Assimilating Cloudy Sky Infrared Brightness Temperatures Using an Ensemble Kalman Filter

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Benefits of Cloudy Sky Infrared Brightness Temperatures

- Infrared observations are highly sensitive to clouds and moisture
    - Sensitivity to clouds is often viewed as a problem, but this is likely to change as data assimilation methodologies improve
    - Provide detailed information about the horizontal and vertical distribution of clouds and their cloud top properties
    - Provide valuable information about the water vapor content in different layers of the troposphere, both in clear sky areas and above the cloud top
- Geosynchronous infrared sensors provide observations with very high spatial (1-2 km) and temporal (1-15 minutes) resolution
    - Provide coverage in data sparse regions (such as over the oceans) and in assimilation-sparse regions (cloudy areas)

Benefits of Cloudy Sky Infrared Brightness Temperatures

- Potential to generate more accurate moisture and cloud analyses at high spatial resolution
    - More accurate precipitation forecasts for high impact weather events, such as thunderstorms, flooding, and blizzards
- More accurate cloud cover forecasts beneficial for solar energy producers by leading to more accurate energy forecasts
- Infrared satellite observations complement radar observations
    - Radar observations provide detailed information about the inner portion of a cloud where cloud particles are larger
    - Satellite observations provide information about optically thin clouds and also near the cloud top where radar observations tend to be less sensitive

Cloudy Sky Assimilation Challenges

- High likelihood of non-Gaussian error statistics
- Errors in the forward radiative transfer models
  - Ice cloud properties are especially challenging
  - Much more accurate than they were 5-10 years ago
- Errors in the forecast model representation of clouds
  - Difficult to assimilate cloudy observations if the forecast model does not first produce realistic cloud properties
  - Different cloud microphysics schemes can produce vastly different cloud fields
- Which model variables should be included in the state vector?
  - Should all cloud variables (mixing ratio, number concentration, etc.) for all cloud species (ice, snow, etc.) be included?

Cloudy Sky Assimilation Challenges

- Representativeness errors
  - Cloudy observations can change rapidly over short distances
  - May need to use different localization radii or observation errors that are a function of cloud type or cloud height
- Vertical spreading of information
  - Satellite observations are sensitive to broad layers
  - Vertical localization is difficult due to changes in the weighting function profile describing where a band is most sensitive
  - Weighting function profile will change depending upon if the grid point is clear or cloudy
- Verification methods
  - Cloud observations are not highly sensitive to atmospheric fields typically used for verification (temperature, heights, etc.)

Data Assimilation System

- Infrared brightness temperature assimilation examined using a regional-scale Observing System Simulation Experiment approach
    - Relative impact of clear and cloudy sky observations
    - Horizontal covariance localization radius employed during the assimilation step
    - Impact of water vapor sensitive infrared bands on precipitation forecasts during a high impact weather event
    - Simultaneous assimilation of radar and satellite observations
- Assimilation experiments were performed using the WRF model and the EnKF algorithm in the DART data assimilation system
- Successive Order of Interaction (SOI) forward radiative transfer model was implemented within the DART framework
- All of the studies assimilated simulated observations from the GOES-R Advanced Baseline Imager sensor to be launched in 2015

Clear vs Cloudy Observation Impact -- OSSE Configuration

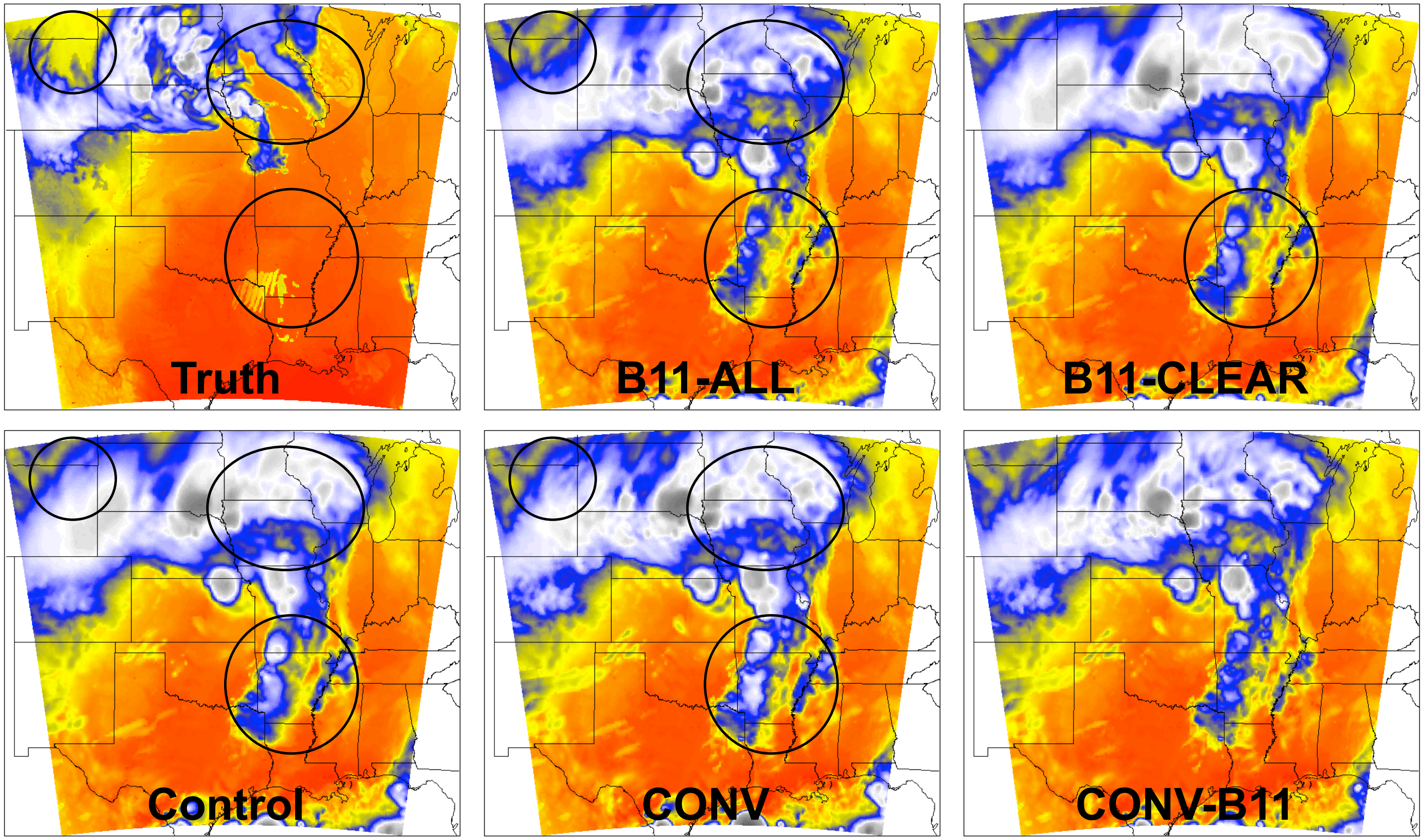
Observations assimilated during each experiment:

- B11-ALL – both clear and cloudy sky ABI 8.5 μm (band 11) T_b
- B11-CLEAR – clear-sky only ABI 8.5 μm T_b
- CONV – conventional observations only
- CONV-B11 – both conventional observations and ABI 8.5 μm T_b
- Control – no observations assimilated

- Assimilation experiments were performed using a 40-member ensemble with 12-km horizontal resolution and 37 vertical levels
- Observations were assimilated once per hour during a 12-hr period

- Otkin, J. A., 2010: Clear and cloudy-sky infrared brightness temperature assimilation using an ensemble Kalman filter. *J. Geophys Res.,* **115, D19207**, *doi:10.1029/2009JD013759.*

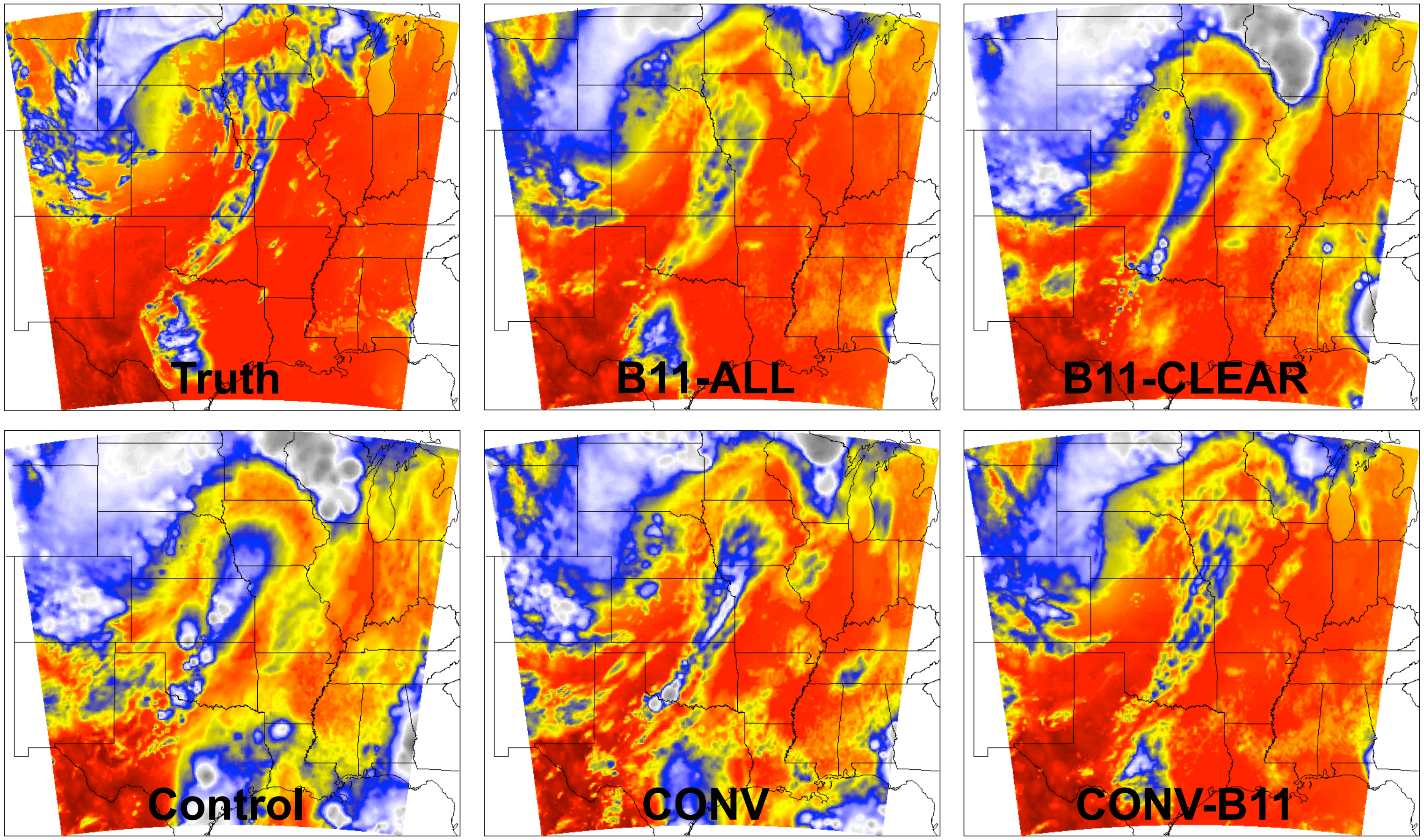
Ensemble-Mean ABI 11.2 μm Brightness Temperatures



Images valid after first data assim-ilation cycle at 12 UTC

• Compared to the conventional-only case, the assimilation of 8.5 μm brightness temperatures had a larger and more immediate impact on the erroneous cloud cover across the southern portion of the domain and also improved the structure of the cloud shield further north

Ensemble-Mean ABI 11.2 μm Brightness Temperatures



Images valid after final data assim-ilation cycle at 00 UTC

- By the end of the assimilation period, the most accurate analysis is achieved when both conventional and 8.5 μm T_b are assimilated
- Comparison of the CONV and B11-ALL images shows that the 8.5 μm Tb have a larger impact than the conventional observations

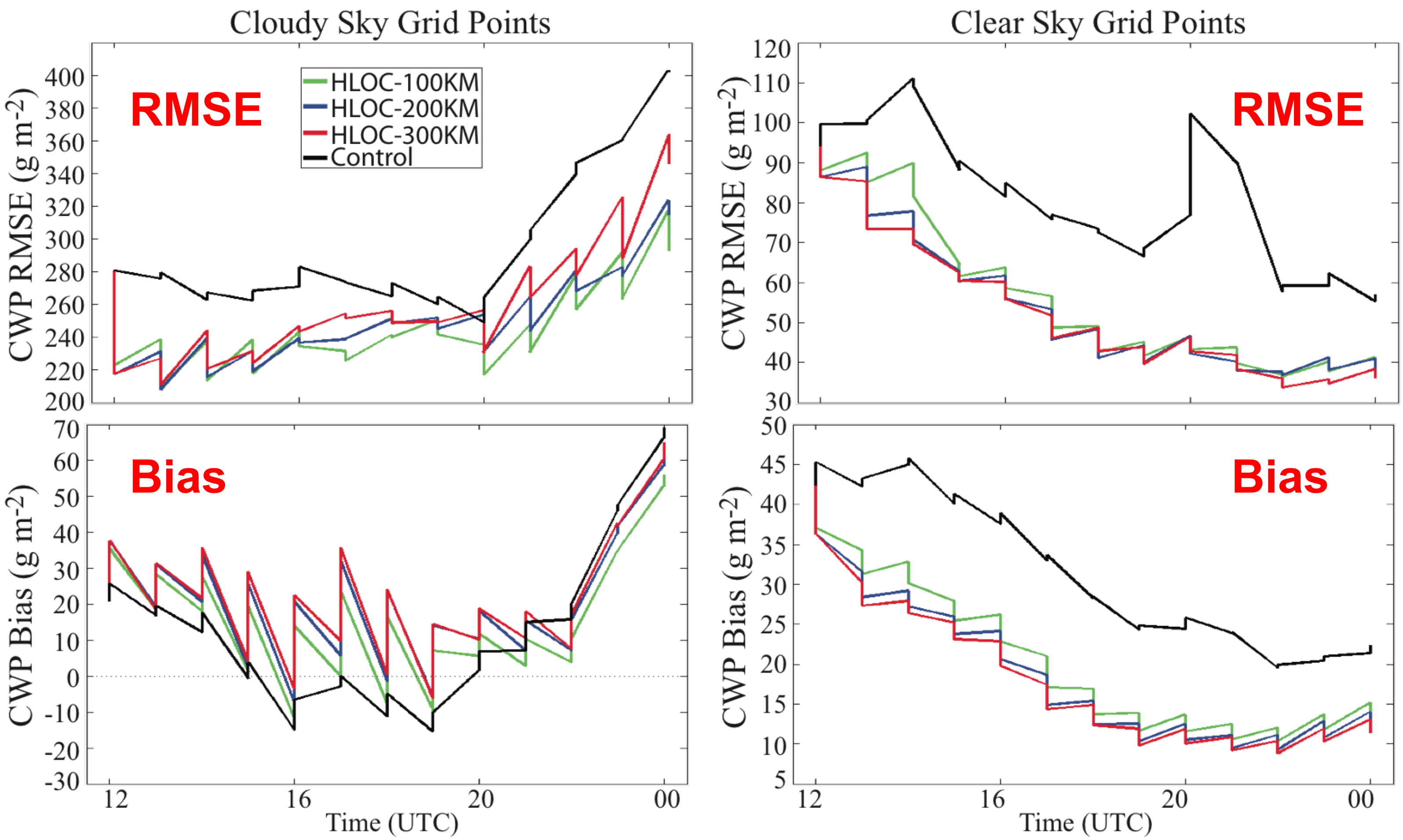
Horizontal Localization Radius Tests -- OSSE Configuration

Four assimilation experiments were performed:

- Control – conventional observations only
- HLOC-100KM – conventional + ABI 8.5 μm T_b (100 km loc. radius)
- HLOC-200KM – conventional + ABI 8.5 μm T_b (200 km loc. radius)
- HLOC-300KM – conventional + ABI 8.5 μm T_b (300 km loc. radius)

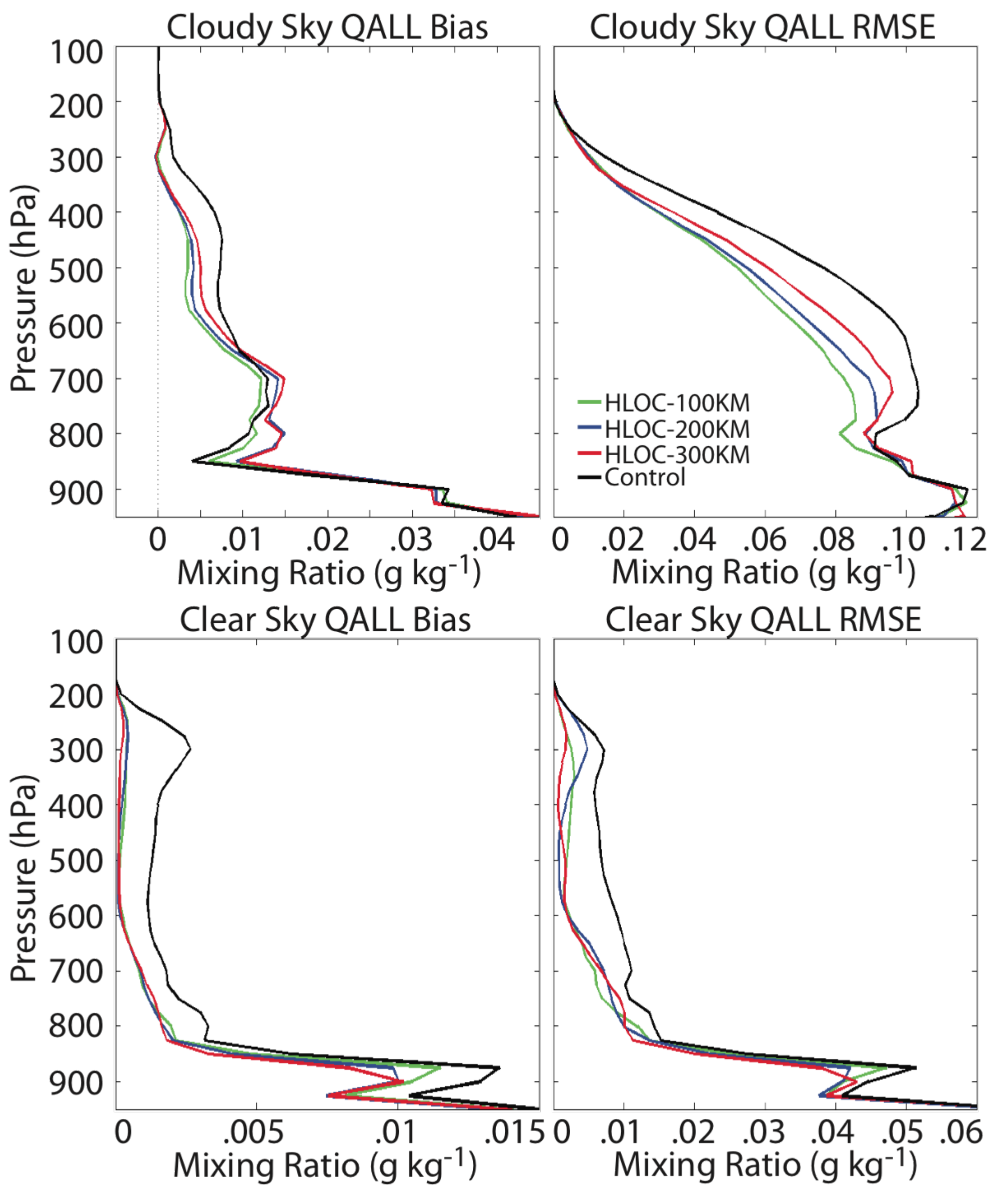
- Assimilation experiments were performed using an 80-member ensemble with 18-km horizontal resolution and 37 vertical levels
- Observations were assimilated once per hour during 12-hr period
- Both clear and cloudy sky ABI 8.5 μm brightness temperatures were assimilated
- Otkin, J. A., 2012: Assessing the impact of the covariance localization radius when assimilating infrared brightness temperature observations using an ensemble Kalman filter. *Mon. Wea. Rev.*, **140**, 543-561.

Cloud Water Path Error Time Series



- Different performance for the clear and cloudy grid points
- Larger localization radius generally better for clear grid points but worsens the analysis in cloudy regions

Cloud Errors After Last Assimilation Cycle



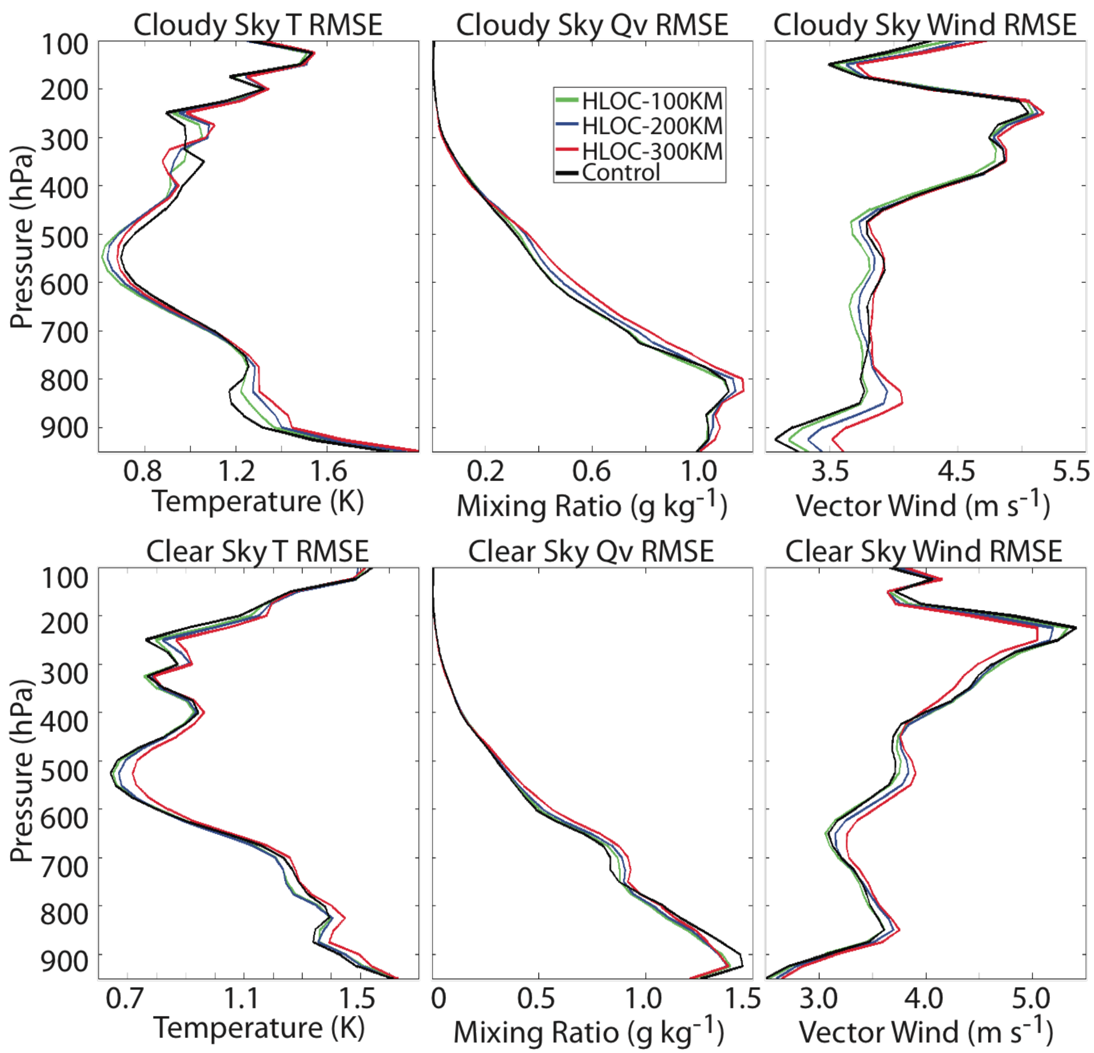
- Total cloud condensate (QALL) errors over the entire model domain after the last assimilation cycle

- Similar errors occurred for the clear sky grid points

- Errors consistently decreased with decreasing localization radius for the cloudy grid points

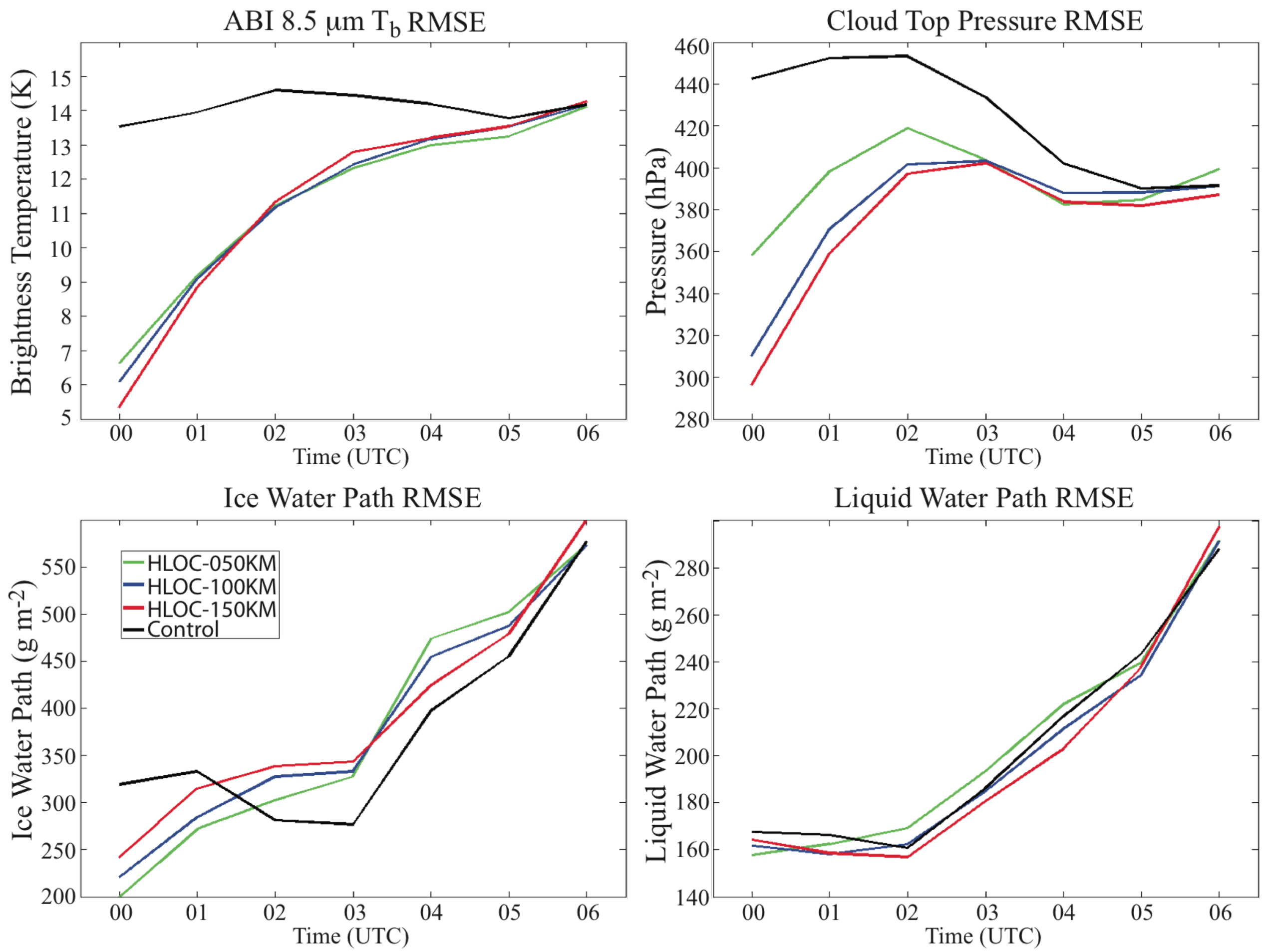
- Suggests different loc. radii should be used for clear and cloudy observations

Thermodynamic Errors After Last Assimilation Cycle



- Thermodynamic and moisture errors after the last assimilation cycle
- Greater degradation tended to occur when a larger radius was used
- These results show that a smaller radius is necessary to maintain accuracy relative to Control case

Short-Range Forecast Impact



- Overall, the initially large positive impact of the infrared observations decreases rapidly with time

- Results show that without improvements in the thermodynamic and moisture fields, it is difficult to preserve initial improvements in the cloud field

Impact of ABI Water Vapor Bands

• A regional-scale OSSE was used to evaluate the impact of the water vapor sensitive ABI bands on the analysis and forecast accuracy during a high impact weather event

• Five assimilation experiments were performed:

- Control – conventional observations only
- Band-08 -- conventional + ABI 6.19 μm T_b (upper-level WV)
- Band-09 -- conventional + ABI 6.95 μm T_b (mid-level WV)
- Band-10 -- conventional + ABI 7.34 μm T_b (lower-level WV)
- Band-11 -- conventional + ABI 8.5 μm T_b (window)

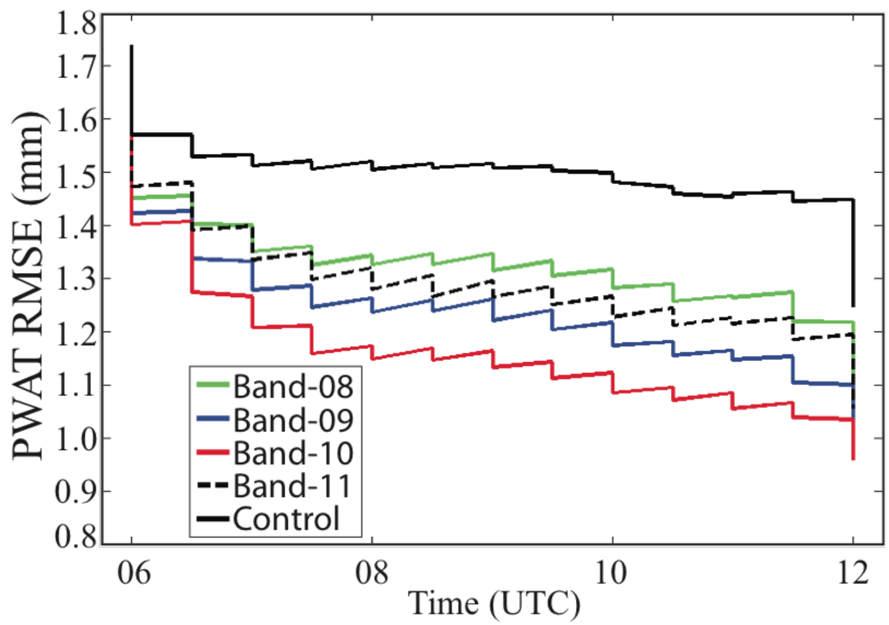
• Assimilation experiments were performed using a 60-member ensemble containing 15-km horizontal resolution and 37 vertical levels

• Observations were assimilated every 30 minutes during a 6-hr period

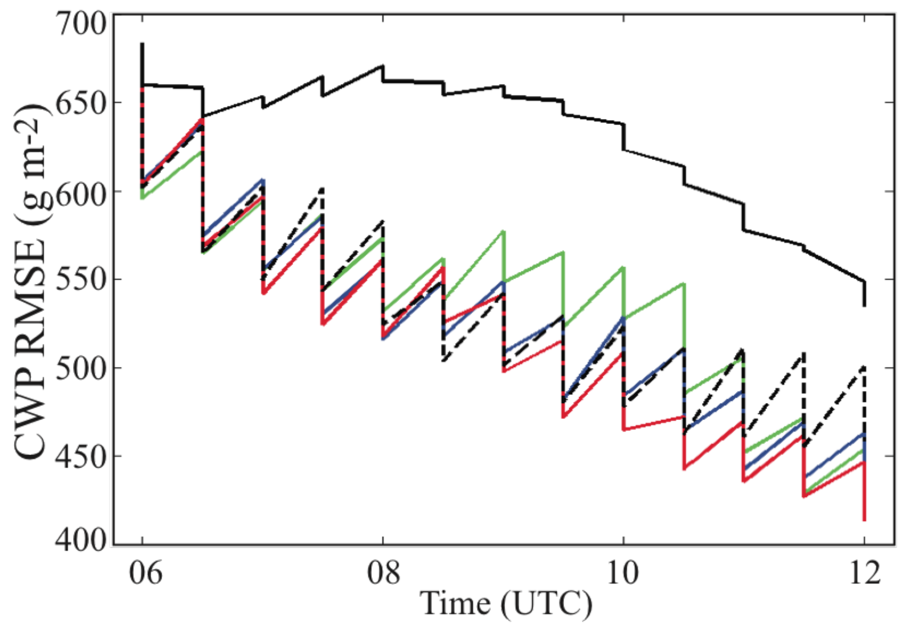
• Otkin, J. A., 2012: Assimilation of water vapor sensitive infrared brightness temperature observations during a high impact weather event. *J. Geophys. Res.*, **117, D19203**, doi:10.1029/2012JD017568.

Impact of ABI Water Vapor Bands

PWAT Analysis Errors

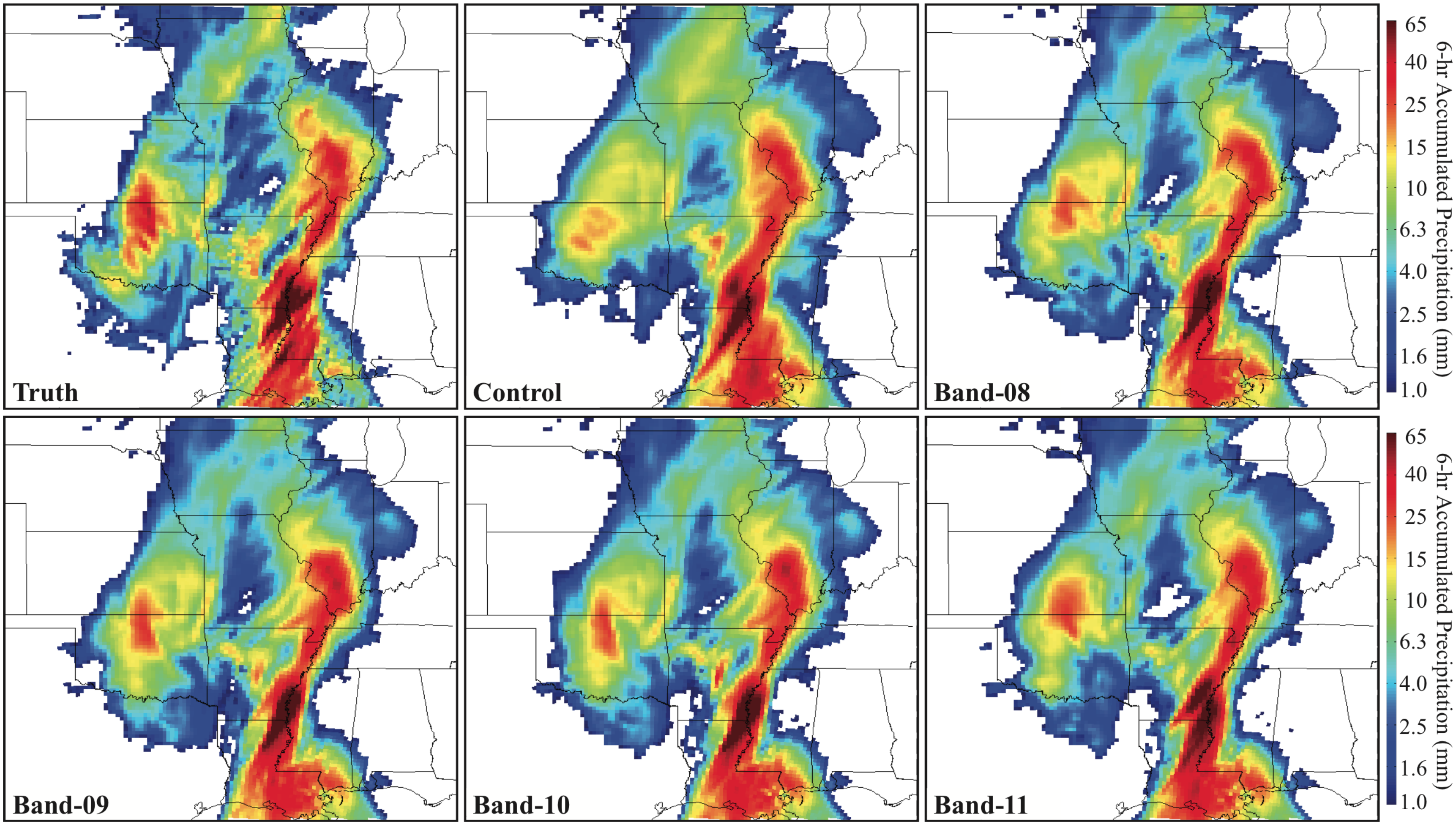


Cloud Analysis Errors



- Large improvements made to the water vapor and cloud analyses after each assimilation cycle regardless of which band was assimilated
- Smallest errors occurred when brightness temperatures from lower-peaking channels were assimilated
- Each of the water vapor band assimilation cases have smaller cloud errors than the Control and window band 11 cases

6-hr Accumulated Precipitation Forecasts



• Precipitation forecasts were more accurate during the brightness temperature assimilation cases.

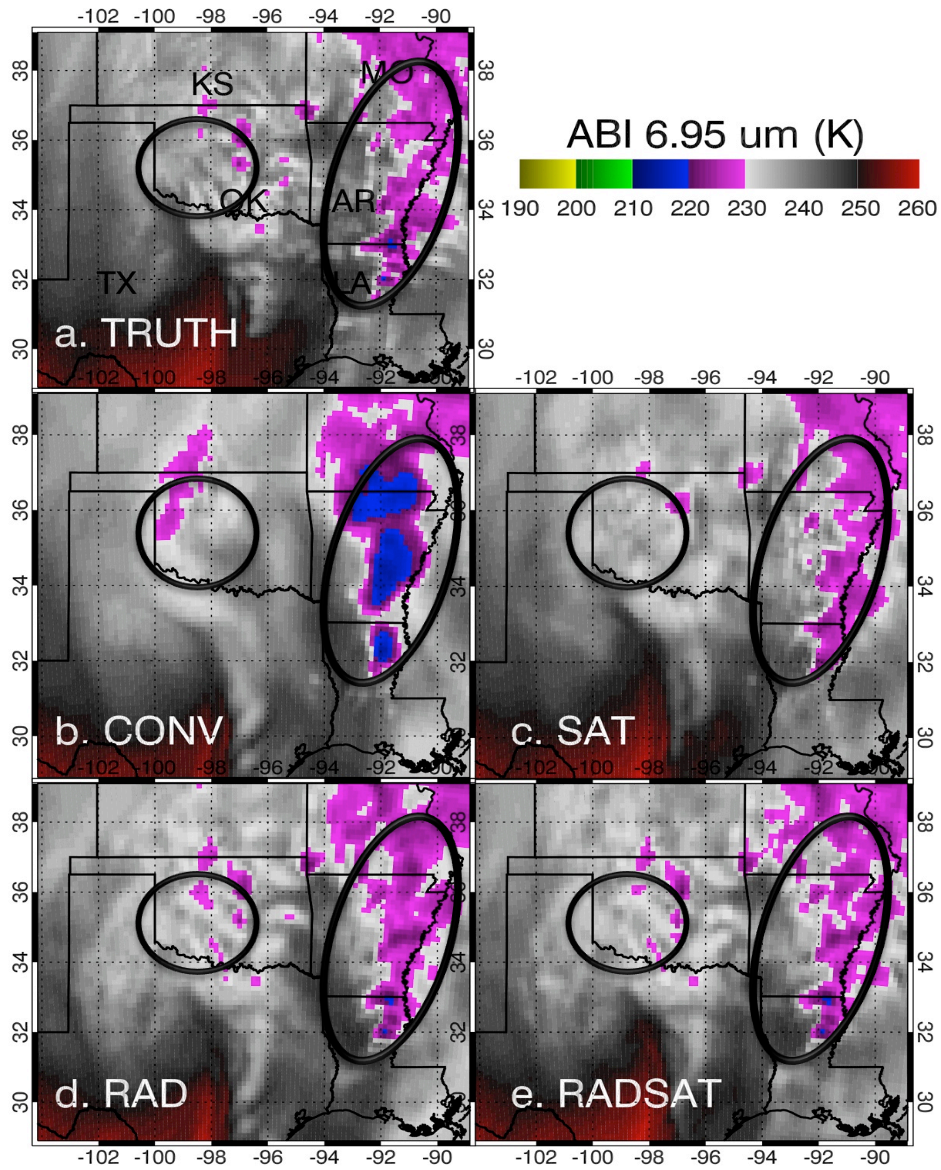
Simultaneous Assimilation of Radar and Satellite Data

- A regional-scale OSSE was used to evaluate how the simultaneous assimilation of radar and satellite observations impacts the analysis and forecast accuracy during a high impact weather event

- Four assimilation experiments were performed:
    - CONV – conventional observations only
    - SAT -- conventional + ABI 6.95 μm T_b (band 9)
    - RAD -- conventional + radar reflectivity and radial velocity
    - RADSAT -- conventional + satellite + radar

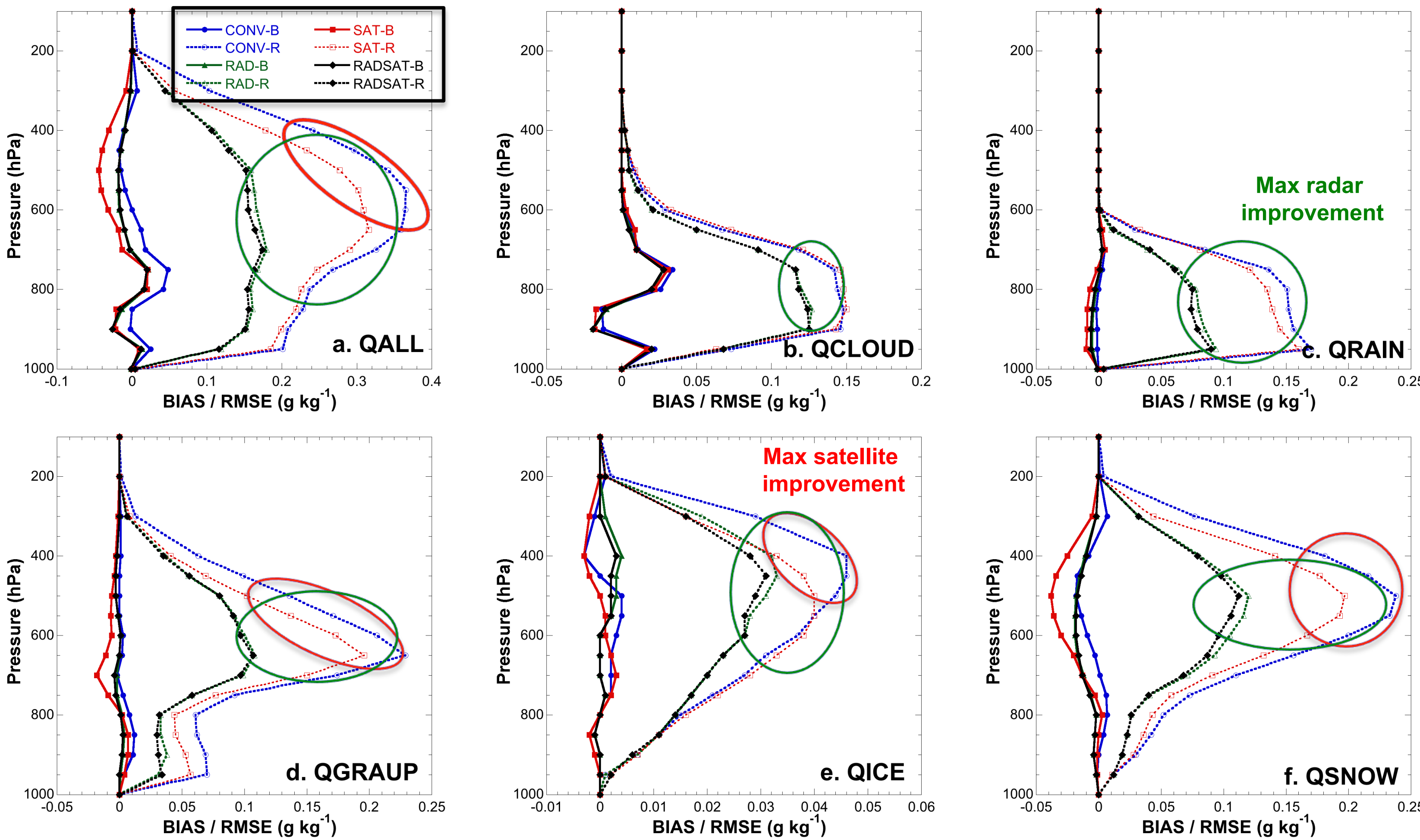
- Assimilation experiments were performed using a 48-member ensemble containing 15-km horizontal resolution and 53 vertical levels
- Observations were assimilated every 5 minutes during a 1-hr period
- Jones, T. A., J. A. Otkin, D. J. Stensrud, and K. Knopfmeier, 2013: Assimilation of simulated GOES-R satellite radiances and WSR-88D Doppler radar reflectivity and velocity using an Observing System Simulation Experiment. *Mon. Wea. Rev.,* **141**, 3273-3299.

Simulated Satellite Imagery Comparison



- Simulated 6.95 μm Tb after the last assimilation cycle at 1200 UTC
- CONV case is too cold and does not have fine scale structures
- SAT, RAD & RADSAT cases all improve analysis accuracy relative to Truth
- Satellite data reduces the cold bias, while radar data adds the finer scale structures

Vertical Error Profiles



- Assimilating radar data has large impact on all variables
- Satellite data has positive impact on mid-upper tropospheric frozen hydrometeor variables (*QGRAUP*, *QICE*, *QSNOW*)