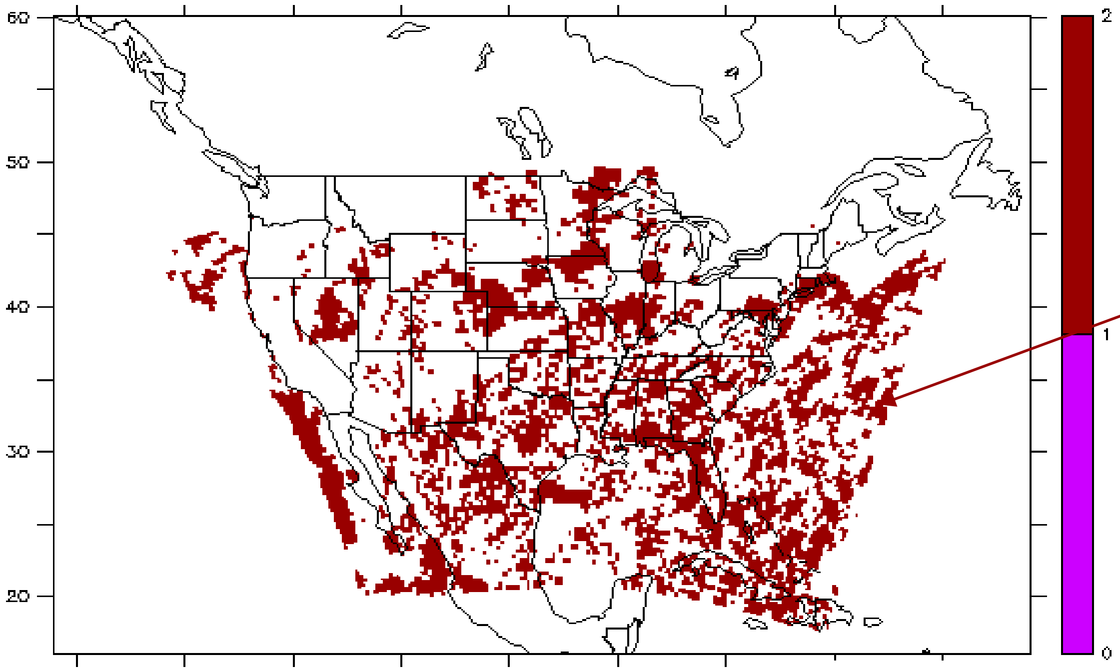
Alternative Simple Approach for Creating Dynamical Support for Clouds

- Obtain threshold vertical velocities and moisture needed to support cloud formation from WRF.
- From GOES observations identify the areas of cloud under-/over-prediction and use the threshold information to obtain the needed vertical velocity in the model to achieve agreement with observations.
- Having the threshold vertical velocity as the target, use one dimensional variational technique to calculate new divergence fields and target horizontal winds.
- Use the new horizontal winds and threshold moisture fields as nudging fields in WRF to sustain the target vertical velocity.

Threshold Table for target W (August 2006 Simulation)

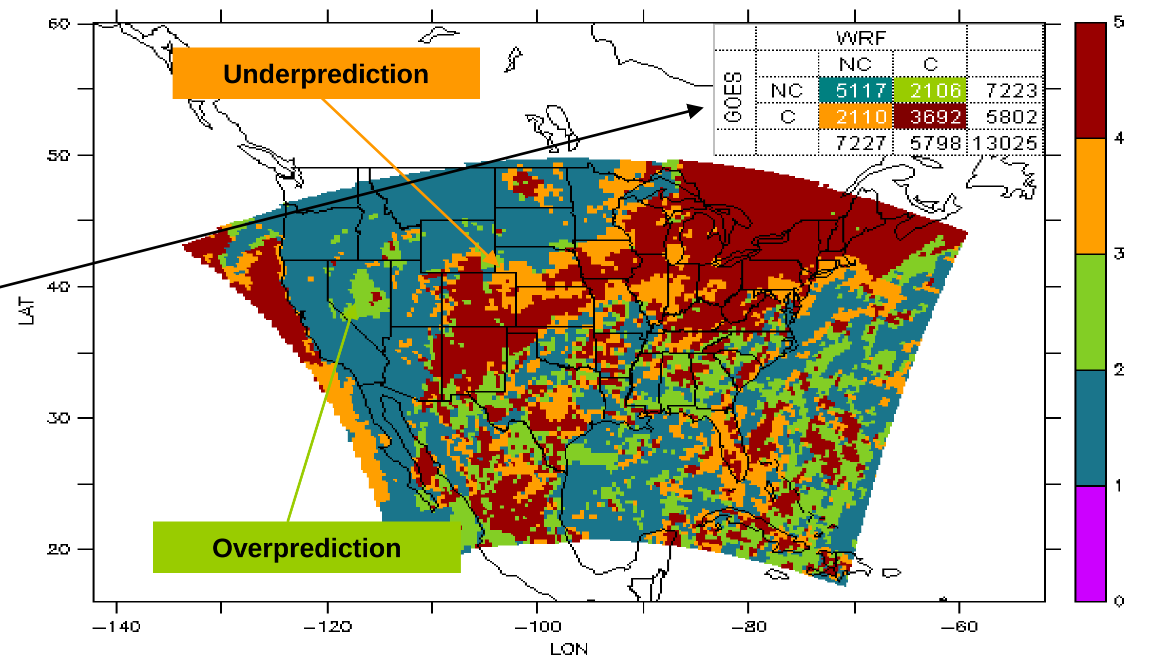
		CLEAR				CLOUD			
		OCEAN		LAND		OCEAN		LAND	
height (m)		w (m/s)	RH (%)	w (m/s)	RH (%)	w (m/s)	RH (%)	w (m/s)	RH (%)
sfc	1000	-0.00253	72.08438	0.00377	39.52232	0.004865	99.12765	0.01269	99.6
1000	2000	-0.00588	59.14449	-0.00278	51.23995	0.034022	97.07111	0.02132	99.9
2000	4000	-0.00499	49.06997	-0.00745	41.42338	0.045954	95.62551	0.04551	100
4000	7000	-0.00608	40.36083	-0.01002	31.64465	0.054684	101.8438	0.06112	100
7000	10000	-0.01260	44.54638	-0.01433	36.94441	0.058007	99.79606	0.05639	98.96
10000	13000	-0.01579	47.13423	-0.01054	33.53775	0.065545	97.62615	0.05350	96.8
13000	~top	0.00018	33.25936	0.00067	19.85797	0.044565	94.18938	0.03255	93.2

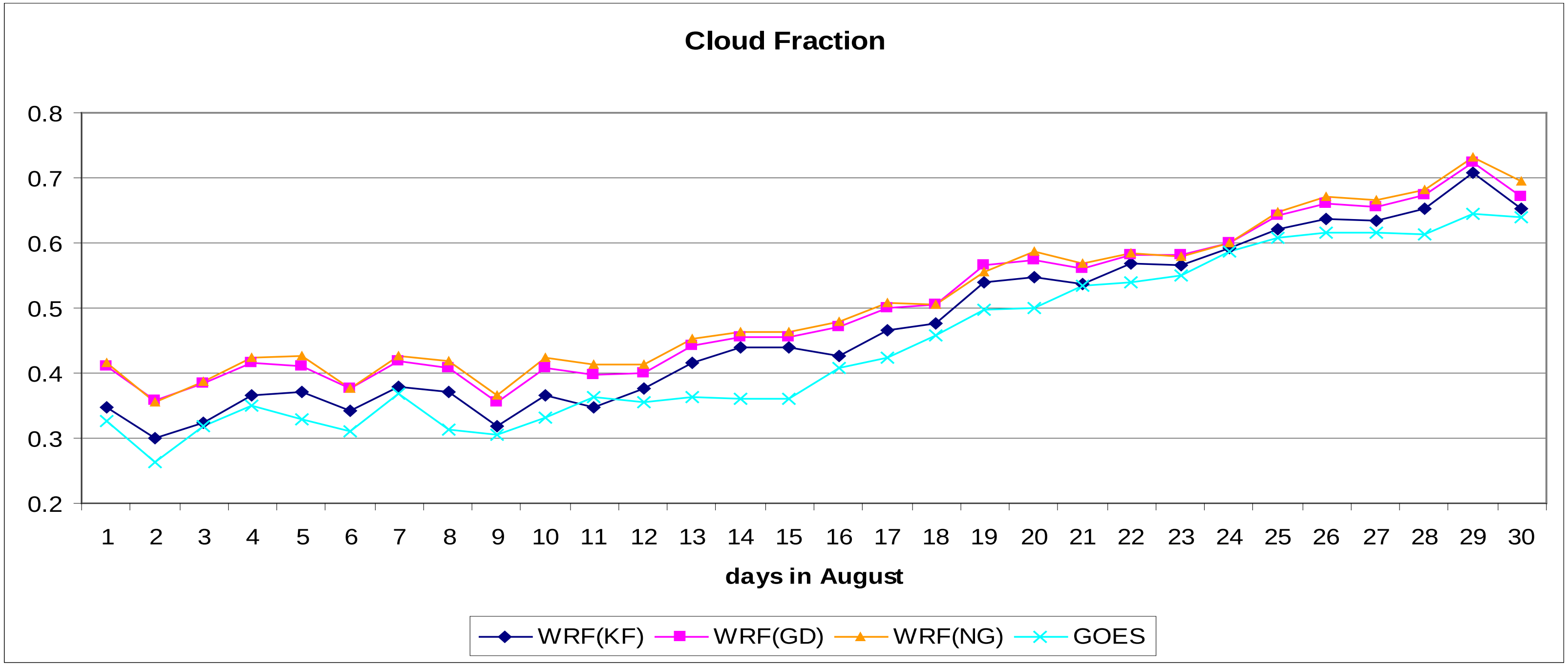
Areas of Underprediction/Overprediction can be identified for Correction

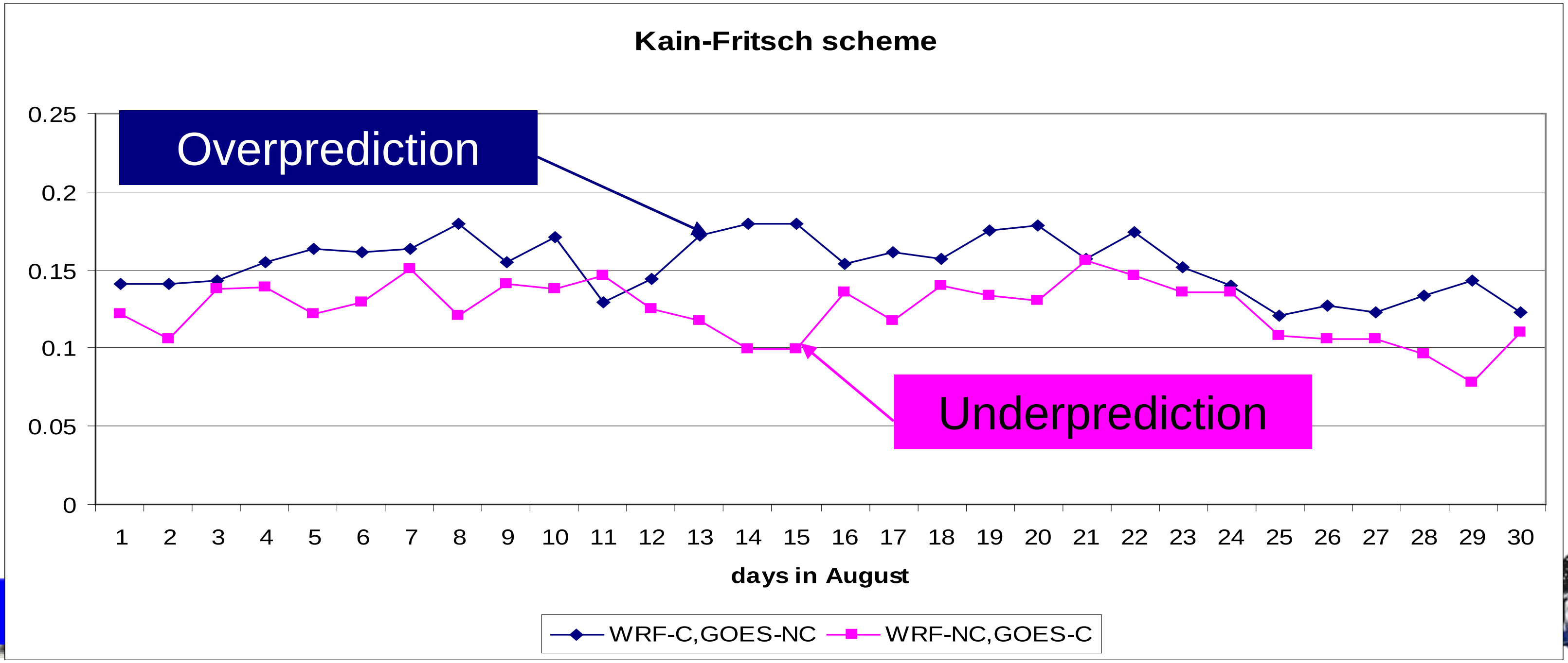


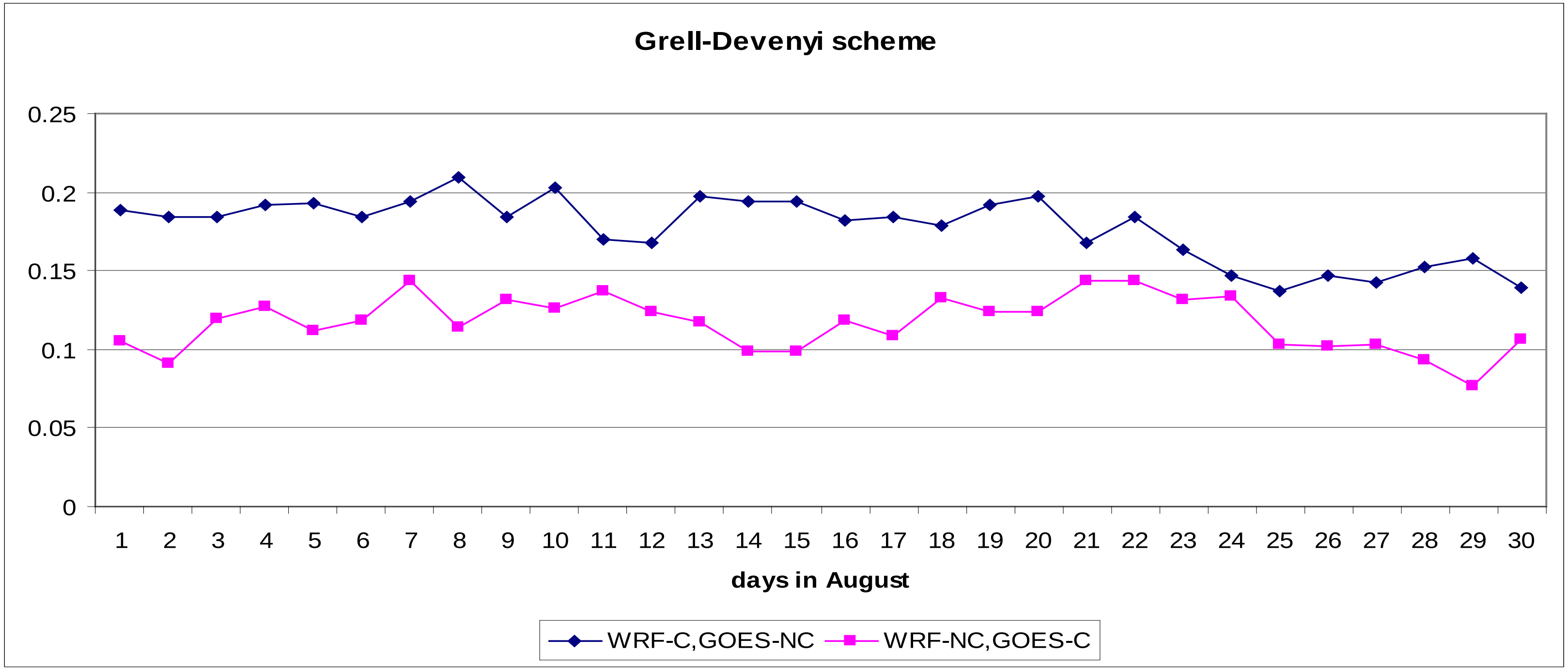
Areas of disagreement between model and satellite observation

A contingency table can be constructed to explain agreement/disagreement with observation

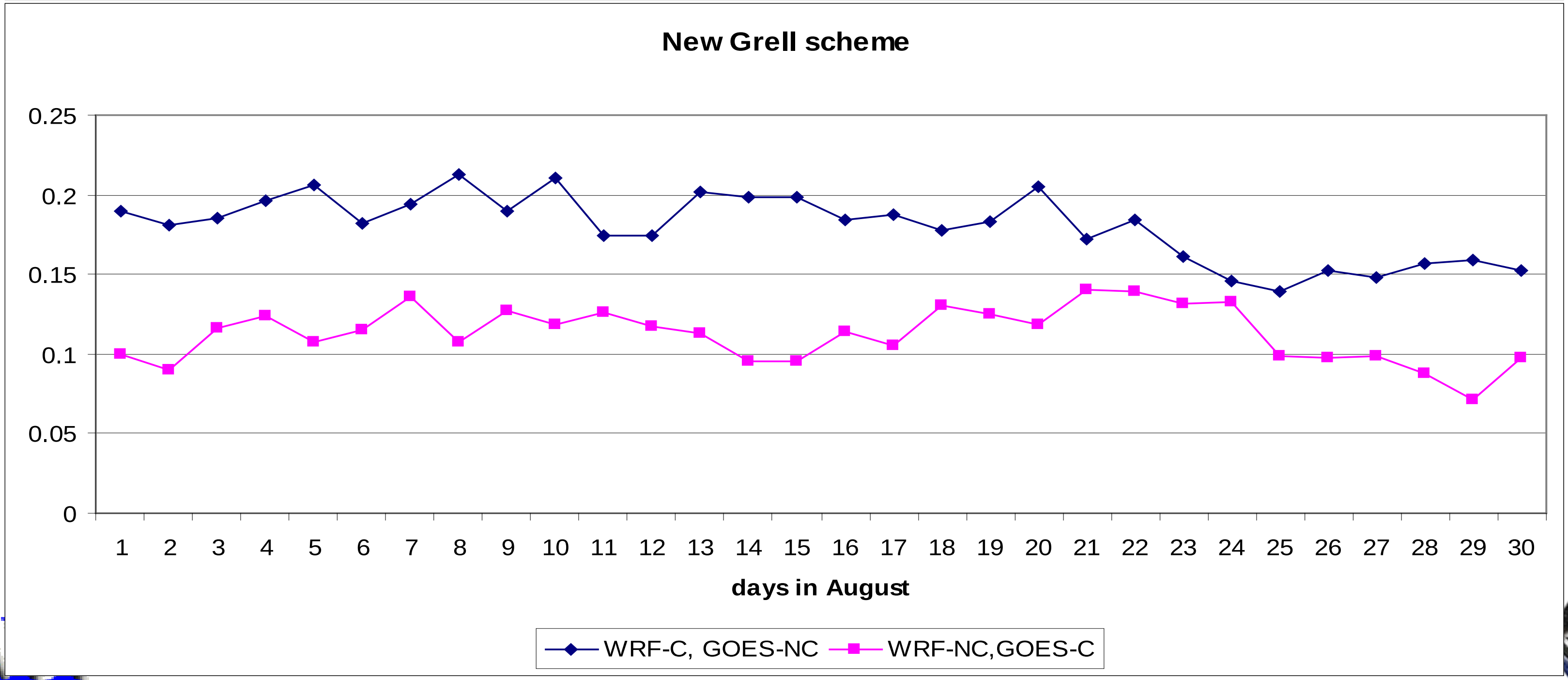



Cloud Fraction
0.8
0.7
0.6
0.5
0.4
0.3
0.2
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
days in August
WRF(KF)
WRF(GD)
WRF(NG)
GOES


Kain-Fritsch scheme
Overprediction
Underprediction
0.25
0.2
0.15
0.1
0.05
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
days in August
WRF-C,GOES-NC
WRF-NC,GOES-C

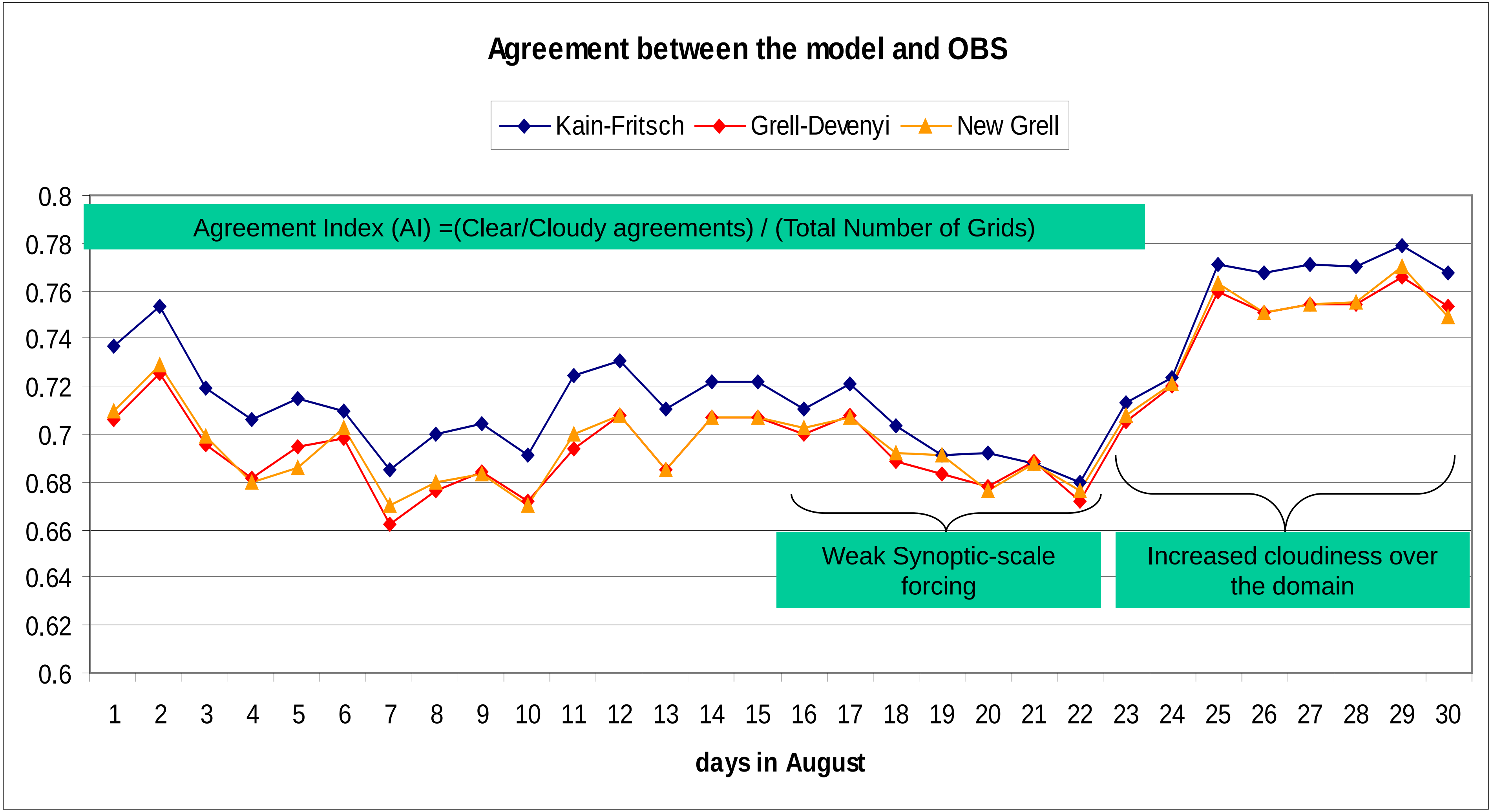


Grell-Devenyi scheme
0.25
0.2
0.15
0.1
0.05
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
days in August
WRF-C,GOES-NC
WRF-NC,GOES-C



New Grell scheme
0.25
0.2
0.15
0.1
0.05
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
days in August
WRF-C, GOES-NC
WRF-NC,GOES-C

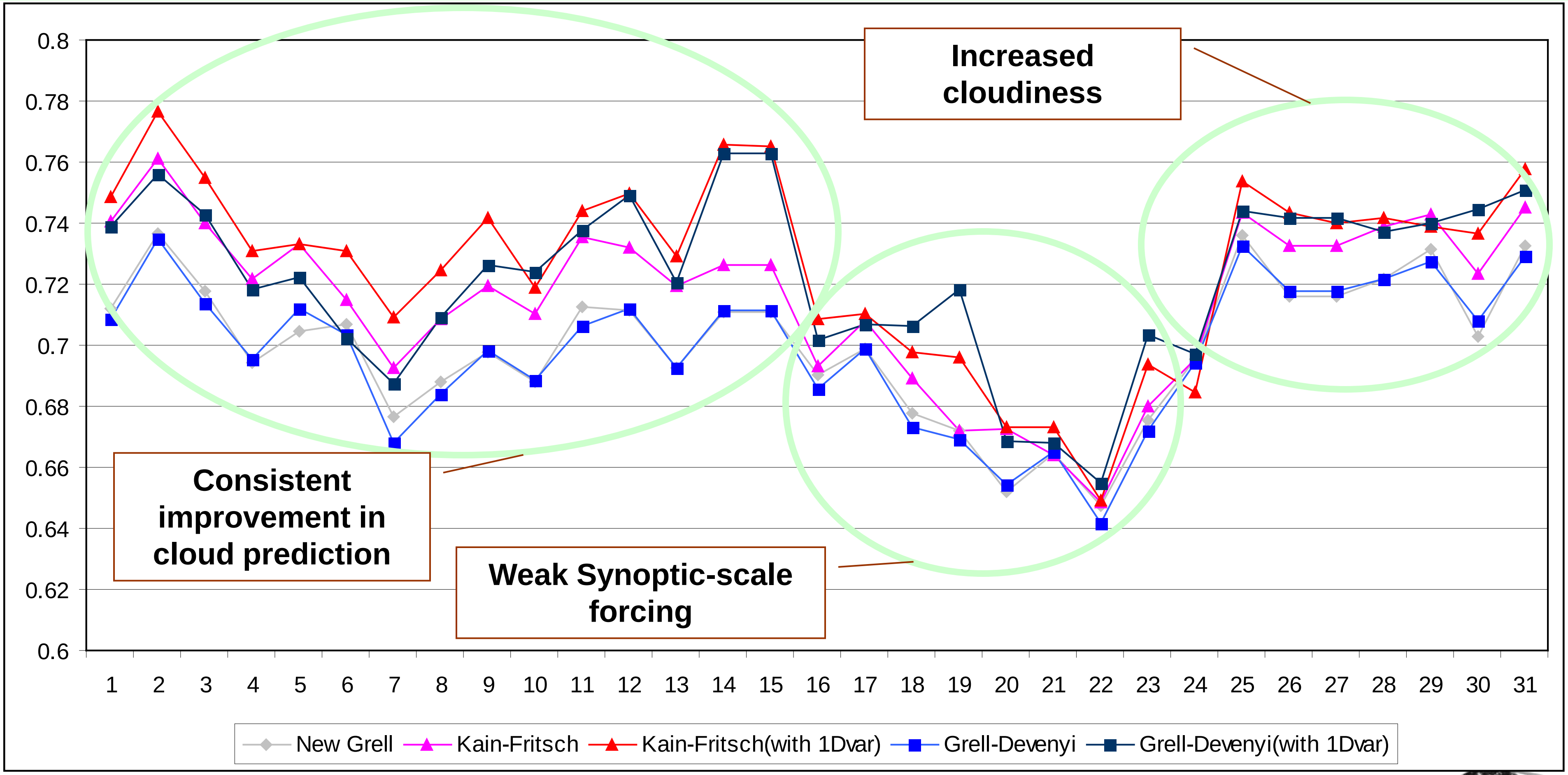
Evaluating Model Cloud Prediction During August 2006



RESULTS FROM MONTH LONG SIMULATION

Regardless of convective parameterization scheme used, cloud assimilation improves model/observation agreement for most days

Agreement Index (AI) =(Clear/Cloudy agreements) / (Total Number of Grids)



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CONCLUSION & FUTURE WORK

- While functional statistical relationships between clouds and WRF model variables were not clear, an examination of coincident relations showed that threshold relations between vertical motion and relative humidity were very robust.
- 98% of the model cloudy grids were associated with positive vertical motions and over 65% of the grids with clear condition were associated with negative vertical motions. This largely confirms the working hypothesis that in a GOES black and white image, white areas are associated with lifting and negative areas with subsidence.
- Adjusting model dynamics based on GOES observations, using threshold vertical velocities demonstrated improvements in model cloud prediction. The technique was tested with Grell-Devenyi and Kain-Fritsch convective parameterization schemes over a month-long simulation and showed improvement over baseline simulations.
- The technique did not perform as expected for some periods in August when a stationary front was present. These periods should be studied in detail.

- While the current results are encouraging, the technique needs further refinements.
- Concurrent adjustment of relative humidity consistent with model statistics is needed to insure the effectiveness of dynamical adjustment.
- Currently the statistical approach in finding target vertical velocity is being replaced with an analytical method.

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