Data Assimilation of Cloud-Affected Radiances

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Outline

- Motivation
- Methodology
- Results
  - Observation operators
  - Assimilation and verification
- Summary and conclusions

Motivation
4D atmospheric data analysis with clouds

- Initialization of atmospheric state with clouds in NWP
- Validation and advanced development of cloud microphysical parameterizations
- Dynamically consistent cloud and state climatology

Research approach: Evaluate feasibility under best scenario

- Use observations with highest expected information content with respect to clouds, including spatial and temporal variability
- Use cloud resolving model
- Use data assimilation method which allows 4D dynamically consistent analysis

OBSERVATIONS
GOES imager
and
ARM

MODEL
CRM with bulk
explicit cloud
microphysics

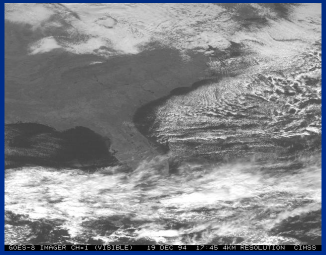
METHOD
4DVAR data assimilation

Collaborators : Tom Greenwald (CIMMS, formerly CIRA), Milija Zupanski (CIRA), Dusanka Zupanski (CIRA), Manajit Sengupta (formerly CIRA), Frank Evans (ATOC/CU) and Rosanne Polkinhorne (ATOC/CU)

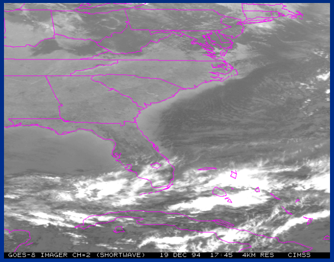
GOES imager

GOES Channel		Wavelength (µm)	Central Wavelength (µm)	Detector Resolution (km)
1		0.52-0.72	0.7	1
2		3.78-4.03	3.9	4
3		6.47-7.02	6.7	8
3	G12	5.77-7.33	6.5	4
4		10.2-11.2	10.7	4
5		11.5-12.5	12.0	4
6	G12	12.9-13.7	13.3	8

15 minute data

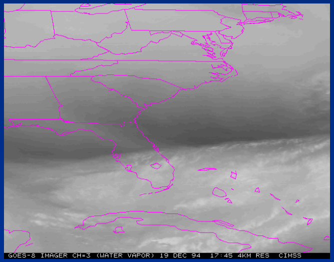


VIS

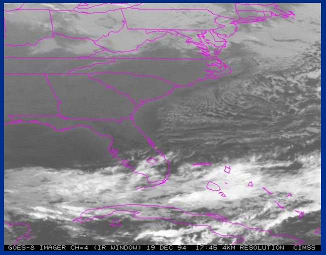


Near IR

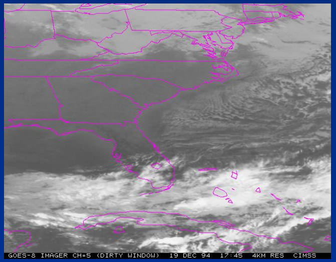
Diff between ice and water clouds



IR upper water vapor



IR clouds and surface

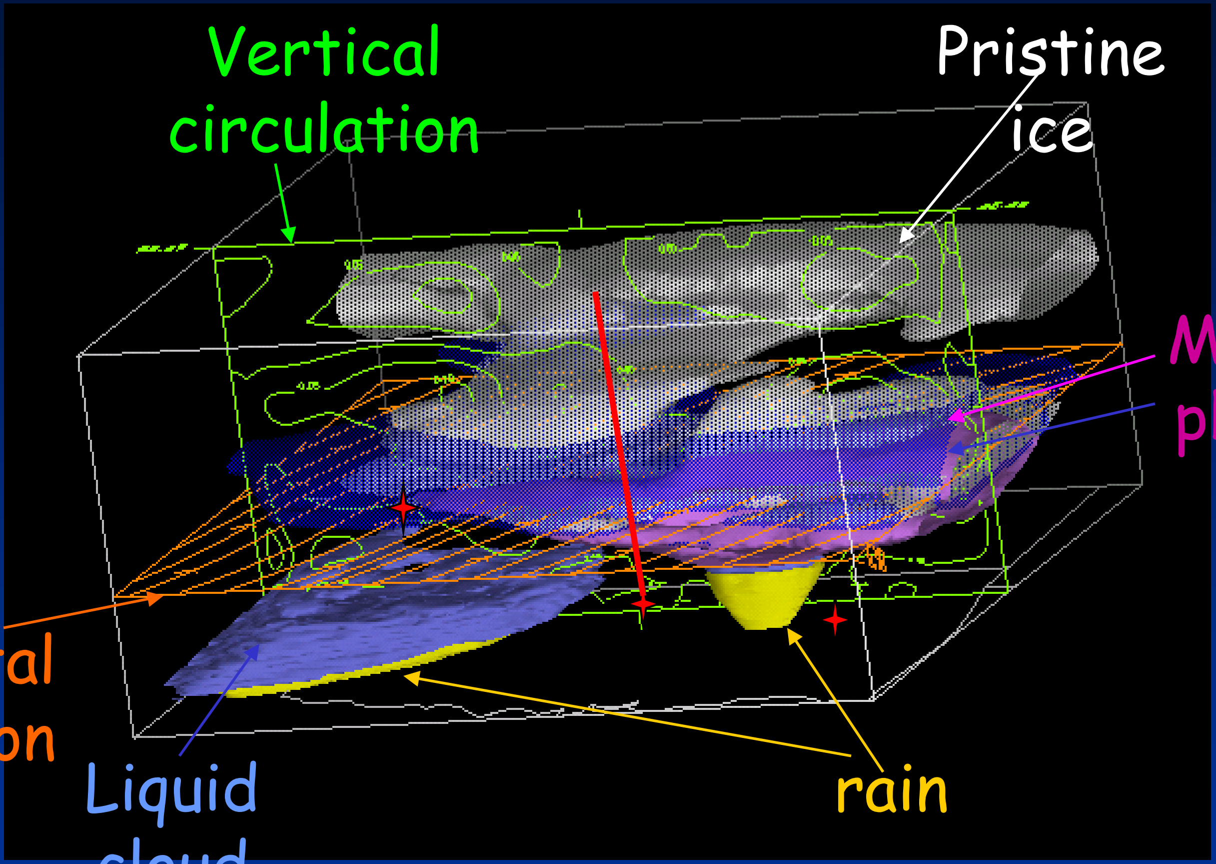


IR clouds, surface and low level vapor

Cloud resolving model representation of cloudy atmosphere

CRTM simulation in 300 x 300 x 17 *km*

domain starting from a crude 3D analysis



CRTMs have skill

CRTM in this study RAMS

- Bulk, 2 moment cloud microphysics for ice: pristine ice, aggregates, snow, graupel and hail
- 1 moment for liquid: cloud droplets and and rain
- Prognostic mixing ratio and number concentration for ice
- Assumed Gamma distribution with prescribed width
- Nonhydrostatic dynamics
- High resolution regional simulations

4DVAR algorithm

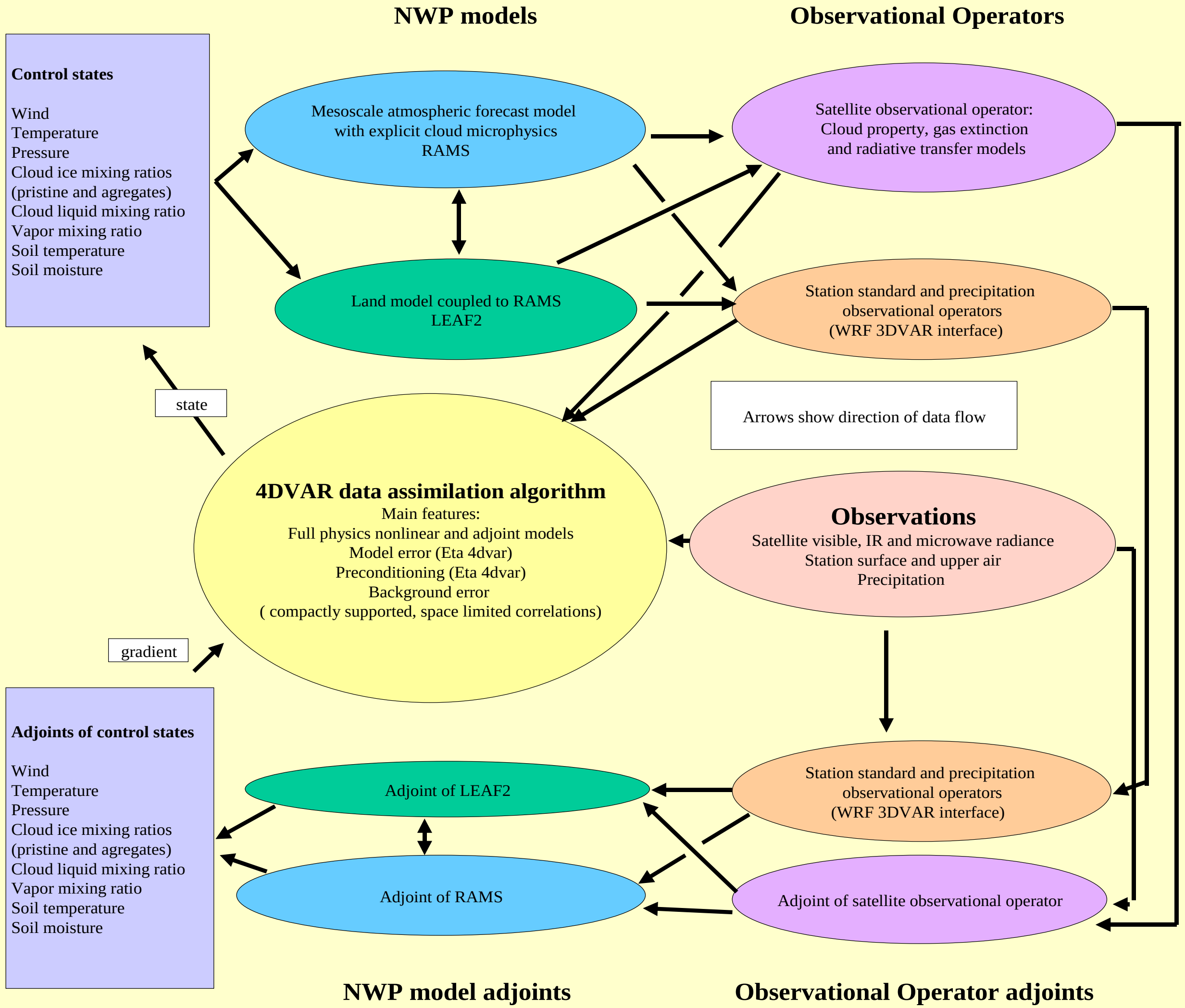
Regional Atmospheric Modeling and Data Assimilation System

Controls include cloud and dynamical variables

(RAMDAS)

Vukicevic et al, 2004,2005

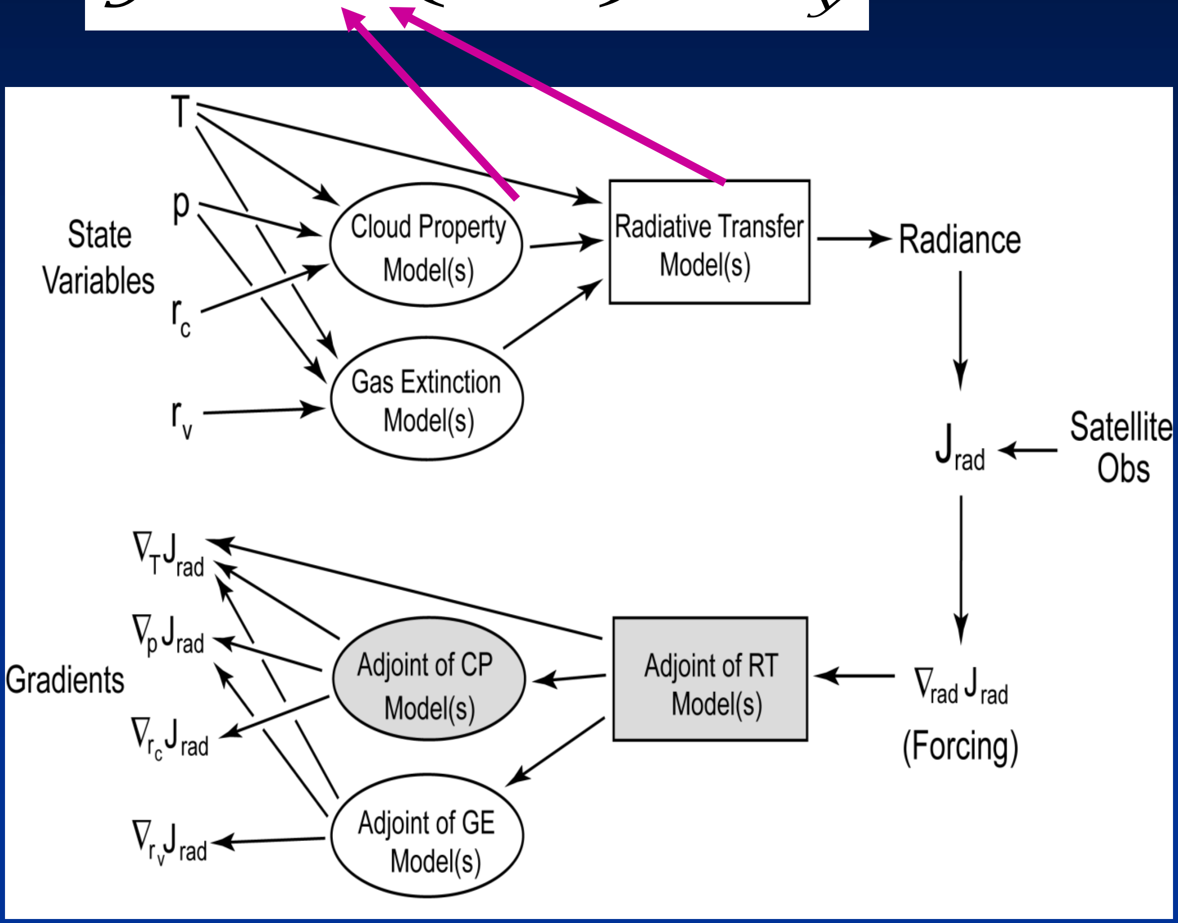
Zupanski et al 2005



Adjoint of cloud microphysics and radiative transfer

Observation operator
VIS and IR radiative transfer

$$y = H(X^t) + \varepsilon_y$$



Version 1

Greenwald et al. 2003

Gas absorption: OPTRAN (McMillin et al., 1995)

Cloud properties:Anomalous Diffraction

Solar: SHDOM (Evans, 1998)

IR: Eddington two-stream (Deeter and Evans 1998)

Version 2

SHDOMPPDA (Evans, 2007)

SHDOMPPDA operator
Evans (2007, JAS)

- Development was supported by JCSDA and NSF-ATM

- Unpolarized, plane parallel RT model with adjoint and tangent linear models
- Hydrometeor optical properties are determined from lookup tables as function of mass mean radius
- Scattering by look-up tables
  - Mie theory for spherical particles with Gamma or Lognormal size distributions
  - Gamma size distribution of mixture of 6 ice crystal shapes (Yang et al., 2005)

Information content of GOES imager observations

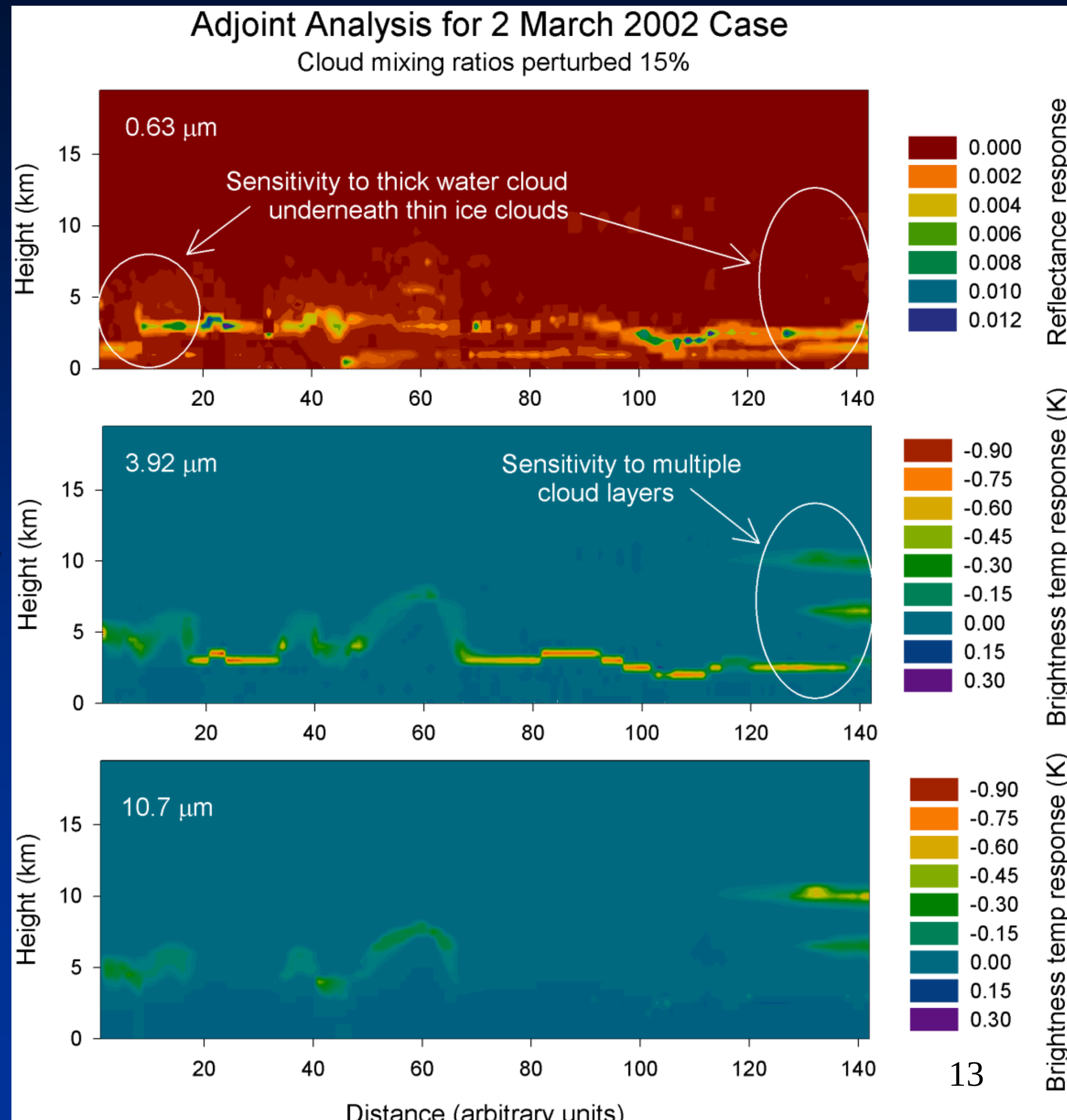
VIS and IR information content analysis

Example of a case with mixed phase clouds

Visible

Near IR

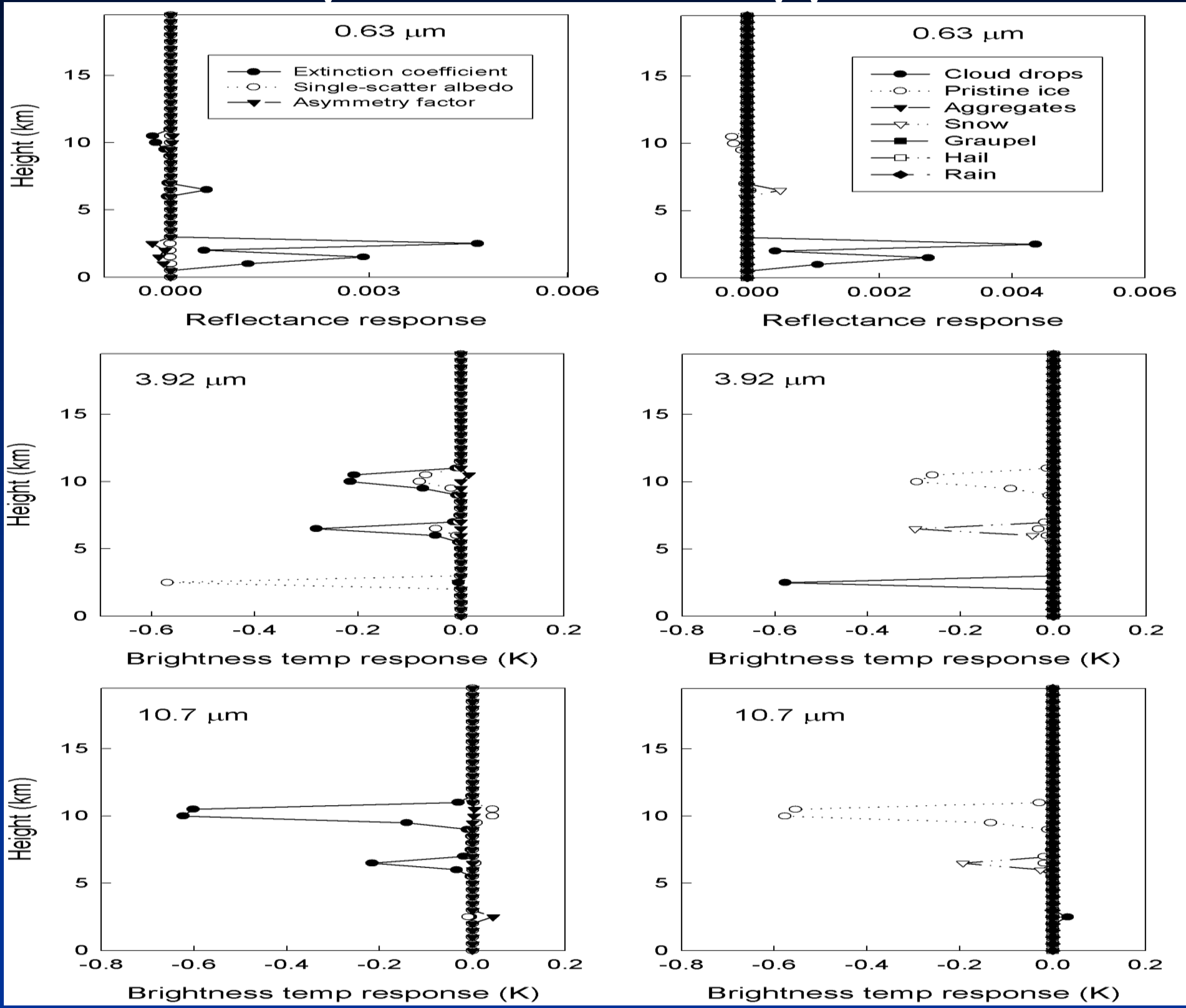
IR



- Vertical and horizontal variability
- Sensitivity to multiple cloud layers

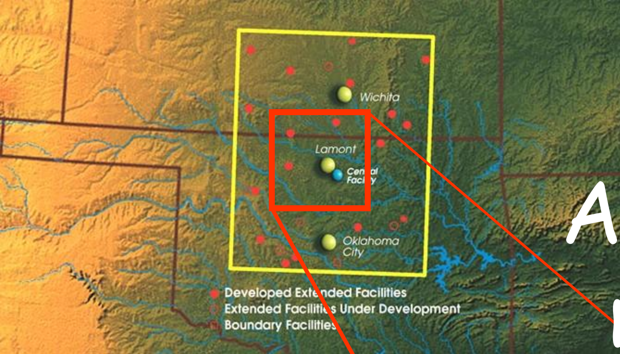
Greenwald et al, 2004

Sensitivity by optical properties and hydrometeor type



Assimilation experiments

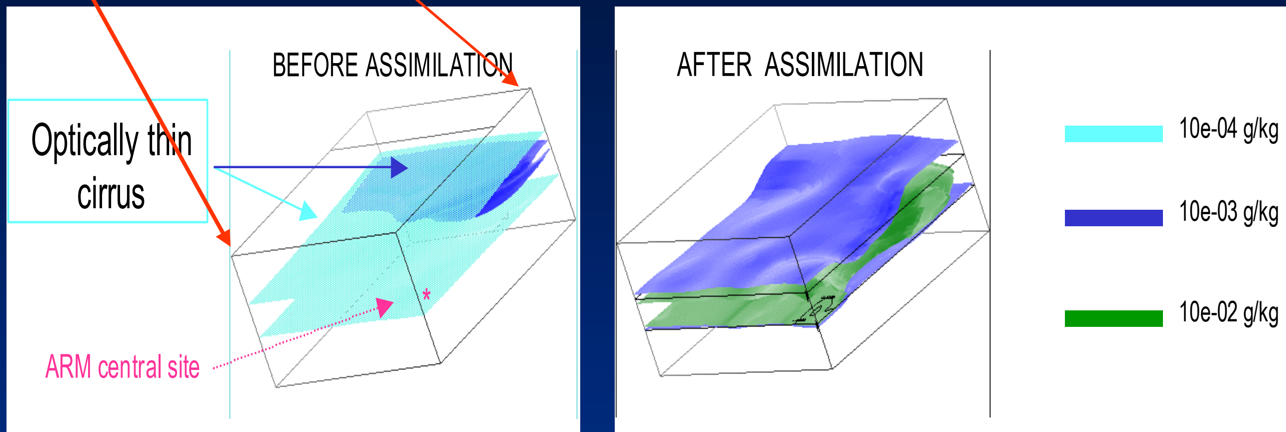
- Set 1 (Version 1 observation operator)
  - Case with 100% cloud cover in the model domain
  - Crude estimates of data assimilation parameters
  - GOES IR only
  - Sensitivity to observations
- Set 2 (SHDOMPPDA operator)
  - Estimates of background biases and error correlation length from model validation with observations
  - Use of cloud mask in quality control
  - Cases with mixed clear and cloudy scenes
  - Sensitivity to data assimilation parameters

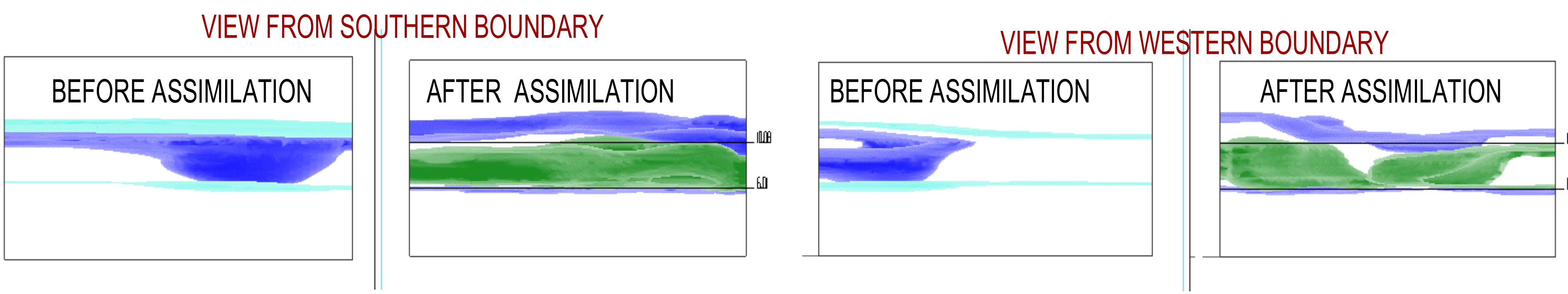


Set 1 (Vukicevic et al, 2004, 2006)

Assimilation of GOES imager IR multi-layered stratiform case

Model 3D cloud

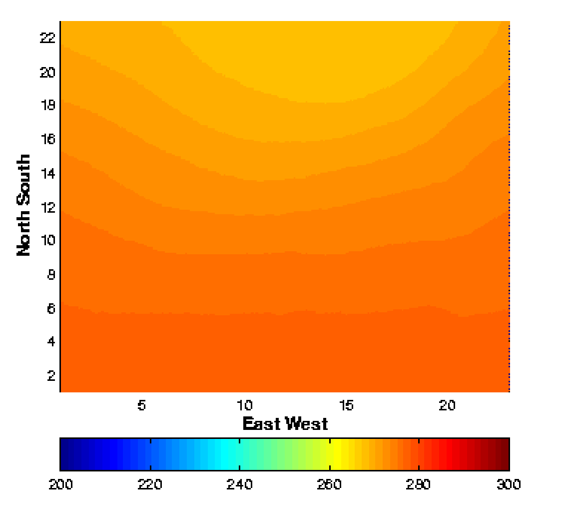




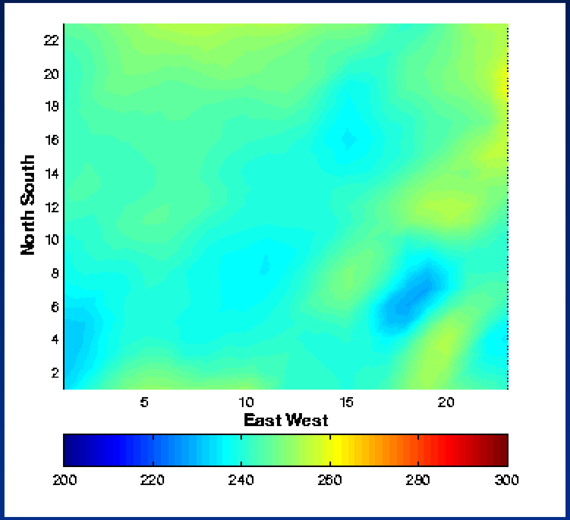
Observations every 15 min

End time shown

Large amplitude bias and poor spatial variability are corrected simultaneously

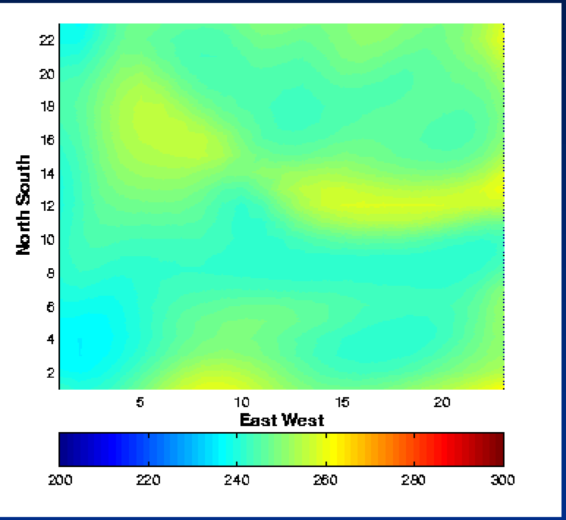


prior



Observations

1 h window, every 15 min
end time shown



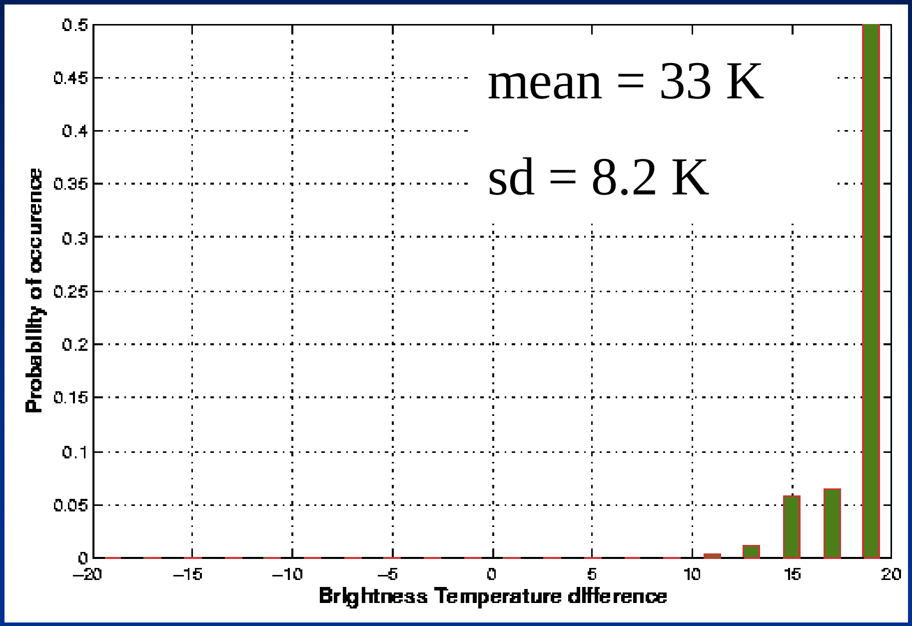
posterior

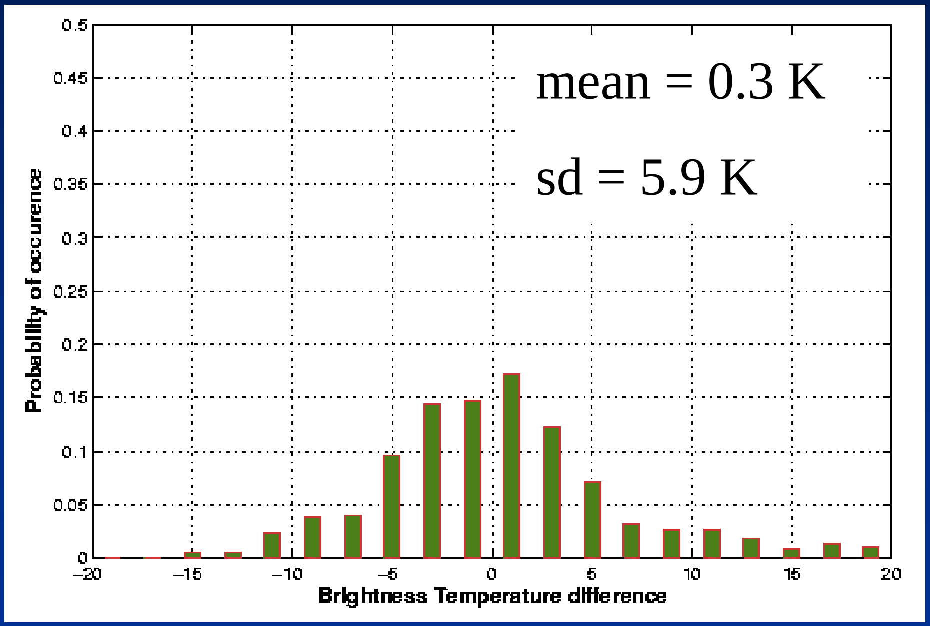
GOES imager IR error statistics (model - observation)

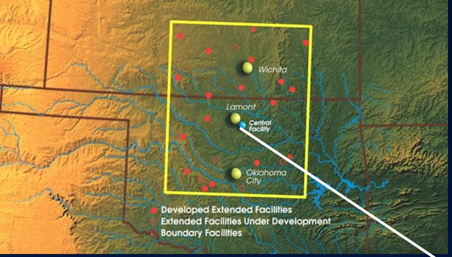
prior

Brightness Temperature

posterior

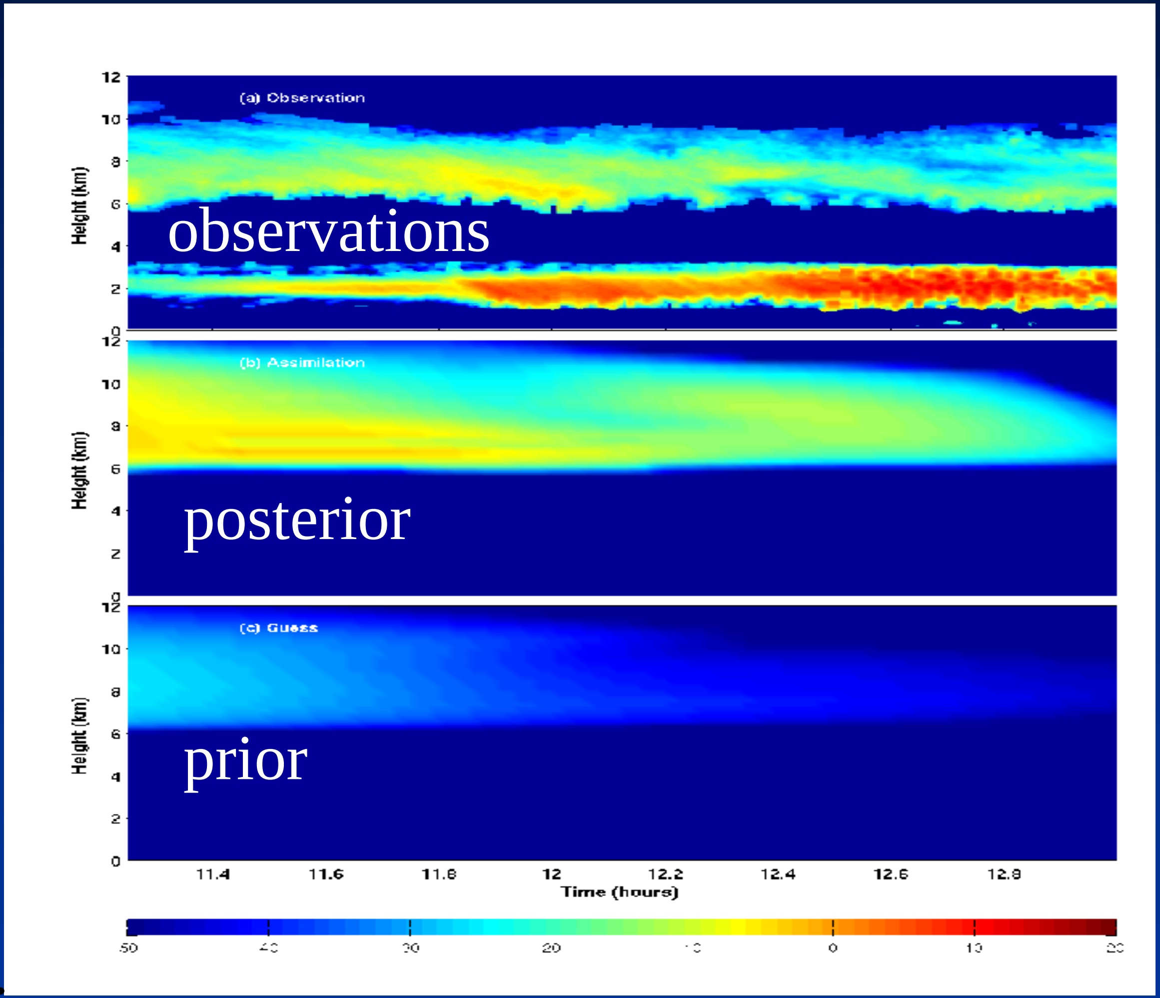






Verification with independent cloud observations

ARM Cloud Radar reflectivity



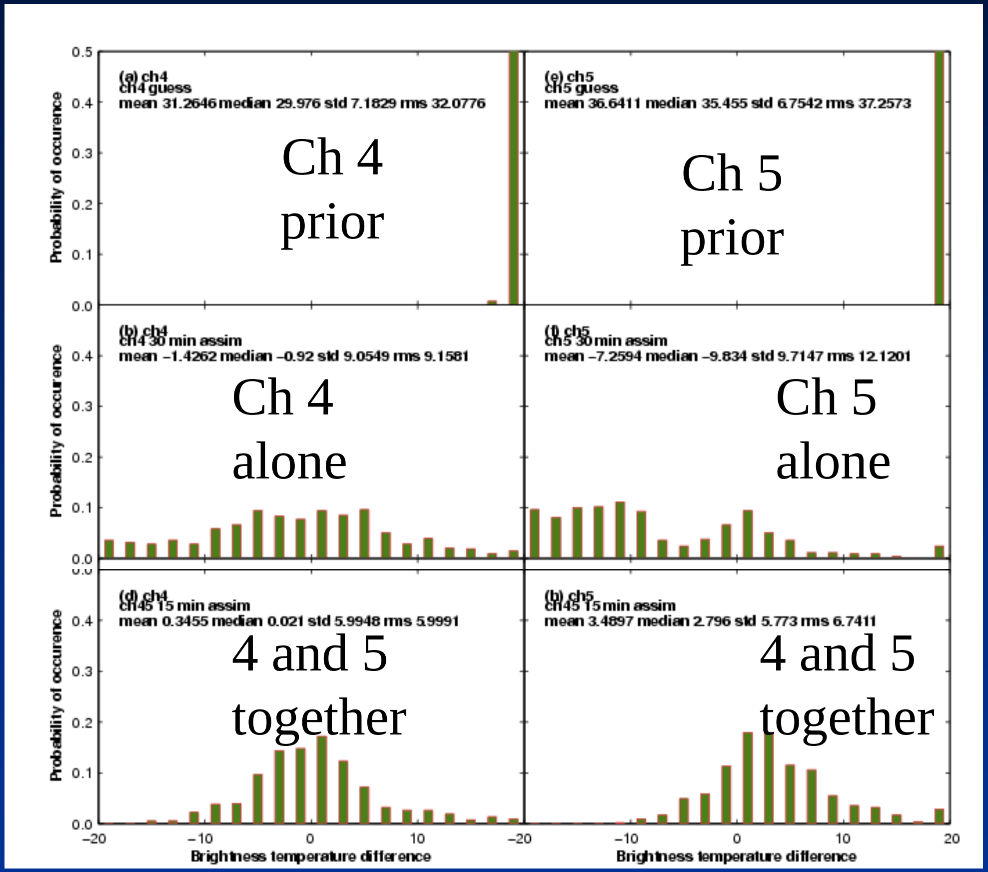
Ice cloud

Liquid cloud

Time

Complementary information from IR channels

Sensitivity of Tb in 10.7nm and 12.0 nm to clouds is very similar.



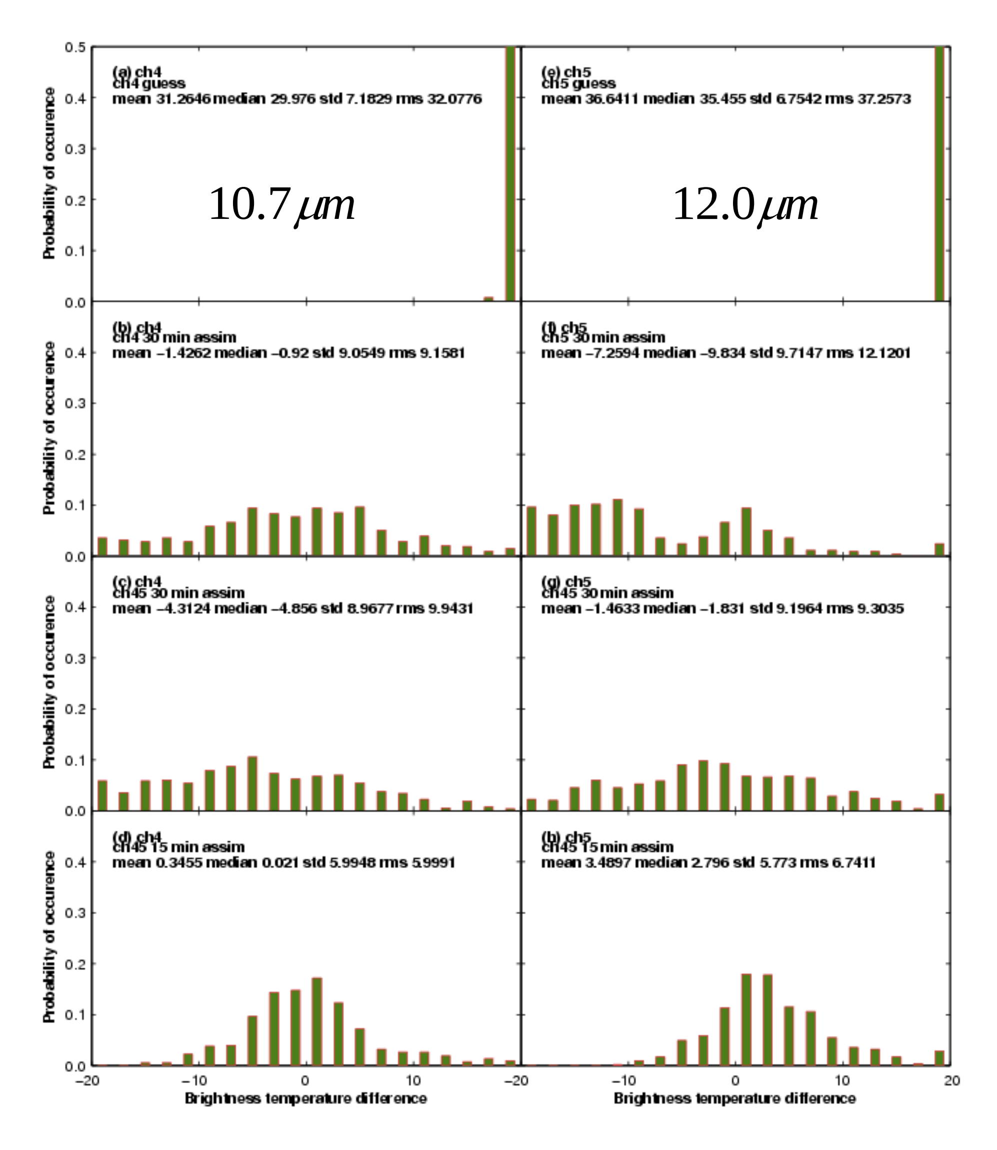
Model – Observations brightness temperature

Sensitivity to observation frequency

Tb errors

Worst

Best



Guess

Single channel assimilations, 30 min frequency

2-channel assimilation, 30 min frequency

2-channel assimilation, 15 min frequency

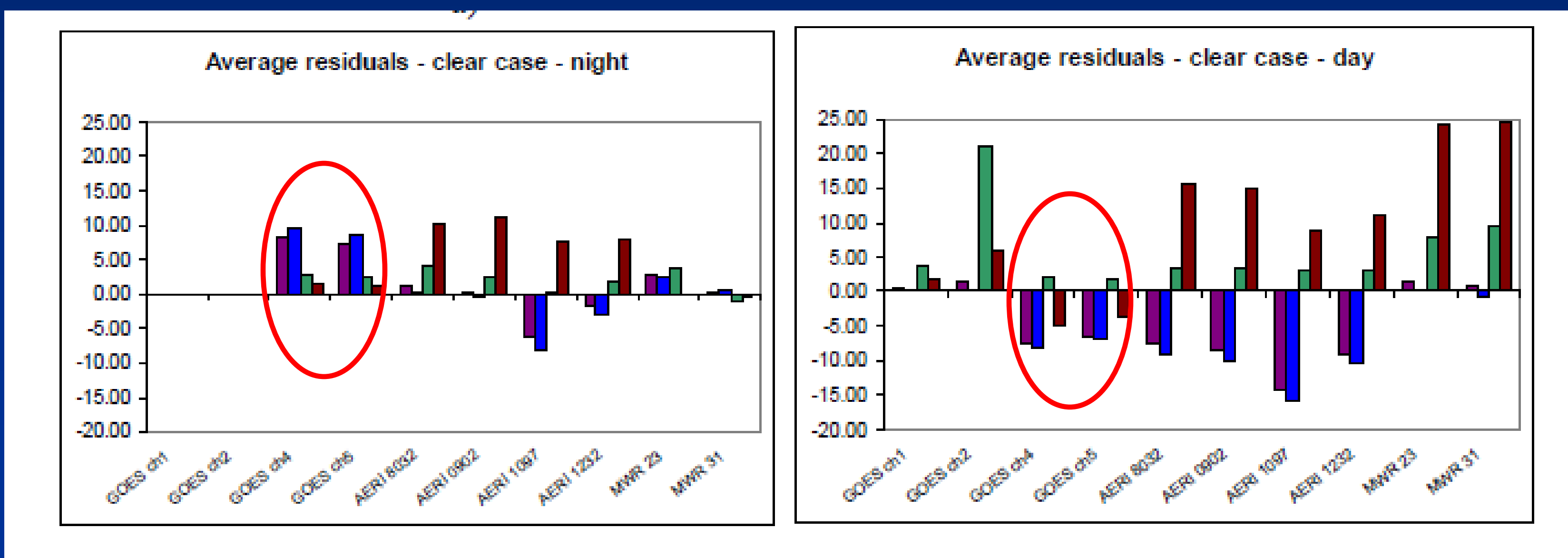
Set 2

- Estimate of background biases and error correlation length from model validation with observations
- Use of cloud mask in quality control
- Cases with mixed clear and cloudy scenes
- Assimilation of visible and ground-based ARM observations
- Sensitivity to data assimilation parameters
    - QC
    - Background error decorrelation length
    - Spatial smoothing in RAMS adjoint
    - Length of assimilation window

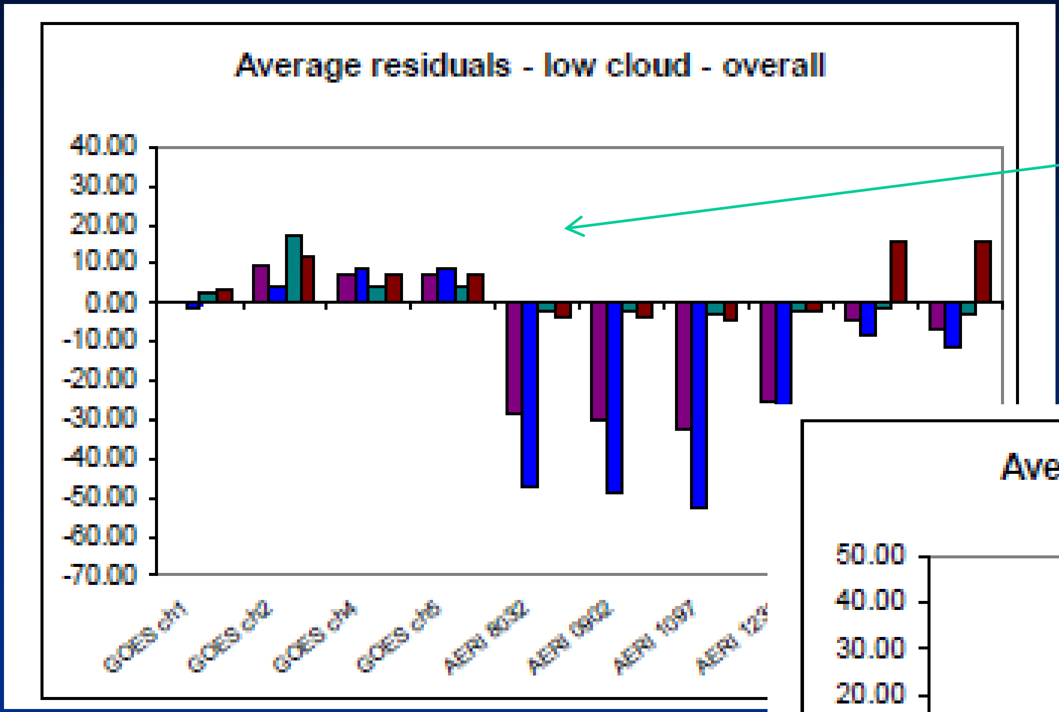
Estimates of background statistics using GOES imager and ARM data (Polkinghorne et al., 2008)

- 280 verification times
- Domain centered on ARM central facility
- grid dx=4km

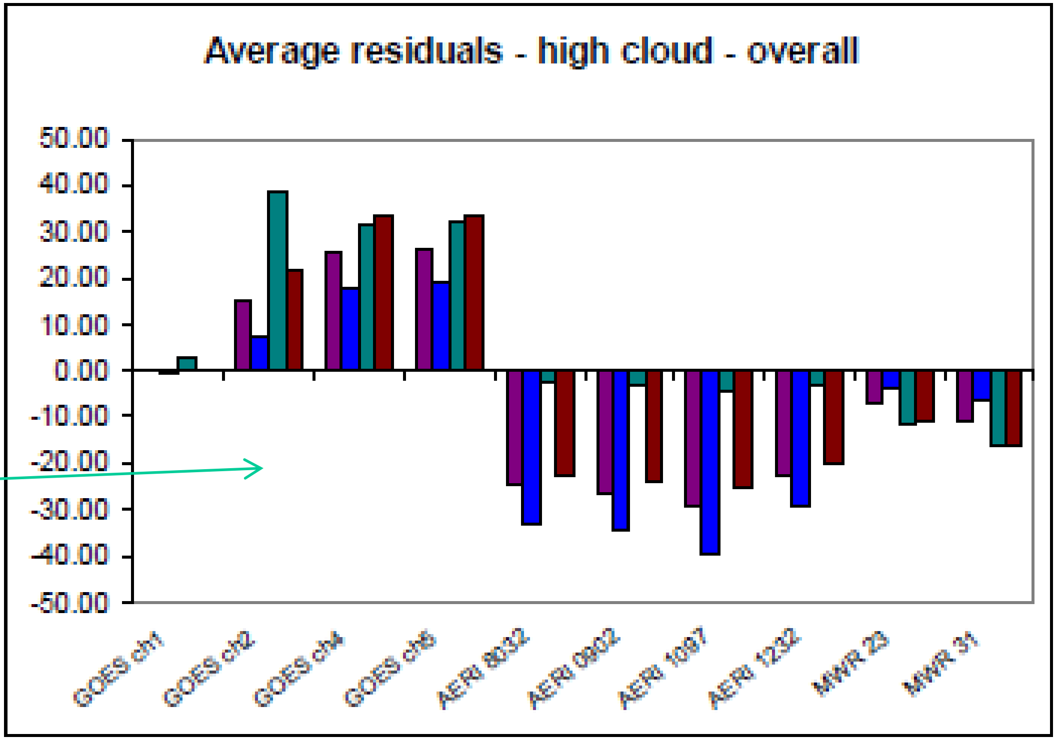
Clear sky : emphasis on surface temperature bias



Biases in cloudy conditions



Low clouds



High clouds

Large biases in cloudy condition motivate design of cloud mask for QC

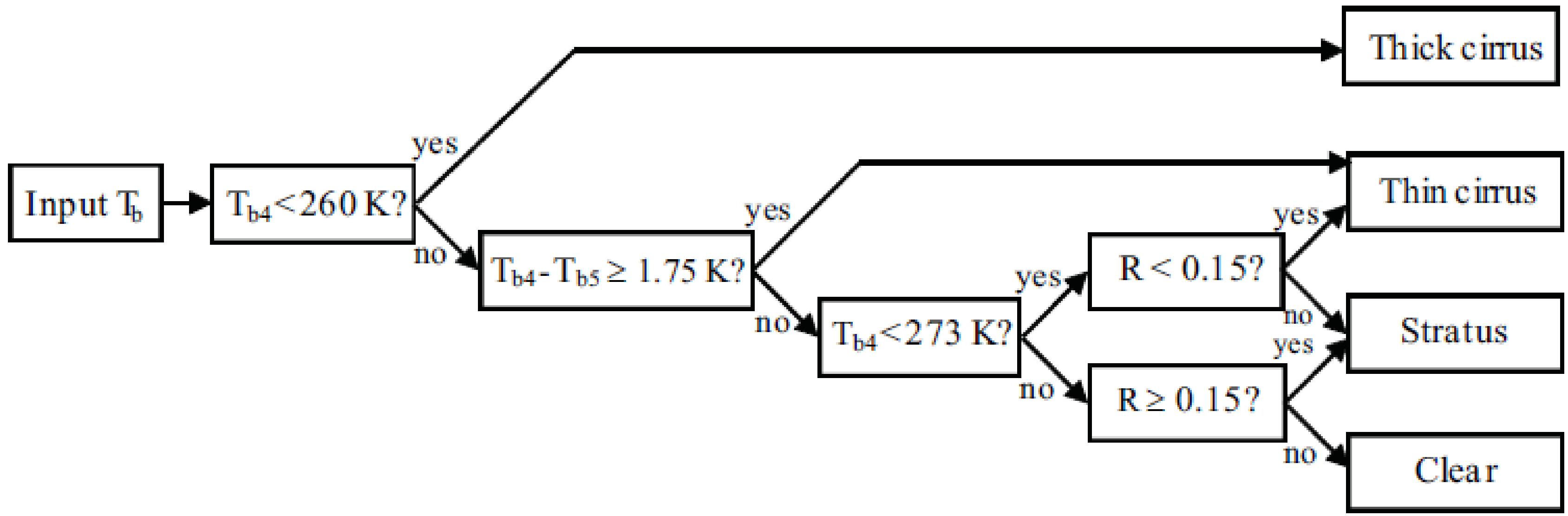
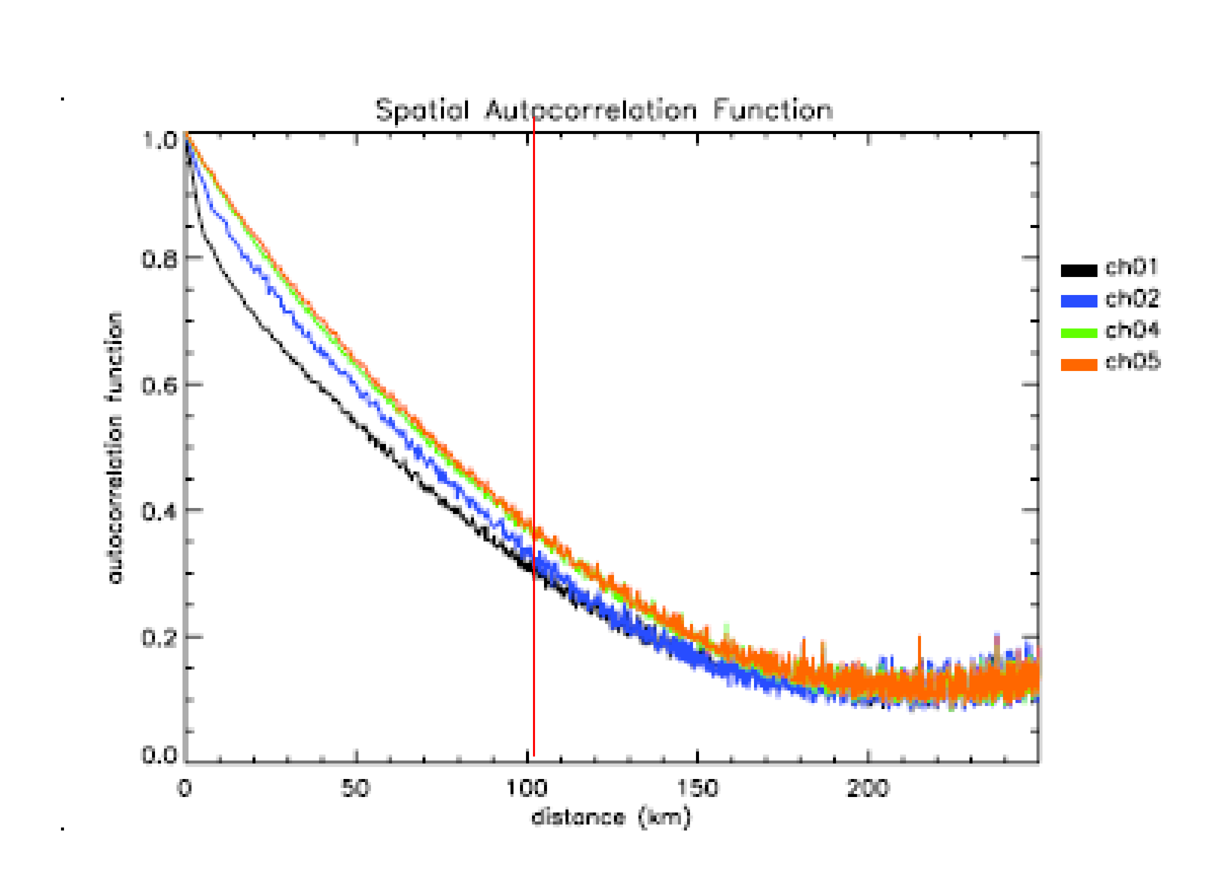


Figure 4: A flowchart representing the cloud mask algorithm. T_b is brightness temperature, T_{b4} is GOES channel 4 brightness temperature, T_{b5} is GOES channel 5 brightness temperature, R is GOES channel 1 reflectivity.

Background error correlation for cloud variables



Experiments with mixed clear and cloudy scenes

(Polkinghorne and Vukicevic, 2010)

Observed and background IR

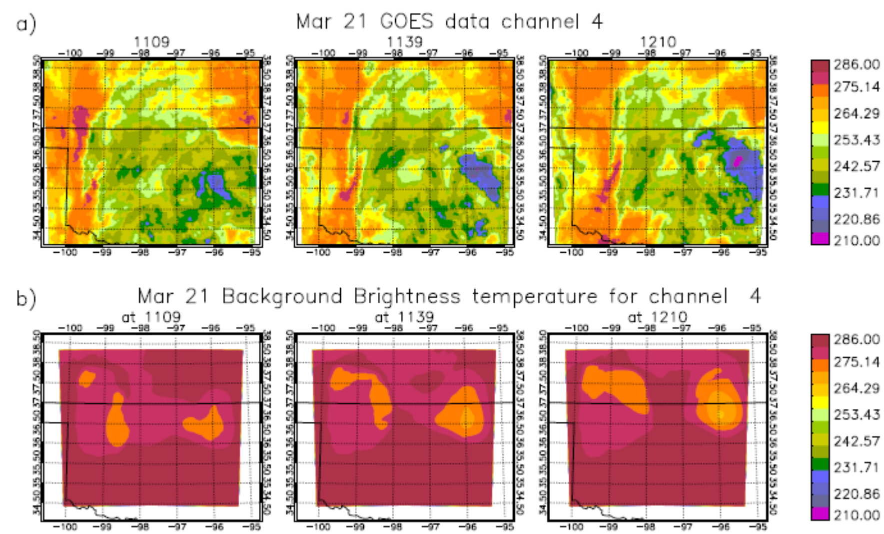


Figure 2: a) observed and b) simulated GOES channel 4 on Mar 21, 2000 at 1109, 1139, and 1210 UTC.

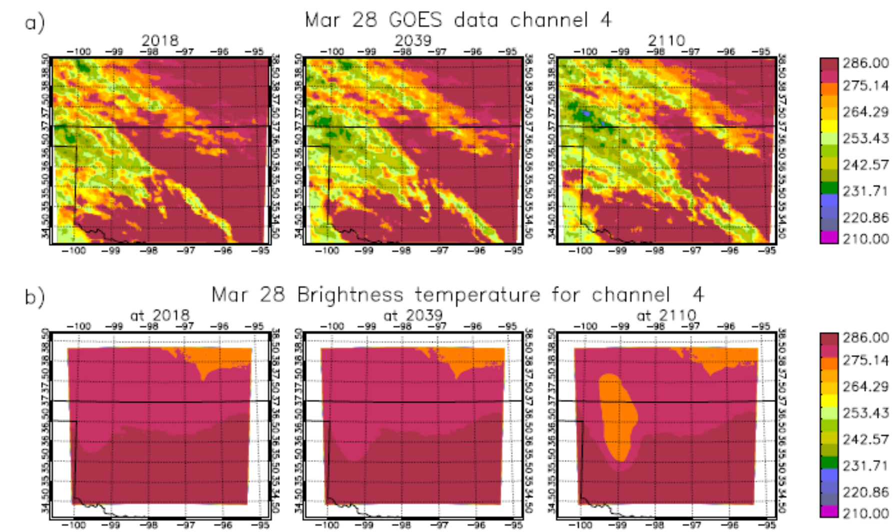


Figure 3: a) observed and b) simulated GOES channel 4 on Mar 28, 2000 at 2018, 2039, and 2110 UTC.

Sensitivity experiments to data assimilation parameters

Exp #	
Control	Simple QC mask, residuals greater than 50 K excluded
1a	Cloud mask applied, hh residuals greater than 20 K excluded
1b	Cloud mask applied, hh residuals greater than 30 K excluded
1c	Cloud mask applied, hh residuals greater than 40 K excluded
1d	Cloud mask applied, hh residuals greater than 50 K excluded
2a	Experiment 1d with smoother applied to the adjoint solution, span=1
2b	Experiment 1d with smoother applied to the adjoint solution, span=2
3	Experiment 1d with background decorrelation length=100 km
4	Experiment 1d with longer assimilation window
5a	Experiment 1d with ground-based data assimilated at satellite assimilation times
5b	Experiment 1d with ground-based data assimilated every 5 minutes
5c	Experiment 5b with the background decorrelation length=100 km
6	Experiment 3 with assimilation of GOES channels 1 and 2

QC based only on maximum residual ; simple estimate of decorrelation length; IR channels ; 1 h window

1 -QC based on cloud mask ; simple estimate of decorrelation length; IR channels ; 1 h window ; variable max residual

2 - As 1d with spatial smoothing of RAMS adjoint solution

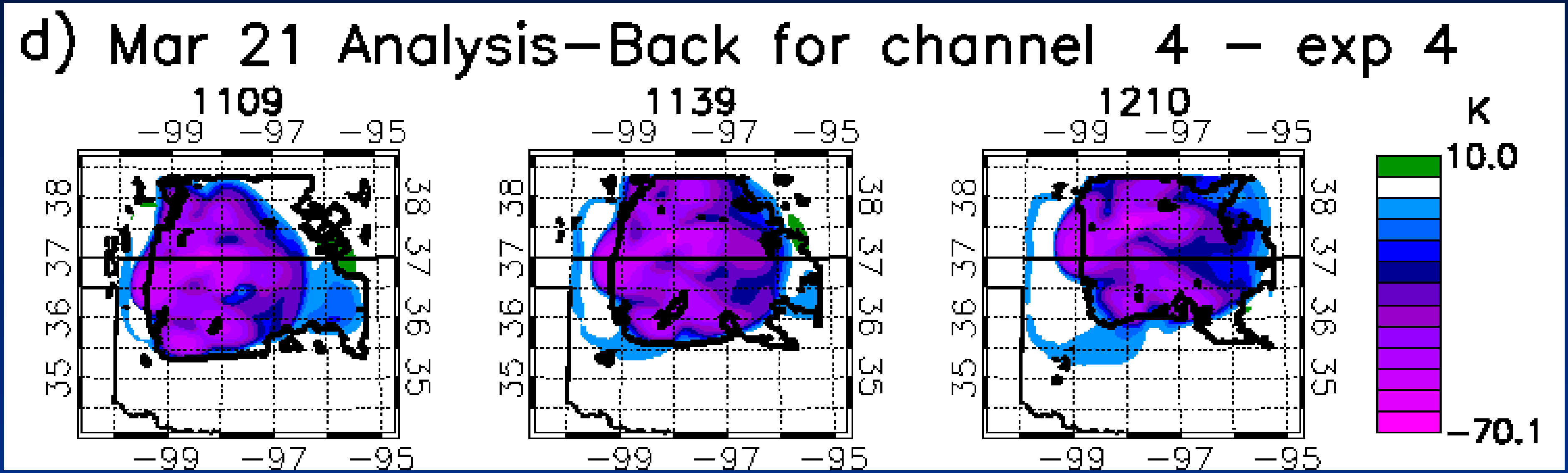
3 – As 1d with observation-based decorrelation length

4 – As 1d with 2 h window

5 – As 1d with ARM observations

6 – As 1d with ARM observations

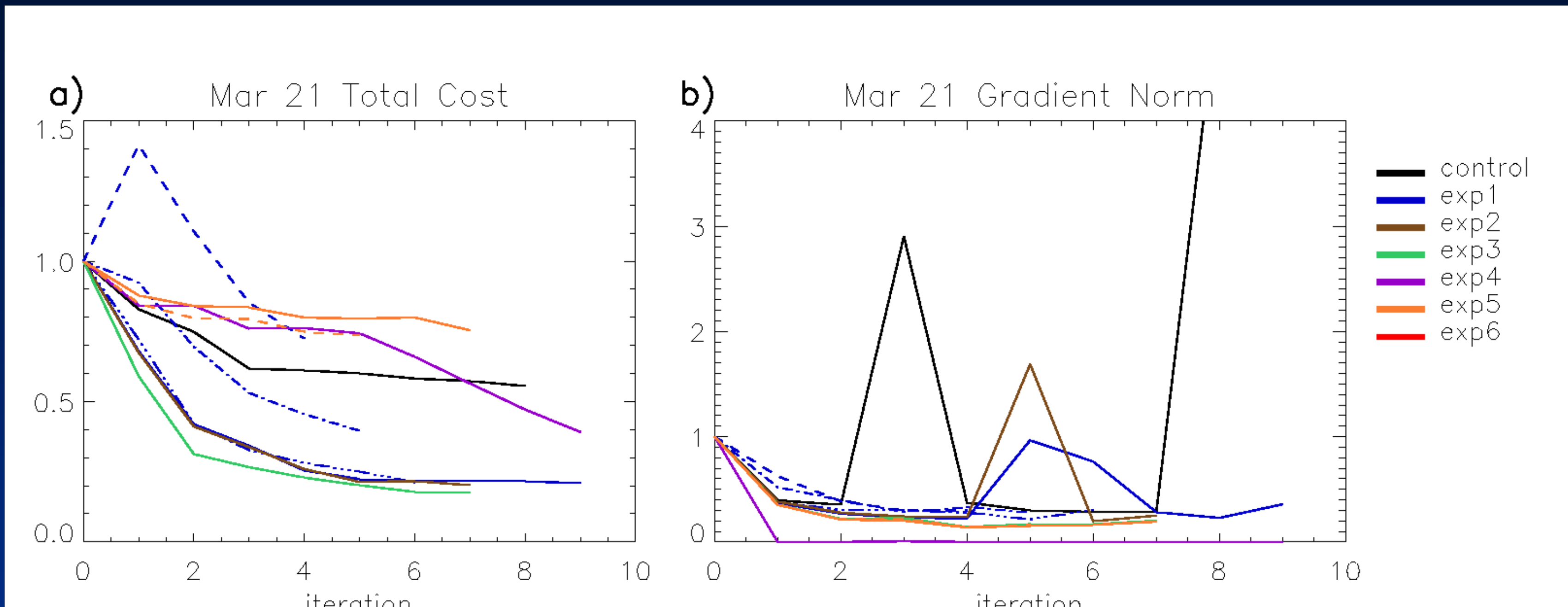
Application of cloud mask in QC

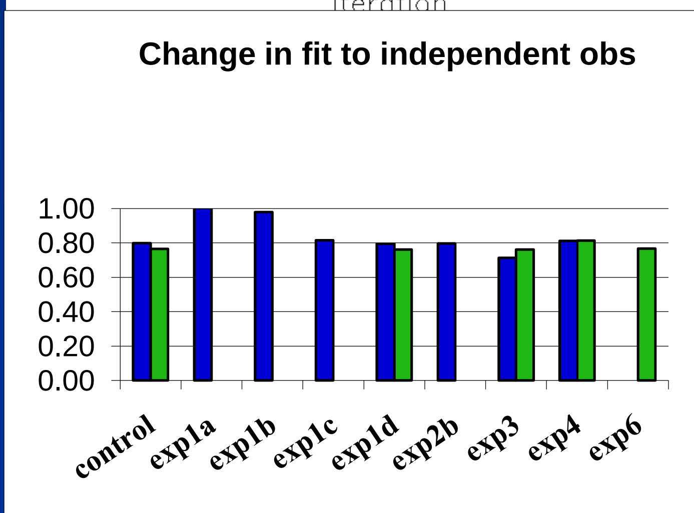


- Black contours mark boundary of regions within which the observations are used in assimilation

- Color shows impact of observations in the experiment with 2 h assimilation window

Bulk results : convergence and global fit to observations





See additional slides for description of experiments

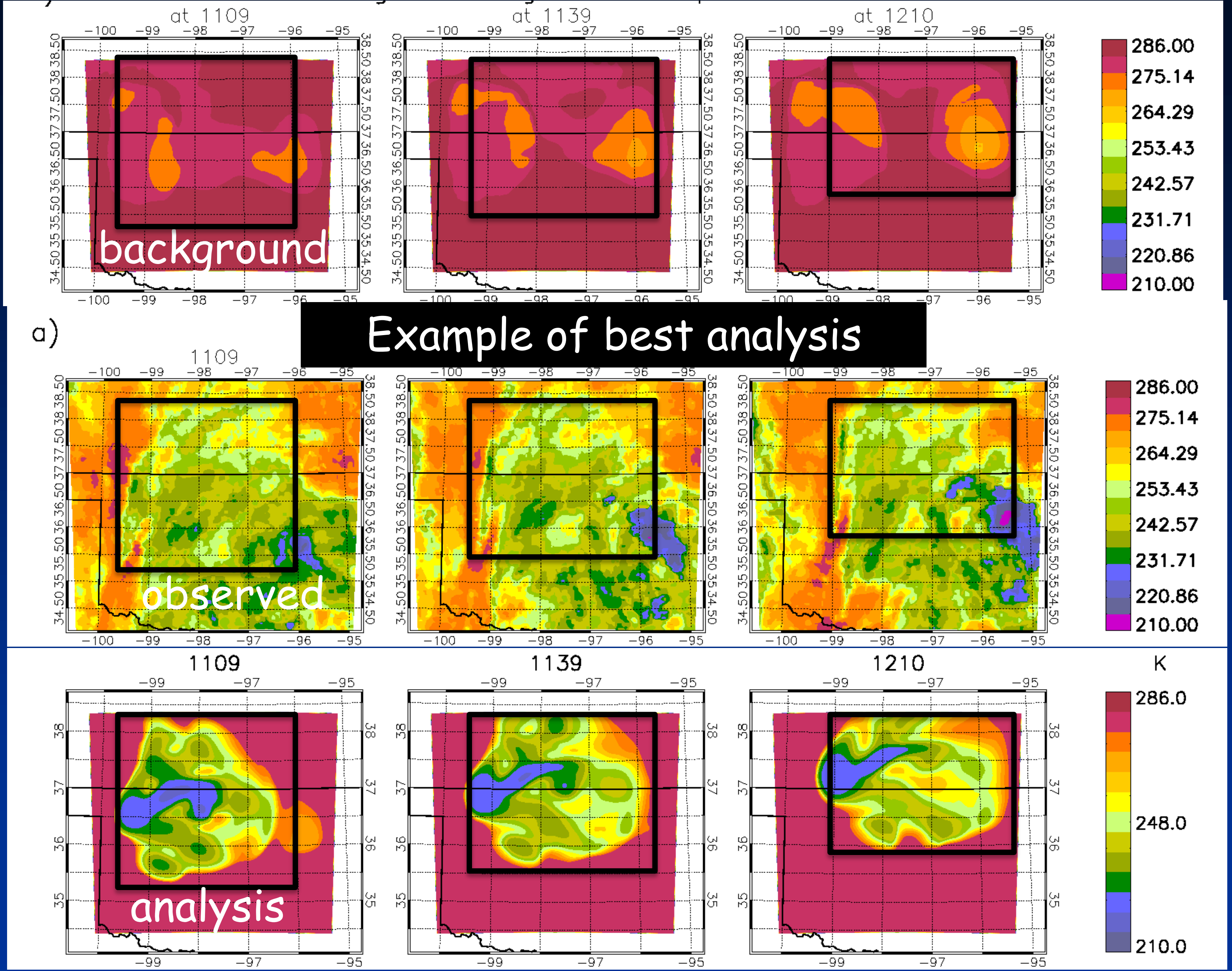
- Different convergence rate
- Similar final global fit to observations

Quality of analysis

- Despite small differences in the global fit to observations there are significant differences in quality of analysis between different experiments

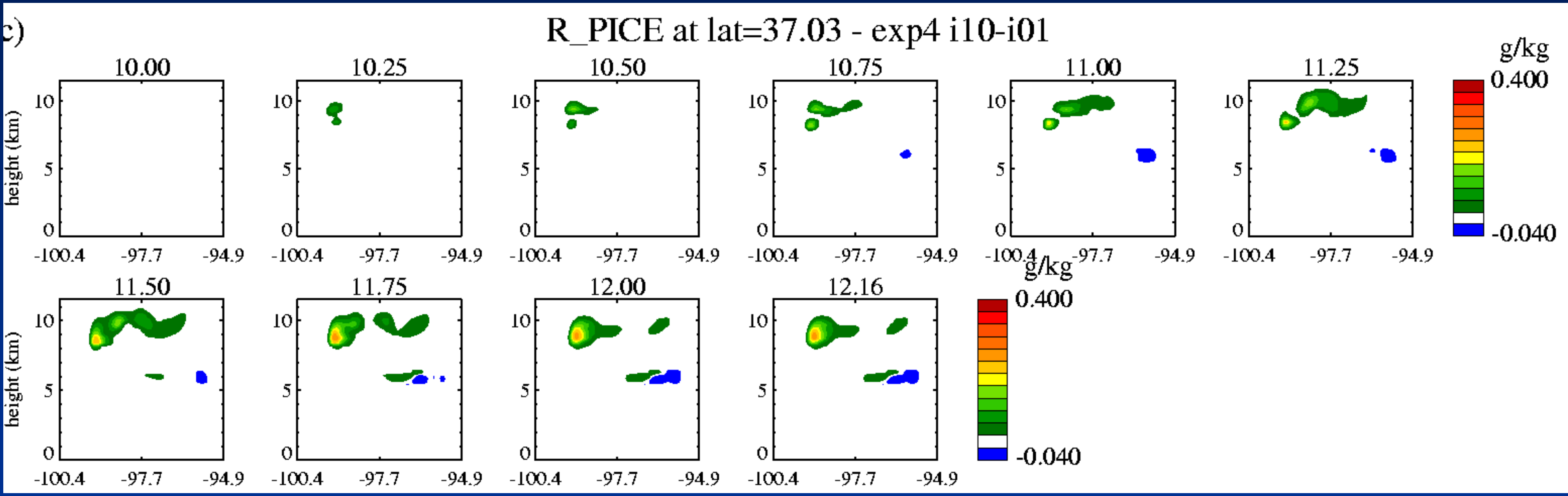
- Best analysis is produced in the experiments that include the cloud mask in QC together with large allowed maximum residual, observation based decorrelation length and longer assimilation window
- Small but positive impact of VIS and ground-based remote sensing observations

Example of best analysis



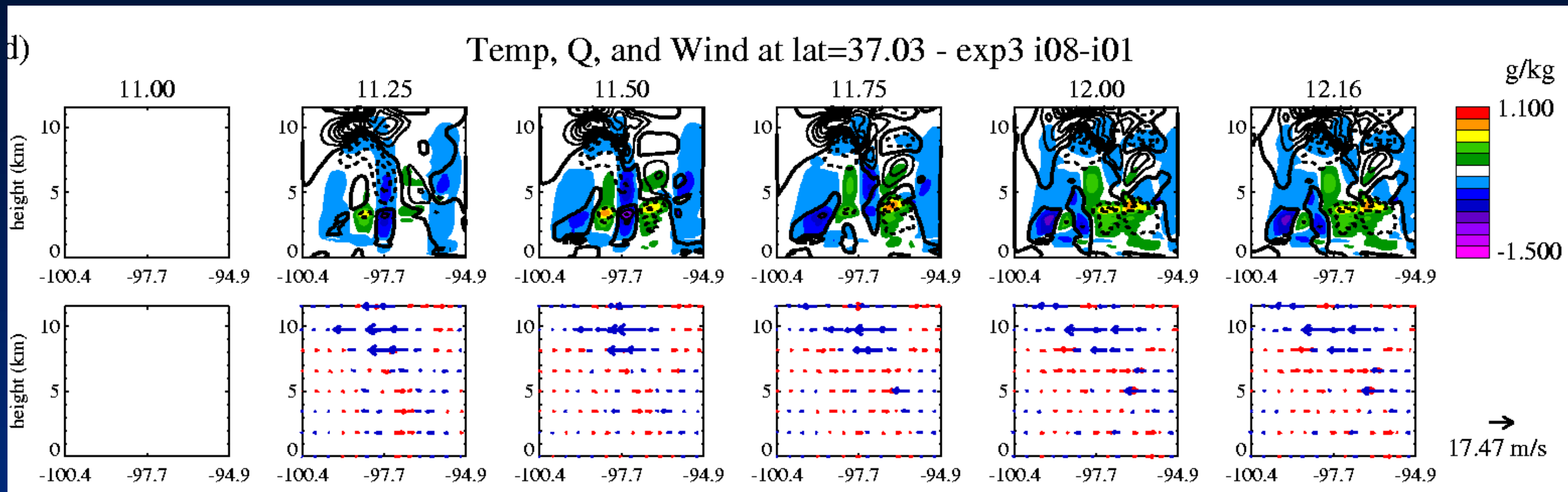
Resulting 4D cloud analysis

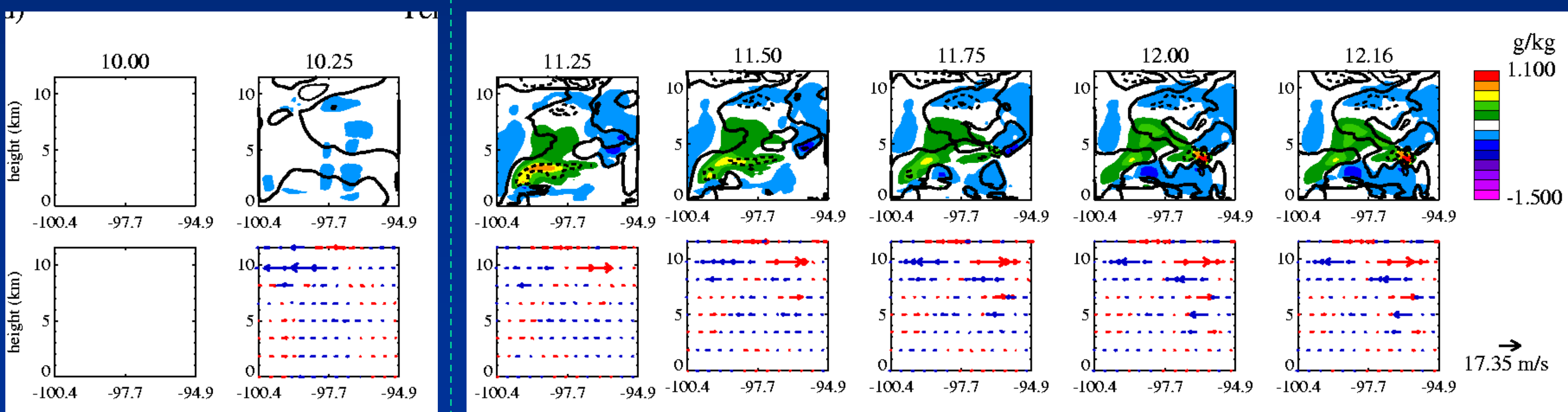
Example vertical cross-section



Impact of longer assimilation window
less noise/more balance

height





time

Summary

- 4D, dynamically consistent analysis of cloudy atmosphere by assimilation of GOES imager observations is feasible
- The assimilation benefits from the use of cloud-mask based QC with large maximum residuals
- Balanced analysis requires sufficiently long assimilation window
- More frequent observations improve the analysis
- Window IR channels have complementary information
- Assimilation of visible observations has small impact in the studied cases that are dominated by ice clouds
- Assimilation of ground based remote sensing has small but positive local impact